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Assessment of Requirements, Costs, and Benefits of Providing Charging Facilities for Battery-Electric Heavy-Duty Trucks at Safety Roadside Rest Areas

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Assessment of Requirements, Costs, and Benefits of Providing Charging Facilities for Battery-Electric Heavy-Duty Trucks at Safety Roadside Rest Areas

February 2022

A Research Report from the National Center for Sustainable Transportation

Andrew Burke, University of California, Davis

National Center for Sustainable Transportation

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16. Abstract

The objective of this research was to determine the possibilities for and barriers to the provision of battery charging infrastructure for heavy-duty electric trucks at roadside rest areas in California. The initial sections of the report deal with the prospects for battery-electric long-haul trucks and the battery technology needed to make those electric trucks practical and the market for them to be successful. Simulations of trucks using present lithium battery technology indicated that for a range of 600 miles, the battery pack would need to store about1200 kWh. It is not practical to fit a battery of that size on the tractor of the truck. Another approach is to design a truck with a 300 mile range and plan to partially charge the battery once or twice during the day at rest areas. The truck could also be charged overnight at the rest areas. The total range per day could be 600 miles or more. The partial charges would put 65% of the capacity of the battery in at the 1C rate (a 60 minute charge). A 450-500 kW charging facility would be needed at the rest areas. The 300 mile range electric truck could operate much like the diesel truck with the driver taking 60 minute breaks every 200-225 miles to charge the battery. The cost analysis of the 300 mile truck indicates its TCO is less than that of the diesel truck. In California, there are Low Carbon Fuel Standards (LCFS) credits to reduce the costs to operate the charging facility. If applicable, the LCFS station credits ($/yr) can be as much as $65k/yr per charger up to the total cost of the facility in about five years. The LCFS electricity credit would permit the cost of electricity to be only $.12/kWh to charge the batteries, because the price includes the LCFS credit to the utility. Hence with LCFS credits, the cost of operating the charging facility could be low in the early years while the market for electric long-haul trucks is developing. Caltrans maintains 86 safety rest areas along highways in California with 53 along Interstate highways. If battery charging facilities were established at about 35 of these rest areas, they would be about 100 miles apart or a little closer. Caltrans could assist private contractors in establishing a network of charging facilities for electric trucks. The total initial cost could be about $50 million. The major barrier to Caltrans participating in the battery charging project is that current law prohibits commercial businesses at the rest areas which would not allow charging for the electricity dispensed. There has been consideration in both California and at the federal level to relax the non-commercial requirements at the rest areas for battery charging because the need for a battery charging network is well recognized.

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Disclaimer

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A National Center for Sustainable Transportation Research Report

February 2022

Andrew Burke, Institute of Transportation Studies, University of California, Davis

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EXECUTIVE SUMMARY

The objective of this research was to determine the possibilities for and barriers to the provision of battery charging infrastructure for heavy-duty electric trucks at roadside rest areas in California. By 2030 it is expected that a significant fraction of the trucks parking at the rest areas will be electrified and some of them will have the need for recharging their batteries. A key issue was to determine if charging at roadside rest areas, especially those along interstate highways, would meet the needs of the electric trucks that require a daily range of 500-600 miles for multi-day trips. The first step in the research was to determine if providing the charging at the rest stops was practical and economic. The second step was to assess how Caltrans could assist in establishing a network of battery charging facilities at the rest areas and what the barriers to that would be.

The initial sections of the report deal with the prospects for battery-electric long-haul trucks and the battery technology needed to make those electric trucks practical and the market for them to be successful. Simulations of trucks using present lithium battery technology (pack energy density of 170 Wh/kg) indicated that for a range of 600 miles, the battery pack would need to store about 1200 kWh, weigh 6300 kg and have a volume of 2700 L. It is not practical to fit a battery of that size on the tractor of the truck. In addition, the cost of the 1200 kWh battery would be very high ($180k). If in the future the pack energy density can be increased to about 400 Wh/kg, the weight and volume of the battery would be greatly reduced so it could fit on the tractor. In addition, the tractor would need to be extensively streamlined to reduce its C_D A to decrease the kWh/mi of the truck. Even if the cost of the battery is reduced to less than $100/kWh, the battery for the electric truck with a range of 600 miles would still be very expensive (at least $100k). The battery could be charged overnight using a 200 kW charger.

Another approach is to design a truck with a 300 mile range and plan to partially charge the battery once or twice during the day at rest areas. The truck would also be charged overnight at the rest areas. The total range per day could be 600 miles or more. The partial charges would put 65% 0f the capacity of the battery in at the 1C rate (a 60 minute charge). A 450-500 kW charging facility would be needed at the rest areas. The charging facility could charge multiple trucks overnight. The 300 mile range electric truck could operate much like the diesel truck with the driver taking 60 minute breaks every 200-225 miles to charge the battery. The cost analysis of the 300 mile truck indicates its total cost of ownership (TCO) is less than that of the diesel truck.

The cost of the battery charging facilities depends primarily on the cost of the charger hardware and its installation. The high-power electrical service to the facility would be provided by the local electric utility as a business expense in support of electrified vehicle infrastructure (Public

Utility Commission regulation). The total cost of a charger would be $750/kW or $375k for each 500W charging unit. If a rest area installed four 500kW charging units, the estimated cost is $1.5 million. The off-peak cost of electricity ($/kWh) dispensed to the trucks would be $.12/kWh from 11 PM–4 PM. The cost of electricity for batter charging is low ($.12/kWh) because the electric utility has been credited with the LCFS credits for electricity. If applicable to charging HD vehicles, the LCFS station credits ($/yr) can be as much as $65k/yr per charger up to the total cost of the facility in about five years. Hence with LCFS credits, the cost of operating the charging facility could be low in the early years while the market for electric long-haul trucks is developing.

Caltrans maintains 86 safety rest areas along highways in California with 53 along Interstate highways. If battery charging facilities were established at about 35 of these rest areas, they could be about 100 miles apart or a little closer. Caltrans could assist private contractors in establishing a network of charging facilities for electric trucks. The total initial cost could be about $50 million. The major barrier to Caltrans participating in the project is that current law prohibits commercial businesses at the rest areas which would not allow charging for the electricity dispensed. There has been consideration in both California and at the federal level to relax the non-commercial requirements at the rest areas for battery charging because the need for a battery charging network is well recognized.

1. Introduction

The California ACT mandate [1] for sales of battery-electric tractor-trailer trucks is 10% by 2026, 20% by 2028, and 30% by 2030. Most of these trucks travel extensively on the inter-state highways of California to deliver freight. It is well recognized that the market for these electric trucks will not develop unless battery charging infrastructure along the highways is established that will make their operation comparable to that of the diesel trucks they will be replacing. A detailed study [2] of providing the charging infrastructure along the I-5 corridor from Seattle to San Diego was conducted by the electric utilities of Washington, Oregon, and California in 2020. The study concluded that 27 charging stations were needed for medium-duty trucks and about 14 stations for the electric HD tractor-trailer trucks. The location of the charging stations are shown in Figure 1. The charging stations for the MD trucks are spaced 50 miles apart and those for the HD trucks 100 miles apart. The MD stations utilized ten 350 kW chargers and the HD stations utilized ten 2 MW chargers to charge the truck batteries in less than 30 minutes. The present study for Caltrans is concerned with the HD electric trucks and whether charging facilities at safety rest areas could be or should be part of the needed network of charging infrastructure for MD/HD electric trucks. The present study considers both the characteristics of the batteries in the HD electric trucks and how they could be charged to allow the electric trucks to give comparable service to that of diesel trucks.

Figure 1. West Coast Clean Transit Corridor Study locations of truck charging stations

2. Objective of the Project

The objective of the research on which this report is based was to define possibilities for and barriers to the provision of battery charging infrastructure for heavy-duty electric trucks at roadside rest areas in California. Caltrans maintains an extensive series of roadside rest areas throughout California that are widely used by long-haul trucks. By 2030 it is expected that a significant fraction of those trucks will be electrified and some of them will have the need for recharging their batteries away from their home base. In this research, it was determined whether charging at roadside rest areas, especially those along interstate highways, are likely to meet the needs of the trucks that have multi-day trips. The first step in the research was to determine whether providing the charging at the rest stops is practical for Caltrans to consider. The second step was to assess whether it is likely that the truck companies and drivers whom will have multiple options for recharging their batteries will utilize charging at rest stops.

3. Prospects for Battery-Electric Long-Haul Trucks

3.1 California Advanced Clean Truck Sales Mandates

On June 25, 2020, the California Air Resources Board adopted the Advanced Clean Truck (ACT) Mandate [1] that required the sale of zero-emission heavy duty (ZEVHD) trucks (battery-electric and hydrogen fuel cell trucks) starting in 2024. The mandate for Class 8 tractor trailer long-haul trucks requires in 2030 that 30% of sales be zero-emission and in 2035, the sales be 40% ZEVs. The complete ACT Mandate for all classes of trucks is shown in Figure 2.

