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# Barriers to Electrification in the Heavy-Duty Trucking Sector

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**Summary**

This paper uses results from semi-structured interviews with fleet decision-makers to explore barriers to the adoption of battery electric heavy-duty trucks in California. The paper explores fleet operators understanding of, and inclinations toward, heavy-duty truck electrification. The study includes fleets who do and do not have experience with zero emission trucks, providing insights into barriers to the initial introduction of zero emission trucks and to increasing the number of electric trucks in a fleet.

*Keywords: EV (electric vehicle), Fleet, Heavy-Duty, Truck*

## 1 INTRODUCTION

This study uses interviews with decision-makers in heavy-duty fleets to understand the barriers to heavy-duty electric truck adoption. The disproportionate emissions of heavy-duty electric trucks and subsequent emergence of zero-emission truck policies necessitates an understanding of the way in which fleet decision-makers perceive these trucks. This paper seeks to fill this need by speaking directly with fleet decision-makers to understand the barriers to heavy-duty electric truck adoption. The results presented here are a truncated version of the full study still pending publication.

Heavy-duty fleet electrification is necessary to achieve zero-emission vehicle, air quality, and greenhouse gas emission reduction goals. The California Air Resources Board has set two regulatory requirements for heavy-duty fleets to transition to zero-emissions trucks. The Advanced Clean Trucks (ACT) program requires medium- and heavy-duty truck manufactures to sell increasing percentages of zero-emission trucks each year from 2024 to 2035, when zero-emission trucks must make up 75% of straight truck and 40% of tractor-trailer sales [6]. The Advanced Clean Fleets (ACF) program is still in development but will place zero emission truck purchase requirements on fleets operating medium- and heavy-duty trucks in California. It currently requires 100% of truck purchases be zero-emission by 2040 [7].

We investigate the barriers to fleet compliance with these rules, focusing on fleets that operate trucks in California, although the fleet may be headquartered outside California. The results of this study come directly from interviews with fleet decision-makers, who are directly involved in truck purchases, but whose perspectives are rarely included. As the transportation sector is increasingly pushed to become more sustainable, findings from this research can support other regions in their push towards electrification.

This paper reports insights from 28 semi-structured interviews with heavy-duty fleet decision-makers on the barriers to electrification of truck purchase and use. We classify the barriers they describe to heavy-duty electric truck adoption into six categories: technological (T), economic (E), social (S), socio-technological (SE), techno-economic (TE), and socio-economic (SE). These categories were created to provide a framework that shows the complexities of heavy-duty truck electrification and the how barriers transcend economic, technological, and social issues to include hybrid barriers. Categories are defined in the Methods section.

### 1.1. OVERVIEW OF THE HEAVY-DUTY TRUCKING SECTOR

For the purpose of this study, heavy-duty trucks are defined according to the Federal Highway Administration's specifications and have a gross vehicle weight rating of over 26,001 lbs. (Class 7 and 8) [12]. Heavy-duty trucks are used in a variety of applications, including moving freight in long-haul, short-haul, and drayage applications. Here, long-haul operations are defined as those where drivers spend multiple nights per week away from home. Trucks used in this application generally account for the largest share of miles driven in the heavy-duty trucking sector, with trucks traveling up to 800 miles per day and 100,000 miles per year [11]. Short haul trucks are those that do not meet the requirements for long-haul classification [14]. These trucks tend to operate in more urban areas and make more frequent stops, often travelling less than 100 miles per day, although they can be used for longer, regional trips [15]. Drayage trucks are any truck that provide pickup or delivery services to a seaport [16]. Drayage is a subset of short-haul which is classified separately as they have a distinct duty cycle and their own set of regulations. These trucks typically have a limited daily mileage and return to a base location at the end of each day [17]. While heavy-duty vehicles are used in non-freight applications (e.g., refuse hauling, coaches and transit buses, and vocational applications such as well-drilling, concrete mixers, and crane trucks), these applications are out of the scope of this study.

## 2. METHOD

### 2.1. Sample

Data are from 28 semi-structured hour-long interviews conducted with fleet decision makers in the first half of 2021. The interviews aimed to understand truck purchase, disposal, and electrification decisions. Sampling was done to reach decision makers in fleets of different sizes and application types. Fleets did not have to be headquartered in California, but they did have to operate trucks in California. All interviewees were considered "decision-makers" within their fleet with some influence over decisions affecting fleet turnover.

To provide an overview of the sample, fleets were classified as either small (under 20 trucks), medium (21-150 trucks), or large (over 151 trucks). These categories account for significant skew towards smaller fleets, i.e., most entities operating heavy-duty trucks are small fleets while most heavy-duty trucks are operated by large fleets. The final sample contained 8 small fleets, 7 medium fleets, and 13 large fleets. These trucks were used in various applications, which were combined into three primary categories: long-haul, short-haul, and drayage. A single fleet can be categorized as multiple fleet applications, so totals in Figure 1 do not add to 28.

Here, experience with electric trucks refers to fleets that have current or previous experience operating at least one battery electric truck, although they do not have to be currently operating it. A total of eight fleets had such experience, seven of which were categorized as large fleets and one of which was categorized as a medium fleet. In some cases, fleets had previously participated in zero emission truck demonstration projects, but no longer operated these trucks in their fleet. Interviewees representing fleets which have experience operating electric trucks provide firsthand accounts of their experiences, while fleets without similar experience report their perceptions of electric trucks presumably based on whatever information they have.

