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ABSTRACT

Many U.S. states are supporting the transition of the heavy-duty vehicle (HDV) sector to zero-emission vehicles (ZEVs), with California leading the way through its policy and regulatory initiatives. Within various HDV fleet segments, California's drayage fleets face stringent targets, requiring all vehicles newly registered in the Truck Regulation Upload, Compliance, and Reporting System to be ZEVs starting January 2024, and all drayage trucks in operation to be zero-emission by 2035. Understanding fleet operator behavior and perspectives is crucial for achieving these goals; however, it remains a critical knowledge gap. This study investigates the preferences and influencing factors for ZEVs among drayage fleet operators in California. We conducted a stated preference choice experiment survey, developed based on previous qualitative studies and literature reviews. With participation from 71 fleets of various sizes and alternative fuel adoption status, we collected 648 choice observations in a dual response design, consisting of a forced choice between ZEVs and a free choice between ZEVs and status quo alternatives. Multinomial logit model analyses revealed driving range and purchase costs as significant factors for ZEV adoption, with charging facility construction costs also critical in hypothetical choices between ZEVs and status quo alternatives. Fleet or organization size also influenced ZEV choices, with large fleets more sensitive to operating costs and small organizations more sensitive to off-site stations. These findings enhance our understanding in this area and provide valuable insights for policymakers dedicated to facilitating the transition of the HDV sector to zero-emission.

Keywords: heavy-duty vehicle, zero-emission fuel, drayage truck, fleet survey, choice experiment

INTRODUCTION

Recognizing the environmental and public health impacts posed by greenhouse gas emissions and air pollutants from medium and heavy-duty vehicles (referred to as 'HDVs,' with a gross vehicle weight rating (GVWR) exceeding 10,000 lbs by the U.S. FHWA), many U.S. states have aligned to support a large-scale transition towards a cleaner HDV sector (*1*). A key element of this initiative is the agreement to ensure that all new HDV sales by 2050 are zero-emission vehicles (ZEVs), such as battery electric or hydrogen fuel cell electric vehicles, which eliminate tailpipe emissions of criteria pollutants (*1*). Among these states, California is leading with policy and regulatory initiatives aimed at achieving a 100% transition of HDV fleets to ZEVs by 2045, wherever feasible, and an accelerated timeline for drayage trucks to transition by 2035 under Executive Order N-79-20 (*2*). To achieve these ambitious targets, California is employing various strategies, including the Advanced Clean Trucks program (*3*) to increase annual sales of zero-emission HDVs, and the fleet-specific requirements under the Advanced Clean Fleets (ACF) regulations (*4*), along with various incentive programs.

Currently, the penetration rate of ZEVs remains marginal, with only 0.2% of HDV registrations in California being ZEVs in 2022 (*5*). As approximately 90% of HDVs are used for business purposes in fleet operations rather than personal transportation (*6*), fleet operators, who make decisions for vehicle procurement within these businesses, play a pivotal role as key demand-side players driving the adoption of clean fuel technologies. Despite their significance, there is a noticeable scarcity of research delving into fleet operator perspectives on this topic, with only a few recent studies (e.g., *7–11*). Furthermore, no prior research has examined fleet operator perspectives, using recent survey data, in light of the current U.S. policy initiatives promoting heavy-duty ZEVs.

To address this critical knowledge gap, this research aims to investigate the preferences and influencing factors for ZEVs among fleet operators using a choice experiment survey, with a specific focus on California's drayage fleets. Drayage trucks are defined as "heavy-duty (Class 8, over 33,000 lbs GVWR) trucks that transport containers and bulk freight between the port and intermodal rail facilities, distribution centers, and other near-port locations" by the U.S. EPA (*12*). These trucks are crucial to port operations, the economy, and air quality (*12*). A drayage fleet in this work is defined as a group of one or more drayage trucks belonging to a drayage company for a business purpose. In California, drayage fleets face the most stringent targets set by the ACF regulations. From January 1, 2024, the ACF requires that only zero-emission drayage trucks can be newly registered in the California Air Resources Board (CARB)'s Truck Regulation Upload, Compliance, and Reporting System, and by 2035, all drayage trucks entering seaports and intermodal railyards must be zero-emission (*13*). Considering this policy context, our work addresses the following research questions:

1) In the context of a ZEV mandate, which necessitates a forced choice between battery electric trucks (BETs) and hydrogen fuel cell electric trucks (HFCETs), what factors influence fleet operator preferences, and how do these factors affect their choices?
2) When given a free choice between ZEVs and status quo alternatives (e.g., diesel and natural gas trucks), what preferences are formed and by which influencing factors?
3) How do preferences for these fuel technologies vary across different fleet segments (e.g., in terms of size and fuel adoption status)?

We developed a survey questionnaire comprising a stated preference choice experiment (*14*) and multiple key sections, building upon our previous qualitative research analyzing fleet interview data (*8*, *9*, *15*) as well as a comprehensive review of existing literature and relevant theories (*16*). To accommodate the contexts with and without the ZEV mandate, we employed a dual response format in the choice experiment, which presents two questions for each choice task – one with and one without a status quo alternative. This approach could potentially provide more accurate parameter estimates for choice models, especially when substantial inertia is present in the status quo option (*17*). We recruited drayage truck fleet operators in California using the Drayage Truck Registry for the Ports of Los Angeles and Long Beach. Through a pilot survey in July 2023 and a main survey from December 2023 to April 2024, a total of 71 drayage companies of various fleet sizes and alternative fuel adoption status participated. Data analysis was performed using multinomial logit models.

