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Zero Emission Concrete Mixer Trucks: Comparison of Battery Electric and Hydrogen Fuel Cell Powertrains

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Zero Emission Concrete Mixer Trucks:

Comparison of Battery Electric and Hydrogen Fuel Cell Powertrains

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Abstract

This study aims to compare the feasibility of battery electric and hydrogen fuel cell powertrains for concrete mixer trucks to determine which is the better zero-emission powertrain for the industry to transition towards. Duty cycle modeling simulations are used to estimate both the component specifications required to meet the operational requirements of the vehicles, and the associated performance of the powertrain technologies. Associated costs for fleets are compared using Total Cost of Ownership (TCO) assessments. The duty cycle modeling results show that a battery electric mixer would consume up to 4 kWh of energy per mile on average when considering the auxiliary loads, which is around twice that of a typical class 8 battery electric truck. A truck with a battery size resulting in only an 80-mile range would have a 10% payload penalty, even with additional weight allowances for zero-emission trucks. A fuel cell electric mixer truck could have a 150-mile range but would still have a payload penalty, even with the additional weight allowances. A battery swap-capable truck could have no payload penalty compared to diesel, but would require swapping before each delivery, and adding battery swapping stations could be an issue at certain plants. The TCO of fuel cell trucks is currently 27% higher than that of diesel trucks. The TCO of battery electric trucks could be lower than that of diesel models as of today, and could be 25% lower than diesel TCO by 2030, while the fuel cell truck TCO would still be 10% higher than diesel, even by 2030. Based on our analysis, a battery swap concrete mixer truck could be the best zero-emission option for this application, but existing chassis are not currently available in the US. The lack of existing battery swap-capable chassis availability in the US will be a substantial barrier for battery swap mixer trucks, and custom solutions for a mixer application will likely not be cost-effective due to the limited yearly sales volume of concrete mixer trucks.

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This project might not have been possible without my two years spent as a concrete mixer truck driver during Covid. This experience allowed me to better understand the operating conditions and considerations for these unique vehicles.

I would like to thank the following coworkers who helped me learn how to drive a concrete mixer or navigate this difficult industry: Samuel Llamas, Jose Padilla, Paul Deford, Steve Liman, Mario Laura, Jake Rogakis, Jose Deanda, Scott Johnson, Gelacio Martinez and Tom Carter.

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1 Introduction

According to the IEA 2023, trucks are responsible for more than 35% of direct emissions from road transport, despite making up less than 8% of on-road vehicles. Emission levels continue to grow and in order to meet climate and urban air quality goals, it is vital to reduce emissions from heavy duty vehicles. One of the most effective ways to reduce emissions from heavy duty vehicles is to replace internal combustion engines with battery electric or hydrogen fuel cell powertrains that don't produce any tailpipe emissions. On some vehicles, particularly class 8 trucks, this can be very difficult due to the costs involved and constraints of the current technologies. There has been extensive research regarding the viability of zero emission powertrains for general purpose class 8 trucks, such as a long haul tractor trailer, but there has been less research regarding speciality vehicles, such as concrete mixer trucks.

Diesel concrete mixer trucks consume large amounts of fuel and produce high levels of emissions despite traveling relatively small distances compared to other truck types. This is due to the fact that the diesel powertrain is inherently inefficient when long idle times are required in order to power auxiliary loads on-board. Alternative powertrain technologies, including diesel hybrid, CNG hybrid, battery electric, and hydrogen combustion or hydrogen fuel cell technologies, could be used in order to reduce emissions. However, all have some limitations or additional costs, so adoption is currently extremely limited for mixer trucks.

This paper will analyze the viability of zero emission powertrains for concrete mixers, and determine whether battery electric or hydrogen fuel cell technology is better suited for these vehicles. We will mostly focus on fixed battery and hydrogen fuel cell options, as these are currently the most popular zero emission options in the United States. Later in the study though we began to consider battery swapping options, as after completing the analysis for fixed battery systems and hydrogen fuel cell it was apparent battery swapping may be an effective solution for zero emission concrete mixer trucks and is a great topic for further research. However, the viability of battery swapping for concrete mixers in the US will depend on the availability of existing swap capable chassis, since rear discharge concrete mixers are not built on custom chassis.

While long haul trucks contribute to the majority of fuel use and emissions from heavy duty trucks, heavy duty vocational trucks, including concrete mixers, often operate in urban areas and reducing these emissions is essential to improving urban air quality. Additionally, alternative powertrains for general purpose trucks are already well studied in the literature and relatively few research projects have been completed regarding heavy-duty vocational trucks with auxiliary loads. Even less research projects have specifically considered concrete mixer trucks.

1.1 Background on Concrete Mixer Trucks

Figure 1: Concrete Mixer Truck in Use

Concrete is the second most consumed substance in the world by weight, behind water. Virtually all construction projects require some amount of concrete. Very often, the best way to deliver concrete to a construction site is using a concrete mixer truck with a rotating drum. The National Ready Mix Concrete Association (NRMCA) estimates that the U.S. ready mix industry produces and delivers approximately 371 million cubic yards of concrete per year. To put that yearly output into perspective, that is the equivalent of a concrete block with the footprint of a football field reaching over 25 miles tall, weighing over 1.5 trillion pounds and requiring over 37 million full truck load deliveries.

Currently all of the approximately 75,000 concrete mixer trucks in the United States are powered by diesel or natural gas, with the vast majority being diesel (NRMCA 2020). Some of these trucks discharge concrete from the front (front discharge), and some discharge concrete from the rear (rear discharge). This paper specifically looks at rear discharge concrete mixers, but the vehicles are operated in a very similar fashion and have similar constraints. According to the NRMCA 2020, rear-discharge mixer trucks still dominate the market in the US.

The purpose of a concrete mixer truck is to load a combination of sand, gravel, cement and water, mix it into what is considered wet concrete and maintain its consistency during transit. The truck delivers the load of concrete to a construction site for a concrete contractor (customer), and afterwords, returns to the concrete batch plant. The concrete is workable for around 2 hours, as long as it is consistently mixed. If the concrete sits still for too long, it will begin to set. After 2 hours of mixing, the concrete will often no longer meet strength requirements, as large amounts of water will need to be added in order to keep the mix from setting. This makes the product extremely perishable and this is why the truck must return to the plant after every delivery, even if full loads weren't required on a specific order.

When loading, the mixer truck engine revs up to its maximum rpm, and the drum is set to 'full charge'. This mixes the materials that are being loaded at the maximum rate. After loading, the truck is quickly washed by the driver in order to remove any materials that might have landed on the truck while loading. During the washing process the drum continues to mix at max speed in order to finish mixing all the materials consistently and start the chemical reaction between the cement powder and water. After the washout is complete the truck leaves the batch plant and begins to drive to the jobsite. When driving towards the jobsite, the drum must continuously mix at a rate of approximately 2 to 5 revolutions per minute in order to maintain the consistency of the mix.

Many routes involve a substantial portion of stop and go driving, where the vehicle is accelerating at its maximum rate to try to keep up with traffic. Other routes may involve highway driving, but the distance is often fairly limited. Most deliveries are around 15 miles each way, and some are as short as 5 miles. This is by design, as some city codes and construction inspectors require concrete that is older than 90 minutes to be rejected. When the vehicle arrives on the jobsite, water is often added to the concrete at the request of the customer and the drum mixes again at a rapid rate to prepare for pouring. After the customer is satisfied with the consistency of the concrete, the vehicle is backed into the location where the concrete needs to be placed, and the drum spins backwards at a slow rate to unload.

Figure 2: Mixer Truck Pouring Bike Path

During the unloading process, the truck may need to move around at slow speeds as directed by the customer. After the truck is emptied, it is washed again to avoid concrete build up inside the drum and on the discharge chutes. After this is complete, the truck is driven back to the batch plant where this processes starts all over again. Upon arriving back at the plant, it may need to be loaded right away or it may wait for an extended period of time if other trucks are waiting to load. During this waiting time (often between 5-15 mins), a battery electric concrete mixer could theoretically charge. However, if the truck needs to be loaded right away, there wouldn't be any opportunity for charging. Many jobs require large numbers of concrete mixer trucks to complete a single delivery and delays in the loading process can be very disruptive to a construction operation. The success of the ready mix concrete company depends on their ability to complete large deliveries efficiently and without delay, as construction companies usually have a choice of multiple different ready mix companies that serve an area.

Since there is a large variability in terms of how long a truck may take to complete a single delivery and orders are time sensitive, drivers do not have a set schedule of deliveries they may complete throughout the day. Dispatch will not know where a specific truck needs to be routed to on the next delivery until it is ready for loading, as the destination depends on which order needs to be loaded at the given time when the truck is ready. For example, if the truck arrives at the plant 5 minutes later, it may be routed to a completely different location. This makes the delivery schedule of a single truck highly irregular. On some days it may complete only 3 deliveries and travel only 50 miles, and on other days it could complete 6 or more deliveries and travel 150 miles. Additionally, the operating hours of a single truck is also highly irregular. On Monday the truck may be in operation from 1am to 6pm, while on Tuesday it may operate from 7am to 3pm. In most fleets, a truck is assigned to a single driver in order to motivate the driver to keep the equipment in good condition. This adds another layer of complication to the scheduling of a single truck, as order schedules vary each day and the companies try and keep the weekly working hours of the drivers as even as possible to minimize spending on overtime. For all these reasons, a truck that can be quickly refueled and has a long driving range is very attractive to a fleet and trucks that take a long time to refuel and have short driving ranges can be very problematic.

1.2 CA Regulations

According to Fulton and Gruen 2024, California is taking an aggressive approach to established policies in order to require manufacturers to produce and sell zero emission trucks and fleets to purchase them. According to CARB 2021, the Advanced Clean Truck regulation (ACT) will require manufactures to sell increasing percentages of zero emission trucks from 2024 to 2035. By 2035, 75% of the class 4-8 straight trucks sold in California must be zero emission and 40% of truck tractors sold must be zero emission.

The vast majority of concrete mixer trucks are in a straight truck configuration, as the tractor trailer mixers are often far too difficult to maneuver in and out of tight job sites. The mixer trucks start as a cab chassis produced by a truck manufacture (usually Kenworth, Peterbilt or Mack) and then get sent to an upfitter like Revolution Concrete Mixers (formerly McNeilus), Contech, or Kimble to receive the mixer body. The ACT regulation will require the truck manufactures to sell an increasing percentage of zero emission cab chassis and therefore, we will see an increase in the number of zero emission concrete mixers being sold. The regulation also requires fleet reporting in order to identify which fleets are best suited for zero emission models.

According to CARB 2023, the Advanced Clean Fleets regulation will require manufactures to sell only zero emission heavy duty vehicles in California starting in 2036. Therefore, all concrete mixers sold in California will need to be zero emission post 2036. They also have other requirements for drayage fleets, as well as federal, state and local agencies that we will not discuss, as they are not relevant to concrete mixers.

High priority fleets, those that have either $50 million in gross annual revenue or operate more than 50 vehicles, have the following requirements: either purchase only zero emission trucks beginning 2024 and begin to remove international combustion models at the end of their useful life or follow the corresponding ZEV Fleet Milestones Compliance Pathway. Most ready mix companies that operate concrete mixer trucks will fall under the high priority fleet requirements, as according to the NRMCA 2021 survey, the average number of trucks per fleet was over 200, with a median of over 150. According to CARB 2023, concrete mixer trucks are considered speciality vehicles and fall under the Milestone Group 3 requirements, shown in Table 1.

Table 1: ACF Milestone Requirements CARB 2023

Percentage of vehicles that must be zero-emission	10%	25%	50%	75%	100%
Milestone Group 1: Box trucks, vans, buses with two axles, yard tractors, light-duty package delivery vehicles	2025	2028	2031	2033	2035 and beyond
Milestone Group 2: Work trucks, day cab tractors, buses with three axles	2027	2030	2033	2036	2039 and beyond
Milestone Group 3: Sleeper cab tractors and specialty vehicles	2030	2033	2036	2039	2042 and beyond

The ACF milestones requirements will put intense pressure on ready mix concrete fleets to purchase zero emission concrete mixer trucks, and that is one of the primary motivations for this study.

In order to comply with ACT and ACF requirements, either battery electric or hydrogen fuel cell powertrain will need to be used. For this reason, this study will only consider those options despite other powertrain technologies like CNG hybrids having the potential to reduce emissions for potentially lower costs. Due to the strong regulatory pressure in California for zero emission trucks, this study generally considers California specific parameters for all applicable aspects of the analysis, such as weight restrictions, fuel prices, taxes and incentives. Despite this, the results and recommendations shown in this study should be generally applicable across the US.

1.3 Literature Review

Central Concrete Company 2022 published a BluePrint for Zero Emission Concrete Logistics that is one of the main inspirations for this study. They find that for concrete mixer trucks, battery electric powertrains have too many limitations in terms of range, charging time and payload equivalency. Therefore, hydrogen fuel cell powertrains will be needed for concrete mixer trucks. However, a major limitation of their study is they used energy consumption values for the diesel, battery electric and hydrogen fuel cell trucks based on a typical class 8 tractor and did not do any analysis in terms of the actual energy consumption of a concrete mixer truck. Since concrete mixer trucks have very high auxiliary loads and a unique duty cycle, it's critical to include these metrics specific to concrete mixer trucks. For example, in table 3 of their report, they reference the diesel concrete mixer truck achieving 7.4 mpg, when according to the NRMCA 2021, it is actually 3.4 mpg. Additionally, their energy consumption values for the battery electric and hydrogen fuel cell truck are also inaccurate to a similar margin of error as the diesel value. This limitation of their study may impact powertrain recommendations and some of the cost analysis in their report. For this reason, this study will complete a duty cycle modeling analysis specific to concrete mixer trucks and provide better estimates of the range of these vehicles, as well as a total cost of ownership analysis with the new energy consumption figures.

Derakhshan 2019 has analyzed battery electric refuse trucks using a similar approach to this study and Gilleon, Penev, and Hunter 2022 has analyzed hydrogen fuel cell refuse trucks. Since refuse trucks have many similarities to concrete mixer trucks including that they have high auxiliary loads, have a unique duty cycle, and operate locally, we build on their approaches in order to draw conclusions specific to concrete mixer trucks.

Basma et al. 2023 finds that battery electric long haul trucks will become cost competitive with diesel models by 2030. However, fuel cell and hydrogen combustion models struggle to become cost competitive. They find that battery electric trucks have significantly lower operating costs than fuel cell and hydrogen combustion models, primarily due to high hydrogen fuel prices in the near and mid term. Hydrogen prices would need to be between \$5 and \$7 per kg to become cost competitive. We will see in this study what hydrogen price would be required in order for fuel cell concrete mixers to become cost competitive.

Zhao et al. 2009 has studied potential energy savings from using a hydraulic hybrid powertrain for a concrete mixer truck, but did not consider battery electric or hydrogen fuel cell powertrains. Gadner et al. 2019 has a report on a prototype of a plug in hybrid concrete mixer truck and stated that a fully electric drum drive system would be used in order to turn the mixer drum, rather than the traditional hydraulic system. Huang, Jiang, and H. Xie 2021, S. Wang et al. 2024, Mapelli et al. 2013, as well as other studies have analyzed hybrid concrete mixer systems. However, the applications of their research are generally specific to the operation of hybrid powertrains in unique situations, rather than broader conclusions about the powertrain choices for concrete mixer trucks.

Lowell and Culkin 2021 and other similar studies have completed extensive reviews of the feasibility of zero emission powertrains for many different truck types but unfortunately do not consider concrete mixer trucks. National Research Council et al. 2010 has a very detailed study on approaches to reduce fuel consumption and emissions from heavy duty vehicles, but also did not consider concrete mixer trucks specifically.