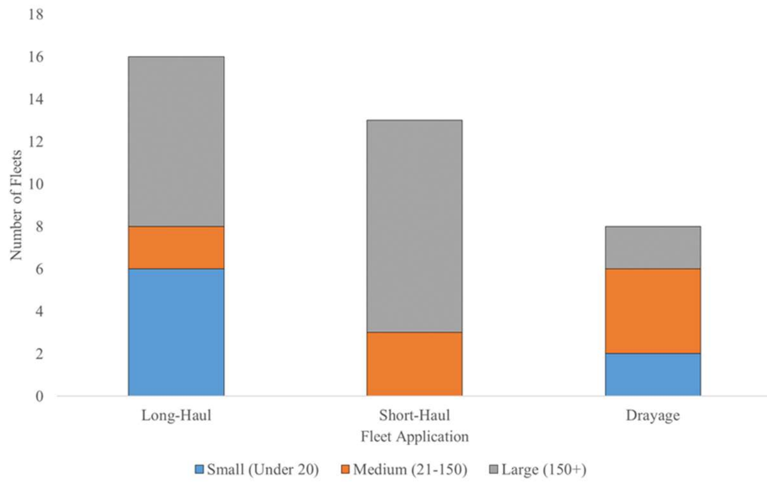


Figure 1: Breakdown of fleets in this study by fleet size and application. ($n_{drayage}$= 8, $n_{short\text{-}haul}$= 14, $n_{long\text{-}haul}$= 16)

## 2.2. Analysis

Interviews were audio recorded and transcribed, transcripts were reviewed for accuracy and coded by one of the interviewers using the software program NVIVO. The dataset was analyzed using a concept-driven thematic coding approach as outlined by Gibbs [24]. This is an inductive process starting with a set of categories derived by the researchers based on patterns and key themes that emerged during the interviews. These initial categories are then expanded, reorganized, and subcategories are created as coding progresses. Codes were derived from the data not from any preexisting codebook, review, or results. Coding involves interpreting each line of the interview as it was stated by the interviewee. The coding and categorization synthesize the data to identify and categorize all the information relevant to the research.

To provide context, quotations are provided throughout the results section. While these quotes are provided to give insight into how responses were categorized, they are not meant to represent the full depth of the conversation. The fleet number and barrier categorization applied to each quote is shown.

# 3. RESULTS

## 3.1. Barrier Categories

Based on the researcher's coding and categorization of interviewee transcripts, we classified barriers to heavy-duty electric truck adoption into six categories including three individual categories (technological (T), economic (E), and social (S)) and three hybrid (techno-economic (TE), socio-economic (SE), and socio-technological (ST)). These barriers provide a framework showing the complexities of heavy-duty truck electrification and how barriers transcend any individual category of economic, technological, and social issues. We determined our classifications based on how interviewees reported and discussed barriers. Technological barriers are defined as functional limitations of an electric truck and its associated infrastructure that inhibit its ability to fulfill the existing and perceived operations of the organization [21]. Such barriers occur when new technologies are seen as unable to perform the established practices of an incumbent technology [25]–[27]. In the case of electric trucks, examples of technological barriers include differences in the driving range per refueling and higher gross vehicle weight impacting an electric truck's ability to transport goods or the ease of transporting cargo in comparison to the incumbent diesel technology [28].

Economic barriers are impediments to the flow of money into and through the market or organization including revenue, capital costs, operational costs, financing, investment, and market prices [28]–[30]. Presently for electric trucks, these include barriers such as higher purchase costs and lower resale value compared to a diesel truck. These economic challenges may outweigh any potential operational cost savings.

Social barriers originate from people's connections and relationships with the truck and its supporting infrastructure. This includes their beliefs, values, understandings, perceptions, preferences, and psychological resistance to the new technology [29]–[31]. These relationships affect user attitudes and willingness to experiment [32]. One example of this would be a decision-maker believing that having trucks running on multiple fuels would increase complexity of buying, scheduling, fueling, maintaining, and retiring trucks.

Interviewees descriptions of barriers often overlap categories, requiring three additional hybrid categories combining pairs of the individual categories. For example, while driving range per charge is a technological barrier arising from the physical functioning and capabilities of presently available electric trucks, shorter ranges may impose operational restrictions in a fleet. If an interviewee connects shorter driving range to reduced earnings, then their description is categorized as techno-economic—combining elements of technological and economic barriers. In cases where the interviewee discusses a barrier as having components of multiple categories, the barrier is classified as a hybrid category: socio-technological, socio-economic, or techno-economic. While these classifications are used to categorize the way interviewees discuss each barrier, they are not an absolute description of the barrier. For example, interviewees reporting range as a purely technological barrier may in fact experience it as techno-economic but may not have made this connection or did not discuss it in the interview. Categorizations are based strictly on the interviewee's descriptions.