The research findings advance our understanding of HDV fleet operator perspectives on zero-emission vehicles, contributing to filling a key research gap in this field. By offering insights from a choice experiment survey, this study provides practical value for policymakers and industry stakeholders to develop effective strategies for facilitating zero-emission transition.

This paper is organized as follows. The next section reviews the relevant literature. The subsequent section describes the methodology used for this study. We then discuss the study results, followed by concluding comments along with future work.

LITERATURE REVIEW

Only a limited number of studies have explored fleet operator perspectives on adopting ZEVs or alternative fuel vehicles within the HDV sector (e.g., *7–11*). Most studies have been conducted in European regions (e.g., *7*, *10*, *11*), with only a few in the U.S. (e.g., *8*, *9*). Among various methodological approaches, choice experiment surveys have been one of the primary tools, particularly in examining future perspectives on clean fuel technologies. Choice experiments incorporate the experimental design features of conjoint analysis, enabling extensive testing of the structure and consistency of stated preferences (*14*). In these experiments, respondents are presented with a set of alternative products, each varying in attribute levels, and are asked to make choices under specific tasks. Given limited HDV-focused research, our literature review encompasses research employing choice experiment surveys that targeted organizations operating light-duty trucks (e.g., *18*, *19*).

Anderhofstadt & Spinler (*7*) conducted a choice experiment survey involving 69 German freight companies to assess key attributes of autonomous and alternative fuel-powered heavy-duty trucks. The study considered attributes such as purchase price, operating costs, driving range, refueling/recharging time, tank-to-wheel emissions, and driving automation across BET, HFCET, and natural gas truck options. Their results showed that driving range and fueling time were crucial, with emissions deemed less important (*7*). In addition, Walter et al. (*11*) surveyed 274 fleet managers in Switzerland and Germany using a choice experiment to evaluate preferences for hydrogen-powered street sweepers compared to conventional diesel and compressed natural gas/biogas options. They analyzed various attributes, finding that purchase price and operating costs were important factors, whereas noise emission was the least important.

Lebeau et al. (*18*) explored the choice of light commercial BETs among urban transport companies in Brussels, involving 45 survey participants. Their experiment included attributes such as payload, purchase costs, operating costs, Ecoscore (an index representing environmental benefits), driving range, and recharging time. The authors recommended expanding charging infrastructure and providing financial incentives to promote BET adoption based on their analysis (*18*). Also, van Rijnsoever et al. (*20*) assessed the preferences of Dutch local governments for alternative fuel vehicles, including battery electric, hydrogen fuel cell electric, and biogas internal combustion options. Their choice experiment survey involved 50 local governments and presented attributes comprising purchase price, fuel price, driving range, refueling time, fuel availability, and emission levels. The study found emissions to be an important criterion, especially for municipalities and provinces (*20*). Lastly, Golob et al. (*19*) analyzed a 1994 survey of 2,000 fleet sites with light and medium-duty vehicles (<14,000 lbs GVWR) in California to study the demand for alternative-fueled commercial vehicles. Their choice experiment design included a comprehensive set of attributes, such as home refueling availability and refueling equipment costs, with electric, natural gas, and methanol as fuel options. They revealed that the tradeoff between vehicle range and vehicle capital cost was $80 per mile of range.

Most of these studies relied on survey data from the early 2010s (e.g., *11*, *20*) or earlier (e.g., *19*), or focused on European countries (e.g., *7*, *11*, *18*, *20*). This underscores the need for our research, which uses recent survey data to capture fleet perspectives on current ZEV technologies and policies in the HDV sector, particularly in California, the U.S. state leading zero-emission initiatives. Our prior research (e.g., *8*, *9*) generated qualitative inferences based on interviews with California fleet operators, and served as a foundation for designing the choice experiment in this work. The next section details our methodologies.

METHODOLOGY

Survey Questionnaire Design

We developed a comprehensive survey questionnaire comprising the following main sections: 1) Basic Fleet Information, 2) Truck Choices, 3) Fleet Management Practices and Strategies, 4) Potential Charging Behavior, and 5) Perceptions. Each section contained 4 to 12 primary survey items, along with relevant follow-up questions where applicable. The initial draft questionnaire was formulated through an extensive examination of prior research findings, including the hypotheses derived from qualitative research studies based on HDV fleet interview data (*8*, *9*, *15*), as well as insights from a comprehensive review of existing literature, theories, and methodologies (*16*). To address any uncertainties in the first draft, further input was obtained through additional fleet interviews in the drayage industry.

For survey implementation, a multi-phase approach was adopted, comprising pretesting, a pilot survey, and a main survey. The developed survey questionnaire was uploaded onto the online survey platform, SurveyEngine (*21*), and underwent internal pretesting to resolve errors, enhance layout, and ensure logical flow. Subsequently, a pilot survey was conducted with a small group of fleet operators with two main objectives: obtaining reliable prior information for designing the choice experiment in the main survey and testing the questionnaire from fleet operator viewpoints. Based on the pilot results, the main survey questionnaire was refined, incorporating an updated choice experiment design using the prior information. While the pilot survey targeted English-speaking fleet operators, we prepared both English and Spanish versions of the questionnaire for the main survey to accommodate Spanish-speaking respondents as well.