While our study was in progress, the ICCT released a draft for their paper in progress about zero emission concrete mixer trucks in the Hainan Providence, China. Niu, Cui, and Y. Xie 2024 finds that battery electric concrete mixer trucks already dominate new sales in Hainan and a large portion of those are battery swap trucks. The market for battery electric heavy duty trucks is much more mature in China when compared to the US and costs for battery electric trucks in China are extremely low compared to the US. Chinese concrete mixers have a few differences in terms of the vehicle and operating characteristics compared to the US models. The round trip delivery distance in China is shorter compared to in the US. The Chinese mixer duty cycle shown does not involve any high speed highway driving and only reaches a max speed of 38mph. The Chinese mixer trucks complete almost twice as many deliveries per day, likely utilizing a second shift which is not common in the US, partially due to labor shortages. Since China is a developing country and is consuming an extremely high amount of concrete, many of these deliveries are likely high volume pours, often involving hundreds of concrete truck deliveries. The high volume pours are designed to be much more time efficient than a small delivery involving only one or two trucks. For example, on a high volume pour a truck might be able to unload in less than 5 minutes and head directly back to the batch plant, often without washing down. On a low volume pour, like sidewalk patchwork, a truck may take over an hour to unload. The time to unload has a large impact on the energy consumption per mile because the idle time increases the energy consumption without increasing the number of miles traveled. For all of these reasons, the Chinese mixer trucks are not directly comparable to the US mixer trucks. However, it does show that there could be success of zero emission powertrains for concrete mixer trucks, particularly for battery swapping technology.

The Central Concrete Company 2022 report only considers fixed-battery electric trucks and hydrogen fuel cell, so we primarily consider those for a US application. However, due to success shown for battery swap trucks in China presented by the Niu, Cui, and Y. Xie 2024, we conduct some additional analysis for battery swap systems to see if it could be a more attractive solution than fixed-battery electric or hydrogen fuel cell. Besides the Central Concrete Company 2022 report, our study will be the only other one so far to compare battery electric and hydrogen fuel cell powertrains for concrete mixer trucks operating in the US, and due to the limitations of their study described above, this report will re-analyze certain parts of their report and see if the findings are the same, as well as complete some initial analysis of battery swap trucks.

1.4 Comparison of Infrastructure Requirements

One of the more difficult aspects of adopting alternative powertrain technologies for class 8 trucks is creating the infrastructure required for refueling or recharging. In this section, we will qualitatively describe the existing literature regarding depot charging for class 8 vehicles, as well as hydrogen station installations. In order to limit the scope of this study, we only quantitatively analyze the vehicle performance characteristics of the different powertrains and the total cost of ownership of the vehicles. The total cost of ownership includes the levelized cost of installing chargers or hydrogen stations but many studies have already accessed this and we make use of those studies and describe them in the cost analysis section.

However, it is important to consider the infrastructure considerations for different powertrain technologies. The Central Concrete Company 2022 report has completed an analysis of the hydrogen station installation considerations for zero emission concrete mixer trucks as part as their study. They found that certain plants would utilize on site hydrogen storage stations, while other plants will utilize mobile wet hose fueling services where a truck would show up each night to refuel all the individual hydrogen vehicles. Major reasons for selecting a wet hose fueling strategy at a particular plant include: lack of additional area for required infrastructure, low quantity of hydrogen vehicles and hydrogen demand, or lack of minimum standoff distance required for safety. Reasons for installing on site infrastructure include: high hydrogen demand on site from large fleets of hydrogen vehicles, space availability on site, and desire for enhanced fuel availability from on site hydrogen storage. Out of the 17 locations they analyzed in the study they recommended installing hydrogen stations at 5 of the locations and using mobile wet hose refueling at the remaining locations. For locations suitable to on site infrastructure, with between 2 and 50 trucks, they recommend on site liquid storage and dispensing. For locations with over 50 trucks, they consider on site hydrogen production from steam methane reforming and electrolysis but find space requirements are far too high, as well as peak electrical demands from electrolysis, reaching up to 5 MW. The space required for a hydrogen storage station that could fill 50 trucks per day was estimated at 4800 sq ft.

They do a more in depth analysis for 3 locations within the Bay Area:

450 Amador Ave has 36 mixer trucks that have an average daily VMT of 43mi and peak daily VMT of 80. 36,000 sqft is available for infrastructure and only 310kW of additional electrical capacity is available. Nearby feeder circuits are available that have over 3MW that could be used for upgrading capacity.

457 Queens Ln has 22 mixer trucks that have an average daily VMT of 78mi and peak daily VMT of 155mi. 8,000 sqft is available for infrastructure and no additional electrical capacity is available. Nearby feeder circuits are available that have over 4MW that could be used for upgrading capacity.

16445 Stanley Blvd has 13 mixer trucks that have an average daily VMT of 92mi and peak daily VMT of 150mi. 7,000 sqft is available for infrastructure and 4MW of additional electrical capacity is available. This location is the least constrained of the 3 studied and has ample area and electrical capacity for the small fleet.

They mention that hydrogen costs per truck are very high when the fleet size is small but can decrease substantially as the fleet size increases. Conversely, battery electric trucks have relatively low infrastructure costs when the fleet size is small, but when utility level upgrades are required with large fleets, costs become substantially larger. They did not do as in-depth of an analysis of the infrastructure requirements for battery electric trucks, as they deemed the technology likely unfit for a mixer application. The capital costs to build hydrogen stations at depot locations could be very high and increase the levelized cost of hydrogen per kg. Bracci, Koleva, and Chung 2024 finds that 2 metric ton per day hydrogen storage stations could cost up to $11 million to purchase and install. According to CTE 2024, the costs for the new NorCal Zero Project totaled $53 million in order to build an 18 metric ton per day hydrogen station for fueling 200 heavy duty trucks and purchase 30 Hyundai Xcient fuel cell class 8 trucks. According to Central Concrete Company 2022, the capital cost for a hydrogen station to fill 25 trucks would cost over $6 million. In the TCO analysis section of this paper, we will go into greater detail as to how the hydrogen station costs impact the levelized hydrogen cost per kg, based on the Bracci, Koleva, and Chung 2024 study.

Borlaug et al. 2021 completed an in-depth analysis of the infrastructure requirements for heavy duty short haul battery electric fleets, determining peak electrical loads and whether electrical substation, feeder breaker or feeder circuit upgrades would be required at various locations. They provide a diagram of the typical electrical equipment used for depot charging, shown in Figure 3. Later in this section we will go into more detail about the levelized costs of heavy duty electric truck truck charging, attributable to utility upgrades.

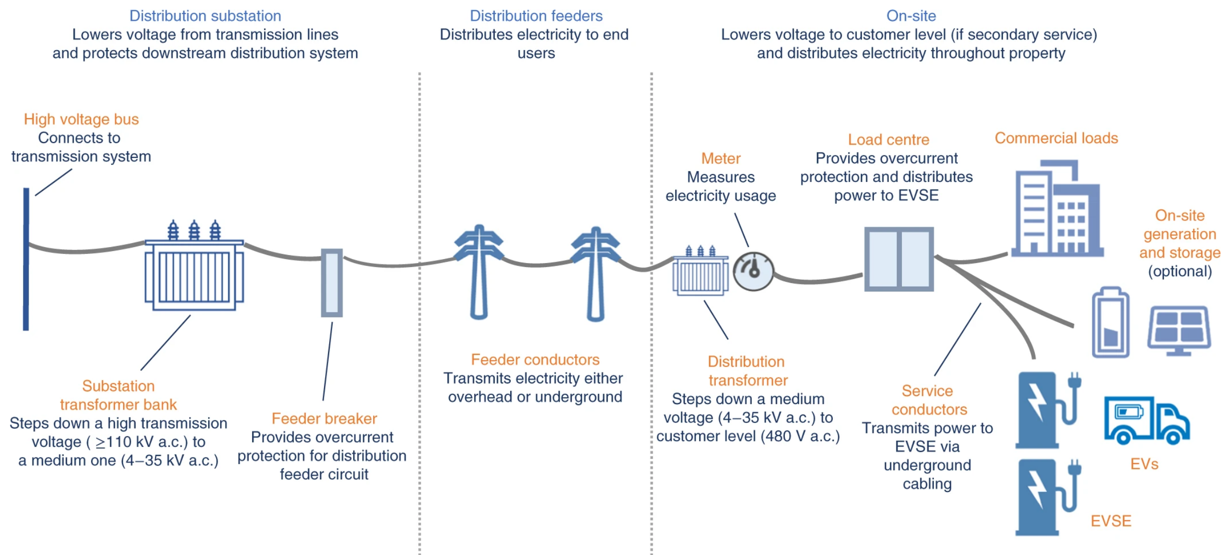


Figure 3: Borlaug et al. 2021 Typical Depot Charging Equipment

Borlaug et al. 2021 used data from 3 fleets in order to complete their analysis. Fleets 1 and 2 have similar average daily mileage to a concrete mixer truck at (65 and 63 miles respectively), and fleet 3 has around double the average daily miles at 152. They assumed the trucks would consume 1.8 kWh per mile, which is around half of what we estimate for a concrete mixer in the Duty Cycle Modeling section of this study. Since their model multiplies the daily VMT by the energy consumption per mile in order to figure out how much energy in kWh a battery demands for charging at the end of the day, a fleet with double the daily VMT and half the energy consumption per mile would provide similar results to one with half the VMT and double the energy consumption per mile. In this regard, we consider fleet 3 to be most similar in terms of energy demands to a mixer fleet, even though the arrival and departure patterns of the trucks are quite different (which the results depend on). The results also depend on the distribution of VMT and coincidence of the off duty periods.

Ideally we could use their open source model provided in the Borlaug et al. 2021 study to estimate our own results for a mixer fleet. However, the model requires daily data on shift start time, shift end time, and VMT on the particular day from individual fleet vehicles, which we were not able to obtain for the purposes of this study.

They provided the costs of electric vehicle chargers and installation at approximately \$150k per 150 kW charger and \$200k per 350 kW charger, taking between 3-10 months to install. Based on the fleets they studied, they determined that 100 kW chargers would be suitable in most cases for overnight charging and peak electrical loads range between 30-70 kW per vehicle on avg. For example, a fleet of 20 trucks could have peak electrical loads up to 1.4 MW.

If fleets used the 100kW chargers, they found that around 25% of depot locations in Texas would require some electrical upgrades for 100 heavy duty electric trucks but less than 10% of depot locations would require upgrades for fleets of 10 trucks. The most common upgrades required were adding feeder breakers ($400k) and adding or upgrading feeder circuits or upgrading feeder breakers ($2-12 million). Out of the situations they analyzed in their study, it was rare for more than 5% of depot locations to require entirely new substations that would cost around $35 million to build. Building entirely new substations takes up to 4 years, potentially causing delays to fleet electrification and increased fleet charging costs.

Their study does not analyze higher powered charging situations for opportunity charging. Using 350 kW or 1 MW chargers could substantially increase peak electrical loads. If battery electric concrete mixers had insufficient battery capacity for full day operation and needed to be fast charged during the day, we could see higher peak electrical loads, requiring electrical grid upgrades, resulting in delays and higher costs.

Basma et al. 2023, one of the studies we make use of in our total cost of ownership analysis, found the following equipment categories would require upgrades to enable heavy duty electric truck charging: sub transmission, substation, distribution, and to the meter equipment. The found the upgrade costs incurred by utilities will be passed onto customers that require charging infrastructure and add 3.97 cents per kWh to charging costs. Approximately half of the increased charging costs were attributable to charger installation costs paid by the utility including, "switch-gear, wiring, onsite construction, and trenching". On top of that, another 4 cents per kWh in levelized charging costs are attributable to charger acquisition costs, assuming the fleets would use 150 kW chargers for overnight charging and have a limited number of 1 MW chargers available. After accounting for all applicable expenses, the levelized cost of charging would be around 50% higher than the current electricity price. For example, in California 2022-2023 electricity rates were 19.57 cents per kWh, and the total levelized costs of charging reaches 29.12 cents per kWh. Due to the current electricity market in California, electricity prices can vary significantly over time and could increase the levelized costs of charging heavy duty electric trucks.

Bhardwaj and Mostofi 2022 has completed a literature review of battery swapping for heavy duty trucks and found that while swapping time can be much quicker than charging for heavy duty trucks, the availability of space for stations can be a concern. Of the 5 swapping companies they reviewed, they found that swap times range from 3 to 15 minutes. Ready mix companies may be able to tolerate a 5 minute swap before loading if battery swap trucks have less limitations in terms of payload loss (using smaller batteries) and lower costs compared to fuel cell or fixed battery powertrains. Arguably one of the main concerns for installing a swapping station at a concrete plant location will be the physical space and electrical load capacity.

Based on a video from China Uncut 2022 about battery swapping electric concrete mixer trucks in

China, we were able to determine some information about the battery swap station. The video describes a concrete plant using the same SANY SYM5310GJB5BEV9 trucks analyzed in Niu, Cui, and Y. Xie 2024. They said that the 282 kWH battery can be swapped out in as little as 5 minutes. The video included aerial footage of the swapping station with a truck next to it. Based on the listed dimensions of the truck at 35 feet long and 8 feet wide, we calculated the truck to be 280 sq feet. Based on those dimensions and the aerial photographs, we calculated the size of the swapping station to be approximately 2000 sq feet. The swapping station contains 8 batteries that can recharge within an hour, so we assumed the chargers were likely rated between 150-350 kW based on the size of the batteries. The charger speed selection for the swapping station would likely depend on the state of charge the batteries typically arrive and leave at, as well as the electrical capacity at a given location. From the range of charger speeds estimated, we determined that the max electrical load could be between 1.2-2.8 MW. The swap station operators would likely try to minimize the size of the chargers and limit the max electrical loads in order to reduce the need for costly electrical upgrades. The roof of the swapping station contains solar panels that assist in the station operation, like powering the equipment used to lift the batteries in and out of the vehicles. The swapping stations could complete up to 8 swaps per hour, so this could limit the number of battery swap capable trucks that could be operated at a particular location.

Of the 3 locations studied in the Central Concrete Company 2022 study described above, all 3 would have sufficient amount of total space for a 2,000 sq ft swapping station but one of the locations may have difficulty with the trucks maneuvering in and out of the swapping station since the available space is located near the boundary of the property. Only one of the locations would have enough electrical capacity without upgrades for a 1.2 MW max load. However, all of the locations could be upgraded to tie into a nearby feeder circuit to increase to a sufficient capacity. Since the station can only perform 8 swaps per hour, the arrival and loading of trucks would need to properly coincide to prevent queuing of the trucks at the swap station. More research will be needed in order to determine how battery swap, as well as other infrastructure options would be integrated into concrete plant locations in the US. However, Niu, Cui, and Y. Xie 2024 has shown success for battery swap concrete mixer trucks in China.

2 Duty Cycle Modeling Methodology and Results

Since there are no currently available battery electric or hydrogen fuel cell concrete mixer trucks operating in the US, we needed to create duty cycle modeling simulations in order to compare the energy use and efficiencies of the different powertrains. The concrete mixer truck has a unique duty cycle, so it is not necessarily comparable to other class 8 vehicles in terms of energy efficiency ratios. Since the mixer truck spends a substantial amount of time idling, it would likely see a large improvement in fuel economy from electrification or hybridization. We need to not only figure out the amount of energy the truck will use during loaded and empty driving trips, but also the amount of energy it would use when mixing concrete on the jobsite and loading at the plant. This requires an analysis of the auxiliary load demands on the concrete mixer truck that will be required in order to complete each delivery. This analysis will be described in the subsequent sections.

In order to calculate the efficiencies of the different powertrains we use the NREL Advanced Vehicle Simulator or ADVISOR model created by Wipke et al. 2000. ADVISOR allows you to create different vehicle profiles and run them on different drive cycles in order to estimate fuel use, emissions and other vehicle performance metrics like acceleration and gradeability. ADVISOR has been used by countless studies on alternative powertrain technologies in order to accurately estimate these metrics. The program requires inputs for all important vehicle parameters, which we will describe in the Vehicle Parameters section of this paper.

