Assessment
of
BYD K11 Battery Electric Bus
operation on the
Albuquerque Rapid Transit (ART)
Service

Submitted by:
The Center for Transportation and the Environment

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Introduction

The City of Albuquerque's Transit Department (ABQ Ride) engaged the Center for Transportation and the Environment (CTE) to conduct a vehicle performance assessment on buses dedicated to Albuquerque's new bus rapid transit (BRT) service. CTE was tasked with evaluating the capability of the BYD K11 60-foot articulated bus for service on ABQ Ride's BRT service branded as Albuquerque Rapid Transit (ART). Specifically, ABQ Ride requested an assessment of fuel efficiency, daily range, charging profiles, and fuel costs that can be expected from deploying the BYD K11 bus on the new ART BRT service.

This document summarizes the results of CTE's scope of work, which included:

- Performance validation and route modeling,
- Charge modeling
- Rate modeling
- Operations and charging assessment

Performance validation and route modeling is used to determine if the selected buses are capable of meeting the expected service for which ABQ Ride purchased them. Charge modeling is used to estimate the charge time required for the buses, the energy consumed during charging, and power demand for charging. Rate modeling is used to estimate the cost of fuel (i.e., electricity) needed to operate the buses. The operations and charging assessment evaluates service blocks and various charging strategies, including depot and on-route charging, that could be used to operate the buses on the blocks. As these assessments are interrelated, the results are presented in a combined fashion.

Field Testing

Since the BYD buses and depot chargers are already delivered and commissioned, CTE chose to collect data on the buses in simulated service rather than perform computer simulations of the service. Based on the observed performance and past experience and engineering calculations, CTE projected the performance of the bus under a variety of operating conditions.

CTE staff visited ABQ Ride's Daytona bus depot on September 4–7, 2018. BYD staff also participated in the testing.

The weather conditions during testing ranged from 64 to 80° Fahrenheit with mostly sunny skies.

CTE designed the test plan and directed the test. BYD provided engineering support and ABQ Ride provided the buses and drivers. The buses were ballasted with water barrels, as needed for specific tests, to simulate passenger loads. ABQ Ride added 18 water barrels, weighing approximately 8,700 lbs., which is the equivalent of 58 passengers when using the same 150 lbs. per passenger defined by FTA.

The test plan utilized three buses: one to operate the BRT routes at curb weight, one to operate the BRT routes with ballast, and one to operate in the parking lot to test HVAC loads. These test conditions were designed so that CTE could project the bus performance under conditions other than those that prevailed on the day of the tests.

A summary of the road test is shown in Table 1.

Bus	Beginning SOC	Distance (miles)	Time (hh:mm)	Ending SOC
1706 (curb weight)	84%	110.2	10:28	26%
1702 (≃8700 lb. ballast)	85%	109.6	10:43	24%

Table 1: Road Test Summary

Table 2 shows the raw data collected during the test of the stationary bus running the HVAC system. The energy usage measured in this test, a study of Albuquerque's climate conditions, and CTE's prior experience with other buses informed CTE's projections of the bus performance on hotter and colder days than experienced during the testing.

Time	SOC	Energy Remaining (kWh)	Energy Used (kWh)	Elapsed Time (min)	Temp (°F)
7:30 AM	94%	506.8	0.0	30	64
8:00 AM	94%	506.8	0.0	30	
8:30 AM	93%	501.4	5.4	30	
9:00 AM	92%	496.0	5.4	30	66
9:30 AM	91%	490.6	5.4	30	
10:00 AM	91%	490.6	0.0	30	
10:30 AM	91%	490.6	0.0	30	
11:00 AM	90%	485.2	5.4	30	
11:30 AM	90%	485.2	0.0	30	
12:00 PM	89%	479.8	5.4	30	73
12:30 PM	87%	469.0	10.8	30	
1:00 PM	87%	469.0	0.0	30	
1:30 PM	86%	463.6	5.4	30	
2:00 PM	84%	452.8	10.8	30	
2:30 PM	84%	452.8	0.0	30	78
3:00 PM	82%	442.1	10.8	30	80
3:30 PM	81%	436.7	5.4	30	80
4:00 PM	80%	431.3	5.4	30	80
4:30 PM	79%	425.9	5.4	30	80
5:00 PM	77%	415.1	10.8	30	80
5:30 PM	76%	409.7	5.4	30	80
6:00 PM	75%	404.3	5.4	30	79
6:20 PM	74%	398.9	5.4	20	