Choice Experiment

The Truck Choices section involved a stated preference choice experiment (*14*) to investigate fleet operator preferences for ZEVs and the potential impact of the ZEV mandate on fuel choice. Each respondent was presented with a set of six choice tasks comprising sets of alternatives, including zero-emission trucks (BET and HFCET) and status quo options (diesel truck for non-adopters, or diesel and compressed natural gas truck (CNGT) for natural gas adopters), based on earlier findings from our interviews with California fleet operators (*8*). Major attributes such as purchase costs, operating costs, maximum driving range, emission levels, availability of off-site stations, construction costs of refueling/charging facilities, and refueling/charging time were selected based on previous research (*9*). Specific attribute levels were designed to represent various ZE technology advancement scenarios from the current level through the 2030s along with possible policy supports (see (*22*) for more detail). Table 1 outlines the attribute design for the choice experiment.

Table 1. ZEV Technology Attributes for the Choice Experiment Design

Alternatives [a] / Attributes [b]	BET	HFCET	CNGT	DT
Purchase cost (relative to a diesel truck)	105% (incentive applied), 115% (incentive applied), 150%, 200%	105% (incentive applied), 115% (incentive applied), 150%, 200%	105% (incentives applied), 130%	100%
Operating cost (relative to a diesel truck)	50%, 70%	90%, 115%, 130%	70%, 90%	100%
Maximum driving range	150 miles, 300 miles, 500 miles	300 miles, 500 miles, 700 miles	700 miles	700 miles
Emission level (relative to diesel truck)	0%	0%	25%	100%
Shortest distance to off-site fueling/charging stations	within 10 min, within 20 min, not available	within 10 min, within 20 min, not available	The same as current status	within 5 min
On-site fueling/charging infrastructure construction costs [c]	25% of total costs (incentives cover 75%), 50% of total costs (incentives cover 50%), 100% of total costs	25% of total costs (incentives cover 75%), 50% of total costs (incentives cover 50%), 100% of total costs	No costs if you already have your own facilities; Full costs, otherwise.	Not applicable
Refueling/charging time [d]	The charging times corresponding to a certain range were presented.	10 min	10 min (fast-fill), 5-9 hr (time-fill)	5 min

Note: (a) BET = battery electric truck, HFCET = hydrogen fuel cell electric truck, CNGT = compressed natural gas truck, DT = diesel truck. (b) The single-level attributes, such as the emission level and the refueling/charging time, were presented in the choice tasks for informational purposes. Their overall impact on the respondents' choices is collectively captured in the alternative-specific constant. (c) Detailed information about the total construction costs was provided in the choice tasks. (d) The time required to charge a BET depends on the charging rate and the battery capacity, the latter of which also influences the maximum driving range. Based on relevant calculations, charging times corresponding to a specific driving range were presented, within a range of 18 min to 6 hr (1 MW to 50 kW charger), 31 min to 10 hr (1 MW to 50kW charger), and 48 min to 16 hr (1 MW to 50 kW charger).

To explore the impact of ZEV mandates on fuel choice, we employed a dual response format (*17*), presenting two questions for each choice task, with and without a status quo alternative. In our survey, respondents were asked to first make a choice between BET and HFCET, and then choose between the previously selected option and the status quo alternative(s). Figure 1 illustrates an example of the choice tasks. To generate the choice experiment design, we used Ngene software (*23*) and the efficient design, which aims for statistical efficiency by leveraging prior information available from literature or pilot data (*24*).

Assume that the following hypothetical set of trucks are available, including a battery electric truck (BET) and a hydrogen fuel cell electric truck (HFCET).

	BET	HFCET	Diesel Truck
Purchase costs (relative to Diesel)	**200** % (incentives unavailable) e.g., $300,000	**105** % (incentives applied) e.g., $158,000	**100** % e.g., $150,000
Operating costs (relative to Diesel)	**70** % e.g., 35 cents/mi	**115** % e.g., 57.5 cents/mi	**100** % e.g., 50 cents/mi
Maximum driving range	**300** miles	**500** miles	**700** miles
Emission levels (relative to Diesel)	**0** %	**0** %	**100** %
Shortest distance to off-site fueling/charging stations	within **10** min	Not available	within **5** min
On-site fueling/charging infrastructure construction costs	**100** % of total costs* (no incentives) e.g., $80,000 to $480,000 per charger	**25** % of total costs* (incentives cover 75%) e.g., $500,000 (fast-fill station)	Not applicable
Refueling/charging time	**31** min to **10** hr (1 MW to 50kW charger)	**10** min	**5** min

Click here for the information about the truck characteristics.

* The total costs for constructing the infrastructure include both the purchase and installation of fueling/charging equipment. Such construction costs vary depending on a scale of the facilities (e.g., the number of chargers or filling hoses). Approximate average costs are as follows:

- For BETs: 1) $80,000 per 50 kW charger; 2) $160,000 per 150 kW charger; 3) $250,000 per 350 kW charger; and 4) $480,000 per 1 MW charger.
- For HFCETs: $2M for a fast-fill station.

If you had to choose between BET and HFCET as your next truck after 2024, which one would you choose? *

Select only one answer.

○ BET	○ HFCET

If a diesel truck was available in the previous question, would you choose it instead of the option you selected before? *

Select only one answer.

○ No, we would still choose the **BET or HFCET**.	○ Yes, we would choose the **diesel truck**.