Figure 2, is a concept map of the identified barriers, the six barrier categories, and their connections. Category classifications are made for each fleet for each barrier based on how it is described by the interviewee, rather than how the researcher views it. These hybrid categories capture the interconnections between primary barriers, which are not assumed to be independent of one another [27]–[30]. Table 1 defines each barrier identified in this study and summarizes the categories they were discussed as.

While these six categories (three individual and three hybrid) are intended to guide discussion of truck electrification, the examples presented here are not necessarily representative of all fleet decisions or all possible categories of barriers. Furthermore, the novelty of heavy-duty electric trucks presents a dynamic landscape with barriers and interactions continuously evolving as technological capabilities and costs associated with electric trucks improve and fleets and drivers gain experience with them.

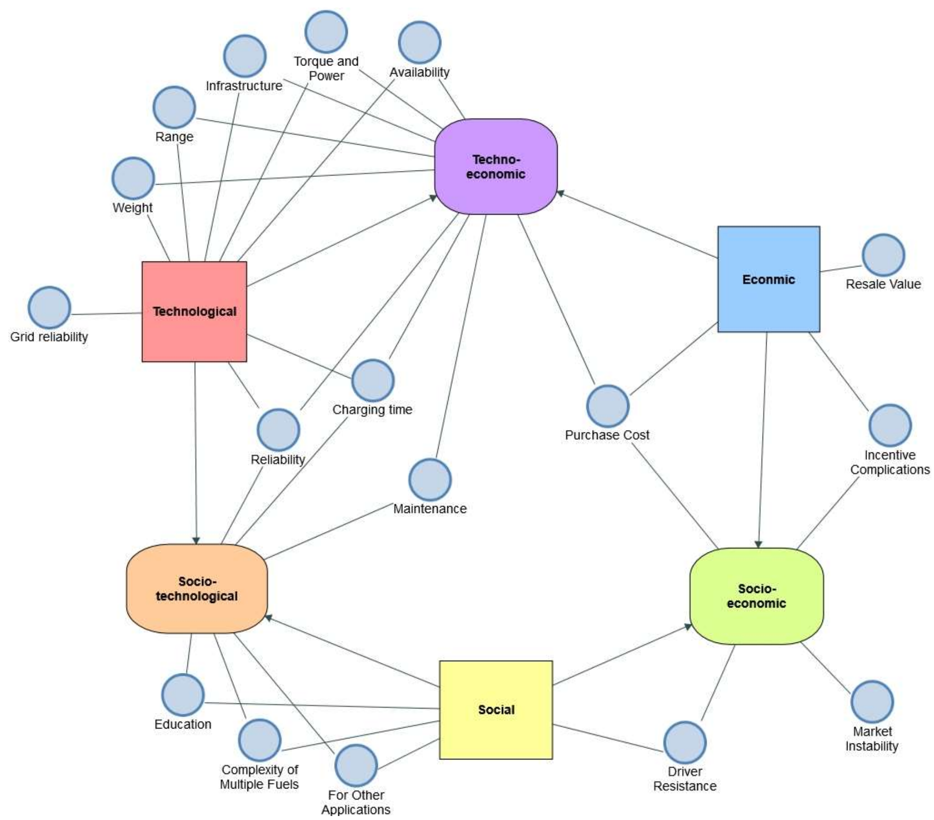


Figure 2: Concept map of barriers to electric truck adoption classified into social, technological, economic, and hybrid categories.

Table 1: Definition of barriers used in this study

| Barrier | Categories | Definition |
|---|---|---|
| **Infrastructure** | T, TE | Any issue related to charging infrastructure including lack of publicly available charging infrastructure and issues with installing private-use charging stations. |
| **Purchase Cost** | TE, E, SE | Issues around the higher purchase cost of heavy-duty electric trucks relative to diesel-fueled trucks. |
| **Range** | T, TE | Limited range of electric trucks per charge, in comparison to distances fleets travel and ranges achievable by diesel trucks. |
| **Availability** | T, TE | Overall lack of electric truck models available, both in specific applications and the industry more generally. |
| **Weight** | T, TE | Increased weight of electric trucks in comparison to that of a diesel truck, when subject to gross vehicle weight regulations. |
| **Charging Time** | T, TE, ST | Amount of time the truck is unable to move goods because of the need to charge. |
| **For other applications** | ST, S | Perception that the interviewee, their fleet, or their application are not responsible for testing out electric trucks; others should be responsible for this. |
| **Driver Resistance** | SE, S | Perception of the interviewee or self-reports of interviewee-drivers that drivers in their fleet are not willing to use electric trucks and may leave the company if forced to. |
| **Maintenance** | TE, ST | Any issue related to deviations in the fleet's current maintenance costs or structures. |
| **Education** | ST, S | Lack of knowledge about new technologies or regulations; self-reported or related to the industry in general. |
| **Reliability** | T, TE, ST | Concerns around the ability of electric trucks to fulfill routes. |
| **Incentive Complications** | E, SE | Issues with applying for or complying with the requirements of grant and incentive programs. |
| **Torque/ Power** | T, TE | Including issues of electric trucks having too much torque/power and with electric trucks not being able to maintain torque/power for extended periods of time. |
| **Market Instability** | SE | Uncertainty caused by frequent changes in regulations. |
| **Resale Value** | E | Any issues related to uncertainty in the resale value for used electric trucks. |
| **Complexity of Multiple Fuels** | ST, S | Concerns around the ability to manage trucks running on multiple fuel types. |
| **Grid Reliability** | T | Concerns with the impacts of potential electric grid outages on the ability of electric trucks to charge and operate. |

## 3.2. Barriers to Heavy-Duty Truck Electrification

Our results describe the barriers to electric truck adoption for fleets operating heavy-duty trucks. Figure 3 shows the distribution of barriers by barrier categories. This provides a breakdown of how fleets are perceiving these barriers and the relative prevalence of certain barrier categories over others.