Table 2: Stationary Vehicle Energy Use

Performance Validation

A common challenge in any battery electric bus deployment is the limited energy storage available as compared to conventionally fueled buses. Albuquerque's BYD buses were designed to have a capacity of 591 kWh when fully charged and BYD recommends using 90% of this capacity for service. *Service energy* is defined as the energy available to power the propulsion system, as well as the HVAC and auxiliary systems (lighting, doors, radios, etc.). Therefore, the service energy for a 591 kWh battery is 532 kWh. Battery capacity may be lower than the design capacity due to battery degradation, which is a phenomenon that reduces the battery capacity through use and the passage of time. If the battery degrades, the available service energy will be lower.

CTE measured the actual capacity of buses 1702 and 1706 by discharging the buses and then fully charging them. Table 3 shows the actual battery capacity of these two buses as measured by BYD data loggers. The batteries in the two buses tested have either suffered degradation or the original capacity did not meet the design capacity.

Bus	Capacity (kWh)	Service Energy (kWh)
BYD K11 Design Goal	591	532
1702 Measured	551 (-7%)	496
1706 Measured	527 (-11%)	474
Capacity Used in CTE Projections	551	496
Expected Capacity at End-of-Life (70% of Design)	414	373

Table 3: Battery Capacity

Charging Power

The BYD buses use an onboard charger rated at 200 kW.

CTE recorded the charge power for both buses during the charge test. The charge power was recorded from the indication on the bus dashboard and is therefore a BYD measurement. The charge power was found to vary across the state of charge range of the battery. In other words, the buses were found to charge slower or faster depending on the state of charge.

According to BYD, the charge power is limited by two main factors: cell voltage and cell temperature. The traction battery is comprised of hundreds of cells each of which must be monitored by the integrated battery management system. It is likely that the battery management system was limiting the charger power by design in order to lower the risk of damaging the batteries.

A standard practice is to reduce the charge rate at high states of charge in order to keep the cell voltage from climbing beyond the maximum allowable cell voltage. CTE observed this effect during the charge process of ABQ Ride's BYD buses, but the charge power at very low states of charge was also limited and the cause is unknown.

CTE observed lower charge rates than the charger rating across the entire range of states of charge. One possibility for the reduced performance is that the battery packs may thermally limit the charge performance. The ART BYD battery packs do not have any type of active cooling system instead relying on natural convection to reject heat. Charge testing after cold soaking the batteries could test this theory. CTE does not currently have enough information to know the reason for the charge limitation that could be unrelated to thermal limitations.

The raw data CTE collected for each bus is shown in Table 4 and Table 5. The state-of-charge column (SOC) and "time-to-full" columns were also recorded from the bus and are therefore BYD measurements.

Time	Elapsed Time (hh:mm)	SOC	Energy (kWh)	Time to Full (hh:mm)	Power (kW)
1:38 PM	0:00	4%	22.05	2:45	
1:47 PM	0:09	11%	60.63	2:34	
2:07 PM	0:29	22%	121.26	3:27	
2:20 PM	0:42	27%	148.82	3:14	125
2:38 PM	1:00	33%	181.90	2:57	125
2:51 PM	1:13	38%	209.46	2:42	125
3:06 PM	1:28	44%	242.53	2:31	124
3:19 PM	1:41	49%	270.09	2:18	124
3:45 PM	2:07	58%	319.70	1:51	123
4:03 PM	2:25	65%	358.28	1:35	123
4:15 PM	2:37	69%	380.33	1:23	123
4:31 PM	2:53	75%	413.40	1:07	122
4:48 PM	3:10	81%	446.47	0:51	122
5:03 PM	3:25	87%	479.54	0:36	122
5:16 PM	3:38	91%	501.59	0:23	123
5:30 PM	3:52	96%	529.15	0:09	123
5:45 PM	4:07	99.5%	548.44	0:02	123
5:48 PM	4:10	99.5%	548.44	0:03	75
5:53 PM	4:15	100%	551.20		