FIGURE 1. An Example of Choice Tasks

Sampling and Recruitment

The target population for this study was 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 (*25*). Of these, around 75% operated at the POLA and POLB while the remaining 25% were associated with other ports (*25*). Although full registration data were inaccessible, POLA's analysis as of June 2023 (*26*) indicated that 72.5% (810 out of 1,117) of drayage companies accessing the port consisted of small fleets with 20 or fewer trucks, and 27.5% (307) were large fleets with over 20 trucks. Most of the drayage trucks accessing the POLA (94.3%) operated on diesel, with 5.2% using natural gas and 0.5% using electricity. For the pilot survey, stratified random sampling was utilized to obtain a representative balance between subpopulations, with fleet sizes and alternative fuel adoption status as stratification variables. 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.

While we aimed to collect a minimum of 60 to 100 valid responses by referring to previous studies (*7*, *27*), around 10% of this sample size was targeted for the pilot survey. Participants were recruited from the POLA/POLB drayage truck registries, which contained around 3,200 fleet operator contacts (*28*, *29*). Invitations for the pilot survey were emailed to 600 companies, a subset of these registries. Twenty fleets expressed willingness to participate in the pilot survey (3.3%), and 12 completed it in July 2023 (2.0%). For the main survey, all remaining companies were contacted. Between December 2023 and April 2024, 88 companies responded positively (2.8%), and 59 completed the survey (1.9%). Consequently, 71 drayage fleet operators participated in our survey. Table 2 summarizes basic characteristics of participating fleets across diverse dimensions.

Table 2. Basic Characteristics of Survey Participants

Category	**Number of organizations**		**Category**	**Number of organizations**	
Fleet size [(a)]			**Fuel adoption status** [(b,c)]		
Small fleet (≤20 trucks)	**50**	**70.4%**	Non-NGV-ZEV fleets	**52**	**73.2%**
1	3	4.2%	Diesel trucks only	42	59.2%
2 - 5	18	25.4%	Biodiesel adopters	9	12.7%
6 - 10	18	25.4%	Renewable diesel adopters	8	11.3%
11 - 20	11	15.5%	NGV adopters	**14**	**19.7%**
Large fleet (> 20 trucks)	**21**	**29.6%**	CNG adopters	11	15.5%
21 - 49	11	15.5%	LNG adopters	4	5.6%
50 - 99	4	5.6%	ZEV adopters	**11**	**15.5%**
≥ 100	6	8.5%	BET adopters	11	15.5%
Approximate annual revenue			HFCET adopters	4	5.6%
< $10M	40	56.3%	**Organization size** (based on fleet size and annual revenue)		
$10M - $15M	8	11.3%	Small organization (≤ 20 trucks and < $15M of annual revenue) [(b)]	49	69.0%
$15M - $30M	5	7.0%	Large organization (> 20 trucks or ≥ $15M in annual revenue)	22	31.0%
> $30M	7	9.9%			
Decline to state	11	15.5%	**Total**	**71**	**100.0%**

Note: (a) The criteria defining a small fleet or organization were informed by CARB's Innovative Small E-Fleet program. (*30*). Fleets with 20 trucks or fewer and those not reporting annual revenue were classified as small organizations in this work. (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.

The pilot participants were given the option of one-on-one online meetings or independent completion of the survey with written feedback submission. Responses to the main survey were independently completed, allowing for flexibility either of a single sitting or multiple sittings. The average duration for survey completion was 41 minutes for one sitting (59 respondents) or 4.4 days for multiple sittings (12 respondents). In appreciation for participation effort, a $100 Amazon eGift card was offered unless declined. All study materials and survey protocols were processed by the Institutional Review Board of the University of California, Irvine.

Survey Data and Analysis Method

A selective set of survey items was chosen to address the research questions, focusing on the truck choice, including ZEVs and status quo alternatives (Truck Choice section), along with fleet size, annual revenue, and fuel technologies used (Basic Fleet Information section). Among the 71 participants, 17 companies were excluded from the Truck Choice section because their other survey responses revealed intentions to discontinue their drayage business (8), relocate to another state (4), or operate non-ZEVs only (5). This left 54 fleet operators planning to continue drayage operations in California and considering ZEVs, who completed the Truck Choice section. Each respondent was assigned six choice tasks, each consisting of a forced choice between different ZEVs and an unforced choice between ZEVs and the status quo alternative(s). This resulted in 648 observations for both forced and unforced choices. The multinomial logit model (*31*) was used to analyze responses from these stated preference tasks. To explore potential differences between fleet segments, such as small versus large fleets and ZEV adopters versus non-adopters, interaction terms were included in the utility functions. Parameters were estimated through a maximum likelihood estimation procedure, using the Apollo R package (*32*).

RESULTS AND DISCUSSION

Characteristics of Participating Fleets

To characterize the participating drayage fleets, we analyzed several survey items from the Basic Fleet Information section, including fleet size, annual revenue, and fuel technologies used (see Table 2). The fleet sizes ranged from 1 truck to over 100 trucks. To facilitate subsequent analyses, we categorized these diverse fleet sizes into two groups, following the CARB's definition (*30*): small fleets with 20 trucks or fewer, comprising 70.4% of survey participants, and large fleets with over 20 trucks, representing 29.6%. Organization size was also determined by annual revenue in addition to fleet size, with criteria from (*30*) classifying companies with annual revenues under $15 million and 20 trucks or fewer as small organizations (69% of participants), and the remainder as large organizations (31%).

We define "adopters" as companies that have adopted at least one truck using alternative fuels in their fleets. Among the 71 participating fleets, 40.8% were adopters of alternative fuel trucks (including gaseous and/or zero-emission fuels), while 59.2% operated solely with diesel trucks. Specifically, 19.7% operated natural gas trucks, 15.5% operated BETs, 5.6% operated HFCETs, 12.7% utilized biodiesel, and 11.3% utilized renewable diesel.