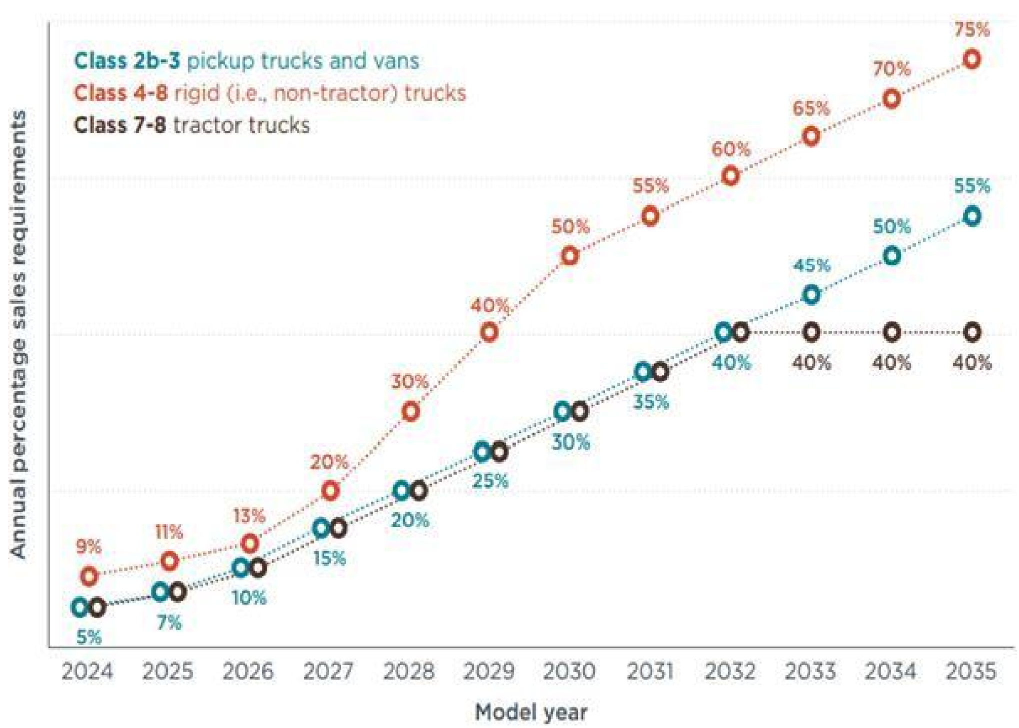


Figure 2. California ACT Mandate [1]

To satisfy the ACT mandate, the truck sale can be either a battery-electric or hydrogen fuel cell vehicle. Prior to 2030, it seems likely that sales of battery-electric vehicles will predominate because battery technology is further developed and lower cost than fuel cell technology. In addition, the infrastructure for battery charging is more available than for refueling hydrogen. After 2030, it is likely that sales of fuel cell trucks will increase because their initial cost will approach that of a diesel truck and hydrogen will be available at a reasonable price. Hence in the next 10 years, the majority of ACT long-haul trucks will be battery-electric and providing battery charging infrastructure will be important to their successful marketing.

3.2 Present Status of HD Electric Trucks

Heavy-duty battery-electric trucks are being developed for the market in the United States and Europe by several large truck manufacturers (Volvo, Daimler/Freightliner) and two well-financed start-ups (Nikola and Tesla). As of October 2021, only Volvo [3] has their electric trucks on the market for sale. The Volvo Class 8 Box trucks are being used in Southern California in the Lights Project [4] involving 25-30 electric trucks to move freight in/from the Los Angeles and Long Beach ports. The Volvo trucks have a 264 kWh battery that can be charged 80% in 70 minutes using a 150 kW charger. The range of the vehicle is 150 miles with an energy consumption of about 1.75 kWh/mi. Daimler/Freightliner [5] are demonstrating their Class 8 electric trucks. The Daimler trucks use battery packs of 210 kWh to 475 kWh and have ranges up to 250 miles. The Daimler batteries can be charged to 80% in 60-90 minutes. Volvo and Daimler will be marketing both Class 8 Box and tractor-trailer electric trucks by 2023. A schematic of the Daimler electric tractor is shown in Figure 3.

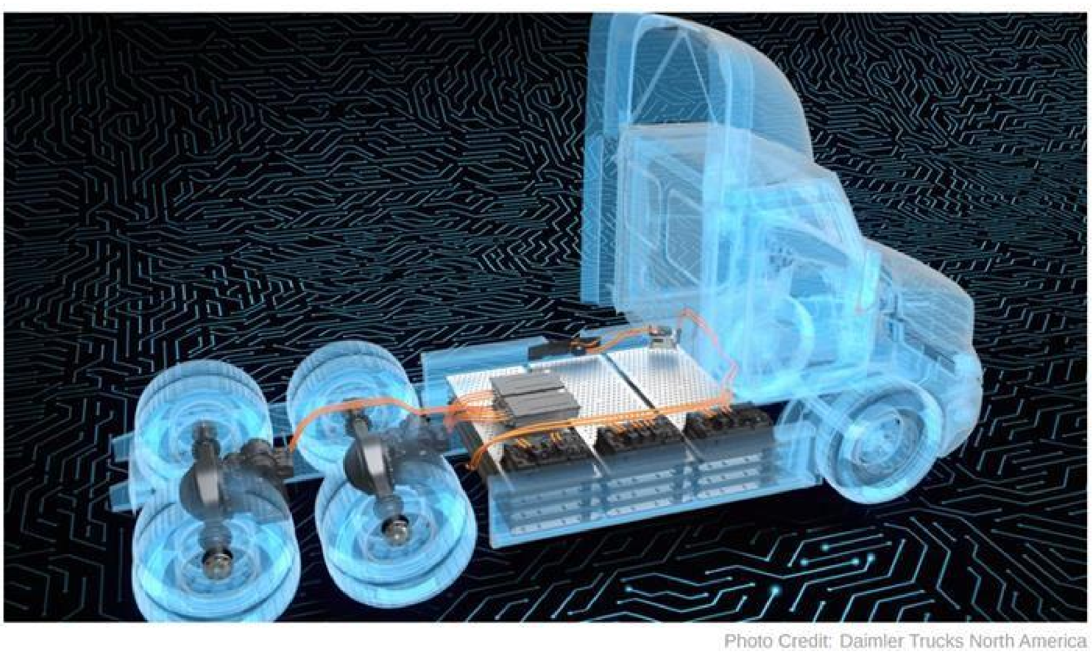


Photo Credit: Daimler Trucks North America

Figure 3. Schematic of the Daimler electric tractor

3.3 Projected Future Long Range Electric Trucks

As noted in the previous section, the range of the Class 8 electric trucks available from Volvo and Freightliner is 150-250 miles which is suitable for regional freight transport, but too short for long-haul applications which require at least 400 miles and more likely a 500-600 mile range. These long range long-haul electric trucks are being designed by Tesla [6] and Nikola who are demonstrating their trucks in a limited manner, but do not have firm plans to as yet to produce the trucks for sale. As shown in Table 1, the batteries needed for the long-range trucks will be very large. This a problem for the long-haul trucks because the batteries must be installed on the tractor which weighs about 8600 kg and has limited space available for the batteries. Table 1 indicates that the energy density of lithium batteries will have to about double from present values in order for 500–600 mile electric long-haul trucks to be practical. A smaller improvement in the energy density of batteries will be needed if the aerodynamic drag (C_D A) of the truck can be significantly reduced. That is the approach being taken by Tesla and Nikola as shown in Figure 4. Both battery improvement and tractor streamlining will be needed to get large numbers of battery-electric long-haul trucks on the market. This is unlikely to occur before 2030.

Table 1. Battery weight and volume for various ranges and battery technologies

Vehicle* Range miles	Battery kWh	Battery weight kg Pack energy density		Battery volume L Pack energy density	
		170 Wh/kg	400 Wh/kg	425 Wh/L	1000 Wh/L
250	450	2647	625	1059	450
400	720	4235	1800	1641	720
500	900	5294	2250	2118	900
600	1080	6353	2700	2541	1080

*vehicle energy use 1.8 kWh/mi

Most diesel tractors have the capacity to carry two 150 gallon fuel tanks. That is a volume of about 1200 L. From Table 1, filling this volume with batteries would result in a range of about 300 miles using present battery technology and 600 miles using projected future battery technology. Refueling a diesel tractor with two 150 gal. tanks would take 15-20 minutes. Recharging the battery in a 600 mile electric semi-truck in 30 minutes would require a charger of over 2 MW.

Figure 4. Streamlined electric long-haul truck

4. Lithium Battery Technology

4.1 Energy Density, Life Cycle, and Cost

In the development and marketing of electric long-haul trucks with ranges of 400-600 miles, the energy density (Wh/kg and Wh/L), cycle life, and cost of the battery will be critical. As shown in Table 1, the battery must store 700-1000 kWh to achieve those long ranges. Unless the energy density of the battery pack is 300-400 Wh/kg, the battery will be too heavy and large to fit on the tractor of the long-haul vehicle. The 2170 lithium cell (5 Ah) presently used in the Tesla passenger cars has energy densities of 250 Wh/kg and 500 Wh/L [7]. In a battery pack, the pack energy densities would be less than about 200 Wh/kg and 350 Wh/L. Commercial 18650 cells with energy density of 690 Wh/kg are available for sale [8,9] from Panasonic. Cells with energy density over 1000 Wh/L are reported in the literature [10] using encapsulated silicon in the anode.

Research projects are underway in the United States and China to develop lithium cells with energy density of 400-500 Wh/kg using lithium metal anodes [11-13]. Recent data [11] from the DOE project is shown in Figure 5. In China, the solid-state cells described in [12] have an energy density of 400 Wh/kg and are ready for mass production. The solid-state cells described in [13] have an energy density of 417 Wh/kg, 935 Wh/l and are also ready for mass production of 107 Ah cells. These results seem to indicate that a pack energy density of 350-400 Wh/kg may be possible by 2030.