Table 4: Bus 1702 Observed Charge Power

Time	Elapsed Time (hh:mm)	SOC	Energy (kWh)	Time to Full (hh:mm)	Power (kW)
2:06 PM	0:00	5%	26.35	2:39	187
2:11 PM	0:05	10%	52.70	2:32	187
2:22 PM	0:16	16%	84.32	2:22	185
2:37 PM	0:31	23%	121.21	3:20	125
2:50 PM	0:44	27%	142.29	3:07	125
3:05 PM	0:59	33%	173.91	2:54	125
3:20 PM	1:14	39%	205.53	2:39	125
3:45 PM	1:39	48%	252.96	2:15	125
4:01 PM	1:55	54%	284.58	2:00	125
4:15 PM	2:09	59%	310.93	1:46	125
4:31 PM	2:25	65%	342.55	1:31	124
4:47 PM	2:41	71%	374.17	1:16	123
5:02 PM	2:56	77%	405.79	1:00	123
5:15 PM	3:09	82%	432.14	0:48	123
5:29 PM	3:23	87%	458.49	0:34	123
5:46 PM	3:40	93%	490.11	0:17	123
6:00 PM	3:54	97%	511.19	0:08	125
6:13 PM	4:07	100%	524.37	0:01	125
6:16 PM	4:10	100%	524.37	0:00	123
6:28 PM	4:22	100%	524.37	0:00	75
6:33 PM	4:27	100%	527.00	0:00	0

Table 5: Bus 1706 Observed Charge Power

Table 6 shows a summary of the charge performance for each bus. The average charge power during the duration was calculated using the beginning and ending state-of-charge and the battery capacity, each as reported by BYD, to estimate the energy replenished. Note that there is some measurement error in the table as one entry has charge performance over the rated limit of the charger. However, CTE is comfortable that the averages presented later are close to the actual performance.

		Duration (hh:mm)	SOC After Duration	Energy Replenished* (kWh)	Power (kW)
1702 (551 kWh)	First 30 Minutes	0:29	22%	99	205
	Until Top-off Charge Begins	3:38	99.5%	427	118
	Total Time	4:15	100%	529	125
1706 (527 kWh)	First 30 Minutes	0:31	23%	95	184
	Until Top-off Charge Begins	3:39	99.5%	403	110
	Total Time	4:27	100%	501	113
Average	First 30 Minutes	0:30	22.5%	97	194
	Until Top-off Charge Begins	3:38	99.5%	415	114
	Total Time	4:21	100%	515	119

Table 6: Charge Performance Summary

The average charge power for each bus was calculated by CTE based on the data recorded from the BYD instrument panel. The results are reported in Table 7. CTE's testing did not include on-route charging. BYD has suggested that charge rates for a short on-route charge would be faster than measured during depot charging. CTE recommends further testing to verify the actual charge rate possible with short charging durations during vehicle operations, simulating on-route charging, to ensure high cell temperatures during the charge. High cell temperatures would be expected to be more of a concern during the summer months.

	Power (kW)
Charger Rated Power	200
1702 Observed Average Power	125
1706 Observed Average Power	113
BYD Estimate for 10 Min. Charge	180

Table 7: Average Charge Power

Capability Analysis

Assumptions for Performance Projections

Battery Capacity

As previously presented, CTE used 551 kWh as the battery capacity for its range projections since this was the observed capacity on 1702. This is lower than the BYD design goal for the battery pack. Bus 1706 had a lower observed battery capacity, however, BYD informed CTE that bus 1706 requires repairs to the battery system. The capacity of 1706 is expected to be at least 551 kWh if BYD is able to complete the repair.

In addition to currently observed battery capacity, CTE also analyzes bus performance when the battery is fully degraded to the warranty level. BYD has warranted the ART buses to 70% degradation, meaning that they will repair or replace the battery system to a capacity above the 70% degradation minimum. Note that degradation is affected by cell manufacturing quality, charge cycles, level of discharge, operating temperature, and the passage of time. Each agency will have a different experience with degradation and it is difficult to predict the timing or level of degradation.