Overview of Choices

The choice experiment in the Truck Choice section of the survey comprised a series of six tasks, each presenting two questions under a specific technology scenario. The first question in each task assumed the implementation of the ZEV mandate, requiring respondents to choose between ZEVs (forced choice). The second question assumed the absence of such regulations, allowing respondents to choose between ZEVs and status quo alternatives (unforced choice). Typically, the status quo alternative was a diesel truck; however, for fleet operators who had already adopted natural gas trucks, their status quo alternatives could include both diesel and natural gas options (*8*). We refer to the former as 'non-NGV fleets' and the latter as 'NGV fleets' in this study.

Figure 2 illustrates an overview of choices across these questions. Out of 324 observations for the forced choices in hypothetical ZEV advancement scenarios from the current level through the 2030s, BETs were chosen 184 times (56.8%), and HFCETs were chosen 140 times (43.2%). Of 324 observations for the unforced choices between the ZEVs and status quo alternatives, ZEVs were selected in 23.8% of cases, while status quo alternatives, either diesel or CNG trucks, were selected 76.2% of the time.

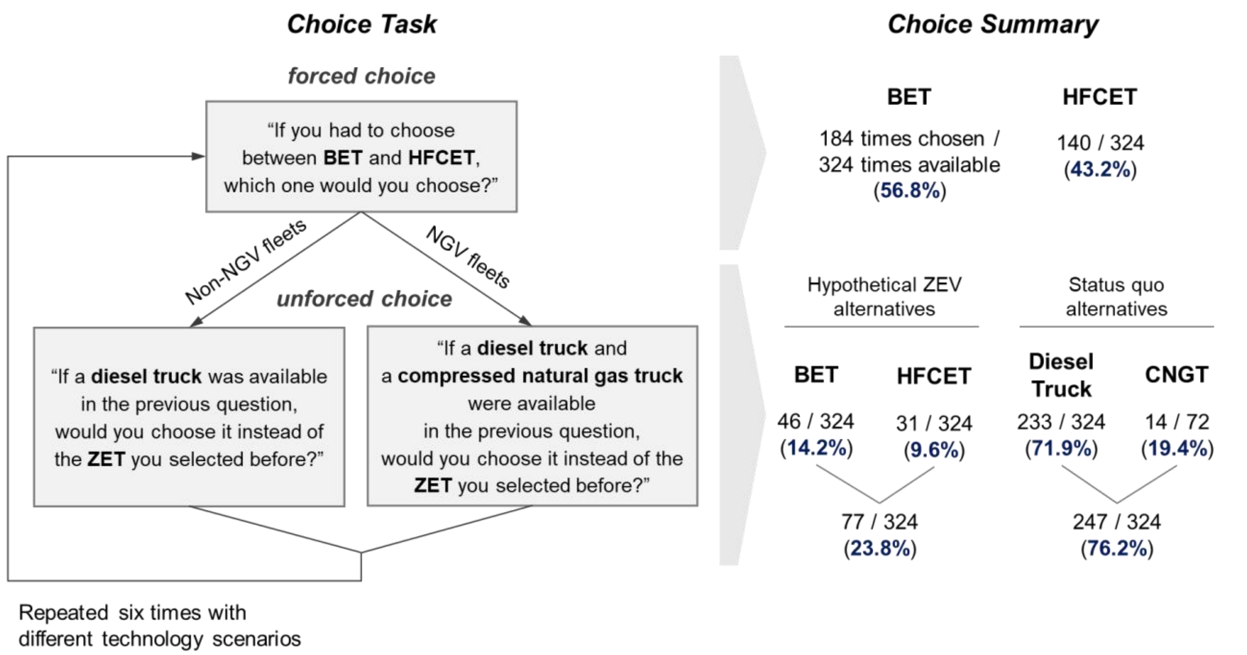

Figure 2. Overview of Choice Tasks and Resulting Selections

Truck Choice Models

Building on previous findings (*8*, *9*, *15*), technology attributes and fleet characteristics were used to specify utility functions in the truck choice models. To address the research questions, three models were developed: 1) a forced choice model between ZEVs, 2) an unforced choice model between ZEVs and status quo alternatives, and 3) a model with joint estimation using both forced and unforced choice data. To explore differences between non-NGV and NGV fleets, relevant scale parameters were applied. Table 3 lists the variables used in these models, and Table 4 details the utility functions. Different sets of interaction terms were selected for each model based on behavioral relevance and model fit measures. The estimation results of multinomial logit models, including estimated parameters, *t*-statistics, and model fit measures, are presented in Table 5.