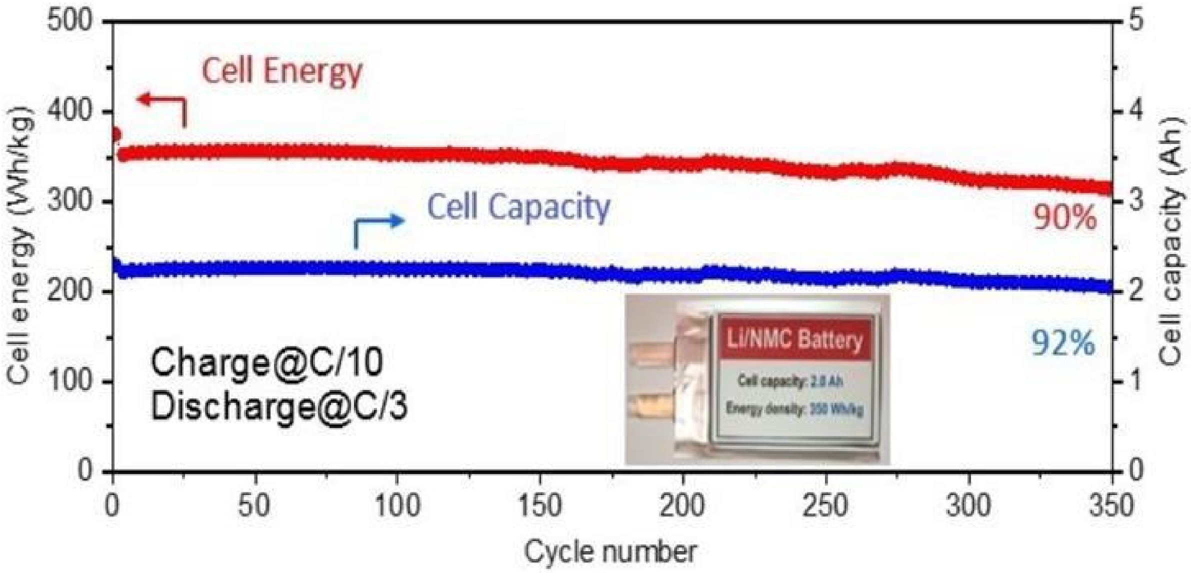


Figure 5. Test data for a laboratory metal anode lithium cell

The battery pack in an electric truck to be marketed must have a cycle life of at least 2000 cycles and a battery cost to the truck manufacturer of less than $150/kWh in 2025 and $100 kWh in 2030. This is likely to be possible using present battery technology, but that may not be the case for the advanced technologies being developed to increase energy density beyond 300 Wh/kg for the pack.

4.2 Battery Charging Characteristics

The large batteries in the electric long-haul trucks will necessarily require high power chargers, but a key issue is the time to charge the battery and what fraction of their energy storage capacity (kWh) will be input during a charge. It was noted in Section 3.2 that Volvo and Daimler specify a charge of 80% of capacity in 60-90 minutes for charging the batteries in their trucks. This corresponds to a charging rate of less than 1C (full capacity in more than 1 hr). This will require a charger power kW of close to the kWh rating of the battery being charged. This means that a full charge of the battery will take significantly longer than 1 hr and likely would be done overnight (3-4 hrs or longer).

The data obtained at UC Davis for fast charging lithium-ion batteries of various chemistries are shown in Table 2 and Table 3. In the case of the NMC batteries used in trucks, full charge cannot be put into the battery before taper is needed even for a 1C charge. At higher charge rates, taper is needed at lower states-of-charge. This is the reason that Volvo and Daimler specify only an 80% charge for their batteries at 1C. Since the battery is not fully discharged at the beginning of the charge, the useable range after a vehicle is charged on the road at 1C or faster is only 60-70% of the maximum range of the vehicle. The design range of the electric vehicle should correspond to using 80-85% of the kWh capacity of the battery pack.

Table 2. Charging characteristics of lithium batteries of various chemistries

Battery chemistry	Ah	Clamp voltage	Charge current A	Time (min.) to clamp V/Ah	Time (min.) to cut-off VAh
NiCoMnO2	20	4.2	20	52/17.3	80/19.6
FePhosphate	15	3.65	15	60/15.2	64/15.4
LiTitanateOx	11	2.8	11	65/11.9	66/11.9

Table 3. Percent of battery capacity input before taper for various battery chemistries

Charge rate	Nickel Cobalt Manganese %	Iron Phosphate %	Lithium Titanate %
1C	88	98	100
2C	85	96	100
3C	81	92	99
4C	76	90	98
5C	72	85	96

* C-rate refers to the time the battery is charging. N C-rate means the battery is charged in 1/N hours. For example, a 4 C rate is a battery charge in ¼ hour (15 minutes); C/2 rate is a battery charge in 2 hours.

4.3 Battery Safety

Battery safety is a very important issue for all electric vehicles, but it is especially of concern for Class 8 trucks that require very large kWh batteries and may have drivers sleeping onboard the vehicle during overnight battery charging. Safety issues relative to on-road vehicles in the United States are handled by the National Highway Traffic Safety Administration (NHTSA) of the US Department of Transportation. NHTSA sets the regulations for vehicle design and operation and initiates recalls of motor vehicles when there are safety problems. NHTSA has been setting regulations for EVs and HEVs for 10-15 years and issues recalls on those vehicles as needed [14]. There are currently safety issues with slow charging and what is presently referred to as fast charging. The main issues are with problems of battery overheating during and after charging and damage to the batteries due to on-road accidents [15-17]. The experience with lithium batteries in light-duty vehicles has shown that battery fires occur very infrequently under normal operating conditions. Nevertheless, vehicle manufacturers monitor the condition of their batteries/cells continuously and analyze the data for any abnormal behavior that might indicate a potential problem in the battery pack. This is done remotely via wireless networks with the data stored in the cloud. Much research [18-20] is being done worldwide to improve the analysis of the data to more reliably identify possible battery failures.

One of the reasons that solid-state batteries are being developed worldwide is that they are inherently safer than lithium-ion batteries using a separator and liquid electrolyte, which is highly flammable. A solid-state battery using a lithium-metal anode and a solid, glass-like electrolyte can be very safe because the flammability of the battery is greatly reduced [21, 22]. This will be the case only if the solid electrolyte is impervious (blocks) to any lithium dendrites that might form at the interface between the lithium-metal anode and the solid electrolyte. Development and manufacturing the solid electrolyte material that both conduct lithium ions and totally blocks dendrites is the major challenge of the development of solid-state batteries.

5. Safety Rest Area Considerations in California

5.1 Locations and Use-Patterns

Caltrans maintains a large number (86) of safety road-side rest areas [23, 24] along the main highways in California. 53 of the rest areas are along Interstate highways (28 along I-5 and 5 along I-80). The average distance between rest areas on the Interstates is about 45 miles.

The characteristics and regulations associated with these rest areas are shown in detail on many Caltrans documents available on the internet. One of these documents entitled “Safety Roadside Rest Stops” [23] is particularly informative as it points to many additional Caltrans webpages with maps and statistics for all the rest areas. A second valuable source of information used in this study was the paper [24], “Putting a Price on Truck Parking: A Planning & Public Health Policy Perspective (A preliminary analysis of fatigue-related collisions and truck parking availability along California I-5 & exploration of pricing parking at public rest areas.)” This paper included detailed data on all the rest stops along I-5.

The Caltrans website [23] is linked to the additional sources of information shown in Table 4. Maps are available for the locations of all the safety roadside rest stops. The map for District 3 is shown in Figure 6. District 3 has several rest areas along I-5, which have relatively high truck parking capacity and high truck traffic. Statistics for selected rest stops are shown in Table 5 and Table 6 taken from [24, 25]. For example, (1) the Willows stop has 55 truck capacity and daily average of 40-45 truck stops per day, (2) the Dunnigan stop has a capacity for 12 trucks and a daily average of 50-60 truck stops per day. Most of the rest areas have a truck capacity of 20-30 trucks and a few have a capacity for 40-50 trucks. The number of trucks that stop per day varies over a wide range from 20 to over 150.