CTE also analyzed the performance of the buses at 590 kWh that is nearly at the design goal level and thus represents a best-case scenario. This analysis is included as an appendix to this document.

Climate Considerations

To project variances in performance between days with different climatic conditions, CTE measured the auxiliary loads as previously discussed. *Auxiliary loads* are defined as the electrical loads on the bus unrelated to propelling the bus. These loads include high voltage loads such as the power steering system and air compressor system as well as low voltage loads like lighting. The largest auxiliary load is the heating and cooling systems for the bus cabin. This is also the only load that varies seasonally.

A study of Albuquerque's climate patterns as well as CTE's previous experience with battery electric buses shows that the air conditioning loads on a hot day are likely to present the most difficult loads for these buses. In other words, range is likely to be lower on hot summer days due to the fact that more energy is required to cool the bus rather than being used to move the bus down the road. Winter heating loads are also expected to greater than auxiliary loads encountered during CTE's testing, but not as bad as summer air conditioning loads and thus are not considered further. CTE chose 99°F as a strenuous summer temperature for its analysis. Although hotter temperatures will be experienced in Albuquerque, they tend to be balanced by cooler morning and evening temperatures.

Based on information provided by BYD and based on CTE's prior experience with modeling similar systems, CTE estimates the strenuous cooling load to be 15 kW as compared to 9.5 kW measured during field-testing. As the field test was conducted on a day with an 80° F high, the strenuous-day cooling load would require significantly more power for the air conditioning.

BYD's feedback, utilizing load information obtained from another project's results, helped to determine this estimate for the cooling load on a 99°F day.

Notes on Weight

CTE found the difference in efficiency between the bus near curb weight and the bus loaded with ballast to simulate passenger loads to be within 8%, whereas the difference in temperature between the morning and afternoon portions of the test result in a 16% change in efficiency. CTE is therefore using the average of curb weight vehicle and ballasted vehicle efficiency measures in its projections. Note that efficiency is likely to be marginally lower as weight is increased beyond the tested weight, but that this effect is not expected to be nearly as dramatic as changes in climatic conditions.

One final note on weight: although CTE did not see a large efficiency difference based on weight, anecdotally the weighted bus was reported to be somewhat sluggish up the hills throughout testing. The unweighted bus was reported sluggish only when the state of charge dropped appreciably. CTE did not further investigate the sluggishness because it was not deemed severe and is common to most battery electric buses when heavily loaded.

Block Analysis

A summary of ART blocks is shown in Table 8. ABQ Ride provided the block data. CTE's estimates of the energy required to operate the block is also shown in the table. Note that the energy required is more than the energy available on the buses even for buses without degraded batteries. The blocks, as designed, would be difficult for any depot-charged battery electric bus to operate due to the range required.

Block	Total Distance (mi)	Layovers	Average Layover (min)	Energy Required (kWh)	
				Observed Day	Hotter Day
1	260	19	10.2	722	882
2	233	18	10.7	649	793
3	212	16	9.6	589	719
4	240	18	9.7	668	816
5	237	18	10.7	661	807
6	240	18	10.6	668	816
7	236	18	10.2	656	802
8	211	17	9.8	588	718
9	238	17	10.6	663	810
10	240	18	10.8	668	816
11	236	18	10.5	656	802
12	233	18	9.9	649	793
13	210	15	9.6	585	715
14	209	15	8.7	582	712
15	206	16	10.2	573	700
Average	230	17	10	639	780

Table 8: ART Blocks

Depot Charging

CTE projected ranges of more strenuous conditions (i.e., hotter days) based on the conditions observed during testing. Ranges for both the observed battery and the fully degraded battery are shown for both observed and strenuous climate conditions in Figure 1. These results assume no on-route charging. The fully degraded battery will have shorter range as indicated by the red portion of the bars. The green portion of the bars shows the increase in range batteries currently have over the fully degraded batteries.