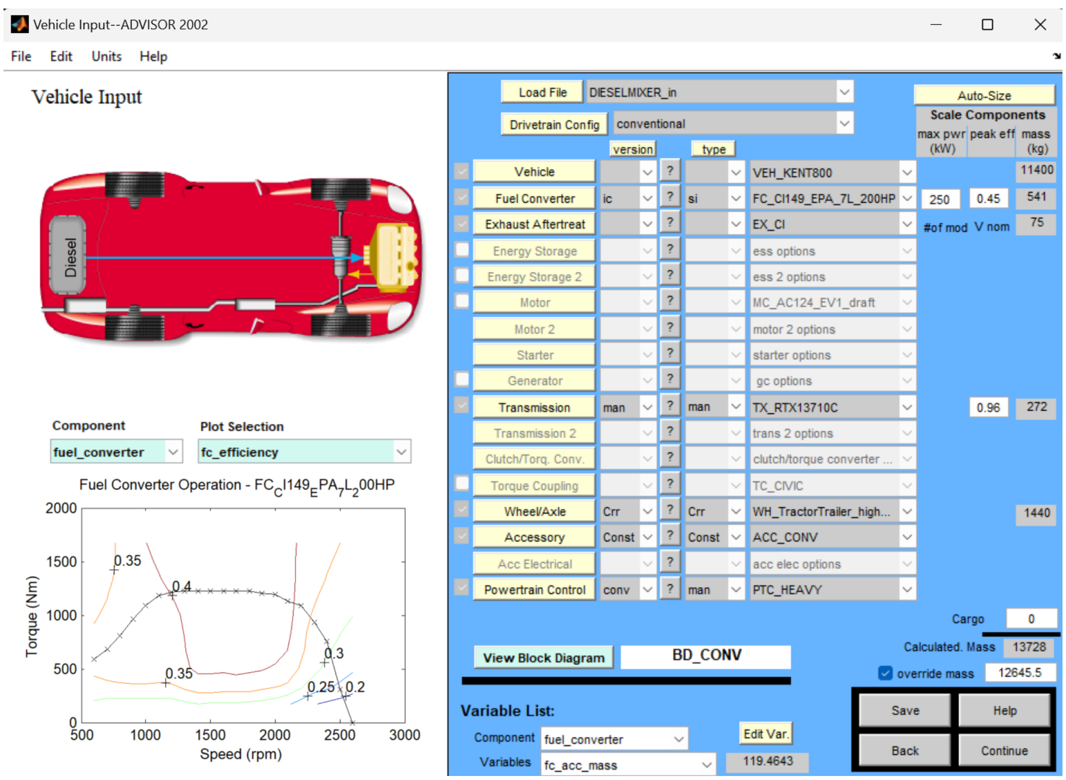


Figure 4: ADVISOR Graphical User Interface

After selecting all vehicle parameters, we select a drive cycle in order to run the vehicle on, which is a nx2 matrix of time(sec) and speed(mph), where n is the total length of the drive cycle in seconds. You can also add other parameters to the drive cycle like the cargo weight, which we vary as the mixer drives to the jobsite with a full load of concrete and heads back to the plant empty. After defining a drive cycle the model estimates the amount of energy used and we can convert this into different fuel economy metrics. The next sections will describe how we created the vehicle parameters and the outputs from the model.

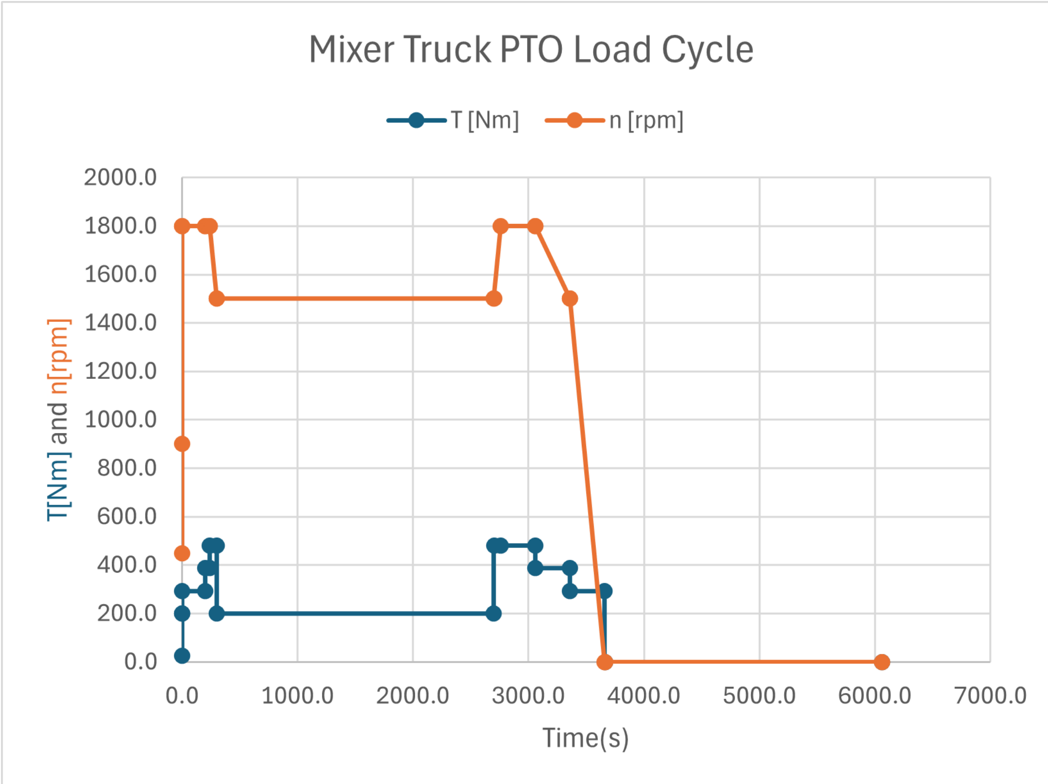
2.1 Vocational Loads

Besides just driving around, the truck needs to be able to continuously mix the drum full of concrete. On a conventional mixer truck, this requires operating a power take off (PTO) system that transfers the rotational energy from the engine to a hydraulic pump in order to power accessories on board. The hydraulic pressure generated by the pump can be used to turn a hydraulic motor, which turns the mixer gearbox, which turns the drum. The hydraulic pressure is also used to power other on board accessories, like the chute ram and bridgemaster load distributing tag axle ram, if equipped. On an electric powertrain, an electric PTO (ePTO) system can be used that mimics the operation of a PTO system but has an electric motor to power the PTO input shaft, rather than an additional drive shaft powered by the engine. However, instead of using an ePTO system, it may be more efficient to use an electric motor to drive the mixer gearbox and electro-hydraulic linear actuators could be used for other accessories.

2.1.1 PTO Load Calculations

We use Ban and Stipetić (2019), a recent study characterizing power requirements for various vocational trucks to compute energy demands for turning the drum when using a PTO system. They provide the torque and rpm required at the PTO input shaft at various time intervals for a representative mixer truck cycle, shown as a graph in Figure 5.

Figure 5: Ban and Stipetić (2019): Mixer Truck PTO Cycle



The power required by the PTO input shaft at a particular time interval is:

$$kW_i = \frac{Torque(N*M)_i * Speed(RPM)_i * 2\pi}{60 * 1000}$$

Soriano et al. (2016)

Let $dt_i = t_{i+1} - t_i$ in hours.

$$kWh_i = kw_i * dt(hours)_i$$

Let AL be the average mechanical load in kW required by the PTO input shaft, when the total representative cycle length is 6060 seconds or 1.683 hours:

$$AL(kW) = (\sum_{i=1}^{n} kWh_i)/1.683hr = 23.87kW$$

Therefore, the duty cycle simulations for the diesel powertrain must include an additional 23.9 kW of mechanical loads to account for the PTO system operation. Since we are using an average load calculated across a representative load cycle, it will be important to have the representative drive cycle have an accurate proportion of idle time for loading, pouring and washing to roughly match the time allocations of the real world vehicle.

If an ePTO system is used on a BEV or FCEV, there will be an additional efficiency loss from using an electric motor to power the PTO input shaft that will bring up our average load value above 25 kW, assuming the electric motor is on average 94% across the torque and rpm values required by the PTO input shaft for the mixer drum cycle. For our duty cycle simulations, we will assume that the BEV or FCEV mixer trucks will use an electric motor direct drive system, rather than an ePTO system, as the increased efficiency significantly reduces auxiliary loads. The next section will quantify the electric motor direct drive system loads and show how they are far lower than if using a ePTO system.

2.1.2 Electric Direct Drum Drive Calculations

In order to estimate the loads from the direct drive option, we consult one of the cited references from Ban and Stipetić (2019), M. Bae, T. Bae, and Kim (2018). M. Bae, T. Bae, and Kim (2018) provides the torque and rpm requirements of the hydraulic motor used in a typical PTO system to turn the mixer gearbox at different stages of the mixer truck delivery cycle (load, drive loaded, unload, wash, drive empty). Each stage of the delivery cycle was assigned an approximate time proportion to be representative of the real world operating cycle. Modifications were made to the time proportions in order to allow for additional waiting time when the truck arrives on a jobsite and must continue to mix the full load, as this is very common and wasn't accounted for in their study.

Figure 6: Truck Waiting to Pour

The mixer truck gearbox was reported to have a 132:1 gear reduction, and after calculating the drum speed based on their rpm values of the hydraulic motor, we determined that the corresponding drum speeds were slower in some cases than real world conditions, so the rpm values when loading and driving loaded were increased in order to better estimate the direct drive electric loads. We assume that approximately a 75kW electric motor will be used to turn the mixer gearbox so we used an efficiency map of a 75 kW electric motor obtained from the ADVISOR software in order to determine the efficiency of the electric motor at various torque and rpm values. Since the 75 kW electric motor selected wasn't able to produce the peak torque values in the cycle, the mixer gearbox could incorporate a further gear reduction and thus the torque and rpm values were recalculated at 198:1, rather than 132:1 by dividing the torque values by 1.5 and multiplying the rpm values by 1.5. Table 2 is from M. Bae, T. Bae, and Kim (2018) after adjusting the time proportion, increasing the drum speed during loaded driving and during loading, regearing to 198:1 from 132:1, calculating the kW as shown in equation 1 above and scaling for the approximate efficiency of a 75 kW electric motor at a particular torque and rpm value. Note that the kW values shown are already scaled for the efficiency by dividing by the given percentage.

Table 2: Electric Drum Drive values from M. Bae, T. Bae, and Kim (2018) with modification:

Activity(i)	T(N*m)	rpm	Time Proportion(p)	Efficiency	kW:
1. Loading	126	3366	4%	90%	49.35
2. Driving and Waiting at Job	126.6	594	50%	77%	10.22
3. Normal Discharge	161.13	990	12%	81%	20.62
4. Max Discharge	189.87	1980	1%	86%	45.78
5. Driving Empty or Waiting at Plant	34.93	396	29%	75%	1.93
6. Washing	34.93	3366	4%	90%	13.68

Let AL be the average electrical load in kW from the electric motor driving the mixer gearbox, which was calculated by multiplying the electrical load for each stage of the delivery cycle by the proportion of time (p) for that activity and summing in order to find a time weighted average electrical load:

$$AL(kW) = \sum_{i=1}^{6} kw_i * p\% = 11.13kW$$

Since we are uncertain how much additional energy the chute ram and bridgemaster ram may require if replaced with electro-hydraulic linear actuators, we round the approximate load value to 12.5 kW to be used for the auxiliary loads for the battery electric and fuel cell trucks. This load is roughly half that of what it would be from an ePTO system and is why we assume that a zero emission concrete mixer truck would likely use an electric motor direct drive system rather than an ePTO system.

2.2 Standard Accessory Loads

The engine files, fuel converter files, and energy storage files in the current version of ADVISOR already account for any accessory loads that are specific to that powertrain. For example, the diesel engine map already includes the energy use for the water pump, alternator, engine fan and oil pump. The fuel converter files for the fuel cell already include the energy use for the fuel cell cooling system. The energy storage files already include the energy use for the battery thermal management system. The remaining accessory loads that we need to account for are: the air compressor system, A/C compressor system and the power steering (PS) pump. These are the results from two studies that include information on the accessory loads for the air compressor system, A/C compressor system and the PS pump on a conventional truck:

Table 3: Accessory Loads for Belt/Gear Driven Components from Literature

Component:	Hendricks and O'Keefe (2002)	Pettersson and Johansson (2006)
Air Compressor (kW)	3.5	3.25
A/C Compressor (kW)	2.2	1.625
PS Pump (kW)	4.5	5
Total Aux Load (kW)	10.2	9.875

We will use the average of the values from their studies as mechanical accessory loads for these components on our diesel truck at approximately 10 kW. Electric trucks will use motor driven accessories that can save power, as they are only operated when needed.

Silvas et al. (2013) found that electric power steering systems consume only 50% of the energy of a belt or gear driven power steering system, and that electric AC compressor systems consume only 40% of the energy of a belt driven AC compressor system due to the fact that the electric versions don't consume any power when unloaded. Redfield et al. (2006) found considerable energy savings from using an electric air compressor system, as it also doesn't consume any power when unloaded, so we will assume that the electric air compressor consumes only 50% of the power of a belt or gear driven air compressor. By multiplying the average component loads from Table 3, by 50% for the air compressor, 40% for the A/C compressor and 50% for the PS pump we can approximate the energy consumption of the electric accessory systems. Note that the belt/gear driven amounts refer to a mechanical accessory load and the electric amounts refer to an electric accessory load.

Table 4: Belt/Gear Driven vs Electric Accessories

Component	Belt/Gear Driven	Electric Equivalent
Air Compressor (kW)	3.375	1.6875
A/C Compressor (kW)	1.9125	0.765
PS Pump (kW)	4.75	2.375
Total Aux Load (kW)	10.0375	4.8275

The electric accessory loads shown are lower, as well as the electric vocational loads (23.9 kW for the PTO system vs 12.5 kW for the electric drum drive) shown in Section 2.1. For our ADVISOR inputs we will specify the total mechanical accessory load for the diesel truck of 34 kW and 17 kW for the total electrical accessory load for the battery electric and fuel cell trucks.

2.3 Vehicle Parameters

Table 5 has the selected inputs for the duty cycle modeling simulations in ADVISOR.

Table 5: ADVISOR Inputs

Variable	Diesel	BEV	FCEV
Fuel Converter (kW/max eff)	250kW/45%	N/A	200kW/ 60%
Motor Controller (kW/max eff)	N/A	350kW/ 94%	350kW/ 94%
Battery (kWh/Volts)	N/A	400 kWh/ 650V	56 kWh/ 650V
H_2 Storage	N/A	N/A	40 kg
Chassis	Kenworth T800	Kenworth T800	Kenworth T800
Transmission	10 speed	2 speed	2 speed
Unloaded Mass (kg)	12627	14943	14431
RRC	0.006497	0.006497	0.006497
FA (m^2)	8.9	8.9	8.9
Tire Radius (m)	0.51	0.51	0.51
C_d	0.77	0.77	0.77
Mechanical Accessory Load (kW)	33.91	N/A	N/A
Electrical Accessory Load (kW)	N/A	17.33	17.33
Final Drive ratio	4.35	7.82	7.82

Generally the diesel engines on concrete mixer trucks will have around a 250 kW power rating, although this varies depending on the preferences of the fleet manager. While this is often severely under-powered for the application, this is typically done to save weight and reduce fuel consumption during extended idling. A sensitivity analysis based on the diesel engine power will be shown in the results section. While many of the class 8 battery electric trucks currently being released have 500 kW motors, like the Peterbilt Motors Company 2024 520EV, a lower power rating on the mixer would likely be more suitable to save weight and excessive power could potentially make concrete spills more likely during hard acceleration. The 350 kW motor would also be suitable for the fuel cell truck due to the same reasons, as well as the fact that the fuel cell power output will be the limiting factor on long climbs. The Fuel Cell power rating is based on the Nikola 2023 TRE FCEV truck. The battery pack size in the battery electric truck is based on the battery pack available in the Peterbilt 520EV, Peterbilt 579EV and Kenworth T680EV. The fuel cell battery pack is based on the Hyzon 2024 Refuse Fuel Cell Truck.

The mass of the vehicles will be discussed in the next section. The accessory loads are discussed in the Vocational Loads and Accessory Loads sections. The Kenworth T800 chassis was selected as it was already available in ADVISOR and is a popular choice for concrete mixer trucks in the US. Generally the diesel mixer trucks will use either an Eaton 9LL transmission with a deep reduction option or an Allison automatic rugged duty series transmission, depending on the preferences of the fleet manager. The 10 speed transmission was selected as it was the closest heavy duty truck transmission available in ADVISOR. Many of the battery electric class 8 trucks currently have a two speed automatic transmission for improved torque at low speeds, and reduced energy consumption on-highway. This will be especially important for concrete mixer trucks as they need to creep smoothly at very slow speeds when pouring, so a two speed transmission was selected for the battery electric and fuel cell models.