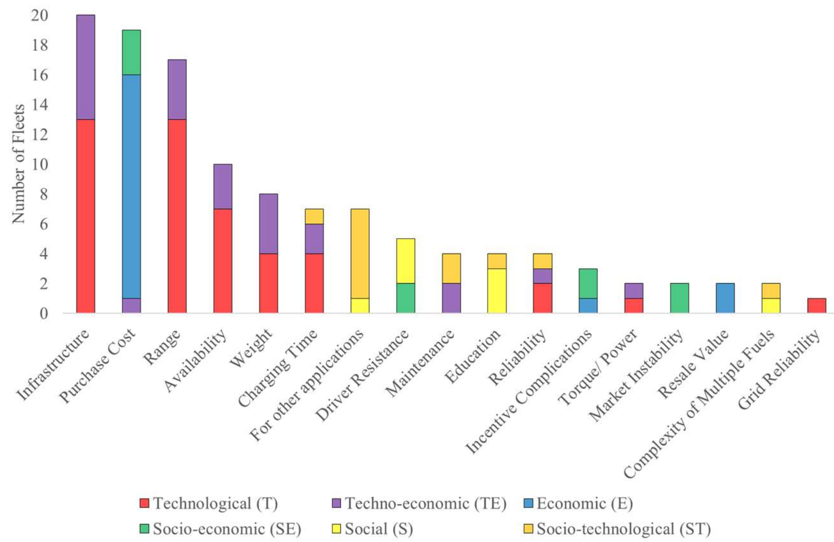


Figure 3: Reported barriers to fleet adoption of electric trucks by barrier category. ($n_{total}$=28)

### 3.2.1. Infrastructure

Lack of charging infrastructure was the most commonly mentioned barrier to heavy-duty truck electrification across fleet size and application as well as experience with electric trucks. This was categorized as both a purely technological barrier and a techno-economic barrier. From a technological perspective, interviewees describe charging infrastructure as almost nonexistent outside of California, making it impossible to drive electric trucks outside of the state. Fleets across application types mentioned refueling their diesel trucks at public stations and would similarly be reliant on public charging stations to recharge electric trucks. They believed that the lack of available public charging stations would prevent them from adopting trucks, even if they travel short distances. As mentioned by one interviewee, the lack of charging infrastructure is particularly an issue in the Midwest where many hubs of the country's trucking operations are located.

> *"For somebody like me who runs quite literally from Alaska to Florida and every place in between, I need something that's going to have infrastructure already in place and readily available."* (Fleet 19, T)

A lack of coast-to-coast network for heavy-duty truck charging was especially noted by interviewees from the long-haul fleet segment as they operate throughout North America. In these applications, it was noted that unless heavy-duty electric truck charging infrastructure is readily available throughout North America, electric trucks will be limited in where they can travel. These limitations prevent them from accepting certain loads, thus impacting profits, leading many fleets to report that they would be unwilling or unable to use them.

In this way, lack of charging infrastructure was determined to pose a techno-economic barrier, given the impact on both physical and financial operations. To combat this issue, many fleets had a dedicated set of trucks that operated solely within California, however, they still reported limited charging infrastructure restricted the routes electric trucks could serve. Each of these fleets noted they would be unable to purchase electric trucks until infrastructure was available.

The cost of installing charging infrastructure at fleet-owned facilities was also classified as a techno-economic barrier. While some fleets identified grant programs that were able to help with these costs, these fleets reported issues that prevented them from applying to these programs.

### 3.2.2. Purchase Cost

High purchase cost was categorized as an economic, socio-economic, and techno-economic barrier. Of the eight fleets who had experience with electric trucks, three have purchased an electric truck. The remaining five were involved in demonstration projects funded through the manufacturer or a government grant program. For fleets without electric truck experience, high purchase cost was cited as a primary reason they were not considering electric trucks, even amongst those who were aware of upcoming requirements for their purchase.

From an economic perspective, fleets mentioned that they would be unable to pass the higher costs on to their customers because they would be outbid by fleets who are operating diesel trucks, so they would be forced to absorb the costs within the company. Some fleet decision-makers noted that they had heard the cost of electric trucks is expected to decline; they would wait for this to happen before seriously considering purchasing them.

> *"I don't know who can afford a brand-new electric truck, there's no 20-fleet company that can afford a half-a-million-dollar trucks, it's just not going to happen."* (Fleet 10, E)

High purchase cost was categorized as a socio-economic barrier for two fleets. They emphasized the strain of increasing costs on the relationships with their customers as the root cause. They believed high purchase costs would not pose as high of a barrier if they were able to pass the increased costs on to their customer. Given the competitive nature of the freight industry, they believed their customers may move to another fleet if they tried to do this, so they were not seriously considering purchasing an electric truck. Another fleet who contracts with owner-operators believed their drivers would rather leave the industry than go into debt paying the high costs of an electric truck. The fleet was not willing to risk upsetting their drivers by requiring these high-cost trucks.