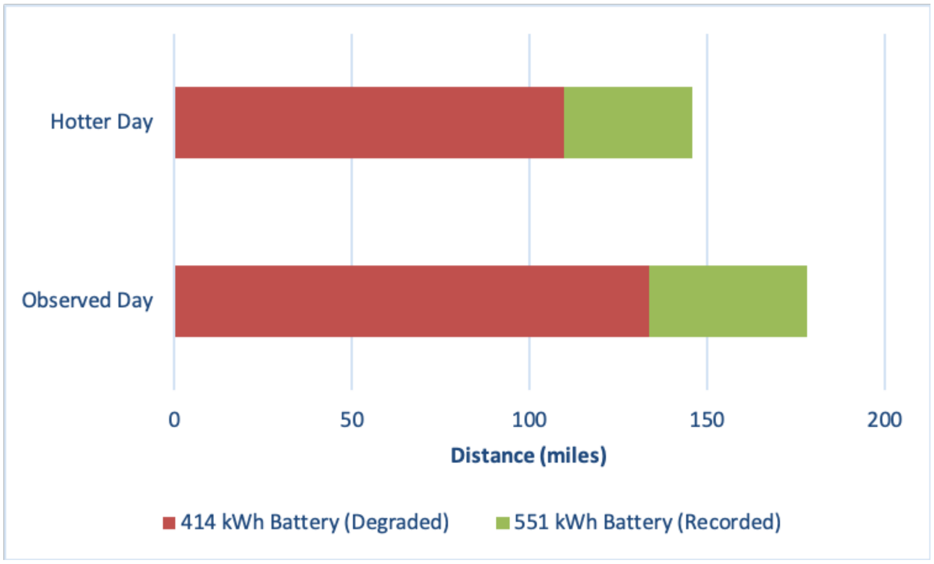

Figure 1: Projected Range Using CTE Estimate of Capacity

Many transit agencies find estimates of endurance more useful than range estimates for block and driver scheduling. *Endurance* is simply a measure of how long the bus can be kept in service measured in hours. CTE's estimate of endurance is shown in Figure 2.

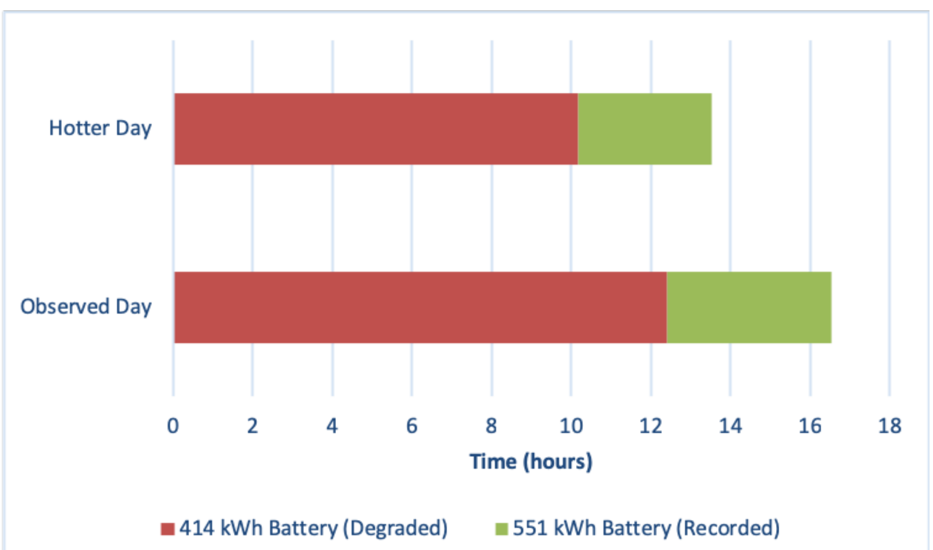

Figure 2: Projected Bus Endurance Using CTE Estimate of Capacity

Endurance can also be visualized as shown in Figure 3, which shows the service energy available for block 12 as the bus operates throughout the service day. Block 12 is an average difficulty block for ART, as can be seen in Table 8 based on the distance traveled, as well as the number and frequency of layovers. As shown in the figure, the buses do not have enough energy to complete block 12 under any condition. As batteries degrade to the warranty level, range and endurance are lower.

The available energy throughout the day is represented by a cone shape in the graph which depicts the variation that can be seen based on passenger loading and weather conditions, with the top edge of the cone representing the available energy remaining on a nominal day and the bottom edge of the cone representative of the strenuous day.