The frontal area was calculated based on the height and width of the truck, subtracting the area underneath the vehicle. The high rolling resistance value in ADVISOR was selected, as some concrete mixer trucks use a more aggressive off road style tire configuration for better traction on jobsites. They are generally sized with an approximately 0.51 meter loaded radius. These are some popular tire sizes for a mixer truck: 425/65R22.5 steer tire, 11R22.5 drive tire. Generally the diesel mixer trucks will use around a 4.35 final drive ratio, as they are generally driving at much lower speeds than the typical on-highway class 8 truck. There weren't any published values for the aerodynamic drag value for a concrete mixer truck, likely due to the fact that this isn't a design priority of the vehicles, since they are predominately driven at lower speeds. Arguably though, the shape of the vehicle is somewhat similar to a flatbed semi with a load, so a coefficient of 0.77 drag coefficient from a flatbed with load was selected from Fitch 1993.

2.4 Vehicle Weight and Size Analysis

Throughout this analysis, we primarily consider the weight of the powertrain components being the limiting factor in terms of powertrain viability, instead of the physical volume of the components. The diesel vehicles typically leave the plant right at their gross vehicle weight rating, so the payload of the zero emission vehicles is an important concern. The mixer trucks in California and most other states are subject to some form of the Federal Bridge Formula, which specifies the max weight of the vehicle not only based on the number of axles, but also the distance between the furthest two axles. This was created in order to limit the stress on bridge components and other roadway structures. This is why the majority of mixers, commonly refereed to as booster or bridgemaster mixers have a trailing axle in order to extend the wheelbase when loaded. Typically, behind the cab, there is multiple feet of empty space before the mixer drum as a side effect of the way the current weight regulations are specified.

According to Caltrans 2024, mixer trucks in California are subject to a modified bridge formula that specifies the max weight of the vehicle only based on the distance between the outer most axles, provided that none of the axles are overloaded. The typical concrete mixer has a 40 foot wheelbase when the trailing axle is down, so in California it receives a 70,000 lb weight rating, which is 2,000 lb lower than the weight rating based on the federal bridge formula for a 4 axle mixer with a 40 foot wheelbase according to FHWA 2019. Additionally, based on the federal bridge formula, a mixer in other states could add additional axles to increase the weight rating beyond 72,000 lbs to 80,000 lbs if equipped with 7 axles. The 7 axle configuration typically requires mounting the water tank behind the cab, which would limit the additional space allowed for the additional size of powertrain related components. However, mounting the water tank behind the cab is not common in California, as there is no motivation to purchase a truck with more than 4 axles due to the way the weight restrictions are designated. According to Nadolny 1994, the standard 40 foot wheelbase is due to the fact that most states limit the length of a straight truck at 40 feet.

Since a mixer truck in California typically has the water tank mounted on the driver-side, beside the frame (for easier access), as mentioned previously there is multiple feet of empty space behind the cab as shown in Figure 7.

Figure 7: Concrete Mixer with Driver-Side Mounted Water Tank

If necessary, this additional space could be used to satisfy the additional space requirements of larger powertrain components for zero emission trucks. For this analysis, it is assumed that if the powertrain components are viable in terms of volume constraints in other trucks like class 8 tractors, it likely won't be an issue for concrete mixers that are subject to versions of the bridge formula that motivate increasing the total wheelbase, resulting in empty space behind the cab.

For example, the Kenworth 2023 T680 Fuel Cell Electric Truck (shown in Figure 8) has a 58 kg hydrogen storage system, 18 kg larger in capacity than our specified mixer and would fit well in a bridge compliant mixer with a driver side mounted water tank.

Figure 8: Kenworth T680FCEV

The current T680FCEV is designed for a dry van trailer application that requires a taller cab for aerodynamic purposes. Since the 40 kg hydrogen storage system on the mixer truck would only require 4 out of the 6 hydrogen tanks on the Kenworth T680FCEV, the height of the cab and hydrogen storage area could be reduced in order to better match the mixer chassis.

Ricardo Strategic Consulting 2022 produced a study describing the weight and cost of all major components in battery electric and fuel cell trucks and compared them to diesel models. A 4 axle diesel mixer truck set up for California weight laws will be approximately 12646 kg empty (with water and diesel tank full). Of that weight, 7528 kg is from the chassis and 5098 kg are from the mixer related components. According to Ricardo Strategic Consulting 2022, the powertrain related components, including the engine, aftertreatment, cooling system, transmission, DEF tank, empty fuel tank and other related accessories for the diesel are approximately 24% of the chassis weight. After subtracting this, we use the remaining 76% of the chassis weight plus the mixer related components to find the total mixer truck weight without powertrain related components to be used in calculating the approximate weight of the battery electric and fuel cell vehicles.

The diesel truck with a payload of 19119 kg can legally haul 10 yards of concrete with around 750 kg of extra payload to allow for concrete build up in the drum or heavier mixes that weigh more than the standard 4050 lbs/yard.

Table 6: Diesel Weight Breakdown (kg)

Chassis	Mixer	Total Empty	Powertrain	Truck w/o powertrain	Payload
7528	5098	12627	1807	10820	19119

The weight of the 400 kWh battery pack is calculated using a pack energy density of 140 Wh/kg according to Ricardo Strategic Consulting 2022. They also provide the approximate weight of a 350 kW motor, inverter and transmission being 800 kg. They provide the approximate weight of the other high voltage components, including: electric air compressor, electric steering pump, electric HVAC systems, on-board charger, DC/DC converter, high voltage distribution system, and battery thermal management for the battery electric truck all totaling 468 kg. We use all these values to calculate the approximate empty weight of the battery electric truck at 14943 kg. When you include the additional 2,000 lbs of weight allowed for zero emission trucks in California, you get a payload of 17711 kg. With a payload of 17711 kg, the truck can no longer legally haul 10 yards of concrete. Keeping a consistent weight buffer for drum build up as the diesel, the BEV could only carry 9.25 yards, so 9 yard load sizes would likely be used, as loads are typically batched to nearest half yard. This would require the fleets to purchase, staff and maintain more trucks to meet their delivery demands. The weight of a battery electric mixer in China from Niu, Cui, and Y. Xie 2024 capable of battery swapping is quoted to weigh 15,300 kg, which is quite similar to our calculated weight of 14943 kg.

Table 7: BEV Weight Breakdown (kg)

Truck w/o powertrain	400 kWh battery	350 kW M,I,T	HV Comp	Empty Weight	Payload
10820	2856	800	468	14943	17711

In order to match the payload of the diesel the pack energy density would need to reach 250 Wh/kg, which currently isn't attainable in heavy duty truck batteries.

The fuel cell component weights are estimated based on Ricardo Strategic Consulting 2022. However, after private discussions with a manufacturer of a fuel cell electric truck, the weight of the hydrogen storage system had to be updated. The weight of a 40 kg hydrogen storage system is estimated at 1729 kg after adjusting our parameters in order to match the total weight to existing class 8 fuel cell models. The fuel cell system is estimated at 327 kg based on a 390 kW fuel cell weighing 647 kg. The battery weight is also estimated using a pack energy density of 140 Wh/kg. The 350 kW motor, inverter and transmission weight is the same as shown in the BEV. Ricardo Strategic Consulting 2022 provides the approximate weight of other high voltage components for a fuel cell truck at approximately 370 kg. The payload is also calculated with an additional 2,000 lbs granted to ZEVs in California.

Table 8: FCEV Weight Breakdown (kg)

Truck w/o powertrain	40 kg H2 Storage	200 kW Fuel Cell	56 kWh battery	350 kW M,I,T	HV Comp	Empty Weight	Payload
10820	1729	327	386	800	370	14432	18221

The fuel cell truck still has a payload loss compared to a diesel, even with the additional 2,000 lb weight allowance and has a very similar payload to the battery electric truck. Payload losses are very problematic for fleets, as it directly reduces the amount of revenue a truck can generate per day. The calculated empty weight of our fuel cell truck is quite similar to the fuel cell truck shown in Niu, Cui, and Y. Xie 2024 at 14730 kg. In order to reduce the weight of the fuel cell truck, the weight of the hydrogen storage system would need to be reduced while still maintaining safety standards.

2.5 Drive Cycle

The mixer truck drive cycle is characterized by a loading phase at the plant, a loaded driving phase to the job site, an unloading phase on the job site and an empty driving phase back to the plant. The truck will typically return to the same plant where it was loaded, but sometimes may travel to another plant if the fleet route optimization software decides it will be more efficient to go to another plant to re-load. Boriboonsomsin et al. 2018 has published a 'Cement Mixer' duty cycle, however they removed extended idling periods over 5 minutes from the published duty cycles. Due to the high auxiliary loads on concrete mixer trucks, the amount of idle time has a large impact on the fuel economy of the vehicle. Additionally, the data was collected from volumetric mixer trucks which are dissimilar to the mixer trucks considered in this study. Volumetric mixer trucks keep the aggregate, water and cement separate until it is mixed in small quantities on the job site, rather than the 'ready-mix' trucks that are considered in this project, that mix before transit to the job site. Volumetric mixer trucks make up a very small proportion of the mixer truck market and exhibit a different driving pattern than a ready-mix truck. The volumetric trucks are typically used for construction projects that require very long waiting times or for delivery to more remote locations without a nearby concrete plant. For these reasons, the duty cycle published by Boriboonsomsin et al. 2018 is not an appropriate fit for this study. No other duty cycles specific to concrete mixer trucks have been published. Due to the time and funding constraints of this study, it was determined that it wouldn't be practical to work with a fleet to collect real world driving data specific to concrete mixer trucks. Alternatively, the California Air Resources Board 2024 Heavy Heavy-Duty Diesel Truck (HHDDT) drive cycle was modified in order to match the operational characteristics of the mixer truck. The cycle used in this study has two modified versions of the HHDDT drive cycle to represent the loaded and empty driving phases, with an idle phase added in between them to represent the unloading phase of the mixer cycle. The proportion of highway driving has been reduced so that roughly one-third of the driving is on highway, as concrete mixer trucks have short delivery distances and do not spend much time on the highway. According to the NRMCA 2020 and NRMCA 2021 the average one way delivery distance is only 14 to 15 miles. After a confidential discussion with a large ready mix fleet, it was determined that a 50 min delivery time is reasonable and the drive cycle shown in Figure 9 is similar to their operations if the truck stays at their home plant throughout the day. However, the truck may often travel to other nearby plants to load after delivery, so a second scenario of the drive cycle was created with an additional 4.5 miles of empty highway driving in order to represent a truck that may travel additional mileage in order to optimize operations. The one way delivery distances in the first scenario is slightly shorter than those shown in the NRMCA 2021 survey, however the survey did not provide average time on job, so it was determined that it would be better to match the proportion of drive-time vs unloading-time as the fleet we discussed the drive cycle with. The effect of reducing the pouring time, analogous to increasing the driving distance is discussed in the sensitivity analysis section. Idle hours were newly added to the NRMCA 2021 survey, however this data point was only provided by 25% of survey recipients and the hours were calculated from truck telematic systems that only begin counting after the vehicle has been stationary for a specified period. Since the trucks need to move short distances very often during pouring, the movement can restart the time count used to detect idling, resulting in an inaccurate count of the idle time. Based on the recommendation from a fleet manager we talked to, it was decided to ignore this benchmark when designing the drive cycle for our analysis.

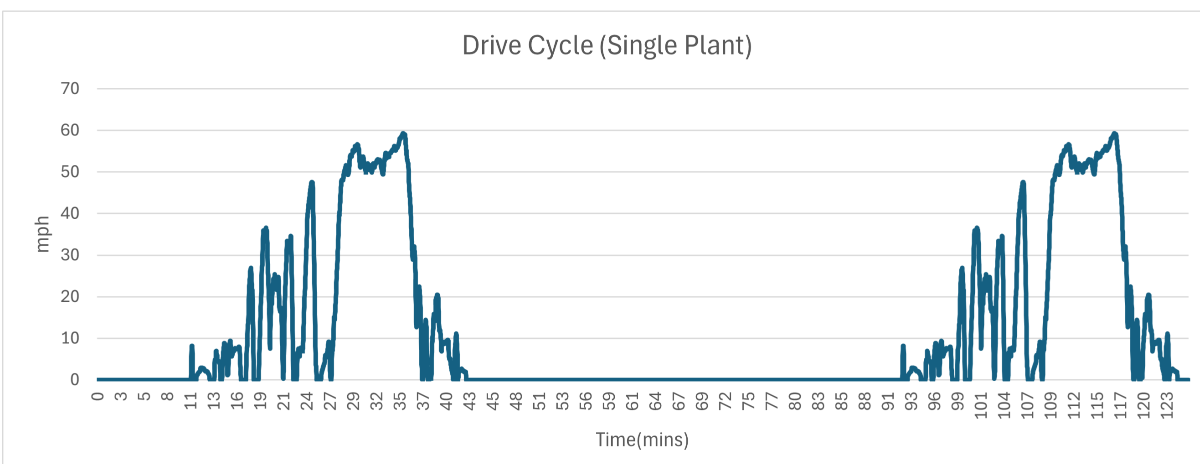


Figure 9: Drive Cycle for Concrete Mixer Truck

The graph of the multi-plant drive cycle is excluded for brevity, as it looks very similar to the single plant drive cycle, just with 4.5 additional miles of empty highway driving inserted into the second half of the drive cycle. The statistics for each drive cycle are shown in Table 9. According to the NRMCA 2021 survey the average load size is 8 cubic yards, and the average max load size is 10 yards. Each drive cycle was run with those two load sizes to show a typical day vs a busy day where each load is full. The first half of the drive cycle has the cargo weight set to 4050 lb per yard times the number of yards, with either 32400 lb (8 yards) or 40,500 lb (10 yards). The cargo weight in the second half of the drive cycle is set to 0 lb as most of the time the truck travels back to the plant empty or with a small amount of leftover concrete.

Table 9: Drive Cycle Stats

	Single Plant (SP)	Multiplant (MP)
Time (s)	7513	7910
Distance (mi)	23.29	27.83
Max Speed (mph)	59.3	59.3
Avg Speed (mph)	11.16	12.67
Max Acc ft/sec^2	4.25	4.25
Max Dec ft/sec^2	-4.06	-4.06
Avg Acc ft/sec^2	0.64	0.63
Avg Dec ft/sec^2	-0.79	-0.74
Idle Time (s)	4138	4250
# of stops	26	26
Grade	0%	0%

2.6 Duty Cycle Modeling Results

Results are shown for single and multi-plant drive cycles, with 8 and 10 yard load sizes. Since the multiplant drive cycles include slightly more empty driving, we expect to see higher fuel economies or lower energy consumption per mile. The average load size for a truck is 8 yards, as some loads are partial loads, but often on busy days, a truck will be carrying full 10 yard loads the entire day. Despite the BEV and FCEV being above the legal weight limit with a 10 yard load, we still included this to keep the results consistent.

These are the fuel economies of the vehicles in the different scenarios in miles per diesel gallon equivalent (38 kWh).

Table 10: Fuel Economies in DGE

(dge)	SP/8yd	SP/10yd	MP/8yd	MP/10yd
Diesel	2.99	2.93	3.27	3.21
BEV	9.65	9.41	10.22	9.99
FCEV	5.14	5.06	5.51	5.43

These are the same results in units commonly used for their powertrain:

Table 11: Fuel Economies in Powertrain Specific Units

	SP/8yd	SP/10yd	MP/8yd	MP/10yd	NRMCA	Company Projection
Diesel (MPG)	2.99	2.93	3.27	3.21	3.34	
BEV (kWh/mi)	3.94	4.04	3.72	3.81		4.01
FCEV (mi/kg)	4.54	4.47	4.88	4.80		

The closest scenario to a typical operating condition is the multiplant 8 yard load cycle, which has a diesel mpg very close to the NRMCA 2021 average. The company IntegralDX 2024 released a printed spec sheet of a not yet released battery electric concrete mixer and based on the given truck specs and range scenarios, we calculated that they estimated the truck would consume approximately 4 kWh per mile, which is very close to the results we independently calculated for the BEV. Niu, Cui, and Y. Xie 2024 published a daily average fuel efficiency rate of a Chinese fuel cell electric mixer truck at 12.5 kg per 100 km or 4.96 miles per kg, which is very close to the multiplant 8 yard load cycle fuel cell result of 4.92 miles per kg. It is also expected that the Chinese trucks will get slightly better fuel economy on electric powertrains because they are generally driving at much lower speeds and subject to less aerodynamic drag. Unfortunately Niu, Cui, and Y. Xie 2024 did not publish a daily average energy consumption for the battery electric, only loaded and empty energy consumption values which do not include the energy use when pouring on a jobsite.

