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The Zero-Emission Freight Revolution: California Case Studies

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Summary

Two projects deploying over 50 pieces of zero-emission freight technology (medium-duty trucks, heavy-duty trucks, and yard tractors) are nearing completion. Data was collected during normal real-world operations and analyzed to assess energy consumption, operational costs, and emissions offset relative to conventional technologies. Results indicate that energy and cost savings are achievable but very much depend on the application and operating constraints. With limited medium- and heavy-duty zero-emission data currently available, these results help quantify the impact of zero-emission solutions in the commercial vehicle space.

Keywords: heavy-duty, EV (electric vehicle), case-study, freight transport, sustainability

1 Deploying Transformative Zero-Emission Technologies

1.1 Background

The State of California has taken extensive measures to transition medium- and heavy-duty (MHD) vehicles to zero-emission (ZE) models as part of its effort to achieve its climate goals.[1] The California Air Resources Board's (CARB) model of targeting emissions from a specific sector, offering incentive funding to spur innovation, funding pilots and demonstrations of low-emission equipment, and then using regulations to mandate adoption within the sector is showing promise [1]. After targeting emissions from commercial vehicles, CARB created the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) to provide vouchers that reduce the upfront cost of clean trucks [2]. Similarly, the Clean Off-Road Equipment Voucher Incentive Project (CORE) provides incentives for off-road equipment [3]. The Low Carbon Fuel Standard (LCFS) is another example and tool: this program set a target of reducing greenhouse gas emissions from transportation by 20% by 2030 [4]. Fleets using less carbon-intensive fuels than a continually decreasing benchmark generate LCFS credits which can be sold to other fleets, effectively lowering the cost of fueling cleaner vehicles.

After creating incentive programs like HVIP, CORE, LCFS, and others, California began implementing regulations to require lower emissions from transportation. In 2018, California adopted the Innovative Clean Transit Rule (ICT) mandating public transit agencies to gradually transition to 100% ZE bus models by 2040. In 2020, the Advanced Clean Trucks (ACT) Regulation was adopted, requiring manufacturers to sell an

[1] Medium-duty is defined under the American system as 10,001-26,000 lbs or 4,536-11,793 kg Gross Vehicle Weight Rating; heavy-duty is >26,001 lbs or >11,794 kg

increasing percentage of ZE MHD vehicles beginning with the 2024 model year [5]. By 2035, 75% of straight truck sales and 40% of tractor sales must be ZE. It is important to note that a successful transition to ZE transportation requires a strategic combination of incentives, regulations, demonstrations, and policies as well as collaboration with utilities and local governments to support permitting and energizing of infrastructure projects.

Not all ZE technology has been commercialized at the same rate, and MHD vehicles have been among the hardest to electrify. In conjunction with CALSTART, CARB created the Beachhead Strategy to address these shortcomings [6]. The Beachhead concept seeks out first-success applications where ZE technologies are currently viable and can serve as cornerstones for the development of future vehicle and equipment applications. A visualization of this process is shown in Figure 1 below.

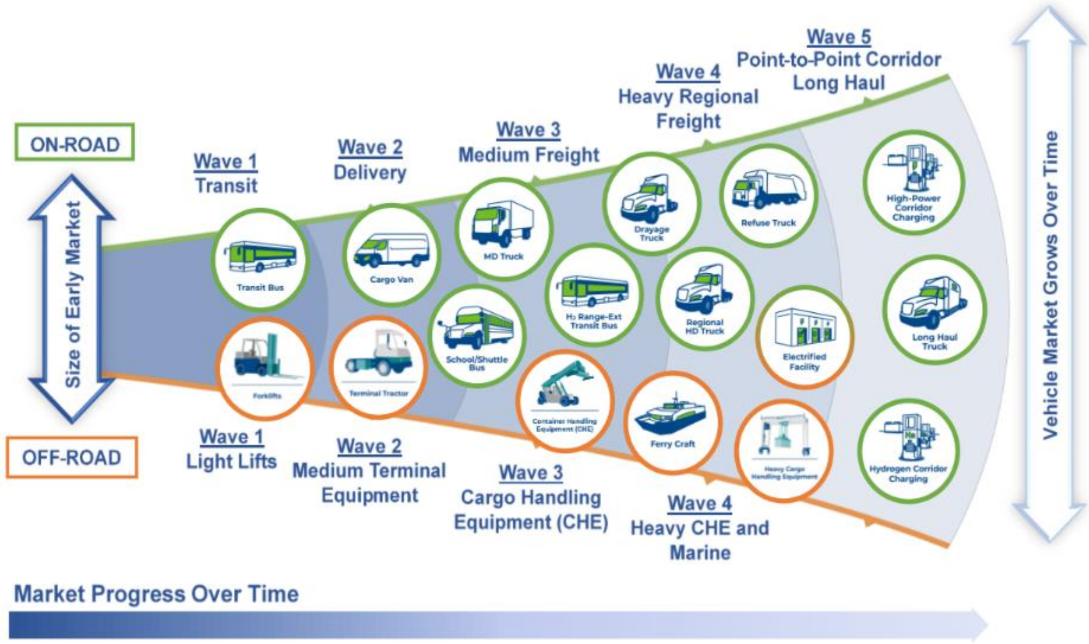

Figure 1: CARB's Beachhead model as of April 2022

Subsequent waves of electrification are presented left to right, with cargo vans and transit buses electrifying before drayage[2] trucks. Advancements from these vehicles are utilized by the technologies that follow. The market in California is currently between waves three and four, with transit buses and yard tractors established as successful applications while MHD zero-emission trucks (ZETs) like drayage and regional delivery trucks are starting to be deployed. As the nascent MHD ZET market develops, investing time and resources to learn from real-world deployments will help in successfully replicating them across California and in other states [7].