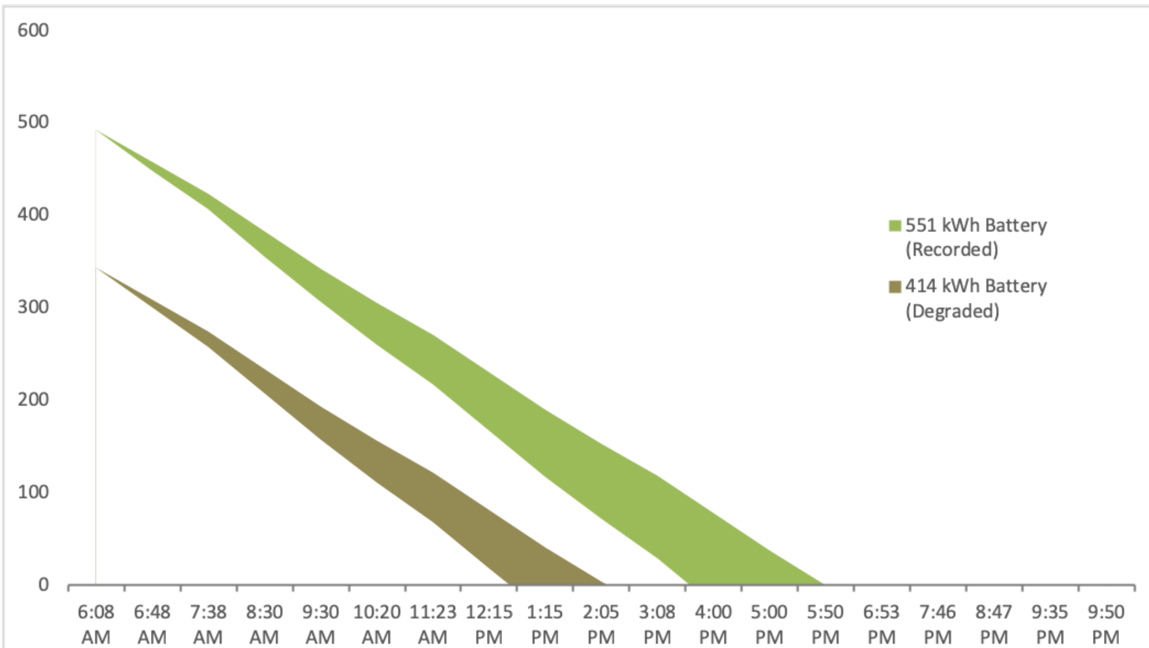

Figure 3: Visualization of Endurance Using CTE Estimate of Capacity for Block 12

Based on our analysis, we can conclude that the proposed BYD K11 buses using only depot charging is inadequate for the intended BRT service, as currently designed. This type of issue is not uncommon for range-limited battery electric buses. To successfully deploy these buses, it would be necessary to modify the service, modify the blocking schedule and add more buses, or add on-route charging.

On-Route Charging

Since the BYD K11 buses delivered to ABQ Ride have insufficient range and endurance to operate the ART service blocks, CTE evaluated an on-route charging strategy.

There are several challenges that must be addressed when considering on-route charging:

1. Charging stations should not be accessible to the public. They must be located in dedicated, restricted access areas.
2. It is recommended to only use overhead conductive or in-ground inductive, automated charging. Plug-in charging is not recommended as it requires an individual on-site during the service day to plug-in the bus, monitor the charge, and un-plug the bus. In addition to labor costs, the charge cabling may be a tripping hazard to the public and liability to the City.
3. Peak demand charges from the electric utility can make on-route charging expensive.
4. There may be insufficient time to add enough energy while charging during bus layovers, particularly if the bus is running late. Or, a bus that is running late will stay behind schedule in order to receive a sufficient charge.

CTE did not evaluate any difficulties that Albuquerque may encounter in locating and operating the chargers in public areas, but CTE encourages ABQ Ride to investigate these challenges further before embarking on this strategy.

CTE did evaluate the costs of on route charging and the results can be found in the rate modeling section.