Table 12: EER Values for Each Duty Cycle

EER	Diesel	BEV	FCEV
SP/8yd	1	3.23	1.72
SP/10yd	1	3.21	1.72
MP/8yd	1	3.13	1.69
MP/10yd	1	3.11	1.69
Avg EER	1	3.17	1.72

2.6.1 Sensitivity Analysis on Drive Cycle Modeling

After analyzing all important parameters of the duty cycle modeling, some of the most important ones that are subject to uncertainty are: diesel engine power rating, pouring time, auxiliary loads, drag coefficients and rolling resistance coefficients. Ideally, we could perform a sensitivity analysis on the drive cycle profile, such as varying the maximum acceleration rate. However, this was considered too time consuming for this project due to the way ADVISOR stores the drive cycle files. As described in the Drive Cycle section, we chose to have two versions of the duty cycle to act as a sensitivity analysis on the drive cycle. the multi-plant and single-plant cycle that have different ratios of empty to loaded driving and we also ran the cycles at the average and maximum load sizes to see whether always having full load sizes have a large impact on the energy consumption per mile. These results are described above in the previous section.

Unfortunately, we could not get a representative elevation profile for this study, so we kept a constant elevation. The duty cycle used in Niu, Cui, and Y. Xie 2024 had a very flat elevation profile. However, a concrete company operating in a mountainous region would have a much steeper elevation profile for the duty cycle, resulting in higher energy consumption levels.

Figure 10: Mountain Delivery

A particularly problematic delivery would be one that drives fully loaded to the top of a mountain and then drives empty back down, in this case, energy consumption levels can be extremely high. A company that routinely makes deliveries in mountainous areas may have more difficulty transitioning to zero emission vehicles with limited energy storage capabilities.

One of the areas of the mixer duty cycle that is subject to the highest level of variability is the pouring time. For the duty cycles, a 50 minute pouring time was added that roughly equates to 40 mins spent waiting and pouring and 10 mins washing down. This is a good average according to a fleet manager we talked to. We decreased the pouring time by 20%, down to a 40 min on-jobsite time and re ran the single plant, 10 yard load cycle. Longer times on-jobsite result in worse fuel economy as the auxiliary loads during idling increase energy consumption without increasing the miles traveled. The results were as follows, after decreasing the on-jobsite time by 20%: the diesel truck increased its miles per diesel gallon by 5%, the battery electric truck increased its miles per diesel gallon equivalent by 3% and the fuel cell truck increased its miles per diesel gallon equivalent by 2%. Roughly speaking that means if the fleets were able to reduce on jobsite time by 20%, they could increase the range of the trucks by between 2 and 5%, depending on the powertrain.

Another area of variability for the diesel truck is the motor power rating in kW. Some fleets choose to have more powerful engines to enable better performance, while others opt for smaller and lighter engines to reduce weight and increase legal payload. This is the relationship between engine power rating and miles per diesel gallon in the single plant, 8 yard load cycle:

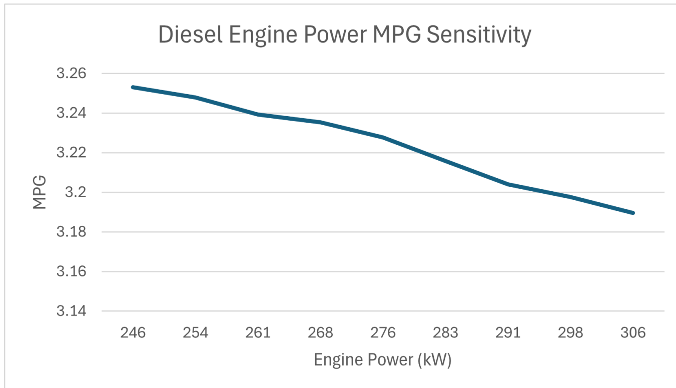


Figure 11: Diesel Engine Power Rating Sensitivity

On the battery electric truck, going from a 350 kW motor to a 500 kW motor reduces the miles per gallon equivalent by 3%.

Note: Sensitivity analysis outputs directly from ADVISOR were used whenever possible, resulting in different graph styles in the section.

This is the effect of the drag coefficient on diesel miles per gallon. Trucks with a similar shape to a concrete mixer, such as a flatbed with a load, have a drag coefficient of approximately 0.77 according to Fitch 1993. We use the same drag coefficient for all powertrain types. While it would certainly be possible to reduce the drag coefficient, doing so would likely require adding weight and would not result in significant improvements since highway driving time is more limited compared to other trucks.

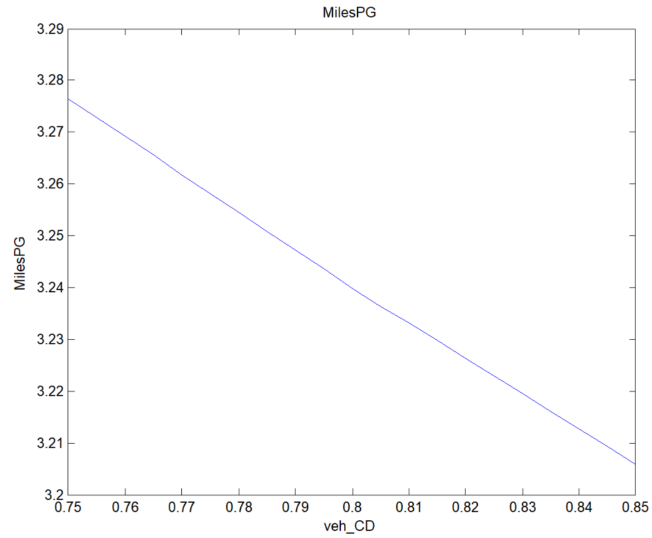


Figure 12: Effect of C_d on diesel MPG

This is the effect of rolling resistance coefficient on diesel miles per gallon. The high rolling resistance value in ADVISOR was used, as most mixer trucks use an off road capable tire so the trucks do not get stuck in off road terrain when pouring concrete. More aggressive off road tires increase the rolling resistance and fuel use. We use the same rolling resistance coefficient of 0.006497 for all the powertain types.

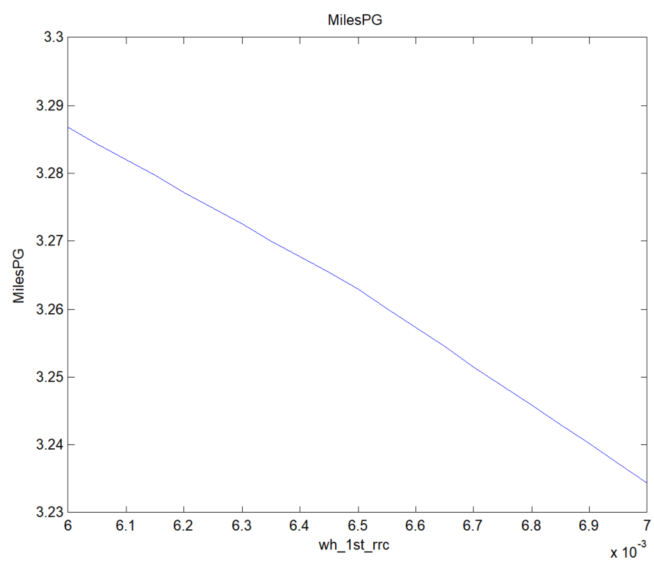


Figure 13: Effect of RRC on diesel MPG

This is the effect of total accessory loads including vocational loads from the mixer drum and standard accessory load on diesel miles per gallon. The total accessory loads for the diesel truck were calculated at 33.91 kW. For more information, see the Vocational Loads and Accessory Loads Section of the report.

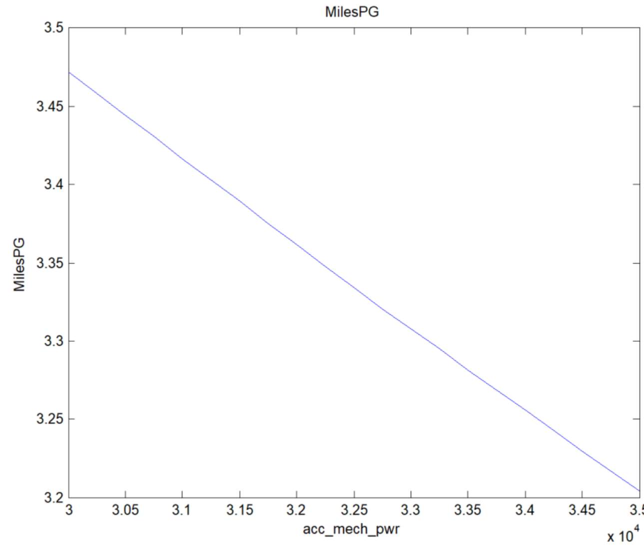


Figure 14: Effect of Total Accessory loads in Watts on Diesel MPG

For the battery electric and fuel cell trucks, an electric drum drive system, as well as electrically driven accessories would be used that would result in substantially lower total accessory loads at 17.33 kW compared to the diesel value of 33.91 kW. This is the sensitivity of the total accessory loads on the battery electric miles per gasoline gallon equivalent. For more information, see the Vocational Loads and Accessory Loads Section of the report.

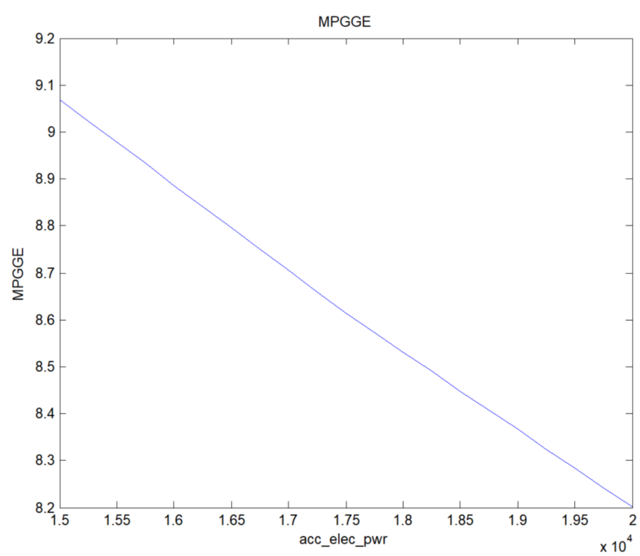


Figure 15: Effect of Total Accessory loads in Watts on BEV MPGGE

While there is some uncertainty in the exact conditions in the real world operation, all of the variables that have significant levels of uncertainty have a linear relationship on the estimated fuel economy. We feel confident using these energy consumption values in order to report the range of the vehicles given a battery or hydrogen tank size, as well as perform total cost of ownership calculations.

2.7 Range and Fueling Times

According to Central Concrete Company 2022, turnaround times at the plants are often less than 15 mins. This would make the opportunities for charging a battery electric truck very limited, especially because the truck needs to move around the plant during the turnaround time multiple times. This is a breakdown of a typical loading sequence at a plant:

Table 13: Plant Turnaround Time Breakdown

Location	Activity	Typical Time
1.	Fill water tank if not completed while loading	0-2 mins
2.	Queue for loading	0-10 mins
3.	Load, Receive Delivery Ticket, Set Booster Pressure, Confirm Delivery Address and Route	2-6 mins
4.	Washdown and Slump Adjustment	3-6 mins

The loading process is completed as quickly as possible and there are many steps a driver must complete safely during these 15 minutes. Ready mix companies put a great deal of effort into making this process as quick as possible because it is one of the time windows the company has control of, as opposed to the time spent sitting in traffic or delayed at a jobsite. The companies spend millions of dollars upgrading plants in order to load trucks as quickly as possible. Many plants can load over 40,000 lbs of concrete into a truck in under 2 minutes. Many companies will time drivers during their washdown and drivers may receive a call from their plant manager if their washdown is even a few minutes above the plant average. In this time and space constrained environment, any delays for charging could be extremely problematic. While there may be occasional opportunities for charging if waiting time is extended, companies wouldn't purchase a truck that would require this to complete a full days worth of deliveries.

Table 14: Range Results

(range in miles)	Diesel	BEV	FCEV
SP/8yd	134.5	81.3	163.6
SP/10yd	131.9	79.2	160.9
MP/8yd	147.1	86.0	175.5
MP/10yd	144.6	84.1	173.0
Avg	139.5	82.7	168.3
Notes	55 gal tank, drain down to 10 gal	400 kWh battery, 80% usable	40 kg tanks, drain down to 10%

Unfortunately, the range results are not comparable to the trucks in Niu, Cui, and Y. Xie 2024, as the diesel mixer's quoted range in that study assumes the equivalent of over 11 miles per gallon, when the US mixer only achieves around 3.3 miles per gallon on average according to NRMCA 2021. It appears that the certified range of the vehicles shown in Niu, Cui, and Y. Xie 2024 are based on empty driving, not real world operating conditions. For our study, it was important to report the range based on real world operating conditions.

These are the vehicle usage patterns by site from the Central Concrete Company 2022 report:

Table 15: Central Concrete Company 2022 Mileage Requirements

Site	Avg Mileage	Peak Mileage
Urban	43	80
Suburban	78	155
Ex-Urban	92	150
Overall Avg	70	120

They also indicate that shift durations occasionally reach up to 20 hours per day, which leaves limited time for overnight charging. While the battery electric powertrain can fulfill the average mileage requirements in all sites but the Ex-Urban, in almost all cases it will run out of range in a peak mileage scenario. As described in the background on concrete mixer trucks section in the introduction, the fleet has very limited control of the miles of a specific truck. Trucks are dispatched dynamically based on the status of all of the concrete orders in the area. For this reason, the range limitations of the battery electric truck could be highly disruptive to operations.

A diesel concrete mixer with a 55 gallon tank can refuel in less than 5 minutes at a private fuel station at the concrete plant. The speed at which a battery electric truck can charge depends on the charger speed in kW, as well as the battery chemistry, current state of charge and time required to balance the cells. The Peterbilt Motors Company 2024 520EV that we base the specs of our battery electric truck off of is quoted to be able to charge in a minimum of 3 hours. In the future, it is likely though that this charging time could be reduced. According to Cunanan et al. 2021 a hydrogen station could dispense at 7.2 kg per minute, which would allow the 40 kg tank to refuel in less than 6 minutes. However, this is currently limited by thermodynamic issues. The compressing of the hydrogen gas inside the tank raises the temperature, which decreases the density of the gas, meaning less fuel can be stored in a given volume. Preventing this requires waiting for the tank to cool and then continuing to fuel, which extends fueling times. Based on the launch event for the FirstElement Fuel 2024 in Oakland, California, the Hyundai Xcient Fuel Cell with a 70 kg tank currently takes around 30 minutes to refuel, but the pumps could dispense fast enough to refuel the truck in as little as 5 minutes.

2.8 Analysis of Battery Swap Trucks

Due to the success of battery swap trucks shown in Niu, Cui, and Y. Xie 2024, we will conduct a brief analysis to see if they would be more attractive to a fleet compared to fixed battery trucks or fuel cell trucks. One of the most significant advantages of a battery swap truck in a mixer truck application is that you can minimize the size of the battery in order to maximize payload and swap the battery at the concrete batch plant before each delivery if needed.

By selecting a 200 kWh battery, you can maximize the use of the 2,000 lb exemption for zero emission trucks in California, as the exemption only applies to the difference in weight between the diesel engine related components and the zero emission related components. The weight of the diesel engine related components on the mixer truck is approximately 4,000 lbs based on Ricardo Strategic Consulting 2022. When selecting a 200 kWh battery, the weight of all of the powertrain related components on a battery electric truck is approximately 4,000 lbs based on Ricardo Strategic Consulting 2022. This is the estimated weight breakdown of a battery swap truck with a 200 kWh battery, assuming the weight of the battery swap system is roughly comparable with a 200 kWh fixed battery system:

Table 16: Battery Swap Truck Weight Breakdown (kg)

Truck w/o powertrain	200 kWh battery	350 kW M,I,T	HV Comp	Empty Weight	Payload
10820	1428	800	468	13515	19138

If these assumptions are correct, the battery swap truck could easily haul 10 yards of concrete with over 1500 lbs to spare.