One interviewee believed that a higher cost could not be justified given the operational restrictions (e.g. length of time the truck operates before charging) imposed by the technology. Based on this, the barrier was identified as a techno-economic barrier. The interviewee noted that the purchase price of electric trucks is beginning to decrease, and when factoring in purchase incentives, electric trucks begin to approach a feasible price.

#### 3.2.3. Range

Range was often categorized as a technological barrier and were mentioned by fleets operating in drayage, short-haul, and long-haul, not exclusive to the long-haul sector. While operating significantly fewer miles per day, interviewees from short-haul and drayage fleets mentioned they did not believe current electric trucks had sufficient range to accomplish tasks. One interviewee noted that the longest range heavy-duty electric truck currently available has 250 miles of range, which may be able to meet their requirements, except "*you're not supposed to charge the battery to 100% all the time, so we're looking at 90%... so then you're limited to 110-mile radius*" (Fleet 10, T). Interviewees also reported hesitations about impacts of cold temperature on battery range stating, *"it's going to be minus 10 tonight. Batteries, they just can't handle that"* (Fleet 02, T).

Some interviewees reported trucks driving up to 740 miles per day, they indicated that if trucks are unable to maintain mileage requirements, this would impact their profits, which prevented them from considering electric trucks. In this way, limited driving range was categorized as a techno-economic barrier and as being insurmountable. One fleet discussed options for purchasing a truck with a larger battery pack to increase range but said that they would not be willing to take this option because it would increase the purchase cost.

#### 3.2.4. Availability

The lack of electric truck options available was another commonly discussed barrier across fleet types, especially for fleets with strict specifications. This was categorized as a technological barrier for fleets discussing only factors such as lack of electric truck availability overall, in certain weight classes, for certain truck types, and in truck length. Fleets operating in short-haul applications who deliver in urban or otherwise physically constrained areas mentioned that available electric models had a longer wheelbase than the equivalent diesel truck, lengthening the truck's turning radius, limiting their ability to deliver to certain areas.

From a techno-economic perspective, one fleet noted that the electric truck they were demonstrating had a wheelbase that was 16 inches longer than that of the trucks they traditionally purchase, so they had to dedicate additional time to getting in and out of stores to which they delivered, slowing delivery speeds, again reducing profits. Some fleets mentioned that even when electric trucks begin to come to market, they want to wait for them to be more widely available and used in their specific application before they try them.

#### 3.2.5. Weight

Interviewees across all fleet types report their trucks often operate near the federal weight limit of 80,000 pounds. Adding weight to the truck in the form of batteries would limit the weight of revenue-earning loads they could carry, with one interviewee noting, *"it's not there from a weight of the truck and us being able to carry the amount of cargo that the customers expect us to carry"* (Fleet 08, TE). One interviewee mentioned they were aware of the additional 2,000-pound allowance for natural gas and electric trucks but felt this was still not enough to make up for the additional weight of the battery. Another fleet called for regulators to increase the gross vehicle weight rating by 10,000 pounds for electric trucks to avoid financially penalizing fleets who make the transition.

*"The battery electric [truck] is coming in anywhere between 23-24,000 pounds where a day cab diesel is about 16,000 and a CNG truck is about 17,500… so you increase [truck weight] almost 6-7,000 pounds. Now that hurts your capacity to transport."* (Fleet 05, TE)

### 3.2.6. Charging Time

Long charging times were also mentioned as a significant barrier to electric truck adoption. In many fleets, long charging times are seen as barriers because they are not aligned with the way fleets currently operate, creating a technological barrier. Interviewees commonly mention charging times should fit in with their current operating structures, including charging for a maximum of one or two 15-30 minute breaks during each 10-hour shift. One owner-operator specified that long charging times would be invasive, and he would not be willing to stop more often than he needed to, indicating a socio-technological barrier.

Some fleets noted that their trucks operate in two shifts each day, leaving less than four hours during which the truck is inactive. They perceive this would not be long enough for the trucks to charge to support their operations for the other 20 hours. One long-haul driver discussed the regulations on their driving hours per day, noting an individual is only allowed to drive a maximum of 11 hours. He stated time spent charging during this period would cut into the time he could be driving, limiting how far he could travel in a day, and reducing profits. Under these constraints, he feels that charging times would need to be reduced to fit into current rest periods of 30 minutes at a time otherwise they pose a techno-economic barrier.

### 3.2.7. Waiting for Other Fleets/Applications to Try Them (For other applications)

Fleets commonly mentioned they did not believe electric trucks would work for their applications and that it was the responsibility of those in other applications to demonstrate their feasibility. Notably, this shifting of responsibility for demonstrations was done across all truck applications and fleet sizes. This barrier was largely socio-technological with fleets suggesting that those with smaller operating territories and more fixed routes would be more suited to electrification because of their lower range requirements. Some fleets specifically pointed to drayage and short-haul applications as being best suited for electrification.