Table 3. Variables used for Choice Models

Category	**Subcategory**	**Variable** [a]	**Description**	**Adjustment in unit** [b]
Dependent variables	Hypothetical alternatives	BET	Binary variable for battery electric truck (1 for chosen, 0 otherwise)	n/a
		HFCET	Binary variable for hydrogen fuel cell electric truck (1 for chosen, 0 otherwise)	n/a
	Status quo alternatives	CNGT	Binary variable for compressed natural gas truck (1 for chosen, 0 otherwise)	n/a
		DT	Binary variable for diesel truck (1 for chosen, 0 otherwise)	n/a
Explanatory variables	Technology characteristics	$FUEL_{pcost}$ [c]	Purchase cost relative to a diesel truck	divided by 100%
		$FUEL_{ocost}$	Operating cost relative to a diesel truck	divided by 100%
		$FUEL_{range}$	Maximum driving range	divided by 100 miles
		$FUEL_{offsite}$	Binary variable indicating the availability of off-site fueling/charging stations within 20 minutes from fleet-site locations (1 for available, 0 otherwise)	n/a
		$FUEL_{onsite}$	On-site fueling/charging infrastructure construction costs with certain levels of financial incentives (relative to total costs)	divided by 100%
	Fleet characteristics	BETadopter	Binary variable for BET adoption status (1 for adopter, 0 otherwise)	n/a
		HFCETadopter	Binary variable for HFCET adoption status (1 for adopter, 0 otherwise)	n/a
		SmallFleet	Binary variable for small fleet (1 for ≤ 20 trucks, 0 otherwise)	n/a
		LargeFleet	Binary variable for large fleet (1 for > 20 trucks, 0 otherwise)	n/a
		SmallOrg	Binary variable for small organization (1 for ≤ 20 trucks and < $15M annual revenue, 0 otherwise)	n/a
		LargeOrg	Binary variable for large organization (1 for > 20 trucks or ≥ $15M annual revenue, 0 otherwise)	n/a

Note: (a) BET = battery electric truck, HFCET = hydrogen fuel cell electric truck, CNGT = compressed natural gas truck, DT = diesel truck. (b) To facilitate the interpretation of the estimates, values of certain variables were adjusted in their units during model estimation. (c) FUEL can represent BET, HFCET, CNGT or DT.

Table 4. Utility Functions

<table>
<tr><td colspan="3">Utility functions – Type A (w/ interaction terms of ZEV adoption status and fleet/organization size)</td></tr>
<tr><td colspan="3">$V_{BET}^{A} = ASC_{BET}^{adj} + b_{pcost} * BET_{pcost} + b_{ocost}^{adj} * BET_{ocost} + b_{range} * BET_{range} + b_{offsite}^{adj} * BET_{offsite} + b_{onsite \cdot BET} * BET_{onsite}$
$V_{HFCET}^{A} = ASC_{HFCET}^{adj} + b_{pcost} * HFCET_{pcost} + b_{ocost}^{adj} * HFCET_{ocost} + b_{range} * HFCET_{range} + b_{offsite}^{adj} * HFCET_{offsite} + b_{onsite \cdot HFCET} * HFCET_{onsite}$
$V_{CNGT}^{A} = ASC_{CNGT} + b_{pcost} * CNGT_{pcost} + b_{ocost}^{adj} * CNGT_{ocost} + b_{range} * CNGT_{range} + b_{offsite}^{adj} * CNGT_{offsite}$
$V_{DT}^{A} = ASC_{DT} + b_{pcost} * DT_{pcost} + b_{ocost}^{adj} * DT_{ocost} + b_{range} * DT_{range} + b_{offsite}^{adj} * DT_{offsite}$</td></tr>
<tr><td colspan="3">Utility functions – Type B (w/ interaction terms of ZEV adoption status)</td></tr>
<tr><td colspan="3">$V_{BET}^{B} = ASC_{BET}^{adj} + b_{pcost} * BET_{pcost} + b_{ocost} * BET_{ocost} + b_{range} * BET_{range} + b_{offsite} * BET_{offsite} + b_{onsite \cdot BET} * BET_{onsite}$
$V_{HFCET}^{B} = ASC_{HFCET}^{adj} + b_{pcost} * HFCET_{pcost} + b_{ocost} * HFCET_{ocost} + b_{range} * HFCET_{range} + b_{offsite} * HFCET_{offsite} + b_{onsite \cdot HFCET} * HFCET_{onsite}$
$V_{CNGT}^{B} = ASC_{CNGT} + b_{pcost} * CNGT_{pcost} + b_{ocost} * CNGT_{ocost} + b_{range} * CNGT_{range} + b_{offsite} * CNGT_{offsite}$
$V_{DT}^{B} = ASC_{DT} + b_{pcost} * DT_{pcost} + b_{ocost} * DT_{ocost} + b_{range} * DT_{range} + b_{offsite} * DT_{offsite}$</td></tr>
<tr><td colspan="3">Interaction terms with fleet characteristics</td></tr>
<tr><td colspan="3">$ASC_{BET}^{adj} = ASC_{BET} + ASC_{BET \cdot adopter} * BETadopter$
$ASC_{HFCET}^{adj} = ASC_{HFCET} + ASC_{HFCET \cdot adopter} * HFCETadopter$
$b_{ocost}^{adj} = b_{ocost \cdot SmallFleet} * SmallFleet + b_{ocost \cdot LargeFleet} * LargeFleet$
$b_{offsite}^{adj} = b_{offsite \cdot SmallOrg} * SmallOrg + b_{ocost \cdot LargeOrg} * LargeOrg$</td></tr>
<tr><td colspan="3">Forced choice model (Utility Type A selected)</td></tr>
<tr><td colspan="3">$V_{Forced \cdot BET} = V_{BET}^{A}$
$V_{Forced \cdot HFCET} = V_{HFCET}^{A}$</td></tr>
<tr><td colspan="3">Unforced choice model (Utility Type B selected)</td></tr>
<tr><td colspan="2">For non-NGV fleets</td><td>For NGV fleets</td></tr>
<tr><td colspan="2">$V_{Unforced \cdot BET} = V_{BET}^{B}$
$V_{Unforced \cdot HFCET} = V_{HFCET}^{B}$
$V_{Unforced \cdot DT} = V_{DT}^{B}$</td><td>$V_{Unforced \cdot BET} = \mu_{ng} * V_{BET}^{B}$
$V_{Unforced \cdot HFCET} = \mu_{ng} * V_{HFCET}^{B}$
$V_{Unforced \cdot CNGT} = \mu_{ng} * V_{CNGT}^{B}$
$V_{Unforced \cdot DT} = \mu_{ng} * V_{DT}^{B}$</td></tr>
<tr><td colspan="3">Joint estimation using both the forced and unforced choice data (Utility Type A selected)</td></tr>
<tr><td>Forced choice</td><td>Unforced choice for non-NGV fleets</td><td>Unforced choice for NGV fleets</td></tr>
<tr><td>$V_{Forced \cdot BET} = V_{BET}^{A}$
$V_{Forced \cdot HFCET} = V_{HFCET}^{A}$</td><td>$V_{Unforced \cdot BET} = \mu_{uf \cdot dsl} * V_{BET}^{A}$
$V_{Unforced \cdot HFCET} = \mu_{uf \cdot dsl} * V_{HFCET}^{A}$
$V_{Unforced \cdot DT} = \mu_{uf \cdot dsl} * V_{DT}^{A}$</td><td>$V_{Unforced \cdot BET} = \mu_{uf \cdot ng} * V_{BET}^{A}$
$V_{Unforced \cdot HFCET} = \mu_{uf \cdot ng} * V_{HFCET}^{A}$
$V_{Unforced \cdot CNGT} = \mu_{uf \cdot ng} * V_{CNGT}^{A}$
$V_{Unforced \cdot DT} = \mu_{uf \cdot ng} * V_{DT}^{A}$</td></tr>
</table>