Based on these values, we re ran the ADVISOR simulations with the updated weight for the battery electric truck and found the energy consumption per mile reduces slightly due to the lower chassis weight:

Table 17: Battery Swap Truck Energy Consumption

	SP/8yd	SP/10yd	MP/8yd	MP/10yd
BEV (kWh/mi)	3.86	3.96	3.64	3.73

After reducing the battery weight, the energy consumption per mile decreases, resulting in an EER (compared to diesel) of approximately 3.23.

Assuming 80% of the 200 kWh battery is usable, these are the ranges of the truck per battery in different scenarios:

Table 18: Battery Swap Truck Range Estimation

	SP/8yd	SP/10yd	MP/8yd	MP/10yd
Range(miles)	41.5	40.4	43.9	42.9

Under real world operating conditions, the truck should get around 40 miles of range per battery, which should be enough for most deliveries, as the average round trip delivery distance is only 30 miles according to the NRMCA 2021. Additionally, for deliveries over 40 miles, the usable capacity of the battery could be pushed past 80%, as well as the fact that increasing the driving distance, while holding the pouring time constant, reduces the energy consumption per mile and thereby increases the range. If the battery pack was charged to 95% after one 10 yard delivery of the single plant duty cycle (23.3 miles), the truck would get to a state of charge of just over 50%. At that point, it could drive another 39 miles empty on the highway until the battery is completely depleted, or 29 miles if fully loaded at 72,000 lbs. This means you could reach a maximum range of between 50-60 miles, assuming only one delivery was completed. The only anticipated issue for this battery size would be deliveries with large elevation gains when loaded. In that case, the battery size likely wouldn't be sufficient.

In terms of payload capacity, the battery swap truck seems like it would be most attractive to fleets, assuming you could setup battery swap stations at each plant and the trucks could swap before being loading for each delivery.

2.9 Vehicle Performance Results Discussed

It was expected based on Central Concrete Company 2022 that fuel cell concrete mixers would be the best option due to their lower weight penalty, quick refueling times, and farther ranges compared to battery electric mixer trucks. However, it appears that the fuel cell concrete mixer truck will still have a payload penalty even with an additional 2,000 lb weight allowance for zero emission trucks. This is primarily due to the fact that the hydrogen storage system is significantly heavier than initially anticipated due to safety requirements for the extremely high pressure tanks. It is possible that even after doubling the suggested weight per kg of the hydrogen storage system, we may have actually still underestimated the weight of the hydrogen fuel cell truck and there may be even further payload losses. Refueling times are quicker for fuel cell electric trucks compared to battery electric trucks, but they still do not match the refueling time of a diesel. One of the biggest advantages of the fuel cell concrete mixer truck would be the further driving ranges. With a 40 kg tank, driving ranges would exceed 150 miles, which is the peak daily mileage in the Central Concrete Fleet.

The battery electric mixer truck has a significantly better energy efficiency ratio compared to diesel and fuel cell models, which will likely result in low costs of ownership. We will analyze this in the second half of this study. The range limitations and payload limitations of a fixed battery electric concrete mixer will likely be a substantial barrier for fleets.

The 80 mile max range of a battery electric concrete mixer will likely only be an option in the densest of urban areas that result in very short delivery distances. Unfortunately, due to quick turnaround times at the plant, limited opportunities will be available for charging during the day. The charging time of the battery electric concrete mixer will likely be at least 2-3 hours for a full charge in the near term. However, that will likely improve significantly in the future, but not enough to allow a significant gain in state of charge during an acceptable waiting time at the plants.

It was initially assumed throughout this analysis that battery swapping wouldn't be a good option primarily due to the fact that existing chassis are not available in the US. Additionally, the swapping time could result in delays, as well as the potential to complicate operations, as it may involve third party companies or have high upfront capital requirements if a third party swapping service is not used. Rear discharge concrete mixers are not built on a custom chassis, so there will need to be demand for battery swap capable chassis in other applications in the US. Despite this hurdle, a significant advantage for a battery swap capable truck is the ability to limit the battery size to the requirements of a single delivery and maintain similar payloads to diesel trucks considering the weight exemption. The time to swap may create delays during loading, however, being able to haul a full 10 yard load allows the companies to maintain the same revenue per trip as the diesel, since the revenue per delivery is directly based on the amount of concrete it can deliver.

Ten yards is the standard and the industry has gone to great lengths in order to adopt trucks that can haul 10 yards. For example, in most states, hauling 10 yards requires using a rear axle that extends the wheelbase beyond the frame. The trucks equipped with these axles can be much more dangerous at high speed and when cornering. The rear trailing axle needs to be equipped with a spring loaded passive steering that allows the rear wheels to turn the opposite direction of the steer tire during the turn. A blowout of one of those tires causes an instant loss of stability to the truck and the majority of the time results in a rollover if it happens at highway speed. This is a clear and well understood safety risk that fleets are willing to accept in order to maximize payloads, as it has such a direct impact on the revenue of a truck. This shows the importance of maximizing payloads and why this is such an important concern when selecting a zero emission powertrain for a mixer application.

More research will be needed to figure out the best way to set up the swapping stations at the plants, how many batteries will be required for a given fleet size and how quickly the batteries need to charge at the station. However, based on this analysis it appears that around a 200 kWh battery pack will be an ideal size for a battery swap concrete mixer in order to maintain similar payloads to diesel and have enough range to complete an entire delivery. Niu, Cui, and Y. Xie 2024 has shown great success in terms of battery swap concrete mixers in China. However, that may be dependent on the preexisting availability of swap station providers and swap capable chassis. The swap services and compatible chassis are not yet assailable for heavy duty trucks in the US, so it is difficult to tell whether this will be a viable option in the US in the near future.

It appears that all zero emission powertrains have some limitations when compared to diesel trucks, so government regulations will be required in order for these technologies to be implemented at scale. However, there may be the potential for significant cost savings from battery electric powertrains.

3 Cost Analysis

In order to calculate the Total Cost of Ownership (TCO) for the different vehicle types, we use the AFLEET online calculator from Argonne National Labratory 2024. Since this study is generally based on a California context, we use California prices, taxes and subsidies where applicable. We calculate the TCO in the current time period (2024) and 2030, to see how the viability of zero emission trucks may improve over the near term. The fuel economy of the vehicles for the TCO calculations is based on our duty cycle modeling results shown in Table 10 from the multiplant 8 yard cycle. We estimate price changes from 2024 to 2030 but leave improvements in fuel economy of the different powertrains from 2024 to 2030 outside the scope of this analysis and keep the MPG of the vehicles the same in both the 2024 and 2030 TCO calculations.

Generally, after its initial useful life, a concrete mixer truck will become a spare truck in the fleet to be used by a driver whose truck is temporarily in the shop for maintenance. Concrete mixer trucks require a significant amount of maintenance and can sometimes spend multiple weeks in the shop per year, especially if replacement parts are out of stock, so it's very important to have plenty of spare trucks available for use. Typically, a fleet will keep the older trucks that don't have any major issues to be used as spares until they are replaced by newer models being phased out of full time use. After this, the truck will be sold for a very low price, since the truck will often no longer be cost effective to operate. Unfortunately, the presence of spare trucks in the fleet makes it slightly difficult to exactly determine the typical annual mile of a truck in full time use from the data that we have available. NRMCA 2020 has average annual miles per truck but these values include spare trucks that log less miles than a truck in full time use. Trucks may also be unused due to driver shortages, which can be common in this industry. The NRMCA 2020 survey indicates that the average fleet utilization rate is only 85%, and the fleet availability rates is 90%. The fleet availability rate is the amount of the fleet that can be actively used in a given time without needing maintenance. The fleet utilization rate also includes vehicles parked due to driver shortages. Due to this discrepancy, we use the value in the appendix section of Central Concrete Company 2022 that has an average annual mileage that likely accounted for this discrepancy at 21,000 miles per year.

According to Central Concrete Company 2022 the useful life of a mixer truck is around 12 years, so we use this in our TCO calculations.

3.1 Mixer Body Cost Comparison

In order to calculate the total vehicle price in the next section, we first need to calculate the cost of the mixer body. Since we assume that the electric and hydrogen fuel cell trucks will use an electric driven mixer system instead of the traditional hydraulic cylinder, we need to estimate how to adjust the mixer body cost for the zero emission mixer models. Some of the parts will be identical or shared between the two systems and some of the components will need a new version. Table 19 has the major mixer parts and their approximate price of replacement parts after consulting various parts catalogs for replacement parts. Since the mixer body up-fitters generally manufacture most of the mixer parts in house, the only pricing estimates we were able to obtain were from replacement part prices. We are unsure of the price markup of replacement parts and how an increase in the cost of parts would impact the final price of the mixer body. The prices are only given to provide a rough idea of the breakdown in prices between the parts that are shared and those that need to be modified.

Some of the components of the hydraulic system could be removed, however, some of the components for the electric system may be substantially more expensive. For example, the cost of the electric drive motor could be 2-3x more expensive than the hydraulic motor. The electro hydraulic actuators for the chute cylinder and bridgemaster cylinder will likely be substantially more expensive. Additionally, the upgraded wire harness and fuse box will also likely be considerably more expensive. Other components, like the cab controls and exterior controls will likely be very similar, but initial costs will likely be higher due to low production volume.

Table 19: Major Mixer Components and Required Modifications for Electric Drive

Component:	∼Price of OE Replacement Part	Modification for Electric Drive
Fuse Box	$6,042	Higher Power Fuse Box
Hydraulic Pump for PTO	$5,853	Remove
Booster Cylinder	$3,400	Electro Hydraulic Cylinder
Hydraulic Motor	$2,779	Replace with $\sim$ 75kW electric motor
Wiring Harness	$2,746	Higher Power Wire Harness
Cab Controls	$2,625	New Production Run
Bridgemaster Compensator	$2,393	Remove
Oil Res	$1,542	Remove
Chute Controls	$1,322	Replace with system of relays
Chute Cylinder	$987	Electro Hydraulic Cylinder
Ext Controls	$959	New Production Run
Drum	$23,160	No Change
Pedestal	$14,000	No Change
Booster	$10,933	No Change
Mixer Gearbox	$7,897	No Change
Water Tank	$3,400	No Change
Main Chute	$3,161	No Change
Charge Hopper	$2,348	No Change
3x Extension	$2,028	No Change
Air Control Manifold	$1,973	No Change
Collector	$1,054	No Change
Fender	$1,708	No Change

For the reasons discussed above, we speculate that the initial upfit price for the electric mixer system may be between 25-50% higher in the near term until higher production volumes can bring costs down. In 2023, the approximate price of a diesel cab chassis that could be used for a mixer truck was around $150k. Final prices for a diesel mixer truck with a traditional hydraulic system in 2023, were between $250-280k, so the mixer body price with installation was approximately $100-120k. We will assume that the electric driven mixer body will cost an additional $50k over the hydraulic mixer body in the near term. Prices will likely come down as production volumes increase in the future, so we will assume that the incremental cost for the electric mixer body will come down to $25k by 2030.

3.2 Estimated Vehicle Prices

After consulting truck listings and discussing with fleet managers, a diesel concrete mixer is currently approximately $250k without federal or state taxes.

Figure 16: New Concrete Mixer Truck at 2024 World of Concrete Expo

In order to calculate the cost of the zero emission models, 2024 and 2030 costs are estimated based on the prices and cost structure shown in Sharpe and Basma 2022 and Ricardo Strategic Consulting 2022.

These are the components we consider when estimating the cost of the trucks: battery pack, DC to DC converter, on board charger, high voltage distribution system, battery and electronics thermal management system, electric HVAC systems, motor, inverter and transmission, electric power steering pump and the 'glider' which includes the entire diesel truck with mixer body minus all powertrain related components. According to Ricardo Strategic Consulting 2022, the powertrain related components on the diesel make up 43% of the cost of the diesel. We take the cost of the chassis cab from the diesel truck and subtract 43% and add back in the cost of the mixer body in order to calculate the glider price including mixer body. As mentioned in the previous section, the electric drum drive system is expected to increase the price of the mixer body by $50k in the 2024 price and then decrease to $25k in additional cost in 2030.

Based on the input prices and knowledge of the specifications of different trucks, such as the battery pack size, motor rating, fuel cell power and hydrogen tank storage size, we can calculate the attributable cost for each component and add them all up including the glider price.

In order to benchmark our calculation method, price quotes for existing zero emission trucks were obtained by contacting various dealers and manufactures. Those prices were not publicly disclosed and we could not publish them in this report. However, the $550k price (calculated without tax) of the Mack LR Electric Refuse truck was publicly listed by Miami Dade County 2023.

We estimated the price of 7 different zero emission trucks we received quotes for and then found the markup value that most closely matches all of the price quotes we received. The markup value only applies to the input costs, not the glider price, as that already includes markup. Based on this, we were able to estimate the price of battery electric and hydrogen fuel cell concrete mixer trucks.

The current prices have a very high markup since production volumes are very low, research and development costs are very high and subsidies are available that inflate prices. In fact, most of the dealers we obtained price quotes from directly stated that the prices are marked up because subsidies are available.

The price of the battery pack and other components are higher than for LDV because they must be ready for more intense duty cycles, as well as the fact that the components used in heavy duty vehicles are not subject to the same discounts from high scale volumes as LDV.

The prices of these components in 2024 and 2030 are obtained from Sharpe and Basma 2022, a study comparing Ricardo Strategic Consulting 2022 to other existing literature on component prices.

Table 20: 2024 BEV Mixer Price based on Ricardo Strategic Consulting 2022 and Sharpe and Basma 2022

Components:	Price per unit	# of units	Markup	Total
Battery pack ($/kWh)	$160	400	2.5	$160,000
DCDC converter / OBC / HV distribution system	$13,160	1	2.5	$32,900
Battery and electronics thermal management	$7,600	1	2.5	$19,000
Electric HVAC systems	$1,450	1	2.5	$3,625
Motor / Inverter / Transmission ($/kW)	$50	350	2.5	$43,750
Electric air brake compressor system	$9,000	1	2.5	$22,500
Electric steering pump system	$2,700	1	2.5	$6,750
Glider Price Including Mixer Body:	$236,518	1	1	$236,518
Total Price:				$525,043

According to Ricardo Strategic Consulting 2022, the prices of the on-board charger, DC/DC converter, as well as other HV components, are expected to reduce by 30% by 2030 so we reduce the price of all the single unit items shown above by 30% in the 2030 prices. Based on Sharpe and Basma 2022, battery pack costs drop from $160/kWh to $100/kWh in 2030. Motor, inverter and transmission costs drop from $50/kW to $25/kW in 2030.

The 2030 markup is reduced to 2, as this is near the midpoint between the current diesel markup shown in Ricardo Strategic Consulting 2022 and our observed markup of the current ZEV trucks, as it is expected that when production volumes increase the manufactures can reduce overhead costs per truck such as research and development. Additionally, HVIP funding is not expected to continue past 2030 and incentives have been significantly inflating pricing. These prices do not include any federal, state, or local taxes, or any incentives, as we will calculate those separately in the next section.

Table 21: 2030 BEV Mixer Price based on Ricardo Strategic Consulting 2022 and Sharpe and Basma 2022

Components:	Price per unit	# of units	Markup	Total
Battery pack ($/kWh)	$100	400	2	$80,000
DCDC converter / OBC / HV distribution system	$9,212	1	2	$18,424
Battery and electronics thermal management	$5,320	1	2	$10,640
Electric HVAC systems	$1,015	1	2	$2,030
Motor / Inverter / Transmission ($/kW)	$25	350	2	$17,500
Electric air brake compressor system	$6,300	1	2	$12,600
Electric steering pump system	$1,890	1	2	$3,780
Glider Price Including Mixer Body:	$211,518	1	1	$211,518
Total Price:				$356,492

The fuel cell model prices are calculated the same way as the battery electric truck prices but include additional components like the fuel cell and hydrogen storage systems. The DC/DC Converter, on board charger, HV distribution system, battery and electronics thermal management system prices are different for the battery electric and fuel cell trucks based on Ricardo Strategic Consulting 2022. While the study considered the fuel cell batteries as having far higher prices per kWh, this is based on the assumption that the fuel cell trucks would have only a 12 kWh battery, when our model, as well as all class 8 fuel cell models available today, have far larger batteries (50-150 kWh) that have similar prices per kWh to battery electric truck batteries.