For two fleets, this was categorized as a social barrier. One decision-maker stated that fleets who operate solely in California should be the first to electrify because that is where the air quality issues are worst and electricity sources are the most regulated. A truck owner-operator stated that it wasn't necessarily that the technology would not work for him, but that he was simply too old to try new technologies. He felt that the younger generations should be left to do these demonstrations.

*"I'll leave [electrification] to younger kids who can invest more time. Like I said, I've only got 6-7 years [left driving] and I'm going to try to do it as cleanly and efficiently and with as less stress as I can."* (Fleet 24, S)

### 3.2.8. Driver Resistance

Driver resistance was mentioned as a social and socio-economic barrier to truck electrification. Discussions of driver resistance categorized as social barriers stem from a wider conversation around driver shortages which were mentioned by nearly all fleets as being an industry-wide phenomenon. They felt that as the workforce ages, fewer people are going into the profession and there is increased competition for drivers between companies.

From a socio-economic perspective, if companies are unable to keep their drivers happy, they risk having too few drivers to meet their needs. Interviewees reported that drivers are generally resistant to any changes and that such a large change as switching fuel types would likely be met with resistance and could lead them to switch companies. Two interviewees with experience contracting with independent owner-drivers stated that the drivers had threatened to leave the trucking business if they were required to purchase an electric truck. One reported that they switched entirely to company-employed drivers because of the shortage of owner-drivers who had emissions compliant trucks. From the fleet's perspective, drivers leaving the company prevents electric truck adoption because this would lessen the amount of goods they can move, lessening profits. In this way, driver resistance is a socio-economic barrier, as it has elements of both social and economic barriers.

> *"Whether I want it or don't still hinges on them wanting it, because if they can't embrace the technology, they might leave me and go somewhere else. Well then I just shot myself in the foot because now I have a truck that nobody wants to use."* (Fleet 02, S)

### 3.2.9. Maintenance

Maintenance concerns were related to both the longevity of the battery life and the inability of the organization's mechanics to work on the trucks. For two fleets this was categorized as a techno-economic barrier. Fleets expressed concern over the lifespan of the battery, stating that a lifespan of five to eight years would increase their costs. One decision-maker believed that continuously fast-charging the battery would damage it, causing them to need to replace it sooner.

From a socio-technological perspective, decision-makers from two other fleets reported that their maintenance teams were unfamiliar with electric trucks so they would have to take the trucks to a dealer for service instead. This could lead them to close their maintenance shops altogether. Notably, maintenance issues were only mentioned by large fleets, with many small fleets reporting that they did not have their own dedicated maintenance team, so this was less of a concern.

### 3.2.10. Lack of industry-wide knowledge (Education)

Interviewees noted that the lack of knowledge about new technologies and emissions regulations posed a challenge throughout the industry. This was primarily categorized as a social barrier with one fleet noting all environmental policies are negatively viewed by the trucking community with people choosing to resist them rather than trying to understand how to make them work. The interviewee believed that technologies and regulations are constantly changing and vary across states, which can make it difficult for everyone to, *"deal with and cope with… they just flat out get angry"* (Fleet 01, S). Because of this, fleets noted that while they would like to be able to try new technologies, they are too busy trying to keep up with current regulations that they do not have time for additional research. These interviewees believed that while larger fleets may have people dedicated to keeping up with new technologies and regulations, smaller fleets are often run by a single person or a small group, making it difficult to keep track of everything. These fleets were seen as needing much more outreach and education before they consider electrifying.

> *"There is a stunning lack of knowledge in the industry, especially as you get down to the medium and small fleets… people start trucking companies and they end up working 70, 80, 90 hours a week and they don't have a lot of time to educate themselves, they just see regulations getting piled on them."* (Fleet 01, S)

One interviewee discussed their own internal lack of knowledge about electric trucks, stating, *"it's been a challenge for me too, I mean I know a lot about internal combustion engines and how they work… but once you start taking about electric, I have no idea what I'm doing"* (Fleet 17, S).

From a socio-technological perspective, one fleet mentioned that they choose not to educate themselves about the technology because, *"they don't have an electric vehicle just yet that will get the mileage that I need to go… and I know that there isn't enough information out there yet, so I haven't even put in the research"* (Fleet 24, ST). In this way, the perceived technological restrictions of the truck created a social barrier in the interviewees unwillingness to dedicate time to research the trucks.

### 3.2.11. Reliability

Concerns over how reliable an electric truck will be were centered around new technologies being seen as unproven. This was categorized as a technological, techno-economic, and socio-technological barrier. On the technological side, one fleet hauling food expressed concerns with the truck's ability to maintain "temperature integrity", fearing that they could get into "food poisoning or hazmat issues" if the truck were to fail. One fleet discussed reliability from a socio-technological perspective, mentioning that if the truck were to break down on the road, it could leave the driver in an unsafe situation. From a techno-economic perspective, fleets were concerned that if the truck were to have a "catastrophic breakdown" they would be unable to fulfill the job for the customer, which could cause them to *"find somebody who can… they will vote with their feet and they will move on to someone that can service them"* (Fleet 03, TE).