In 2018, CARB launched the Zero- and Near-Zero Emission Freight Facilities (ZANZEFF) Program, awarding nearly $200 million dollars to 11 projects showcasing commercial battery-electric vehicles (BEVs) and infrastructure together with other efficiency improvements at freight facilities [8]. ZANZEFF projects include comprehensive data collection and analysis to demonstrate technology performance within real fleet operations, reducing reliance on assumptions or unrealistic test conditions.

CALSTART, in partnership with the University of California, Riverside (UCR), is currently completing analysis of two advanced demonstrations of fleet electrification. Both projects focus on comprehensive vehicle data collection and analysis to demonstrate BEV technology across multiple platforms in daily operations and quantify the benefits they provide in emissions and energy savings. This analysis offers a unique look into the electrification efforts the freight transport sector will need to achieve in coming years.

The goal of this paper is to share findings and lessons learned from three fleets deploying BEV equipment across the two ZANZEFF projects to support the accelerated adoption of these technologies. The first project

[2] Drayage is defined as the transport of freight in MHD trucks from a port to a destination, usually a warehouse or distribution facility [9]

is the Volvo Low Impact Heavy Transport Solutions (LIGHTS) Project. Volvo LIGHTS involves two fleets conducting port drayage operations and regional deliveries in Southern California [10]. Fleet A demonstrated BE off-road vehicles and BE HD trucks in drayage duty cycles between the Port of Los Angeles and it's Ontario, CA facility. Fleet B also used drayage routes to their facility in Chino, CA. The second project involves Fleet C, located in California's Central Valley, which is converting nearly all transportation equipment at a 500,000 ft^2 manufacturing facility to BEVs.

1.2 Technology Deployment Overview

In total, 69 BEVs, including 24 HD trucks, six MD trucks, seven yard tractors, and 34 forklifts were deployed as part of these projects. Five of the battery-electric (BE) HD trucks were deployed by Fleets A and B for intensive data collection, alongside 4 BE yard tractors. At the time of writing, Fleet C had deployed three BE yard tractors and six BE MD box trucks. For each type deployed, data was also collected on a similar conventional diesel vehicle. Table 1 summarizes the BE and conventional equipment that is the subject of this analysis.

Table 1: Vehicles used for data collection; parentheses denote onboard battery capacity in kilowatt-hours (kWh)

		Fleet A	Fleet B	Fleet C	Manufacturers
Yard Tractors	BEV	2 (160 & 80 kWh)	2 (176 kWh)	3 (209 kWh)	Orange EV, Kalmar, BYD
	Diesel	2	2	1	Cummins, Kalmar
Heavy-Duty Trucks	BEV	4 (264 & 396 kWh)	1 (264 kWh)	-	Volvo Trucks North America
	Diesel	4	4	3	Cummins, Detroit Diesel, Volvo Trucks North America
Medium-Duty Trucks	BEV	-	-	6 (148 kWh)	Peterbilt

2 Methodology

2.1 Data Collection

Multiple sources of data were collected and analyzed. Onboard data loggers were used to collect vehicle performance parameters such as miles driven, hours in operation, and energy consumed. Duty cycle and vehicle performance information was derived from these data alongside fleet insights. The vehicle data was supplemented with charger data that captured information including energy charged and charging times which allowed us to calculate total energy consumption and efficiency. Energy costs were calculated by applying charger-side data to the relevant rate structure or directly from utility bills. Maintenance cost data came from fleet and OEM maintenance logs.

Tailpipe emissions from the conventional vehicles were quantified by UCR's Center for Environmental Research and Technology (CE-CERT) using portable emissions measurement systems (PEMS) that tested for greenhouse gases including CO_2 and other pollutant emissions such as NO_x, providing precise, actual measurements. The PEMS are the same used and approved by the federal register for the evaluation of heavy truck compliance for in-use testing programs and the results allowed for the extrapolation of annual emissions offset from fleets transitioning to BEVs. The team took extensive measures to validate all the data by comparing results before drawing conclusions. All data in this paper has been reviewed and validated by the fleets, and in many cases by the manufacturers as well.