Table 5. Estimation Results for Multinomial Logit Models

Parameter	Forced choice model			Unforced choice model			Joint estimation results [c]		
	Estimate [a]	*t*-statistic	Robust *t*-stat [b]	Estimate	*t*-statistic	Robust *t*-stat	Estimate	*t*-statistic	Robust *t*-stat
ASC_{BET}	0.000	n/a	n/a	0.000	n/a	n/a	0.000	n/a	n/a
$ASC_{BET \bullet adopter}$	**1.650*****	3.388	4.051	**1.544*****	3.056	2.013	**1.341*****	3.462	3.798
ASC_{HFCET}	-1.085	-1.079	-0.919	**-2.235*****	-2.244	-3.240	**-1.078****	-2.215	-2.443
$ASC_{HFCET \bullet adopter}$	**2.178*****	3.310	2.652	**3.987*****	2.898	1.441	**2.086*****	3.790	2.276
ASC_{CNGT}	—	—	—	**-2.077***	-1.764	-0.893	-0.983	-1.568	-0.723
ASC_{DT}	—	—	—	-0.392	-0.513	-0.583	0.302	0.693	0.579
b_{pcost}	**-0.288***	-1.543	-1.911	**-0.852***	-1.828	-1.397	**-0.358****	-2.290	-2.334
b_{ocost}	—	—	—	-0.151	-0.125	-0.141	—	—	—
$b_{ocost \bullet SmallFleet}$ [d]	-0.763	-1.434	-1.265	—	—	—	-0.645	-1.405	-1.122
$b_{ocost \bullet LargeFleet}$	**-1.133***	-1.889	-1.712	—	—	—	**-0.954***	-1.823	-1.481
b_{range}	**0.240*****	5.021	4.390	**0.394*****	3.557	4.095	**0.248*****	5.627	4.625
$b_{offsite}$	—	—	—	0.190	0.561	0.474	—	—	—
$b_{offsite \bullet SmallOrg}$	**0.359****	1.969	1.799	—	—	—	**0.267***	1.655	1.144
$b_{offsite \bullet LargeOrg}$	-0.146	-0.556	-0.600	—	—	—	0.013	0.063	0.055
$b_{onsite \bullet BET}$	-1.108	-1.273	-1.074	**-1.608****	-2.141	-2.294	**-1.024****	-2.439	-2.462
$b_{onsite \bullet HFCET}$	0.437	0.497	0.408	0.219	0.283	0.450	0.283	0.687	0.759
μ_{ng}	—	—	—	**0.353*****	2.741	1.306	—	—	—
$\mu_{uf \bullet dsl}$	—	—	—	—	—	—	**1.368*****	3.701	3.510
$\mu_{uf \bullet ng}$	—	—	—	—	—	—	**0.594****	2.481	1.312
Log-likelihood at equal shares, LL(0)	-224.58			-376.66			-601.24		
Log-likelihood at observed shares, LL(C)	-221.58			-240.64			-462.22		
Log-likelihood at convergence, LL(final)	-196.86			-224.63			-424.36		
Rho-squared vs equal shares	0.123			0.404			0.294		
Rho-squared vs observed shares	0.112			0.067			0.082		
Number of parameters	11			12			15		
Number of respondents	54			54			54		
Number of choice observations	324			324			648		

Note: (a) Significance levels based on (robust) *t*-statistic are indicated as follows: * $p < 0.10$, ** $p < 0.05$, and *** $p < 0.01$. "—" indicates that the variable was not included in the model. "n/a" means the estimate was fixed at 0. (b) Robust *t*-statistics accommodate the survey's panel nature where individual choices from the same respondent are not independent (*32*). (c) Joint estimation was performed using both the choice and unforced choice data. (d) In the unforced choice model, interaction terms with size variables were explored in an alternative specification, but the parameters were not significant and thus excluded from the final model.