Table 22: 2024 FCEV Mixer Price based on Ricardo Strategic Consulting 2022 and Sharpe and Basma 2022

Components:	Price per unit	# of units	Markup	Total
Battery pack ($/kWh)	$160	56	2.5	$22,400
DCDC converter / OBC / HV distribution system	$9,732	1	2.5	$24,330
Battery and electronics thermal management	$3,200	1	2.5	$8,000
Electric HVAC systems	$1,450	1	2.5	$3,625
Motor / Inverter / Transmission ($/kW)	$50	350	2.5	$43,750
Electric air brake compressor system	$9,000	1	2.5	$22,500
Electric steering pump system	$2,700	1	2.5	$6,750
Fuel Cell ($/kW)	$500	200	2.5	$250,000
Hydrogen Storage System ($/kg)	$1,000	40	2.5	$100,000
Glider Price Including Mixer Body:	$236,518	1	1	$236,518
Total Price:				$717,873

According to Sharpe and Basma 2022, there are large decreases in the fuel cell and hydrogen storage system prices in 2030, as the fuel cell truck market become more mature. Fuel cell costs drop from $500 per kW to only $300 per kW and the hydrogen storage system costs drop from $1000 per kg to only $700 per kg.

Table 23: 2030 FCEV Mixer Price based on Ricardo Strategic Consulting 2022 and Sharpe and Basma 2022

Components:	Price per unit	# of units	Markup	Total
Battery pack ($/kWh)	$100	56	2	$11,200
DCDC converter / OBC / HV distribution system	$6,812	1	2	$13,625
Battery and electronics thermal management	$2,240	1	2	$4,480
Electric HVAC systems	$1,015	1	2	$2,030
Motor / Inverter / Transmission ($/kW)	$25	350	2	$17,500
Electric air brake compressor system	$6,300	1	2	$12,600
Electric steering pump system	$1,890	1	2	$3,780
Fuel Cell ($/kW)	$300	200	2	$120,000
Hydrogen Storage System ($/kg)	$700	40	2	$56,000
Glider Price Including Mixer Body:	$211,518	1	1	$211,518
Total Price:				$452,733

The 2030 prices decrease significantly for ZEV concrete mixer trucks compared to the current prices but we expect incentives to decrease as well. The next section will consider the impact of all taxes and subsidies in 2024 and 2030 based on these estimates.

3.3 Net Pricing with Sales Tax and Incentives

According to the CARB 2024, eligible class 8 battery electric trucks receive $120k and class 8 fuel cell trucks receive $240k under the Hybrid and Zero Emission Truck and Bus Voucher Incentive Project (HVIP). The IRS 2024 provides a $40k tax credit for zero emission trucks over 14k lbs under the Commercial Clean Vehicle Tax Credit (CCVC) program (45W). While this incentive is not paid at the point of sale, it can be used as a credit on quarterly tax payments, so we assume that companies will not significantly discount its value.

Class 8 trucks for on-highway use are subject to a federal excise tax (FET) of 12% at the time of first purchase, according to Zemelman 2022. The FET is paid by the dealer, but is included in the final purchase price unless negotiated otherwise as a discount to the buyer. In California, there is also state and local tax of approximately 8.5% of the purchase price imposed on new vehicles at the time of first registration, according to the CA DMV 2024. Since the purchase prices of zero emission trucks are higher, both the FET and the state and local taxes are higher for zero emission models, making it more expensive for fleets to purchase these trucks.

Table 24: Estimated Current Net Pricing

	Diesel	BEV	FCEV
Base Price	$254,464	$525,043	$717,873
Federal Tax (12%)	$30,536	$63,005	$86,145
State and Local Tax (8.25%)	$20,993	$43,316	$59,225
HVIP	$0	-$120,000	-$240,000
IRS CCVC (45W)	$0	-$40,000	-$40,000
Net Price	$305,993	$471,364	$583,242

We assume that HVIP funding will not extend past 2030 and remove that from our 2030 net pricing. The 2030 diesel model is expected to cost an additional $18k in order to comply with more stringent emissions requirements according to Basma et al. 2023 and Y. Xie, Basma, and Rodrigues 2023.

Table 25: Estimated 2030 Net Pricing

	Diesel	BEV	FCEV
Base Price	$266,464	$356,492	$452,773
Federal Tax (12%)	$31,976	$42,779	$54,328
State and Local Tax (8.25%)	$21,983	$29,441	$37,350
HVIP	$0	$0	$0
IRS CCVC (45W)	$0	-$40,000	-$40,000
Net Price	$320,423	$388,681	$504,441

Figure 17 has a graph of the net prices in Table 24 and 25.

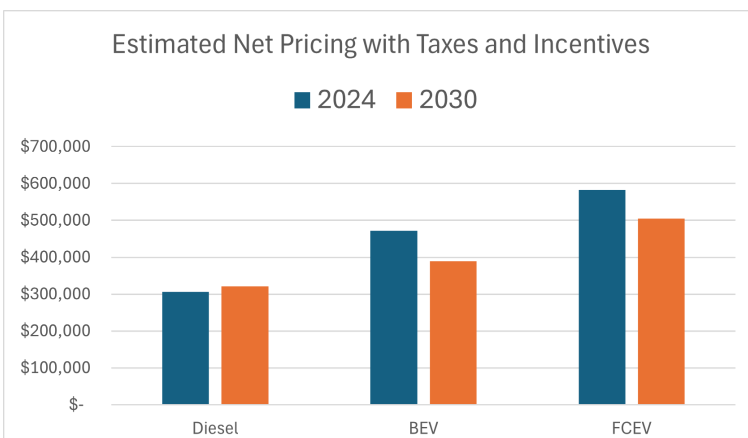


Figure 17: Estimated Net Pricing by Powertrain Type in 2024 and 2030

As shown in Figure 17, 2030 net prices for the ZEVs do not significantly decrease, because we assume HVIP funding will no longer be available and the tax liability is still higher.

3.4 Insurance, Registration, LCFS Credits, Financing and Discount Rate

Discount rates are set at 4.1% based on the Gilleon, Penev, and Hunter 2022 study on the TCO of hydrogen refuse trucks. It is assumed that the fleets will not require financing, as it is fairly common for a ready mix company to pay in full for truck purchases. Insurance rates for liability coverage are set to zero since they will be identical across the powertrains. Physical damage coverage is set at 3% of the initial truck purchase cost annually or $30 per $1000 based on Basma et al. 2023.

The vehicle registration fees are calculated based on the CA DMV 2024 website. The expected registration fees change based on the purchase price of the vehicle and other attributes such as registration location, fuel type and gross vehicle weight rating. The 2030 expected registration fees are calculated based on the 2030 price expectations of the vehicles.

Table 26: Estimated Annual Registration Fees in California

	2024	2030
Diesel	$ 3,733	$ 3,811
BEV	$ 3,802	$ 2,768
FCEV	$ 5,375	$ 3,327

For the current model year vehicles, the ZEV registration fees are more expensive. Based on the 2030 model year vehicles, the registration fees for the ZEVs are actually cheaper since the purchase prices go down and electric vehicles get a discount, all else being equal. The additional 2,000 lbs granted for ZEV trucks in California is unlikely to impact the registration gross vehicle weight rating because our understanding of the law is that the vehicle is allowed 2,000 lbs over the gross vehicle weight rating, not that the gross vehicle weight rating is increased by 2,000 lbs, according to the California Vehicle Code 2024.

The LCFS credits for the hydrogen trucks are calculated based on the Central Concrete Company 2022 report and scaled for the current LCFS credit price of approximately $71 per ton, which results in a credit of approximately $2,800 per year. Based on the Pacific Gas and Electric Fleet Program 2024 LCFS credit calculator, a battery electric mixer truck could earn approximately $7,500 per year if it uses 84,000 kWh per year (4 kWh/mile * 21,000 miles per year). Since the credit revenue will change based on current fuel carbon intensities, as well as other market factors, the LCFS credit revenue calculations are subject to a large level of uncertainty. These calculations are only intended to approximate how the LCFS program might impact the relative TCO amounts between competing powertrain types.

3.5 Maintenance Costs

Diesel maintenance costs were obtained from NRMCA 2020. Maintenance costs were provided in the following categories on a per yard basis: Total, Mixer Parts, Engine, Shop Time, Outside Shop, and Tires. In order to estimate the total maintenance expense per truck in a given year, we multiply by the average yards delivered per truck (4,949 yd) in the survey. To estimate the maintenance cost per mile, we divide by the average miles (15,990 mi) for the trucks in the survey. Please note that the total of the maintenance costs in each category don't exactly equal the total maintenance costs. This is due to the fact that the sum of averages isn't always the same as the average of the sums.

Table 27: Diesel Maintenance Costs from NRCMA Survey

	Mixer Parts	Engine	Shop	Outside	Tires	Total
Maintenance ($/yd)	$ 0.66	$ 1.15	$ 1.59	$ 0.55	$ 0.45	$ 4.03
Maintenance ($/yr)	$ 3,266.34	$ 5,691.35	$ 7,868.91	$ 2,721.95	$ 2,227.05	$ 19,944.47
Cost Per Mile:	$ 0.20	$ 0.36	$ 0.49	$ 0.17	$ 0.14	$ 1.25
Percent Breakdown	16%	29%	39%	14%	11%	

As shown in Table 27, we calculated the total maintenance cost of the diesel mixer to be approximately $1.25 per mile.

G. Wang, Miller, and Fulton 2022 has estimated the maintenance costs for class 8, long haul battery electric and fuel cell trucks compared to diesels, shown in Table 28 with current (C) and future (F) values:

Table 28: G. Wang, Miller, and Fulton 2022 Maintenance Cost Comparison

Cost Category:	Diesel	BEV-C	BEV-F	FC-C	FC-F
Common Components	$ 0.07	$ 0.07	$ 0.07	$ 0.07	$ 0.07
Engine Related	$ 0.10				
Added Costs for Breaking	$ 0.01				
Added costs for tranmission	$ 0.02				
Power Electronics		$ 0.03	$ 0.02	$ 0.03	$ 0.02
Battery Related		$ 0.08	$ 0.05		
FC and Battery Related				$ 0.09	$ 0.05
Hydrogen Storage				$ 0.01	$ 0.01
Total	$ 0.20	$ 0.18	$ 0.14	$ 0.20	$ 0.15
Cost Reduction r.t. Diesel	100%	-12%	-29%	0%	-25%

Tire wear is considered under 'Common Components'. Since our mixer components will also see reduced maintenance from eliminating the hydraulic systems and replacing them will electric systems, we will make a simplifying assumption and multiply our total maintenance costs per mile by the multipliers shown in Table 28. Table 29 has the assumed maintenance costs per mile for the various powertrain technologies of concrete mixer trucks in the current and future, based on NRMCA 2020 and G. Wang, Miller, and Fulton

2022. We use the current maintenance costs in the 2024 TCO comparison and the future TCO costs in the 2030 TCO comparison.

Table 29: Maintenance Costs Per Mile for Different Mixer Truck Powertrains

Time Horizon	Diesel	BEV	FCEV
Current	$ 1.25	$ 1.10	$ 1.25
Future	$ 1.25	$ 0.89	$ 0.94

Battery electric shows the largest reduction in maintenance costs, especially in the future. Also, it is likely that future maintenance costs for diesels could become higher than the value shown in Table 29, as emissions standards become increasingly strict and after-treatment systems become more complicated. However, this was not considered in G. Wang, Miller, and Fulton 2022.

3.6 Fuel Costs

Almost all concrete plants have onsite fuel stations for either diesel or compressed natural gas (if used for the fleet), in order to reduce fuel expenses and labor expenses. If the plant is not equipped with a fuel station, mobile fuel delivery is completed overnight for the trucks. A driver going out of the way to a local station could add a considerable amount of time to their on duty time. The driver does not know their day is complete until they receive a message on their tablet when at the plant, so it wouldn't be practical to send them back out to refuel at the end of the day. The dispatch does not know this ahead of time. If two trucks are returning to a plant that has one load remaining, whichever truck arrives first gets loaded and the other truck gets washed out, refueled and parked. It also wouldn't be practical to do this during the day even if on their route, as a loaded truck must drive directly to the jobsite and an empty truck must drive directly back to the plant to prevent delays. For these reasons, we will assume that concrete companies will continue the industry standard practice of installing fuel stations on site, whatever that fuel might be.

For the current diesel price, we will use the AFLEET California private station value of $5.42 per gal. According to EIA 2023a, diesel prices will fall by 6% from 2023 to 2030, so we will use $5.09 per gal for the 2030 diesel price. The private station prices are lower than retail prices, as the concrete plants get diesel delivered in bulk so they don't have to pay the retail price markup. Diesel exhaust fluid prices are set at $2.80 cents based on AFLEET defaults.

In the case of battery electric trucks, chargers would need to be installed on-site. Basma et al. 2023 has analyzed the levelized cost of charging in $/kWh for battery electric class 8 trucks including current electricity rates and the following amortized expenses: maintenance, land, chargers, behind the meter costs, to the meter costs, as well as distribution equipment and substation upgrades. They find that current

California levelized cost of charging for heavy duty battery electric trucks will be approximately $0.29/kWh. We use this as the current electricity price for the TCO calculations, and for the 2030 costs we scale the portion of the levelized cost attributable to electricity rates based on a 12% reduction in electricity rates from 2023 to 2030 according to EIA 2023b. After this adjustment, the 2030 levelized cost of charging is at $0.27 per kWh. Due to the current regulatory environment in California, electricity prices can vary significantly over time. These estimates are subject to uncertainty and could impact the estimated levelized charging costs for battery electric vehicles, as well as the hydrogen fuel costs to a lesser degree. In the 'TCO Without Tax Or Subsidy' section we provide the levelized costs of charging that would result in a break even TCO calculation. Bracci, Koleva, and Chung 2024 analyzed the levelized costs of hydrogen fuel for heavy duty trucks in $/kg for various station sizes between 2 and 18 metric tons per day (MTPD) and utilization rates between 30-80%. Central Concrete Company 2022 mentions that some strategically selected plants would have on-site fueling stations, and other smaller plants may need to have mobile delivery in the near term. We will assume that they might install 2 metric ton per day stations that could hypothetically fill 50 trucks per day at 100% utilization if each truck consumed 40 kg per day. It is unlikely that most plants would install larger stations. These are the following levelized costs of hydrogen (LCOH) in 2030 with liquid hydrogen delivery:

Table 30: Bracci, Koleva, and Chung 2024 LCOH for 2 MTPD Station in 2030 with LH2 Delivery

Utilization Rates:	30%	50%	80%
Refueling Station	$ 5.90	$ 3.60	$ 2.40
Transport and Terminal	$ 0.40	$ 0.40	$ 0.40
Liquefaction	$ 3.40	$ 3.40	$ 3.40
Production	$ 1.50	$ 1.50	$ 1.50
Total ($/kg)	$ 11.20	$ 8.90	$ 7.70

These prices do not include any station level markup, which is appropriate, because as mentioned, concrete trucks almost always fill up at onsite fuel stations in order to save time and cost. We assume that the current costs for hydrogen if a station was installed would be around the 30% utilization costs, while future costs could reach the 80% utilization costs. For the TCO analysis we approximate the current hydrogen costs with the 30% utilization rate cost, and 2030 costs at the 50% utilization rate. Since these costs are based on 2030 assumptions, the current costs at the 30% utilization rate may actually be an underestimate of the prices. However, the TCO of the hydrogen fuel cell truck will still be higher than the diesel and battery electric even at this potentially optimistic fuel price. These prices do not include any subsidies, so the DOE 2023 Clean Hydrogen Production Tax Credit could potentially lower prices. However, the production price assumptions of $1.50/kg used in this study were based on steam methane reforming hydrogen production that would not be eligible for the $3/kg credit. Lower levelized cost of hydrogen prices would only be possible with green hydrogen production prices lower than $4.50/kg during the remaining 9.5 years of the program, which we assume to be unlikely. Other subsidy programs mentioned in the study that are currently available are not likely to result in significantly lower levelized costs of hydrogen.

We will see in the results section what levelized costs of hydrogen would be required in order to reach TCO parity to diesel.