2.2 Analysis

We compared the performance of the BE equipment with comparable baseline equipment in terms of duty cycle suitability, energy efficiency, cost efficiency, and emissions offset. Duty cycle metrics include daily mileage, average speed, idle time percentage, and number of stops. Fulfilling the duty cycle requirements is the first question a user fleet has regarding the suitability of the technology and requires data such as vehicle range, hours in operation, and required charging time. We compared data between BE and conventional technology to ensure similar duty cycles. Energy and cost analyses were performed by investigating energy consumed, energy efficiency, daily operational costs, maintenance costs, and overall lifetime costs expressed as total cost of ownership (TCO). Finally, the emissions data were used to assess the environmental benefits of transitioning to BE operations.

The TCO analyses discussed in this report are calculated by summing upfront costs (vehicle, charger, and incentive funding) and operating costs (fueling, maintenance, insurance, and LCFS credits) for both BE and baseline vehicles. Annual hours in operation were standardized and the TCO calculated costs were based on the number of years each vehicle type is expected to be in service. Upfront vehicle and infrastructure costs came from fleet and OEM discussions and documentation. Incentives amounts were defined by CORE and HVIP. The cost of yard tractor and Class 6 chargers ranged from $6,000-$69,000 while Class 7-8 chargers were $85,000. TCO infrastructure costs do not include construction, installation, and commissioning as these can vary greatly by site and region. Infrastructure costs were divided by the number of vehicles charging on each charger. Based on input from fleets, insurance costs were assumed to be zero for yard tractors and 5.5% of the upfront costs for Class 6-8 trucks. California sales tax of 8% was applied to all vehicles and the federal excise tax of 12% was applied to the Class 6-8 trucks. Yard tractors are excluded from the federal excise tax because they are considered off-highway [11].

3 Results

3.1 Yard Tractors

3.1.1 Duty Cycle

Yard tractors present an excellent use case for BEVs because their duty cycle is characterized by low speeds, low mileage, and long idle periods. We collected data on the BE yard tractors at fleets A, B, and C for one year, nine months, and 5-10 months, respectively. Fleet A acquired two Orange EV BE yard tractors replacing two diesel units. BEV 1 had a battery capacity of 80 kWh and BEV 2 had 160 kWh. The fleet wanted to test a bigger battery with the goal of minimizing charging during shifts. After their successful deployment, they plan to continue purchasing BE yard tractors with larger batteries to allow for longer shifts. However, state of charge was rarely observed below 60% due to opportunity charging during shift breaks. Both yard tractor operated 9-13 hours per day and did not leave the yard, so there were many chances to charge. Three to eight hours per day were spent charging on 22 kW chargers, and both yard tractors combined, charged 125 kWh. Chargers did not distinguish between vehicles so total energy charged was split between BE yard tractors proportional to time in use. Table 2 describes the yard tractor duty cycle at Fleet A and key operating metrics.

Table 2: Fleet A yard tractor duty cycle comparison of average metrics with 95% confidence interval (CI) ranges

Fleet	Vehicle Type	Daily Key-on Time (hours)	95% CI	Daily Charging Time (hours)	95% CI	Daily Energy Charged (kWh)	95% CI
Fleet A	BEV 1	9.4	± 0.3-1.3	2.9	± 0.2-0.3	35	NA
	BEV 2	12.6		7.7		92	
	Diesel	11.7		-		-	

Fleet B adopted two 176 kWh Kalmar Ottawa BE yard tractors. They shuttled freight, moved trailers between or within facilities, readied trailers for pick up, and received returned trailers. Three shifts were operated throughout the day but, depending on workload, a yard tractor could be used for only a single shift, so operating and charging times varied. Table 3 compares the yard tractor duty cycles for fleet B.

Table 3: Fleet B yard tractor duty cycle comparison of average metrics with 95% CI ranges

Fleet	Fuel Type	Daily Key-on Time (hours)	95% CI	Daily Charging Time (hours)	95% CI	Daily Energy Charged (kWh)	95% CI
Fleet B	BEV 1	8.9	± 0.5-0.7	2.3	± 0.2-0.2	75	± 6.1-6.7
	BEV 2	7.9		2.8		87.4	
	Diesel	9.3		-		-	

The BE yard tractors averaged 8-9 hours per day in operation, often evenly split between driving and idling. This is typical of yard tractors as they spend significant amounts of time waiting for trailers to be readied for transfer. While the diesel yard tractors operated up to 14 hours per day, the fleet reported that the BE yard tractors met their required duty cycles. The BE yard tractors charged 2-3 hours per day and consumed 75-90 kWh each.

Fleet C adopted three 218 kWh BYD BE yard tractors alongside their five diesel units. Their operations are highly dependent on these units, and they were used intensively, regularly operating 14-16 hours, each moving 175 trailers per day. Table 4 displays their duty cycle metrics.