Table 4. Additional sources of data on CA Rest Stops [23]

Information Centers	• Safety Roadside Rest Area Master Plan (PDF) • Rest Area System Maps (From Master Plan Appendix C) (PDF) • Statewide Rest Area System Map (Requires Google Earth)
Background Matrices	• Current Projected Use (PDF) • Parking Deficiencies (PDF) • Unauthorized Truck Parking (PDF)

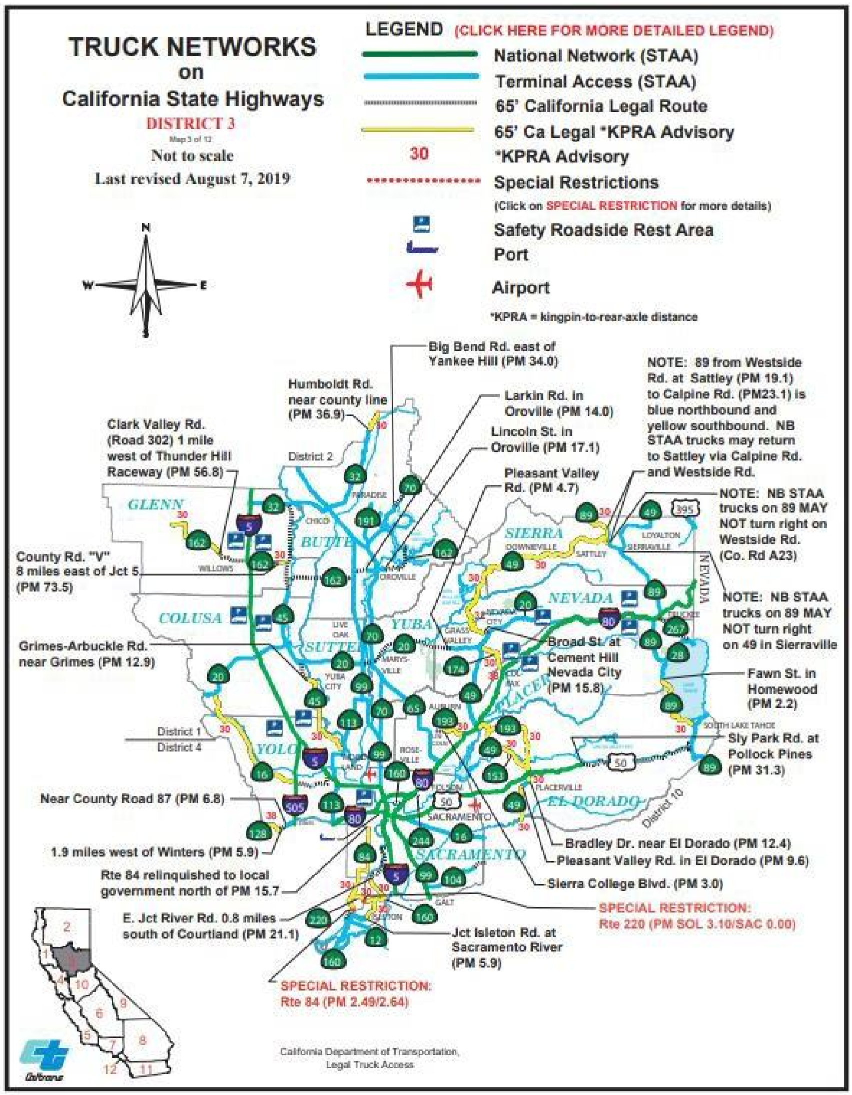


Figure 6. Map showing Rest Stops in CA District 3

Table 5. Use statistics for selected CA rest stops [25]

Current & Projected SRRA Usage																
District	County	Route	Post Mile	Rest Area	Direction	Mainline Traffic Volume (AADT) – Both	SRRA Ramp Volume AADT			Total Current 2009/10 SRRA AADT	Estimate Current Stopping Factor	20-Year AADT Growth Factor	Estimated 2029/30 SRRA AADT	Date Ramp Counts Taken	2009/10 Annual SRRA Use	2029/30 Forecasted Annual SRRA Use
							Cars	Trucks	Buses							
1	DN	199	33.3	Collier Tunnel	Both	3,000	328	45	3	**376**	12.5%	1.22	**458**	Sept. 19 – Oct. 5, 2009	**263,588**	**321,073**
1	Hum	101	105.9	Trinidad	NB	5,000	235	36	1	**272**	10.9%	1.22	**332**	June 18 – June 24, 2007	**185,286**	**226,158**
1	Hum	101	105.2	Trinidad	SB	5,000	205	36	2	**243**	9.7%	1.22	**296**	June 18 – June 24, 2007	**168,824**	**205,646**
1	Men	101	58.9	Moss Cove	SB	6,700	349	58	3	**410**	12.2%	1.33	**544**	July 23 – July 29, 2007	**283,672**	**376,384**
1	Men	101	61.5	Irvine Lodge	NB	6,700	251	41	2	**294**	8.8%	1.33	**392**	June 25 – July 1, 2007	**207,259**	**276,345**
1	Men	101	82.5	Empire Camp	NB	6,400	191	19	0	**210**	6.6%	1.33	**281**	June 25 – July 1, 2007	**146,958**	**196,644**
2	Las	44	14.5	Bogard	Both	1,675	262	62	9	**333**	19.9%	1.24	**413**	Sept. 25 – Oct. 1, 2009	**230,577**	**285,971**
2	Las	395	49.6	Honey Lake	Both	5,400	224	58	8	**290**	5.4%	1.47	**429**	Sept. 25 – Oct. 1, 2009	**183,250**	**271,084**
2	Las	395	96.5	Secret Valley	Both	1,200	70	21	4	**95**	7.9%	1.24	**118**	Oct. 3 – Oct. 9, 2009	**63,401**	**78,751**
2	Plu	36	12.8	Lake Almanor	Both	3,650	59	9	0	**68**	1.9%	1.72	**119**	Sept. 25 – Oct. 1, 2009	**46,616**	**81,578**
2	Plu	70	49.8	Massack	Both	3,750	90	15	1	**106**	2.8%	1.57	**165**	Sept. 24 – Sept. 30, 2009	**71,195**	**110,822**
2	Plu	70	79.1	L.T. Davis	Both	3,425	58	10	1	**69**	2.0%	2.16	**148**	Aug. 30 – Sept. 1, 2009	**46,473**	**99,681**
2	Sha	5	31.1	O'Brien	NB	19,100	451	155	22	**628**	6.6%	1.68	**1,059**	Oct. 1 – Oct. 7, 2009	**478,386**	**806,705**
2	Sha	5	43.2	Lakehead	SB	17,100	603	247	43	**893**	10.4%	1.57	**1,396**	Sept. 25 – Oct. 1, 2009	**691,861**	**1,081,565**

Current & Projected SRRA Usage																	
District	County	Route	Post Mile	Rest Area	Direction	Mainline Traffic Volume (AADT) – Both	SRRA Ramp Volume AADT			Total Current 2009/10 SRRA AADT	Estimate Current Stopping Factor	20-Year AADT Growth Factor	Estimated 2029/30 SRRA AADT	Date Ramp Counts Taken	2009/10 Annual SRRA Use	2029/30 Forecasted Annual SRRA Use
							Cars	Trucks	Buses							
2	Sha	44	34.7	Shingletown	Both	4,300	80	24	2	**106**	2.5%	1.46	**157**	Sept. 25 – Oct. 1, 2009	**69,304**	**102,648**
2	Sha	299	60.6	Hillcrest	Both	3,100	63	12	1	**76**	2.5%	1.39	**108**	Sept. 25 – Oct. 1, 2009	**51,190**	**72,744**
2	Sis	5	25.6	Weed Airport	NB	14,700	567	291	46	**904**	12.3%	1.36	**1,230**	Sept. 26 – Oct. 2, 2009	**693,472**	**943,552**
2	Sis	5	25.6	Weed Airport	SB	14,700	562	293	45	**900**	12.2%	1.36	**1,220**	Sept. 26 – Oct. 2, 2009	**684,386**	**927,723**

Table 6. Parking capacity statistics for selected Ca rest stops along I-5 [24]

County	Rest Area	Current Truck Parking	2030 Parking Demand Projections	Able to Add More Parking at Current Site*	Urban or Rural Area	Expected Deficit
Shasta	O'Brien NB	9	14	N	Rural	Deficit
Shasta	Lakehead SB	18	24	Y	Rural	Deficit
Siskiyou	Weed Airport NB	18	26	N	Rural	Deficit
Siskiyou	Weed Airport SB	18	27	Y	Rural	Deficit
Siskiyou	R.E. Collier NB & SB	38	16	-	Rural	No Deficit
Tehama	Lt. John Helmick NB	11	16	Y	Rural	Deficit
Tehama	Lt. John Helmick SB	13	13	-	Rural	No Deficit
Tehama	Herbert S. Miles NB	14	24	Y	Rural	Deficit
Tehama	Herbert S. Miles SB	23	20	-	Rural	No Deficit
Colusa	Maxwell NB	44	11	Y	Rural	No Deficit
Colusa	Maxwell SB	44	10	-	Rural	No Deficit
Colusa	Willows NB	55	12	-	Rural	No Deficit
Colusa	Willows SB	55	24	-	Rural	No Deficit
Sacramento	Elkhorn SB	14	12	-	Urban	No Deficit

5.2 Special Considerations for Battery-Electric Trucks

A key issue concerning the use of the rest areas by long-haul trucks is how long (minutes) the truck is likely to stay at the rest stop. For conventional diesel trucks, this will depend on the reason the driver decided to stop. They could have needed a toilet break or needed to have a short rest to relax. These stops would be short of 15 minutes or less. The second reason to stop could be to satisfy the legal limits on the time a driver can drive without a break and the total time a driver can be on duty without an extended period to sleep. The breaks from driving are 30 minutes after 8 hours of driving. The extended rest period must be at least 10 hours after a maximum of 11 hours on duty with the vehicle. For a long-haul truck, 8 hours of driving is 400-500 miles. It seems unlikely the driver would drive 8 hours non-stop so assume they will stop every 4 hours or 200-250 miles. If they were driving an electric truck with a range of about 300 miles, they could stop for about 45-60 minutes at a rest stop and charge the battery to drive an additional 4 hours, 200-250 miles. This would require a 450 kW charger to do this. If needed to complete the trip, they could stop for another 45-60 minute break to charge the battery again and then drive for 2-3 hours for a total of about 600 miles in a day. Shorter trips would require less time battery charging. It seems clear that driving electric trucks will require longer breaks than seem customary with diesel trucks.