Table 31 has a summary of the fuel costs discussed above to be used in the TCO calculations, where LCOE is the levelized cost of electricity and LCOH is the levelized cost of hydrogen:

Table 31: Fuel Costs Summarized (2022 $)

	Current	2030
Diesel ($/gal)	$ 5.42	$ 5.09
LCOE ($/kWh)	$ 0.29	$ 0.27
LCOH ($/kg)	$ 11.20	$ 8.90

3.7 TCO Results from AFLEET

Using Argonne National Labratory 2024 AFLEET model, and all of the costs and assumptions in this section, as well as the miles per diesel gallon equivalent ratings from the duty cycle modeling section (8 yard multiplant drive cycle), we estimate the total cost of ownership of the vehicles as shown in Figure 18 and Table 32. LCFS credit revenue is subtracted from total fuel costs, shown as 'Fuel-LCFS'. Table 32 has amounts rounded to the nearest thousand.

Table 32: Mixer Truck Total Cost of Ownership

Powertrain	Depreciation	Fuel-LCFS	DEF	Maintenance	Insurance	License	TCO
2024 Diesel	$243,000	$360,000	$4,000	$363,000	$66,000	$36,000	$1,072,000
2024 BEV	$374,000	$157,000	$0	$314,000	$101,000	$37,000	$983,000
2024 FCEV	$462,000	$468,000	$0	$360,000	$125,000	$52,000	$1,468,000
2030 Diesel	$255,000	$338,000	$4,000	$361,000	$69,000	$37,000	$1,069,000
2030 BEV	$309,000	$139,000	$0	$255,000	$83,000	$27,000	$813,000
2030 FCEV	$401,000	$363,000	$0	$266,000	$108,000	$32,000	$1,170,000

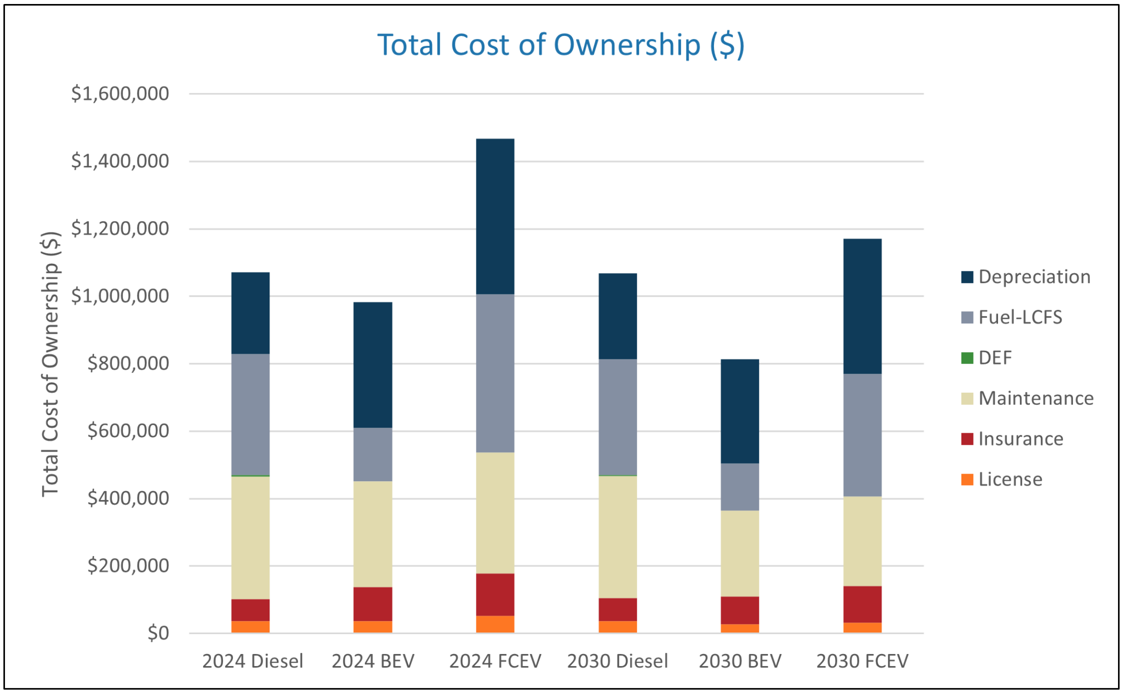


Figure 18: TCO Comparison

Even in 2024, it is estimated that the total cost of ownership for battery electric concrete mixer trucks is lower than diesel models due to the incentives available and the higher energy efficiency values identified in the duty cycle modeling section. The total cost of ownership of the fuel cell models is considerably higher than the diesel vehicle in the near term and is still more expensive even in 2030.

3.7.1 TCO Without Tax Or Subsidies

As an alternative scenario of the TCO analysis, this is the total cost of ownership when ignoring the federal excise tax, state sales tax, all purchase incentives and LCFS credits:

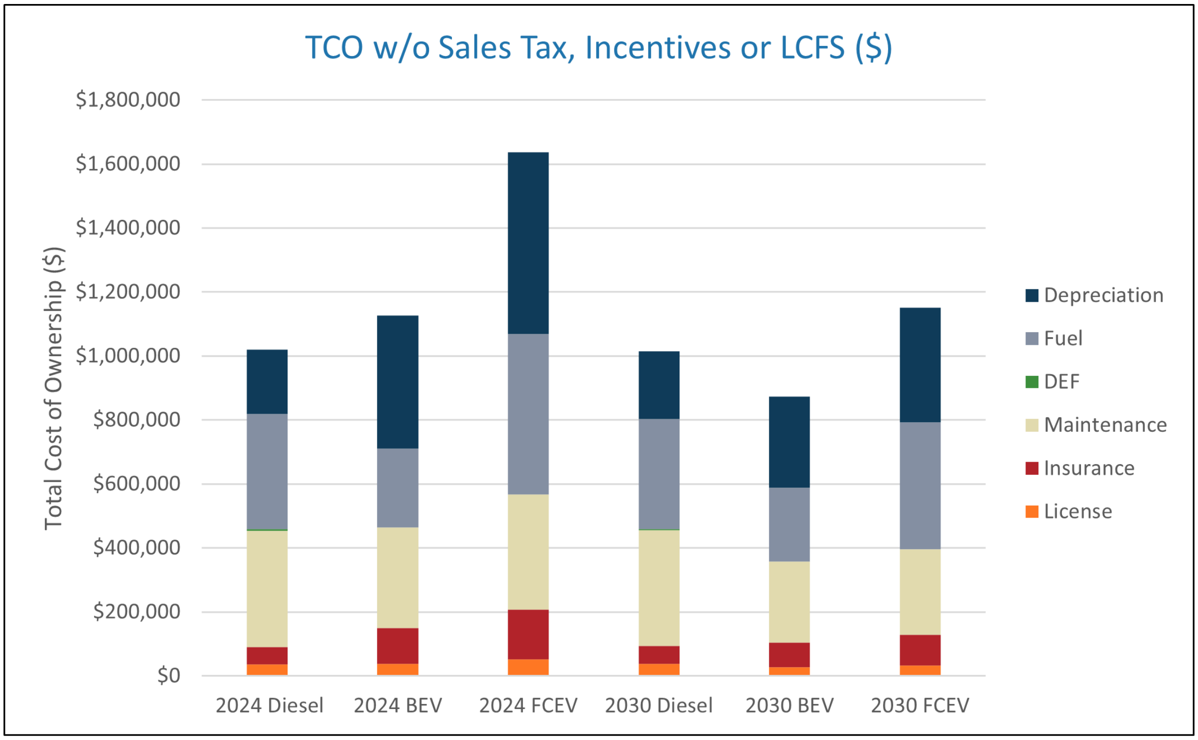


Figure 19: TCO Without Sales Tax, Incentives or LCFS Credits

When ignoring sales tax, subsidy (including LCFS credits) or tax, these are the approximate break even points in terms of vehicle price at current fuel prices: Diesel: increase from \$254k to \$350k, BEV: \$525k, FCEV: decrease \$760k to \$220k.

When ignoring sales tax, subsidy or tax, these are the approximate break even points in terms of fuel price at 2030 vehicle prices: Diesel-\$5.09/gal, LCOC: increase from \$0.27/kWh to \$0.43/kWh, LCOH: \$8.90/kg to \$6.10/kg

Based on the break even points, it requires significant subsidies in terms of vehicle cost and hydrogen price in order to make a hydrogen fuel cell concrete mixer cost competitive from a total cost of ownership perspective.

3.8 Literature Review of Battery Swap Costs

While we were not able to do our own TCO analysis of battery swap trucks during this study, we can draw on insights learned from Niu, Cui, and Y. Xie 2024. The fleets analyzed in their study contract a third party company to operate the battery swapping stations as a battery as a service (BaaS) model that allows them not to have to make an upfront investment in the batteries or swapping stations. The fleets pay a battery rental fee and a battery swapping fee, along with the electricity costs in order to operate the battery swap trucks. The initial purchase price of battery swap trucks are substantially cheaper than a fixed battery truck, since the price of the battery is not included in the upfront costs. According to their study, the truck insurance prices are also much cheaper, around half the price. The insurance prices for the trucks are partially based on the price of the truck and the truck prices are lower for battery swap trucks. Their results indicate that the TCO of the battery swap trucks being used in the Hainan providence in China are currently 17% lower than the diesel trucks, and the TCO of the fixed battery systems are a bit higher but still 15% cheaper than the diesels. It is currently unclear if this result would also apply to a fleet operating in the US, as it partially depends on the fees charged by the BaaS provider and this service is currently not available in the US for heavy duty trucks. Another interesting aspect of their study is that in the Hainan providence the zero emission models are currently exempt from ownership and registration taxes. If the US could adopt a similar policy and exempt the zero emission models from the Federal Excise Tax (12% of truck price), as well as state and local tax (8.5% of truck price in CA), it would save the fleets a significant amount of money. Despite all of the Chinese truck models being a small fraction of the US truck prices, the multipliers between the price of the fuel types for our current price estimates is quite similar to the prices shown in Niu, Cui, and Y. Xie 2024. Based on the information in their study and the analysis conducted in this study, it appears that if a cost competitive BaaS provider was established in the US for heavy duty trucks, a battery swap concrete mixer could be a cost effective solution for zero emission concrete mixer trucks.

3.9 TCO Results Discussed

Despite very high costs in the near-term for battery electric models, due to the low operating costs and incentive availability, the total cost of ownership of battery electric mixer trucks may be lower than a diesel even in the near-term. By 2030, we are expecting to see almost a 25% lower cost of ownership for battery electric concrete mixer trucks compared to diesel. Currently, fuel cell trucks are around 27% more expensive to own and operate compared to diesel. By 2030, fuel cell trucks are still almost 10% more expensive to own and operate compared to a diesel and over 30% more expensive compared to a battery electric model. These numbers, however, do not consider any revenue losses from payload limitations or the requirements to purchase more trucks to meet demand. These metrics would depend highly on a fleet to fleet basis and were too difficult to consider in this study. Despite this limitation of our study, it is clear that battery electric is the winner in terms of cost compared to fuel cell, unless significantly more trucks were required in order to meet demand.

Since the TCO of fuel cell trucks are considerably higher than both diesel and battery electric, there would need to be significant benefits for fuel cell concrete mixer trucks. As shown in the duty cycle modeling section, despite the range of the fuel cell truck being double that of the battery electric and meeting the needs of the fleets we considered, there is still a payload loss that will be extremely disruptive to fleets. For this reason, we think that fuel cell trucks may be a tough sell to ready mix companies when considering the high total cost of ownership we calculated. Fixed battery trucks are the clear winner in terms of costs but fleets may struggle with the range and payload limitations. While it does require further research, it appears that battery swap capable concrete mixer trucks may be the best option in terms of cost if the US can see similar economics to what we see in China, since Niu, Cui, and Y. Xie 2024 found the lowest TCO for battery swap mixer trucks in China.

4 Conclusions

There are a variety of improvements required for widespread adoption of zero emission concrete mixers. For fixed battery systems, we will need to see an improvement in the energy density of the batteries up to 250 Wh/kg in order to match the payload of the diesel (even with the 2,000 lb weight exemption). Pack energy densities above 200 Wh/kg have been achieved for LDV batteries. However, we have yet to see similar energy densities on currently available heavy duty truck batteries. Since heavy duty truck batteries would require significantly longer life span than LDV, it is currently difficult to match pack energy densities. There will likely always be a trade-off between cost, energy density, power, lifespan, charging speed and safety for lithium batteries. Increasing the weight exemption to 4,000 lbs would also be another way to make battery electric concrete mixers competitive with diesels on a payload basis. However, there is very limited support for this among government agencies that are tasked with maintaining roadways. Payload limitations aside, we would also need to see improvements in charging speed in order to extend the currently limiting 80 mile range from the 400 kWh battery pack. If the trucks were able to support a 1MW charging standard in the future and plants had sufficient electrical capacity, opportunity charging when waiting at the plants to load would likely be able to boost the range to meet peak daily mileage scenarios. Pending data availability, further research could determine the minimum charging speeds required to meet opportunity charging requirements for concrete mixers and their associated electrical loads using the energy consumption rates calculated in this study. The cost analysis has shown that the current incentives are likely sufficient in order to allow a low total cost of ownership for battery electric concrete mixers today and further cost reductions in 2030 will allow for substantial reductions in cost compared to diesel.

For fuel cell concrete mixers, notable challenges include the weight of the hydrogen storage system, vehicle prices and fuel/fueling infrastructure prices. While it was initially assumed that the fuel cell concrete mixer trucks would have a large payload advantage compared to a battery electric truck, that is not currently the case in this particular vehicle application. The weight of the hydrogen storage system would need to be reduced, which is difficult given the safety requirements for high pressure hydrogen tanks. Vehicle prices for hydrogen fuel cell trucks are currently very high. We estimate that if a hydrogen fuel cell mixer truck was produced today, it would cost almost double that of a diesel model even with $280k in incentives from the federal and state government. A large portion of the incentives need to be used to offset the additional tax liability imposed on these trucks due to the high purchase prices. It is expected that fuel cell vehicle prices will be significantly reduced by 2030, but would likely still require substantial incentives in order to reach cost parity with diesel models. Prices for hydrogen fuel are currently prohibitively expensive, and the lower energy efficiency ratio for fuel cell vehicles compared to battery electric makes operation expenses high for fuel cell mixer trucks. Greater subsidies for hydrogen fuel and the associated infrastructure will be required in order to make this an economically viable solution.

While not as thoroughly studied in this analysis, battery swap concrete mixers seem to offer far less limitations in terms of cost and performance trade-offs compared to fixed battery and hydrogen fuel cell. The main benefit of the battery swap system in this application would be the opportunity to reduce battery sizes to what is required for a single delivery, maintaining payloads and revenue per delivery for the ready mix companies. It appears that increases in energy density, charging speed, or weight exemptions would not be required for battery swap concrete mixers. As shown in Y. Xie, Basma, and Rodrigues 2023, the TCO for battery swap concrete mixers is already low in China, but more research will be needed in order to analyze the total cost of ownership if they became available in the US. As mentioned previously, the success of battery swap concrete mixers will depend on existing chassis model availability, as sales volume for concrete mixer trucks is low compared to other trucks and this is why rear discharge mixers use existing chassis in order to save cost. At the time of publication, there are currently no class 8 trucks capable of battery swapping available in the US. To become economically viable, there would need to be demands in other applications that the mixer trucks could share a chassis with. It is also unclear how the swap stations would be operated and how much the providers may charge.

These limitations we discussed are not intended to suggest that there are not substantial benefits from zero emission concrete mixer trucks. Countless studies have shown reductions in life cycle greenhouse gas emissions and substantial improvements in urban air quality from electrifying heavy duty vehicles. However, it is important to quantify the challenges associated with transitioning away from traditional fuels. The private sector will continue to work to address technology limitations for zero emission powertrains, however, there are many opportunities for additional policy measures that could be used to accelerate the deployment of zero emission powertrains in concrete mixer trucks. We recommend a combination of the following measures: increasing the weight allowance to 4,000 lbs for zero emission trucks, modifying the federal excise tax and state sales tax for vehicles in order to not penalize zero emission trucks (based on their higher purchase prices), and increasing incentive availability for hydrogen fueling infrastructure and renewable hydrogen on a per kilogram basis beyond what is currently offered. All of these policy measures would make it much easier for fleets to meet the strict requirements in the Advanced Clean Fleets regulation.

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