### 3.2.12. Incentive Complications

While interviewees mentioned there are grant programs available to help fleets deal with high upfront costs, many found it difficult to comply with these programs. Some fleets noted that the program deadlines are too short, and that trucks often take a year or more to arrive after they are ordered, making it impossible to procure trucks within the specified timelines. The mismatched timelines and requirements of different programs also created complications for fleets. One interviewee noted the utility would only begin working with the fleet once they committed to purchasing electric trucks, but that grants to purchase electric trucks were set to expire before the trucks are available. The interviewee stated that all the deadlines and requirements were overwhelming and "almost too much to handle." Others noted that the funding is too limited to make the costs comparable, specifically referring to one program which they believed offered $80,000 incentives, which does not reduce the $500,000 price tag of an electric truck enough to make the purchase viable.

Fleets with CNG experience noted that they had made initial investments into these trucks with the help of grant and incentive programs, but that the funding for this had since diminished. They noted that programs were created to get fleets out of their diesel trucks and into alternative fuel trucks, but that once the lifetime of the CNG truck was up, there was no support for the purchase of additional CNG trucks. Given that their purchase price was not yet comparable to diesel, they had to either find additional funding sources or revert to diesel trucks. This shows that there is a need for continued funding of fuels beyond the initial deployment. Fleets feel that if funding won't be able to support them in the future, then there is a greater likelihood that their investments will lose their value. Similarly, while complications with incentive programs and market instability are primarily economic, they are also social. Both of these are based on the decision-maker's perception that the fleet would be financially penalized for electrifying or the need to change the way they purchase to accommodate electric trucks.

### 3.2.13. Torque/ Power

The torque and power of an electric truck were mentioned by two fleet decision-makers as being a concern. One interviewee in a fleet without experience with electric trucks mentioned that he had heard electric trucks have good power but was concerned about how durable this would be under a rigorous duty cycle. If the truck could not maintain the needed power, it would create a techno-economic barrier in that they would be unable to move the goods they were hired to move.

This was categorized as a technological barrier for another fleet with experience operating electric trucks. The interviewee stated electric trucks had too much torque, creating a safety hazard. The fleet was using the electric truck to haul chemicals over short distances and drivers reported feeling unsafe with how the truck's acceleration would pull the cargo around. After sending it back to the manufacturer twice to get the torque adjusted, they decided to remove the vehicles from the fleet, noting they would revisit the idea in five years.

### 3.2.14. Market Instability

A common concern with alternative fuels is that fleets are uncertain where the market and regulations are moving towards. This lack of market stability was seen as creating a socio-economic barrier. Interviewees noted that regulations previously pushed them to invest in CNG trucks and infrastructure. Since then, regulations had changed, and fleets now need to invest in zero emission fuels to be regulatorily compliant. Some fleets feel that they are being punished for having been early adopters of natural gas trucks as they are now being told they cannot use them anymore. This led to similar comments about how being early investors in zero emission trucks may create complications as they may also fall out of favor as a new technology comes along. This led to calls for a guarantee that if they invest in a zero-emission fleet, it will not be a waste of funding or become obsolete in the future.

> *"We have a $3.5 million CNG slow fill station out there that within 10 years may be obsolete because all those vehicles need to be electric. If we invest millions of dollars in electrical infrastructure, who's to say in 10 years whether that may not become out modeled in some way?"* (Fleet 11, SE)

### 3.2.15. Resale Value

Many fleets reported using resale value as a part of their truck cost calculations. One of these fleets believed that there is less of a market for used alternative fuel trucks, including electric trucks, which would impact the truck's lifecycle costs. Another fleet stated that they had received pushback from the bank when asking about financing for electric trucks because the bank was unable to determine the residual value of the truck, which is a primary factor in determining leasing rates. While the interviewee was able to negotiate with the bank and reach an agreement, they felt that the uncertain resale value will challenge other fleets looking to lease these trucks until better data becomes available.

### 3.2.16. Complexity of Operating Trucks with Multiple Fuels (Complexity of Multiple Fuels)

One interviewee operating a small long-haul fleet discussed operating trucks running on multiple fuel types as a socio-technological issue. The decision-maker did not feel they would be able to accommodate electric trucks because it would be too complicated to have multiple fuel types in the fleet. The interviewee noted that he would need to find new places to fuel the trucks and would have to adjust the routes to accommodate their range restrictions. He felt that larger fleets would more easily be able to experiment with electric trucks, but with so few, they did not have the capacity to do these trials. Another interviewee noted this as a social issue, stating that having the drivers handle multiple fuels causes issues.

> *I can't get my drivers to put the right fuel in a vehicle, gas or diesel. Having them plug a vehicle in every night may be a little touchy."* (Fleet 26, S)

### 3.2.17. Grid Reliability

The ability of the electric grid to support electric truck charging was also mentioned as a barrier to truck electrification. The interviewee did not believe that the electric grid would be able to support the additional load that electric trucks would add. This concern extended to whether his facilities would be able to get sufficient power and whether it would be reliable, given the potential for Public Safety Power Shutoffs (in which the electric grid is preemptively powered off to prevent power lines from sparking wildfires in extreme weather scenarios) at his California facility. With the power being off for hours to weeks, he feared that his operations would need to shut down in these events.