This approach for using electric trucks would be possible with present battery technology and permit long-haul freight trips of 500-600 miles or even longer. Our long-haul truck cost study [26] indicates that the total cost of ownership (TCO) in 2030 of an electric truck with a range of 300 miles can be lower than that of the diesel truck. The details of the cost analysis are shown in Table 7 and Table 8. The initial cost of the electric truck will decrease between 2030 and 2040 due to the reduced cost of the batteries and the lower energy costs of operating the electric truck compared to the diesel truck, making their TCO lower.

Table 7. Comparisons of BEVs and diesel trucks for inter-city applications [26]

Vehicle	2030 BEV	2040 Bev	Diesel
Long-haul 300 miles	$190K initial cost TCO $.74/mi	$155K initial cost TCO $.64/mi	$137K initial cost TCO $.80/mi
Long-haul 500 miles	$231K TCO .76	$191K TCO .70	$134K TCO .77

Table 8. Key cost inputs to cost analysis [26]

Mid-range assumed values	2020	2030	2040
Battery costs ($/kWh)	225	100	70
Electricity costs ($/kWh)	$0.15	$0.15	$0.15
Diesel fuel cost ($/gal)	$4.50	$4.50	$4.50

5.3 Government Policies on the use of Rest Areas

There are many recent articles [27-29] on the internet discussing parking for trucks along/near the main highways in the United States. It is clear that truck drivers make steady use of the parking in rest areas when they are available. In fact, many of the articles indicate that there is a significant shortage of parking areas for trucks in most States. California is often cited as one of the States with a critical shortage. The Truck Parking Safety Improvement Act, was introduced to the Congress, House of Representatives, on March 26, 2021 to build new truck parking facilities and expand truck parking at existing rest areas [30].

Starting in 2016, the U.S. Department of Transportation (FHWA) started to develop a national network [31, 32] of "alternative fuel" corridors spanning 35 states. The network will include fuel for electric, hydrogen, propane, and natural gas vehicles. Battery charging facilities for electric trucks along highways will be an important element of the network. Placement of battery chargers at safety rest areas is already being discussed in the literature [33, 34]. The Federal government has loan guarantee programs to support the building of the network. As of July 2020, over 145,000 miles of the National Highway System (see Figure 7) have been designated as part of the network and 48,200 miles are to charge electric vehicles (cars and trucks). To be “corridor ready” for electric vehicles, FHWA requires that DC Fast Charging facilities are available every 50 miles.

1. Designated EV Corridors, Rounds 1 – 4. Credit: FHWA

Figure 7. The designated alternative fuel corridors in 2020

One of the complications of placing battery charging in safety rest areas is that there are Federal and State restrictions/bans on providing commercial services at rest areas. The Federal ban applies to rest areas on non-tolled interstates. Service areas on toll roads can provide commercial services and they are already considering adding battery charging facilities to their gasoline stations. The Federal ban would mean that there could be no charge ($) to the users of battery charging stations placed at rest areas along interstates in California. In general, California has a ban on commercial services at rest areas except for vending machines. Caltrans is authorized [35. 36] to construct and operate up to six new rest areas as a joint economic development/ demonstration project, provided there is a need, and that the proposal will result in an economic savings to the State. Contracts must be awarded on a competitive basis; the rest areas may include traveler-related commercial services; and the Department is interested in a significant savings in the capital costs of construction (land and development [35]. It seems reasonable to consider battery charging as a travel-related service.

There have been studies [36] to rethink the Federal ban on commercial services at rest areas especially with the need for battery charging facilities along highways. Bills to change the ban have been introduced in Congress, but none have been successful. In March 2021, the FHWA announced it would issue guidance on how transportation departments could use the Federal right-of-way surrounding highways to setup charging stations for electric vehicles [33]. It appears likely that both Federal and California regulations will be changed in the near-term to permit commercial charging stations along interstate and other highways.

6. Battery Charging Requirements for Electric Long-Haul Trucks

6.1 Power Requirements for Battery Chargers

The size (kWh) of the battery in the truck strongly effects both the cost of the truck and the charging infrastructure needed. The kWh of the battery depends on the energy consumption (kWh/mi) and the desired range of the truck. The kWh/mi depends primarily on the weight of the truck, its C_DA, and the speed at which it is driven. The maximum loaded weight is set by federal law as 36000 kg. A series of Advisor runs were made for long-haul electric trucks for different weights, C_DA, and constant speeds of 55 and 65 mph. The results are shown in Table 9. It is clear from Table 9 that to achieve kWh/mi of 2.0 or less will require streamlining the tractor and trailer and limiting the speed driven for fully loaded trucks. As shown in Table 1, the battery weight and volume for an electric truck having a range of 300-600 miles are very large. It appears that to have a range greater than 300 miles will require a pack energy density of at least 300 Wh/kg. Since the range of any electric truck is uncertain and difficult to predict for a particular trip, it may be better to designate electric trucks by the size/kWh of the battery in the truck rather than its design range. The Volvo truck has a 264 kWh battery [3] and a stated range of 150 miles. The Daimler truck has a 475 kWh battery [5] and a stated range of 250 miles. The useful range of both trucks is likely to be significantly less than their stated range for most trips.

Table 9. kWh/mi for long-haul trucks

		kWh/mi*	
Weight kg	**C_D**	**Speed 55mph**	**Speed 65mph**
36000	.55	2.49	2.89
30000	.55	2.25	2.65
24000	.55	2.0	2.41
18000	.55	1.77	2.17
Streamlined trucks			
36000	.35	2.11	2.36
30000	.35	1.87	2.12
24000	.35	1.63	1.88
18000	.35	1.40	1.65

* A_f =9.5, f_r =.007, $P_{access.}$ =1.5 kW, P_{EM} = 400 kW

The size/power (kW) of the charger needed to charge the battery pack will depend on both the size (kWh) of the battery and the rate (hr) at what the battery is to be charged. The charger power for charging is given approximately by $(kWh)_{bat}/t_{chag}$. The charging power for ranges from 200-600 miles are shown in Table 10 for charging times of 30 minutes to 5 hours. The charger operating conditions (V, I) depend on the voltage of the battery pack and Ah of the cells used to assemble the pack. For lithium-ion batteries, the number of cells (N_{ser}) in series is $V_{bat}/4$ and the effective Ah of the cells (series and parallel) is $((kWh)_{bat}/N_{ser})/(4xN_{par}))x1000$. For example, V_{pack} =800 V, N_{par} =10, $(kWh)_{bat}$=800, $(Ah)_{cell}$ =100. For this battery pack, the C/1 charging rate would require a current of 1000A and a power of 800 kW. Charging at the 2C rate would require 2000A and 1600 kW. Clearly charging battery packs for trucks with greater than a 400 mile range in less than an hour will require MWs of power.

Table 10. Charger power requirements for various ranges and charging times

Vehicle range mi	Battery kWh*	Charger power kW					
		Charge time hours	.5	1	2	3	5
200	400		800	400	200	133	80
300	600		1200	600	300	200	120
400	800		1600	800	400	267	160
500	1000		2000	1000	500	333	200
600	1200		2400	1200	600	400	240

* truck kWh/mi=2.0

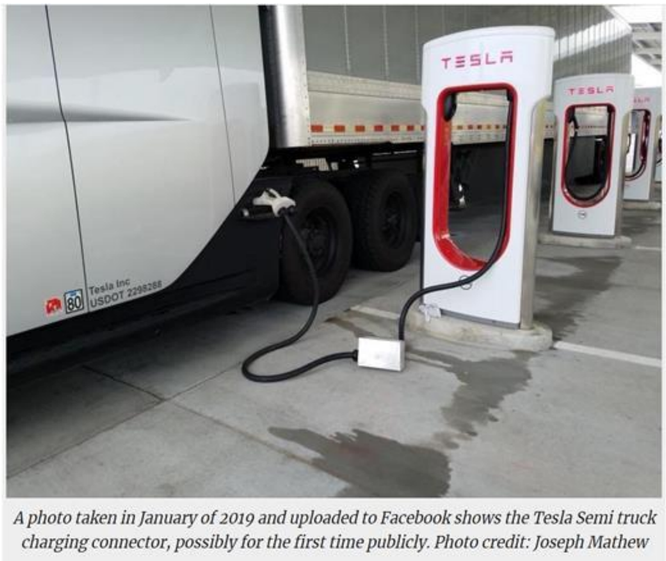
6.2 Available High Power Battery Chargers

There are many companies developing high power DC battery chargers for vehicle applications [37, 38]. Most of the chargers commercially available are intended for charging batteries in light-duty vehicles- passenger cars, SUVs, and small trucks. The power of these chargers are 50 kW and 150 kW. The highest power chargers being developed for LDV applications are 350 kW for fast charging the batteries in 30 minutes or less. The 150 kW chargers would be adequate for charging the large truck batteries overnight in 5 hours or longer, but not in 3 hours or less. Those large truck applications will require much higher power chargers of at least 400-800 kW. At the present time, large electric trucks in demonstration fleets like in the Volvo Lights Program [4] utilize fast chargers developed for fast charging LDVs.