CTE also evaluated the available layover time for charging both in an “on-time” scenario and a “behind schedule” scenario (i.e. buses are running three minutes late). Note that ART was designed using bus rapid transit principles that are designed to keep the system running on time such as bus lanes, traffic signal priority, and embarkation from any door.

Assumptions

CTE assumed that chargers would be installed at UTC, CUTC, and TRWEN that are the termination points of the route. CTE further assumed that a charger was available each time a bus arrived at one of these locations for a layover. CTE assumed that it would take a combined two minutes to plug and unplug the bus at the station and so this time was excluded from the available charge time.

For on-route charging, the charge rate is critical. BYD offered to augment overnight, plug-in depot charging with plug-in on-route charging. Thus, CTE assumed the same BYD plug-in chargers that are installed in ART’s depot. CTE used a variable charge rate dependent on state-of-charge because that is the performance CTE observed and also because that method was recommended by BYD. In addition to the charge power observed, CTE also analyzed the charge power that BYD says they can sustain during a ten-minute charge. CTE recommends that this charge rate is tested and confirmed before accepting this solution.

Results

Figure 4 below shows the updated capabilities of the BYD bus on Block 12 when on-route charging is included in the model and the bus battery capacity is assumed to 551 kWh. Charge power is limited to 115 kW above 23% state-of-charge and 180 kW below 23% state-of-charge, based on CTE's observations. With this battery capacity and these charging capabilities, the block can be completed under most conditions. However, if the battery degrades further, these charging capabilities are not expected to meet what is necessary for the bus to complete the block. Because CTE did not conduct road tests of simulated on-route charging, CTE would recommend conducting such tests before utilizing on-route charging with these buses.

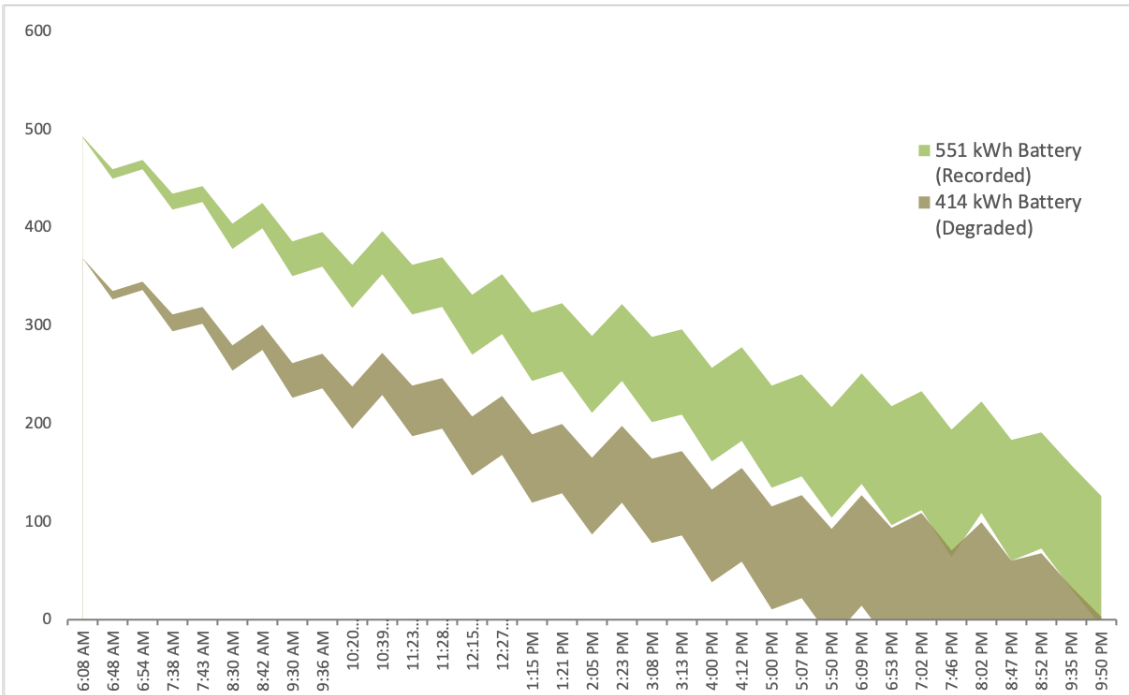

Figure 4: Visualization of Endurance Using CTE Estimate of Capacity and Charge Capabilities for Block 12

The energy usage for on-route charging is shown in Table 9. These values are based on the average usage by each block, and so must be scaled up to represent a day's usage. The associated costs are discussed in the rate model section of this report.