In the forced choice model, significant parameters for technology attributes across all fleet segments are maximum driving range (b_{range}) and relative purchase costs (b_{pcost}). The driving range estimate is highly significant at the 1% level, with a positive sign, indicating that a longer range increases utility. The estimate for relative purchase cost is negative and significant at the 10% level, suggesting that lower purchase costs also increase utility. For example, a 100-mile increase in driving range (e.g., from 200 to 300 miles) increases utility by 0.240, while a 100% decrease in relative purchase cost (e.g., from 250% to 150%) increases utility by 0.288.

Interaction terms for size variables revealed significant effects ($b_{ocost \bullet LargeFleet}$ and $b_{offsite \bullet SmallOrg}$). Lower operating costs increase utility for large fleets but not for small fleets. This could be due to large fleets' greater sensitivity to operating costs from total longer VMT and/or more detailed cost calculations (*33*). For small organizations, offsite charging/fueling station availability was important, consistent with previous findings on infrastructure decisions among alternative fuel adopter fleets (*15*). The presence of an offsite station near base locations of small organizations increases utility (+0.359) more than a 100-mile range increase (+0.240) or a 100% decrease in relative purchase cost (+0.288). Meanwhile, the shift parameters of alternative-specific constants (ASCs) for BET and HFCET adopters are highly significant at the 1% level (+1.650 and +2.178, respectively), indicating a strong tendency among early adopter participants to continue procuring the zero-emission trucks they had already adopted.

In the unforced choice model, significant technology parameters across all fleet segments are maximum driving range, BET charging facility construction costs, and relative purchase costs. Lack of financial incentives for BET infrastructure could significantly discourage BET adoption (-1.608 in utility) along with lower ranges and higher purchase costs. For HFCET adoption, a strong disinclination was observed, with ASC_{HFCET} estimated as -2.235 at the 1% level, possibly due to unfamiliarity with hydrogen trucks and perceived unreadiness of the technology. However, similarly to the forced choice model, BET and HFCET adopters have a propensity toward zero-emission options, with positively estimated shift parameters ($ASC_{BET \bullet adopter}$ and $ASC_{HFCET \bullet adopter}$).

Notable findings reveal the behavior of natural gas adopter fleets. The ASC_{CNGT} estimated at -2.077 indicates that these fleets prefer BET less than CNGT after controlling for other attributes, even assuming full payment for BET infrastructure costs. This might be attributed to increased awareness of California's ZEV policies among CNG adopters, who were early adopters of alternative fuels. Meanwhile, the scale parameter for NGV fleets (μ_{ng}) in the unforced choice model was 0.353 (less than 1), indicating that their unforced choices are less deterministic compared to non-NGV fleets. Also, the two scale parameters in the joint estimation were statistically significant. For non-NGV fleets, the scaling parameter is 1.368 (>1), suggesting their unforced choices (between ZEVs and a diesel truck) are more deterministic than their forced choice between ZEVs. In contrast, the scaling parameter for NGV fleets is 0.594, indicating that their unforced choices (between ZEVs, CNGT, and a diesel truck) are less deterministic than forced choices. A possible explanation for this may lie in the increased complexity of decisions among NGV fleets, involving four alternatives including zero-emission, alternative fuel, and diesel trucks.

The research findings highlight several policy implications. First, they confirm the necessity of policy support to overcome known barriers to ZEV adoption, such as vehicle purchase incentives, financial aid for on-site infrastructure construction, and manufacturer efforts to extend driving range. In addition, tailoring support to specific fleet segments appears more effective. For instance, large fleets may recognize the advantages in reduced operating costs, and small organizations may benefit from off-site station availability or other innovative infrastructure solutions. Furthermore, given the significant shift parameters for ZEV adopters, expanding trial opportunities across wider non-adopter fleet segments may effectively accelerate the ZEV transition. Lastly, trade-off analyses can aid in prioritizing various policy supports. For example, fully incentivizing infrastructure construction costs, compared to full payment, increases utility by 1.608, which is equivalent to an 189% decrease in relative purchase costs, or a 400-mile increase in driving range. Considering the costs associated with implementing these policies and their impact on fleet decisions, further analysis will help in strategic policy prioritization.

CONCLUDING COMMENTS

Understanding fleet operator behavior and perspectives is crucial for achieving U.S. ZEV policy goals. Our choice experiment survey identified driving range and purchase costs as significant factors for ZEV adoption, with charging facility construction costs also critical in choices between ZEVs and status quo alternatives. These findings highlight the importance of reducing upfront costs, providing compatible range, and supporting infrastructure for a smooth transition to zero-emission fleets. Fleet or organization size also influences ZEV choices, with large fleets more sensitive to operating costs and small organizations more sensitive to off-site station availability. Tailored policy support is imperative for these segments.

The limitations of this study suggest directions for future research. It is worthwhile to explore the long-term impacts of these policy supports on fleet decisions and the overall ZEV transition. Data from other parts of our survey, particularly on fleet management strategies under the mandate, should aid in this investigation. Further sophisticated choice models, including cluster analysis and hybrid choice models utilizing our survey's Likert-scale data on fleet perception, will enhance understanding. These insights will be valuable for California and other states in developing effective strategies for transitioning HDV fleets to zero-emission.

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AUTHOR CONTRIBUTION STATEMENT

The authors confirm contribution to the paper as follows: study conception and design: YB, SGR, and CRR; 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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