One of the developers and manufacturers of high-power chargers is Tritium, an Australian company, with offices in the United States and Europe. A photograph of a Tritium 350 kW charger is shown in Figure 8. Tritium is also developing a 450 kW charger that would be suitable for large truck applications. There is considerable development of MW chargers and associated cooling and control systems [39]. Tesla has had multiple news releases [40, 41] concerning the mega-chargers for their electric semi-truck which will require a 2MW charging system to charge the battery in their 500 mile truck to 80% SOC in 30 minutes. A photograph of a Tesla truck being charged using multiple passenger chargers is shown in Figure 9.

At the present time, the practical power limit for charging is about 400 kW corresponding to 500A and 800V. Charging at 500A requires water-cooling [42] of the connecting cable to the vehicle (see Figure 10). MW charging will require higher battery voltages up to 1500V and currents up to 1000A. That development is currently underway [43, 44]. Charging 600-700 kWh batteries in electric semi-truck in 30 minutes or less will require high voltage packs, MW chargers, and thermal managed connector cables, which are not presently available.

Figure 8. The Tritium 350 kW charger [37]



A photo taken in January of 2019 and uploaded to Facebook shows the Tesla Semi truck charging connector, possibly for the first time publicly. Photo credit: Joseph Mathew

Figure 9. the Tesla electric semi-truck being charged

Figure 10. A water-cooled connecting cable for battery charging at 500A [42]

6.3 Battery Charging Strategies

There are several strategies that can be used to charge the batteries in the large electric trucks depending on the design range of the truck, its use-pattern, and the availability of battery charging infrastructure. The simplest approach is to have the electric truck return to a home terminal and do all the battery charging over-night. In this case, the batteries can be charged in 4-6 hours using battery chargers used to fast charge batteries in LDVs. This approach can work well for electric tractor-trailers trucks (semi-trucks) in regional service, but not for electric semi-trucks that travel multiple days using highway rest areas and truck stops before returning to home base. These electric trucks need other strategies to keep their batteries charged and could be candidates to use the battery charging facilities being discussed in this report. The general strategy for these trucks is to charge the battery partially once or more during the day as the truck travels and makes deliveries and then charge the battery completely over-night as the driver takes a long break after 11 hours of driving. This general strategy will permit the electric truck to be driven daily total miles significantly greater than the design range of the truck when needed. The battery in the truck can be sized/kWh for a stated range of 300-400 miles and by opportunity charging, its useful daily range can be extended to 500-600 miles like for diesel fueled trucks. The opportunity, partial charges of about 60 minutes will necessarily be only 60-65% of the battery capacity due to the power rating of available chargers and the ability of the battery to accept high charge currents near full charge conditions (Section 4.2).

Consider the following example of opportunity charging of an electric semi-truck with a 600 kWh battery and stated range of 300 miles. The first charge of a day occurs when the battery SOC is 15% and the truck has traveled 255 miles in about 4.5 hours. The battery can accept recharge up to 80% SOC at the 1C current. Charging the battery in the truck from 15-80% SOC will require 390 kWh in 60 minutes from a 450 kW charger. The added range of the truck will be about 195 miles or 3.5 hours of driving. After the initial opportunity charge, the electric semi-truck will have traveled 450 miles in 9 hours for an average speed of 50 mph. A second opportunity charge could extend the range to over 600 miles in an extended day of about 12 total hours and 11 hours of driving with two 60 minute breaks for the driver while the batteries were being charged. After traveling 600 miles, the driver would find a charging station or truck stop to charge the battery completely in 4-6 hours. This battery charge of about 600 kWh would require a charger of 100-150 kW. This charging strategy could involve both safety rest areas and conventional truck stops if they had facilities for battery charging. As shown in Table 7, both the initial cost and TCO of the 300 mile electric semi-truck is more attractive than one with a stated range of 500 miles.

7. Battery Charging Facilities at Safety Rest Areas

7.1 Facility Lay-Out

The layout of the battery charging facility consists of a series of lanes each equipped with a high power battery charger. The lanes need to be configured that more than one truck can use a particular charger if the charging times of each truck connected to the charger will be significantly greater than 60 minutes as for overnight charging. The chargers will be connected to the grid with the cost of the electricity to charge the batteries set by the California Public Utility Commission. This is the simplest approach and lowest capital cost for establishing battery charging facilities at safety rest areas. A more complex approach would be to consider on-site generation of electricity using solar panels with large battery storage. The capital cost of this approach would be much higher and the contribution of LCFS credits toward profitability much more complex. For these reasons, the incorporation of solar panels into the project does not seem to be appropriate.

To be useful for opportunity charging, the charging facilities at the rest areas need to be about 100 miles apart. In developing the rest area charging network, the establishment of charging at multiple rest areas is more important than larger charging facilities at a few areas. For electric semi-trucks to travel throughout California, battery charging would be needed at rest areas along I-5 and I-80 and along C-4, C-99, C-70, and C-120. The minimum time to charge the batteries (30–60 minutes) of the electric trucks is much longer than the time (10–15 minutes) to refuel the diesel trucks. As a result, there will be a need for many battery charging facilities along the interstate highways.

Photographs of electric semi-trucks charging at truck stops are shown in Figure 11, Figure 12, and Figure 13. The Watt EV Truck stop (Figure 13Figure 1) will initially have 12 chargers with a total capacity of 4 MW supplied from on-site solar panels and battery storage [45, 46]. Drivers will have a choice of 250 kW, 350 kW, and 1 MW chargers. The 1 MW charger will be used to charge batteries in 30 minutes or less.

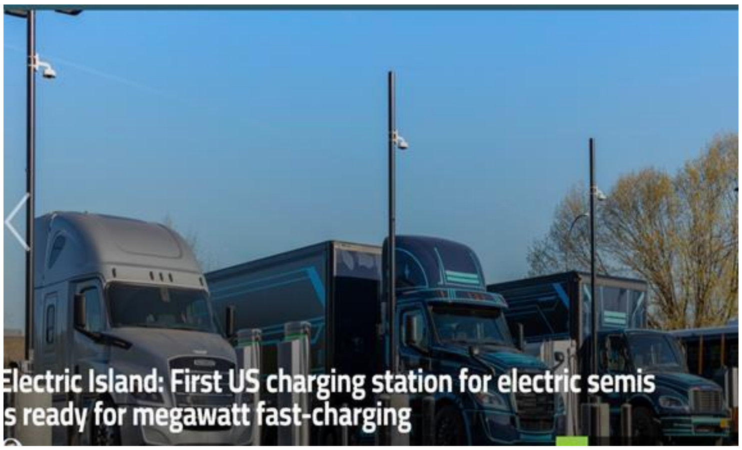


Figure 11. A typical battery charging station for trucks

Figure 12. A truck connected to a high power charger

Figure 13. The Watt EV Battery Charging truck stop near Bakersfield (being built) [45. 46]

7.2 Electric Power Access

As discussed in Section 5.1, Caltrans provides on the internet detailed information on safety rest stops along main highways in California [23, 25]. The following rest stops appeared to be good candidates for battery charging as they have facilities for trucks going in both directions on I-5 and very high truck usage at the rest area.

1. Willows (Glenn county)
2. Dunnigan (Yolo county)
3. Westley (Stanislaus county)
4. Coalinga/Avenal (Fresno county)
5. Button willow (Kings county)
6. Tejon Pass (Kern county)

PG&E was asked to look at these locations along I-5 regarding the availability of high electrical power (2-5 MW) for battery charging. Rest areas 1-3 were in the PG&E territory. In those cases, there was power available, but most of it had already been allocated to other customers, but they thought that re-arranging the allocations to accommodate battery charging would be possible without great difficulty or high expense. In any case, the California state policy is that the cost of providing service for electric vehicle infrastructure is covered by the electric utility as a business expense. Hence, the cost of establishing a battery charging facility at a rest area to Caltrans or a contractor will be primarily the cost of the battery chargers and their installation. That cost will be discussed in the next section of the report.

7.3 Projected Cost of Charging Facility

The battery charging facility would be build on the grounds of the safety rest area. At the present time, there is space for parking a reasonable number of diesel long-haul trucks at rest areas. It probably would be best to setup a new area for the electric trucks. In that area, the battery chargers would be installed in an arrangement that would permit both opportunity and overnight charging. Initially, the number of chargers would be limited due to the relatively small number of electric trucks that would be on the highways early in the development of the market for the electric trucks. Expanding the facility as the market develops should not be a problem, because the hardware for battery chargers is very modular. However, it will be necessary to increase the maximum power available to the charging facility.

The cost of establishing the battery charging facility will depend on the cost of the charger hardware and the cost of their installation after the electric utility has made available the electric service required to operate the chargers. From discussions with Tritium [37], the hardware consists of large high-power rectifiers to convert AC power to DC power and the battery charger unit to dispense the electrical energy to the truck. A photograph of a typical charger site with rectifier and multiple chargers is shown in Figure 14. The highest power charger presently available is 360 kW. Higher power charging could be arranged by separating the battery pack into two equal parts and charging each part with a 250 kW charger. The high-power rectifiers (Table 11) can be connected in parallel (up to 6) to provide 2.1 MW of DC power. For 500 kW for opportunity charging of four (4) trucks, six (6) rectifiers and eight (8) 250 kW chargers would be needed. Assuming $50k for each of the 360 kW rectifiers, $67.5k for the 360 kW chargers, and $48k for the 250 kW chargers, both the 360 kW and 500 kW charging setups cost $340/kW or $122k and $170k, respectively, for the hardware. The installation costs are much more difficult to estimate, but a spreadsheet model of costs from Tritium indicate installation costs could be 1.2 times the cost of the charger hardware. Hence the total cost of a charger would be $750/kW or $375k for each 500W charging unit. If a rest area installed four 500kW charging units, the estimated cost is $1.5 million.