# 4. DISCUSSION

While some barriers mentioned by fleet decision-makers in this study have been previously reported in the literature, interviewees discussed these as other than purely technological or economic. Discussions include social and hybrid barriers. Hybrid barriers transcend the boundaries between technological, economic, and social categories and provide an important distinction from them by describing the way these barriers manifest within the fleet. While some fleets discuss barriers from a purely technological perspective, these issues tie back to the economic effects they have on the organization or their ability to operate profitably.

This study additionally identified barriers that were not widely discussed in previous literature with two barriers (for other applications and market instability) found to be absent. These lesser mentioned barriers were more commonly social and social-hybrid barriers, which were revealed through the interviews, and which may have been undetectable without speaking with decision-makers.

Our research showed the prevalence of infrastructure, purchase costs, and range as barriers to heavy-duty truck electrification. Each of these was mentioned by over half of the interviewees indicating that they are on the forefront of fleet's perceptions about electric trucks and that these need to be resolved before they can more fully consider heavy-duty truck electrification. Other less frequently discussed barriers may loom equally large once they capture the attention of fleet decision-makers.

Many of the barriers presented were discussed as such because of their deviance from the characteristics of incumbent diesel trucks. Factors such as range, weight, and cost were discussed as economic or technological barriers to electric truck adoption, however, operational or social changes may present solutions. For example, the limited range of electric trucks per charge can be mitigated through increased charging frequency or altering existing routes to allow for electric truck use. Upfront cost constraints suggest the need for financial models that instead focus on total cost of ownership or creating partnerships with manufacturers or governments to participate in demonstration or grant programs.

Fleet purchase mandates, such as California's forthcoming ACF regulation, may encourage fleets to seek new solutions to barriers such as availability, market instability, and perceptions that the truck is best suited for other applications. Increased supply and demand from these regulations increases economies of scale, driving innovation, indirectly reducing barriers such as purchase cost, education, and resale value.

Other barriers may require education and outreach campaigns to address driver resistance and disproportionate difficulties of smaller fleets. These can help mitigate the effects of social, socio-economic, and socio-technological barriers, which are based in people's perceptions of the vehicle and its value. Interviewee descriptions of these barriers extend beyond the fleet, involving external stakeholders whose participation in educational campaigns would influence a fleet's ability to adopt electric heavy-duty trucks. This includes individuals at electric utilities, ports, and freight customers.

The discussions with interviewees revealed government grant programs that were available in the long-term and provided enough support to cover the incremental costs of zero emission trucks were viewed most highly. Additionally, many fleets relied on demonstration projects to help experiment with new technologies without the risk of investing in their purchase. They noted that by bringing demonstration projects to fleets where they currently operate, such as truck stops, dealerships, and warehouses, fleets do not have to take additional time and effort to learn about new technologies arriving on the market. These insights can provide important lessons for the successful deployment of zero-emission trucks.

# 5. CONCLUSION AND FUTURE RESEARCH

We investigate barriers to adoption of electric heavy-duty trucks in fleets operating in California as perceived and reported by decision-makers within such fleets. We assign barriers to heavy-duty truck electrification into six categories: technological, economic, social, socio-economic, socio-technological, and techno-economic. These categories allow for a deeper understanding of the impacts of each barrier on fleets including how barriers are not purely technical, economic, or social. These barriers may need to be addressed first for fleets to consider truck electrification which may implicate actors and decision makers outside of a single fleet. These insights inform solutions to these barriers that are sensitive to differences between fleets. While talking to additional fleets may elicit additional barriers or allow discussions of barriers to manifest in new ways, these interviews provide important insights into fleets' apprehension towards heavy-duty truck electrification.

Meeting heavy-duty truck electrification goals, such as ACF and ACT will require substantial amounts of support. Truck manufacturers are working to improve their battery technologies to increase range and charging speed while decreasing weight [37], [39]. Limited range can also be addressed through operational changes such as increasing charging frequency or changing routes to accommodate those an electric truck can cover. To address weight constraints, in the European Union, zero emission trucks are allowed to carry an additional 2 metric tons (4,400 pounds), allowing fleets to adopt electric trucks without sacrificing their ability to transport [40]. As the technology matures, purchase prices are expected to decline, decreasing in this barrier, although government support may be essential for adoption in the interim.

Policies which expand the availability of charging infrastructure and provide financial assistance for the purchase of electric vehicles have helped overcome some of these same barriers for light-duty electric vehicles [41], [42]. These policies may serve as a model for reducing technical and economic barriers for heavy-duty truck electrification. Given the differences in duty cycle and vehicle technologies, programs should be tailored to the needs of the heavy-duty sector. While these policies can be used to target barriers that overlap with those of the light-duty sector, other heavy-duty specific barriers will require targeted solutions. For example, social-based barriers may require programs to introduce drivers and decision-makers to the technology [25], [43].

This study highlights the ways in which barriers to heavy duty truck electrification are varied and transcend technological, economic, and social issues to include socio-technological, techno-economic, and socio-economic issues. This framework is intended to inform future research into these issues to better inform stakeholders about issues which needed to be addressed in the pursuit of reaching 100% electric trucks.

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