Table 4: Fleet C yard tractor duty cycle comparison of average metrics with 95% CI ranges

Fleet	Fuel Type	Daily Key-on Time (hours)	95% CI	Daily Charging Time (hours)	95% CI	Daily Energy Charged (kWh)	95% CI
Fleet C	BEV 1	16.0	± 0.3-0.9	2.1	± 0.1-0.2	164.8	± 9.3-15.0
	BEV 2	16.1		2.1		150.6	
	BEV 3	14.4		1.9		148.0	
	Diesel	11.0		-		-	

The BE yard tractors met this demanding duty cycle due to opportunity charging during breaks and shift changes. The vehicles only charged for 2 hours in total per day on chargers rated at 125 kW. Actual power was limited to 80 kW via smart charging software. The Class 6 BE box trucks (discussed in Section 0 below) shared these chargers, but the yard tractors were prioritized to keep them running as much as possible. Fleet C's yard tractors had the most demanding duty cycle and needed the fastest chargers to keep pace with 24-hour operations. All three fleets generally maintained a state of charge above 60% due to taking advantage of opportunity charging during breaks and between shifts.

3.1.2 Energy Use and Costs

Table 5 and Table 6 below compare energy efficiency between diesel and BE yard tractors across the fleets studied using three different metrics: diesel gallon equivalents per hour (DGE/hr), kWh/hr, and kWh/mile.

Table 5: Fleets A and B yard tractor energy efficiency comparison of average metrics with 95% CI ranges

Fleet	Vehicle Type	Energy Used per Hour (DGE/hr)[3]	95% CI	Efficiency (kWh/hr)	95% CI	Efficiency (kWh/mi)	95% CI
Fleet A	BEV 1	0.16	± 0.0-0.1	6.0	± 0.1-4.3	2.3	± 0.1-0.5
	BEV 2	0.18		6.9		2.7	
	Diesel	0.81		31.0		16.5	
Fleet B	BEV 1	0.34		13.0		2.5	
	BEV 2	0.39		15.1		2.9	
	Diesel	1.1		42.1		22.4	

Table 6: Fleet C yard tractor energy efficiency comparison of average metrics with 95% CI ranges

Fleet	Vehicle Type	Energy Used per Hour (DGE/hr)	95% CI	Efficiency (kWh/hr)	95% CI	Efficiency (kWh/mi)	95% CI
Fleet C	BEV 1	0.24	± 0.0	9.3	± 0.3-0.6	3.7	± 0.1-0.3
	BEV 2	0.24		9.2		3.4	
	BEV 3	0.25		9.7		3.9	
	Diesel	1.4		53.6		15.3	

The BE yard tractors offered substantial savings in terms of both energy and cost, being five to seven times more energy efficient per hour than diesel units. While efficiency per hour is a more common metric for off-road vehicles, other recent estimates have used kWh per mile. A 2022 study of three yard tractors reported between 2.12-4.06 kWh/mi, and another study using a chassis dynamometer found an average of 2.9 kWh/mi over three distinct test cycles, with a range of 1.6-4.4 kWh/mi [12, 13].

Energy (or fuelling) cost was calculated by applying charger energy consumption data to the local utility rate structure for Fleets A and B[4] and directly from utility bills at Fleet C. Only Fleet C incurred demand charges[5] which can make up a substantial portion of the utility bill, especially due to the power demand from high-

[3] An energy conversion of 38.29 kWh/DGE was used to convert between kWh/hr and DGE/hr [14]

[4] Fleets A and B are both on Southern California Edison's TOU-EV-8 rate plan, a time-of-use rate plan which charges different rates per kWh charged at different hours of the day and season [15]

[5] Demand charges are fees assessed by the electricity provider based on the highest power draw in kilowatts (kW) during the previous month; this is in addition to the energy consumed in kilowatt-hours (kWh) that month

power chargers (125kW). Fleet C's monthly demand charges were $10 per kW after the first 20 kW and comprised half of the total electricity bill. Some utilities in California have waived demand charges for BEVs to encourage early deployments, as is the case for Fleets A and B. It is unclear what demand charge fees will look like once demand charges return in 2024. Figure 2 compares average yard tractor fuel costs with and without LCFS credits.[6] Diesel fuelling data came from fleet records as either annual cost (Fleets A and B) or annual fuel consumption and an assumed cost depending on data availability[7] (Fleet C).

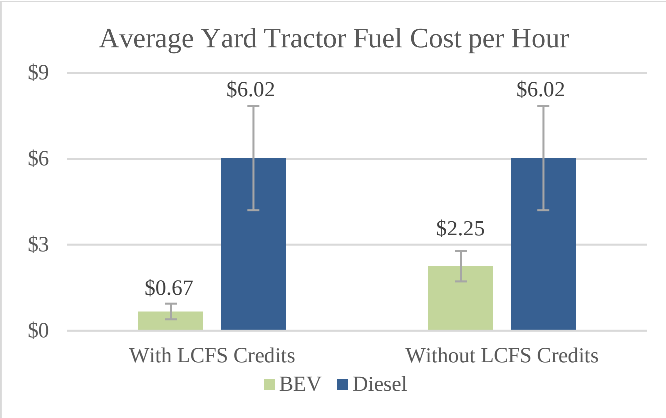

Figure 2: Average fuel cost per hour for diesel and BE yard tractors with 95% CI ranges. Data is averaged across all three fleets and shown with and without LCFS credits.