Figure 14. A rectifier with multiple chargers

Table 11. Characteristics of the 300 kW Tritium DC Bus rectifier unit [37]

Item	USA (480VAC)
Input	480VAC 3ph +/-10% Derating applied on low line level and phase imbalance 60Hz 450A nominal 480A maximum
Input Overvoltage Category	Category III
Output Power	Up to 360kW total
Efficiency	Highest efficiency > 98.1%, 97.85% at full load

There are LCFS credits to off-set part of the cost of establishing charging facilities for light-duty electric vehicles, but at the present time, they do not apply to charging facilities for heavy-duty trucks. If applicable, the LCFS credits would allow the builder of the charging facility to recover its cost as the facility is in operation. The LCFS station credit [47] is calculated as follows:

$$(\$/yr)_{cgag\ LCFS} = (CI_{Diesel} - CI_{elec}/EER)*EER*3.3*10^{\wedge}-6*43*(kW_{chag})^{\wedge}.45*365*\$/MtCO2$$

The LCFS charging facility credit ($/yr) for the rest area charging facility are shown in Table 12 for 2020-2040. The regulations for the LCFS credits [47] limit the total credits for a project to its cost. In the case of the rest area project, LCFS credits would be received for six years collecting about $61k per year. Hence the LCFS credits would make the project affordable. As of December 2021, the LCFS station credits only apply for charging light-duty vehicles, but it is possible those credits may be made available by CARB in the future for charging medium- and heavy-duty vehicles.

Table 12. LCFS charging infrastructure credits (k$/yr) [43]

Year	diesel CI	Electricity CI Grid	$/MtCO2	LCFS sta. Credit k$/yr *
2020	92	110	200	64.8
2025	86	100	190	58.1
2030	80	90	180	51.7
2035	73	75	170	45.7
2040	65	50	160	40.7

*500 kW charger

7.4 Projected Cost of Electricity for Battery Charging

The electricity (kWh) used by the truck would be essentially the same as if the truck did not need opportunity charging to extend its range. The energy use would be the kWh/mi for the truck for each trip. The cost ($/mi) would be simply

$/mi = (kWh/mi) ($/kWh)

The electricity would be taken from the grid at the current price, which would likely vary with time of day the charging takes place (see Figure 15). In general, the electricity price would be highest from 4-9 PM and lowest from 11 PM-4 PM [48]. Hence overnight charging should be done after 11 PM and opportunity charging should be done before 2 PM if possible. If the charging facility contracted with an electric utility like PG&E to purchase electricity, the costs could be like those shown in Table 13 [49] that are being considered by the California Public Utilities Commission. In that case for charging off-peak, the electricity cost would be $.12/kWh. For an electric semi using 2 kWh/mi, the energy cost would be $.24/mi. For high power battery charging, there will also be demand charges. These costs are dependent on the power (kW) of the charger. The demand charges according to Table 13 are $(\text{kW})_{\text{charger}}$ x $3.3/kW each month. For the 450 kW charger, the demand charges would be about $1,485/month. If the charger is used to charge 25 trucks per day or 750 trucks per month and each charge is 390 kWh, the total electricity charged per month would be 292 MWh. The cost per month from the utility for electricity would be $35,000 for the electricity and $1,485 demand charges. Hence for electric semi-trucks, demand charges will be relatively small (5%) when the charging stations are well utilized (market well developed). Hence, the total cost of the electricity per year to charge a single truck would be about $17K. If the rest stop averaged 25 trucks/day, the total cost of electricity would be about $425K/yr/rest stop.

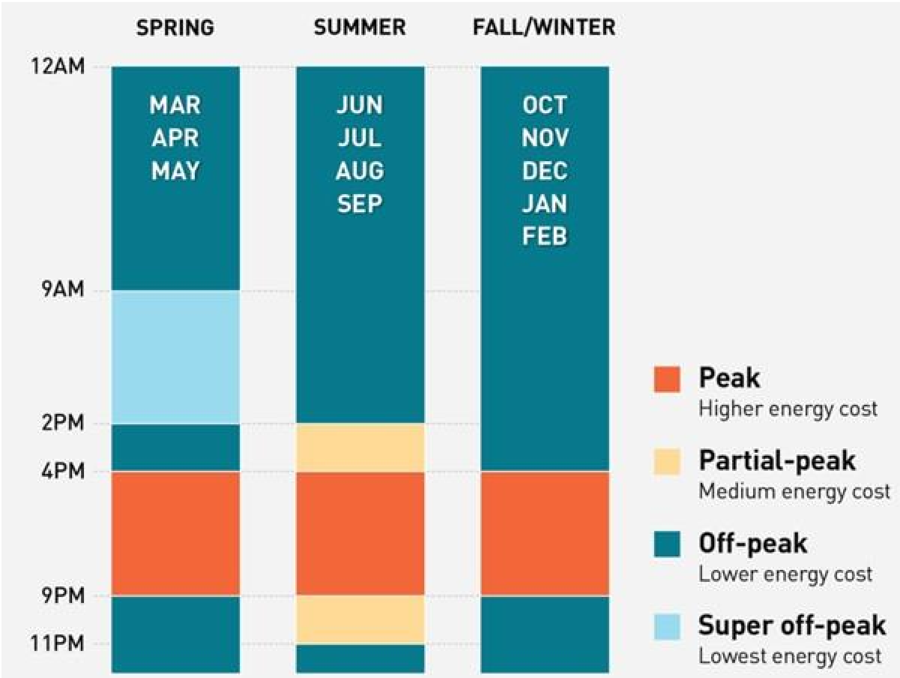


Figure 15. Variation of grid electricity prices with time of day and month of the year [48]

Table 13. PG&E battery charging cost [49]

Rate Element	**CEV-S[1]**	**CEV-L-S[2]**	**CEV-L-P[3]**
Subscription Charge per Kilowatt (kW) of Peak Demand	$21.17 / 10kW block	$167.75 / 50kW block	$153.41 / 50kW block
Peak Energy Charge	$0.32166 / kilowatt-hour (kWh)	$0.33410 / kWh	$0.32611 / kWh
Off-Peak Energy Charge	$0.12966 / kWh	$0.12086 / kWh	$0.11723 / kWh
Super Off-Peak Energy Charge	$0.10299 / kWh	$0.09760 / kWh	$0.09457 / kWh

[1] For those customers with peak demands of 100kW or less.

[2] For those customers with peak demands of more than 100kW taking service on secondary voltage.

[3] For those customers with peak demands of more than 100kW taking service on primary voltage.

In California, the cost of the electricity to charge the batteries is reduced by the Low Carbon Fuel Standard (LCFS) credit [50], which is based on the reduction in CO_2 emissions by substituting electricity for energy/fuels using fossil sources. The credits depend on the relative carbon emissions (gCO_2 /mi) of the electric vehicle using a fossil fuel and electricity. The LCFS credit can be calculated using the formula shown below.

Electricity LCFS Credit ($/kWh) = $(CI_{diesel} - CI_{elec,}/(EER)_{EV})*(EER)_{EV}*3.6*10^{-6}*$ ($/Mt CO2),
EER_{EV} =3.5–5 for heavy duty trucks

It is expected that in 2020-2050 the carbon intensities (CI) of diesel and electricity will decrease markedly in California due to policies currently in place. The value of a LCFS credit is also dependent on the value of a ton of CO_2 ($/mt$CO_2$) set by state auction, which is expected to be $150-200. The magnitude of the LCFS credits for electricity shown in Table 14 are large although they decrease significantly by 2035. The cost of electricity in Table 13 includes the LCFS credit to the utility and is the reason the cost ($.12/kWh) is so low.

Table 14. LCFS Credits for 2020-2050

Year	diesel CI	Electricity CI		$/MtCO2	LCFS Credit $/kWh	
		Grid	renbl		Grid	renbl
2020	92	110	10	200	.25	.32
2025	86	100	10	190	.22	.28
2030	80	90	10	180	.20	.25
2035	73	75	10	170	.17	.21
2040	65	50	10	160	.16	.18
2045	51	30	10	155	.12	.13
2050	41	15	10	150	.10	.10

The on-peak cost of electricity is much higher being $.32/kWh. Assuming that most of the charging is done during the off-peak hours, the annual cost of electricity/charge/day would be about $20K. In other words, if a charger charged 25 trucks per day, the cost of electricity to operate that charger would be about $500K per year. Hence the cost of electricity to operate the charging facility at a rest stop is high and the trucks would have to pay for the electricity. If truck charging facilities were eligible for the LCFS station credits [47], the operator of the facility would recover its cost in about 5 years ($68K/yr). As a result, Caltrans would recover their investment in the facility in 5–6 years.

8. Projected use of Battery Charging at Safety Rest Areas

8.1 Overnight Charging

Electric semi-trucks could stop at the rest areas at any time during the day or night to recharge their batteries. Most of the stops would be about 60 minutes for opportunity charging to extend the range of the truck. However, late in the day or evening, the driver would need a long break of over 10 hours and they could get a complete charge of the battery. They could sleep in the truck over-night while the battery was charging and be ready to start their trip for the next day. A 600 kWh battery could be charged in about 5 hours including the taper needed to complete the charge. That would allow three electric trucks to be charged over-night from a single 450 kW charger. The driver would need to take care of breakfast and bathing just as was the case for drivers sleeping in the cab of the conventional diesel truck. The intent of the opportunity charging is to make driving the electric semi-truck as much as possible the same as driving the conventional diesel truck. The electricity for overnight charging would be about 500 kWh and cost about $60 per charge. Assuming two overnight charges per charger each day, the cost of electricity per year would be about $43K per charger for each rest stop.

8.2 Opportunity Charging

Much of the charging at the rest area will be opportunity charging of about 60 minutes to extend the range of the electric semi-truck. As discussed in Section 6.3, the charger will put 60-65% of the battery capacity (360-390 kWh) into the battery. The range extension (miles) will depend on the truck's energy consumption (kWh/mi) for that trip. The driver will need to track the battery SOC and plan to stop at a charging station when the battery state-of-charge (SOC_{ch}) reaches 15-20%. This will be the case regardless of the size (kWh) of the battery in the electric truck they are driving. The driver can estimate the extended range from the 60 minute opportunity charge as a function of the $(kW)_{charger}$ available and the energy consumption (mi_1) of their truck

$$(kWh/mi) = (1 - SOC_{ch})(kWh)_{bat} / (mi_1)$$

$$\text{Range extension} = (kW)_{charger} / (kWh/mi)$$

For an example, $(kW)_{charger} = 350$, $(mi_1) = 325$, $SOC_{ch} = .15$, and $(kWh)_{bat} = 650$, miles extension= 206 miles. With 500 kW charging capability, the range extension could be 255 miles. All these calculations can be done automatically for the driver using data available from the vehicle's control computer and data from the charger. Subsequent opportunity charges of the electric semi-truck would also add 200-225 miles to the daily range of the truck. In this way, drivers of the electric trucks would cover the same distance in 12-14 hours as in diesel trucks and have more regular rest periods.

9. Caltrans Options Related to Electric Long-Haul Trucks

It seems well recognized [2, 33] that to electrify freight movement in the United States, a network of battery charging stations along the inter-state and main state highways will be needed. The discussions in the previous sections have indicated that the safety rest areas have the potential for use as part of that network in California. The primary barrier to establishing battery charging stations at rest areas is the general prohibition of commercial services at the rest areas which would not allow collecting money for the electricity dispensed at the stations. There has been consideration given by Caltrans to changing this regulation according to the following statement taken from [35],

"Caltrans is authorized to construct and operate up to six new rest areas as a joint economic development demonstration project, provided there is a need, and that the proposal will result in an economic savings to the State. Contracts must be awarded on a competitive basis; the rest areas may include traveler-related commercial services; and the Department is interested in a significant savings in the capital costs of construction (land and development)".

There have also been discussions in Congress to allow commercialization at state established rest areas along federal inter-state highways. However, as indicated in the following internet statement, there is much resistance by private businesses to making that change in the current law [34].

"ALEXANDRIA, Va., Feb. 22, 2021 /PRNewswire/ -- NATSO, representing truck stops and travel plazas, and a diverse coalition that includes restaurants, fuel retailers, city governments, trucking firms and blind entrepreneurs today urged lawmakers to oppose efforts to commercialize Interstate rest areas as Congress considers infrastructure legislation. The groups, which represent hundreds of thousands of mostly small businesses that operate near the Interstate Highway System, urged lawmakers to reject proposals to carve out any exceptions to the longstanding ban that prohibits state departments of transportation from unfairly competing against the private sector by selling food, fuel or other commercial services, including electric vehicle charging, at Interstate rest areas."

In 2021, Caltrans installed 22 new EV fast chargers at nine locations along state highways in the central valley [51]. The Level 3 DC fast chargers provide an approximate 80% charge in 30 minutes to light-duty EVs with fast-charge capability. The charging is free with no time limit. A photograph of one of the chargers is shown in Figure 16. The following statement from the news release on the project indicates California's rationale for installing the chargers [51].

"This project is a tremendous example of how public agencies can collaborate with the private sector to fill gaps in the zero emission vehicle (ZEV) market. More chargers throughout the state will help to incentivize the purchase of EVs, getting us closer to Governor Newsom's goal of 100 percent ZEV sales by 2035."

Tyson Eckerle, Deputy Director of ZEV Market Development at the Governor's Office of Business and Economic Development (GO-Biz)

Figure 16. A DC charger installed by Caltrans [51]

Based on the recent statements cited, it appears there has been some discussion within Caltrans concerning the need for battery charging at rest areas and how some form of public-private partnership could permit the establishment of battery charging facilities at rest areas in California. This would allow the State of California to assist in the development of the battery charging infrastructure for electric trucks while their numbers are relatively small and a significant network is still required to develop the market as required by the CARB ACT mandate (Figure 2). The charging stations would be built and operated by private contractors. The initial cost of the charging facilities could be borne disproportionately by Caltrans with reimbursement for the cost received from operating revenue of the facility and LCFS credits. Over time as the electric truck market develops, the charging facilities would operate as near-private businesses. The initial network of highway charging facilities established by Caltrans could be 25 at rest areas along Interstate highways and 10 at rest areas along other California highways. These charging facilities would be about 100 miles apart which is consistent with the proposed location of charging stations in the electric utilities West Coast Clean Transit Corridor Initiative study [2]. The number of high-power chargers at each rest area facility would vary depending on the anticipated use of the facility in the near-term, but would likely be 2-6 chargers. The total initial cost of establishing the battery charging facilities could be about $50 million for the 35 rest areas. If the rest stops serviced 25 trucks per day, the cost of electricity per year for each rest stop would be about $450,000.

10. Summary and Conclusions

The objective of this research was to determine the possibilities for and barriers to the provision of battery charging infrastructure for heavy-duty electric trucks at roadside rest areas in California. The initial sections of the report deal with the prospects for battery-electric long-haul trucks and the battery technology needed to make those electric trucks practical and the market for them to be successful. Simulations of trucks using present lithium battery technology (pack energy density of 170 Wh/kg) indicated that for a range of 600 miles, the battery pack would need to store about 1200 kWh. It is not practical to fit a battery of that size on the tractor of the truck. Another approach is to design a truck with a 300-mile range and plan to partially charge the battery once or twice during the day at rest areas. The truck would also be charged overnight at the rest areas. The total range per day could be 600 miles or more. The partial charges would put 65% of the capacity of the battery in at the 1C rate (a 60 minute charge). A 500 kW charging facility would be needed at the rest areas. The 300 mile range electric truck could operate much like the diesel truck with the driver taking 30 minute breaks every 200-225 miles to charge the battery. The cost analysis of the 300 mile truck indicates its TCO is less than that of the diesel truck.

The cost of the battery charging facilities depends primarily on the cost of the charger hardware and its installation. The high-power electrical service to the facility would be provided by the local electric utility as a business expense in support of electrified vehicle infrastructure. The total cost of a charger would be $750/kW or $375k for each 500W charging unit. If a rest area installed four 500kW charging units, the estimated cost is $1.5 million. The off-peak cost of electricity ($/kWh) dispensed to the trucks would be $.12/kWh from 11 PM–4 PM. The cost of electricity for battery charging is low ($.12/kWh) because the electric utility has been credited with the LCFS credits for electricity. The on-peak cost of electricity is much higher being $.32/kWh. Assuming that most of the charging is done during the off-peak hours, the annual cost of electricity/charge/day would be about $20K. In other words, if a charger charged 25 trucks per day, the cost of electricity to operate that charger would be about $500K per year. Hence the cost of electricity to operate the charging facility at a rest stop is high and the trucks would have to pay for the electricity. If truck charging facilities were eligible the LCFS station credits [47], the operator of the facility could recover its cost in about 5 years ($68K/yr). As a result, Caltrans could recover their investment in the facility in 5–6 years

Caltrans maintains 86 safety rest areas along highways in California with 53 along Interstate highways. If battery charging facilities were established at about 35 of these rest areas, they could be about 100 miles apart or a little closer. Caltrans could assist private contractors in establishing a network of charging facilities for electric trucks. The total initial cost could be about $50 million. The major barrier to Caltrans participating in the project is that current law prohibits commercial businesses at the rest areas which would not allow charging for the electricity dispensed. There has been consideration in both California and at the federal level to relax the non-commercial requirements at the rest areas for battery charging because the need for a battery charging network is well recognized.

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Data Summary

Products of Research

Most of the data used in this study were generated during the course of the study using either vehicle simulation programs that have been used at UC Davis over the last 10-15 years, or Excel spreadsheet models that were developed as part of the study. The results of the vehicle simulations and the spreadsheet models are given in table form throughout the report.

Data Format and Content

The data are presented in the tables in the report in forms suitable to describe its proper interpretation and understanding in each section of the report.

Data Access and Sharing

The Excel spreadsheet models are provided as part of the data sharing with the report and can be used by anyone reading the report.

Reuse and Redistribution

The data used in the report are available to all readers. The same is true of the Excel spreadsheet models are available in the dataset provided with the report.