Diesel yard tractor operations were nearly three times as expensive without LCFS credits and nearly ten times as expensive with LCFS credits; for one fleet, charging costs were close to zero thanks to the LCFS program.[4] However, it is important to point out that fleets can only claim LCFS credits when they own and operate the BE chargers. If a third-party owns the chargers, the fleets will not receive LCFS credits.

Lifetime maintenance costs are inherently difficult to establish over one to two years of data collection for a vehicle that will last more than a decade. Some maintenance work is covered under warranty or performed by the OEM at no cost during these projects. However, our early analysis shows that BEV maintenance will likely be significantly lower than diesel vehicles. BEVs do not require oil changes, frequent brake changes, or other services that contribute to cost and downtime. The disparity between the BE and diesel yard tractor maintenance costs is likely to grow as the vehicles age as diesel yard tractors become very expensive to maintain after about five years. When maintenance, fuel, and incentives are considered, the BE yard tractor total cost of ownership (TCO) is lower than diesel over their lifetimes (Figure 3).

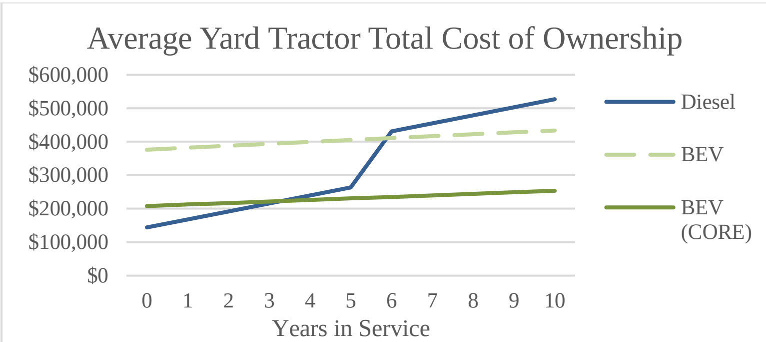

Figure 3: TCO comparison for yard tractors, including maintenance, fuel, LCFS credits, and with and without the CORE purchase incentive for BE off-road vehicles[8]

[6] $0.20/kWh charged used as LCFS credit value but credit prices are expected to vary over time [16]

[7] A cost of $5.46 per gallon diesel was used based on the most recent monthly average cost in the state of California of $6.418 and assuming a fleet bulk discount of 15%; actual fleet fuel rates were not disclosed [17]

[8] Figure 3 averages the yard tractor data from all three fleets and accounts for the cost of the vehicle, charger, federal excise tax (12%), sales tax (8%), charging including LCFS, and maintenance. CORE funding offered $120,000 per yard tractor. Fleets reported to keep diesel yard tractors in service for 5 years compared to 8 for electric yard tractors. The jump in diesel costs between years five and six is from purchasing a second diesel yard tractor.

In Figure 3, a positive return on investment is indicated when the blue line surpasses the solid and dotted green lines along the y-axis. The return-on-investment date varied from three years with CORE incentives to six years without. Other reports have suggested a timeline of eight years or more, but it is unclear whether this was based on actual measured data [12]. Upfront purchase incentives clearly play a substantial role, however, even without the incentives and diesel replacement in year six, the lifetime cost of the BEV is about $80,000 less. With incentives, enough money is saved to purchase a second BE yard tractor.

3.1.3 Emissions Offset

In-use emissions measurements were made on the diesel yard tractors, lasting 4-8.6 hours. Table 7 contains the results of the in-use emissions testing.

Table 7: Diesel yard tractor average tailpipe emissions as measured using PEMS; standard deviation shown for vehicles with two tests performed

Fleet	Emissions (g/hr)			Annual Emissions (kg)	
	CO_2	NO_x		CO_2	NO_x
Fleet A (3,000 hr/year)	11,223 ± 1,174	22.2 ± 9.4		33,669	67
Fleet B (3,000 hr/year)	7,221 ± 148	21.0 ± 11.1		21,662	63
Fleet C (4,500 hr/year)	9,428	37.5		42,425	169
Average	9,391 ± 1,637	26.9 ± 7.5	**Total**	97,756	299

Transitioning to BE yard tractors is an excellent way to reduce emissions at freight facilities. When scaled to a year of operation, each yard tractor offsets about 30,000 kg CO_2, equivalent to taking 6.6 passenger cars off the road. Recent California Executive Order N-79-20 calls for a full transition to ZE off-road equipment by 2035, where feasible [18]. Yard tractors make up 33% of the NO_x emissions from cargo handling equipment at the Port of Los Angeles (the largest of any equipment type) and 2.1% of the total Port NO_x emissions [19]. If all California yard tractors were converted to BEVs, an estimated 31,000 passenger cars emissions would be offset.[9]

3.2 Trucks (Class 6, 7, and 8)

3.2.1 Duty Cycle

Fleet A deployed one BE Class 7 box truck and three BE Class 8 trucks on drayage routes to the Los Angeles Port complex and warehouses in Southern California. Table 8 shows the operation metrics of Class 7 box trucks and Class 8 diesel tractors at Fleet A.

Table 8: Fleet A on-road truck duty cycle comparison of average metrics with 95% CI ranges

Fleet	Class	Vehicle Type	Daily Distance (mi)	95% CI	Daily Key on Time (hours)	95% CI	Daily Charging Time (hours)	95% CI	Daily Energy Charged (kWh)	95% CI
Fleet A	Class 7	BEV 1	66	± 3-11	5.0	± 0.3-0.5	1.3	± 0.1-0.3	110	± 10.3-19.2
		Diesel	83		5.4		-		-	
	Class 8	BEV 1	85		5.3		2.1		159	
		BEV 2	72		6.5		1.2		124	
		BEV 3	102		5.9		2.0		206	
		Diesel	312	±129	10.2	±2.1	-			-

The BE and diesel Class 7 trucks operated roughly the same duty cycle – 60 miles and 3 hours per day. The maximum range recorded was 120 miles on a single charge, which would allow the fleet to meet 50-60% of their operations. The BEVs spent about 1 hour per day charging for an average of 120 kWh.

Due to range limitations, the BE Class 8 trucks were used in different duty cycles than their diesel counterparts. They were assigned shorter routes allowing them to recharge between shifts, returning to base for a 45-minutes and replenishing approximately 80% of the battery's state of charge (SOC). The BE Class 8 trucks drove about 90 miles per day over 4 hours and charged for 2 hours for a total of 200 kWh. The

[9] Estimated 4,700 yard tractors in California [20]

maximum daily range recorded was 200 miles, excluding them from routes longer than 150-200 miles. For shorter routes, however, BE trucks met the demands and were widely praised by operators who appreciated their silent, smog-free operations. The diesel tractors averaged over 300 miles per day over 10 hours, completing twice as many routes. However, there was a lot of variability in the daily distance metric as shown by the large range of the confidence interval.

Fleet B deployed two BE Class 8 trucks on drayage routes delivering freight to and from the Los Angeles Port complex. As at Fleet A, Fleet B's BE Class 8 trucks were limited to shorter routes and a single shift per day. The BE Class 8 trucks averaged 110 miles per day, about 60% of what the diesel tractors drove. Table 9 lists the metrics of Fleet B's BE and diesel Class 8 truck operations.

Table 9: Fleet B on-road truck duty cycle comparison of average metrics with 95% CI ranges shown

Fleet	Class	Fuel Type	Daily Distance (mi)	95% CI	Daily Key on Time (hours)	95% CI	Daily Charging Time (hours)	95% CI	Daily Energy Charged (kWh)	95% CI
Fleet B	Class 8	BEV 1	108	± 4-11	4.9	± 0.5-1.1	1.5	± 0.1	195	± 19.1
		Diesel	173		7.3		-		-	

Fleet C, which previously used Class 8 trucks for all deliveries, deployed six BE Class 6 trucks on new, shorter routes for local delivery within their range abilities. The diesel trucks drove much further routes, averaging 300 miles per day compared to 52 miles per day for the BE Class 6 trucks. While in this case there is not a direct comparison that can be made between technologies, the fleet benefitted from deploying their first BE trucks and learning how to manage their different operational needs. The BEVs spent around 3 hours operating and 3 hours charging about 81 kWh per day. Table 10 shows the operations of Fleet C's BE and diesel Class 6 truck operations.

Table 10: Fleet C on-road truck duty cycle comparison of average metrics with 95% CI ranges shown

Fleet	Class	Fuel Type	Daily Distance (mi)	95% CI	Daily Key on Time (hours)	95% CI	Daily Charging Time (hours)	95% CI	Daily Energy Charged (kWh)	95% CI
Fleet C	Class 6	BEV 1	60	± 2-12	2.7	± 0.2-0.3	3.2	± 0.2-0.3	86	± 2.8-5.6
		BEV 2	53		3.4		3.1		79	
		BEV 3	52		4.1		3.5		87	
		BEV 4	41		3.8		2.7		70	
		BEV 5	47		3.1		3.1		73	
		BEV 6	60		2.7		3.6		89	
	Class 8	Diesel	300		7.7		-		-	

3.2.2 Energy Use and Costs

As expected, the BE trucks were significantly more efficient. Energy efficiency is compared in terms of miles per diesel gallon equivalent (MPDGE), a metric common to diesel trucks, and kWh/mi. Table 11 compares the efficiency of Class 7 and 8 trucks at Fleet A.

Table 11: Fleet A on-road truck average energy efficiency comparison with 95% CI ranges

Fleet	Class	Fuel Type	Efficiency (MPDGE)	95% CI	Efficiency (kWh/mile)	95% CI
Fleet A	Class 7	BEV 1	22.7	± 0.4-0.9	1.8	± 0.0-0.5
		Diesel	7.6		5.1	
	Class 8	BEV 1	26.0		1.5	
		BEV 2	18.9		2.0	
		BEV 3	17.7		2.2	
		Diesel	6.5		5.7	

At Fleet A, the BE Class 7 trucks were about three times more efficient than diesel alternatives and the BE Class 8 trucks were over two times more efficient. The BEVs achieved 1.7-2.2 kWh/mi. Understanding these values over the long term can help other fleets estimate the energy required by their duty cycles and thus the battery size and charger power as well. Table 12 provides energy efficiency for the Class 8 trucks deployed at Fleet B.

Table 12: Fleet B on-road truck average energy efficiency comparison with 95% CI ranges

Fleet	Class	Fuel Type	Efficiency (MPDGE)	95% CI	Efficiency (kWh/mile)	95% CI
Fleet B	Class 8	BEV 1	22.7	± 0.4-0.7	1.7	± 0.1-0.5
		Diesel	7.3		5.1	

Fleet B's Class 8 trucks were slightly more efficient at 1.7 kWh/mile, more than three times as efficient as the diesel tractors. Other studies found higher energy consumption for BE Class 8 trucks (2.67 kWh/mi) [21]. Possible reasons for the slight increase in efficiency compared to Fleet A's BE Class 8 trucks are lighter payload or environmental conditions such as temperature. Research using chassis dynamometer testing found an average of 2.2 kWh/mi over three different drive cycles, close to these findings [13]. Table 13 provides the energy efficiency of the Fleet C trucks.

Table 13: Fleet C on-road truck average energy efficiency comparison with 95% CI ranges

Fleet	Class	Fuel Type	Efficiency (MPDGE)	95% CI	Efficiency (kWh/mile)	95% CI
Fleet C	Class 6	BEV 1	27.4	± 0.2-0.7	1.4	± 0.0-0.9
		BEV 2	25.5		1.5	
		BEV 3	25.5		1.5	
		BEV 4	22.5		1.7	
		BEV 5	27.4		1.4	
		BEV 6	27.4		1.4	
	Class 8	Diesel	7.0		11.8	

The Class 6 BE box trucks at Fleet C were more than three times as energy efficient as Class 8 diesel tractors. Although they were able to carry only half the payload, these BEVs presented an excellent use case for lighter loads traveling shorter ranges. Data was collected on fueling costs with results displayed in Figure 4.

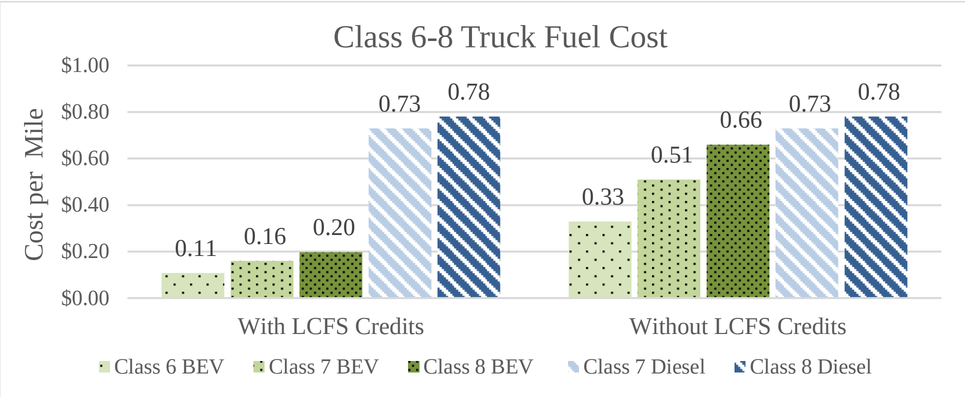

Figure 4: Electric and diesel truck fuel cost per mile, with and without LCFS credits

Class 7 and 8 diesel truck fuel costs were about $0.80 per mile. The BEV counterparts' electricity costs were 10-35% less without LCFS credit revenue and 73-80% less with LCFS. This will vary based on diesel prices and savings may be even higher now that diesel costs more than the assumed $5.46/mile. Here again, it is important to point out that the fleets can claim the LCFS credits when they own and operate the chargers. Third-party charging equipment would not result in LCFS credits for the fleet. Additionally, not all fleets are in a position to manage the administrative process.

The BE Class 6 trucks cost the least to operate, as would be expected from a lighter weight class. Demand charges were only included for Fleet C (Fleet A and B are not currently subject to demand charges).

Charging infrastructure costs can vary depending on the specifics of each site. Typical expenses include charging hardware, electrical and civil engineering designs and upgrades, and fees (local government, utilities, and contractors). For the TCO analysis, we used $85,500 for the charger costs (150kW units) and do not include the construction and installation costs. Maintenance costs for BE trucks still require more data collection. Very minimal maintenance was required by Fleets A and B over the course of the project. Fleets will most likely save significantly on maintenance costs, but it is still too early to get lifetime numerical estimates. Several OEMs of electric trucks are planning to include full coverage maintenance at a set price.

The TCO analysis revealed that the BE Class 8 trucks will not achieve cost parity in an average vehicle lifetime. Although annual fuel cost savings of $9,000 were observed, by the end of year ten, BE trucks with incentive funding would still cost approximately $122,000 more than diesel. One of the main reasons is that the BE trucks have a price tag 2-3 times higher than their diesel counterparts. This is compounded by a federal excise tax of 12%, California sales tax of 8%, and the California registration fee which sum to an additional $90,000-100,000 added to the upfront cost. Fleets expressed concern that these taxes [22] and the registration fee were barriers to adoption that should be addressed. Insurance was estimated at 5.5% of the upfront cost of the vehicle annually based on input from fleets, meaning electric truck insurance can be more than twice as expensive as insuring diesel trucks. This practical aspect has not been considered in many of the TCO analyses to-date. Some insurance organizations also consider several other factors in determining a fleet's insurance rate, including exposure to risk in the driving area, level of driver experience, and other factors which can minimize the difference in insurance rates. Fleets can expect upfront and insurance costs to decrease as BE trucks production increases and battery technology improves. Incentives will play a key role in supporting production increases and making BE trucks affordable for fleets in the short-term.

3.2.3 Emissions Offset

Converting to BE Class 7 and 8 trucks has the potential to reduce emissions drastically. Class 7-8 tractors make up 12% of California's Class 2b-8 truck population yet produce nearly 50% of the NO_x produced. A full summary of diesel truck tailpipe emissions from PEMS measurement during normal operations is presented in Table 14.

Table 14: On-road truck tailpipe emissions as measured using PEMS

Fleet	Vehicle Type	Emissions (g/mile)			Annual Emissions (kg)	
		CO_2	NO_x		CO_2	NO_x
Fleet A (Class 7 - 15,000 mi/year) (Class 8 - 125,000 mi/year)	Class 7	1,603	0.5		24,045	7.5
	Class 8	1,706	4.8		213,219	604
Fleet B (40,000 mi/year)	Class 8	1,295	1.6		51,790	66
Fleet C (92,000 mi/year)	Class 8	1,082	2.0		99,575	184
Average	Class 8	1,361 ± 259	2.8 ± 1.4	**Total**	364,584	854

Over the 10-year lifetime of a diesel truck, over 200,000 gallons of diesel can be burned, equivalent to operating nearly 500 passenger cars for a year. While these trucks consume the most energy in freight applications, and therefore have the most emissions offset potential, not all duty cycles are ready to transition to BEVs yet. Range limitations, higher upfront costs, reduced payload capacity, and long lead times for infrastructure installation affect the fleet business case and will require more work. Still, the newest BE trucks can now meet duty cycles of up to 220 miles per day. Range and charging speeds have increased rapidly in recent years and this trend is expected to continue as the market scales and costs drop.

4 Conclusion

These two projects offer unique insight into the current state of freight facility electrification. The variety of BE vehicles deployed, along with the comparison to conventional equipment, provides a glimpse of what the near future could look like for commercial transportation. The results show significantly reduced energy consumption, fueling costs, and emissions. Across all product categories, operators were proud to be leading the transition to a ZE future and valued the smooth, silent, and odorless operations of BEVs. It has been calculated that "Removing diesel trucks from the roads…would lower [California's] carbon dioxide emissions by 17 million metric tons, roughly the same amount as pollution from burning almost 100,000 rail cars' worth of coal, and save truck operators $6 billion in fuel costs" [23]. The benefits are clear, but what has been shown here will take time to scale.

BE yard tractors met all duty cycles and had a lower total cost of ownership than diesel yard tractors at all three fleets. Class 6, 7, and 8 BEVs could not meet all conventional vehicle routes but were effective when deployed strategically on shorter routes. For example, the 120-mile range offered by the BE Class 7 trucks only met 50-60% of Fleet A's box truck operations nationwide, but they still provide annual fuel cost and emissions savings. Deploying BE trucks where possible now is a good way for fleets to gain experience and plan for the wider-scale transition that will be required of them while longer range vehicles are developed. Range capabilities are expected to reach 200-400 miles per day in the coming years, allowing BEVs to cover nearly all conventional duty cycles [24]. Plus, tailpipe emissions and fuel cost savings can be realized from day one.

The high price of BE Class 8 trucks will result in higher insurance costs and taxes. Subsidies such as cash rebates and elimination of disincentives in the form of taxes will enable the widescale deployment of BE trucks. Additionally, incentives for low-carbon fuels and charging infrastructure, like LCFS, will help achieve a favorable TCO. New programs such as California Energy Commission's EnergIIZE provides funding incentives for commercial BEV electric charging and hydrogen refueling infrastructure [25]. Actively avoiding charging during on-peak hours will help minimize costs, and minimizing peak power demand by staggering charging times, reducing charging power, or investing in energy storage will improve the business case. More data from such real-world deployments of BE Class 6-8 trucks needs to be collected, analyzed, and shared as key knowledge gaps remain, including lifetime maintenance cost estimations.

BE freight-handling technology is rapidly meeting the needs of industry. BE yard tractors can successfully perform demanding duty cycles and save fleets money. On-road BE trucks may be restricted to shorter routes for now, but range is expected to increase significantly over the coming years. HD BE trucks are not expected to achieve cost parity with diesel yet, but fuel subsidies like LCFS, upfront cost incentives, and strategic charging can help balance out the equation. Policy regulations, financial incentives, and increasing fleet awareness of BEV capabilities are all critical to transform the freight sector and meet the needs of our climate crisis.

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