		UTC		CUTC		TRWEN		Garage
	Weather Conditions	On-Peak Energy (kWh)	Off-Peak Energy (kWh)	On-Peak Energy (kWh)	Off-Peak Energy (kWh)	On-Peak Energy (kWh)	Off-Peak Energy (kWh)	Off-Peak Energy (kWh)
CTE-Observed Charging	Observed Day	116	13	70	18	73	17	264
	Hotter Day	123	18	77	21	80	20	386
Number of Chargers required at each station		2		3		1		1 per bus

Table 9: Estimates of Average Facility Energy Usage Per Block

Rate Model

The total daily energy demand for each facility was calculated using the Table 9 values scaled up by fifteen total blocks. With this information and the rate information, along with the on-peak energy demand based on the charging rate and the maximum number of vehicles charging within the same fifteen-minute window, the cost of fueling can be calculated. The complete charging system is assumed to be 90% efficient, meaning that 90% of the energy purchased from the grid will end up as usable energy in the battery. ABQ Ride provided CTE with the applicable PNM Rate 3B utility tariff schedule.

Figure 5 shows the estimated annual fuel cost at each charging station to operate the ART service with on-route charging. Cost estimates are based on the performance characteristics observed during CTE's road and charging tests. It is important to note that these results do not account for the capital cost of the facility modifications to add on-route charging to the ART service. The cost estimates are calculated using the average of the observed and hot weather scenarios for simplicity in demonstration. Actual costs may vary.

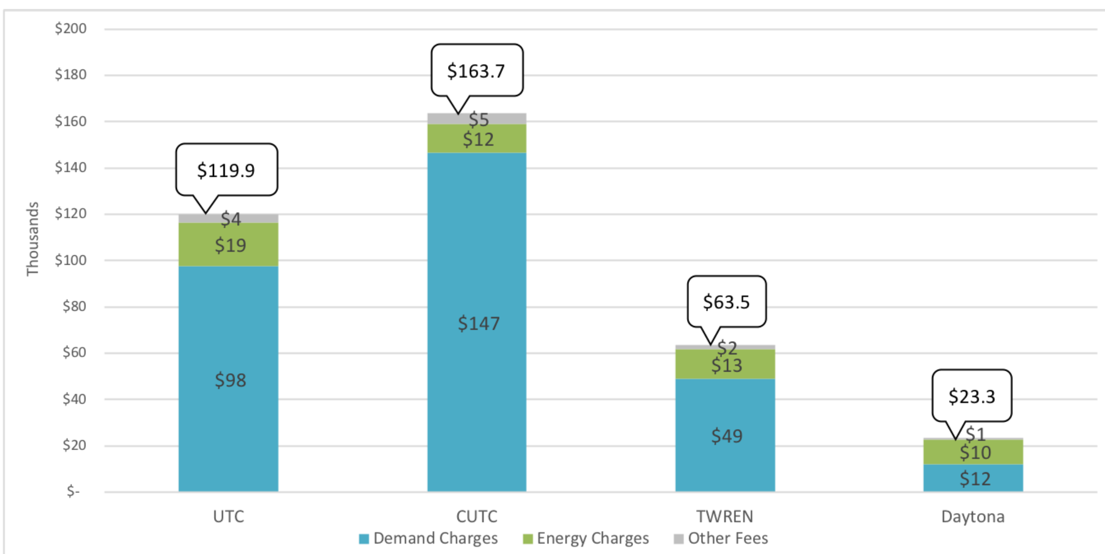

Figure 5: Annual Costs with CTE-Observed Capacity and Charge Rate

Figure 6 shows the total of all charging station fuel costs as a per-mile cost, and compares this against a diesel baseline which assumes 2.55 miles per gallon for a 60' diesel vehicle, and a price of $2.50 per gallon.

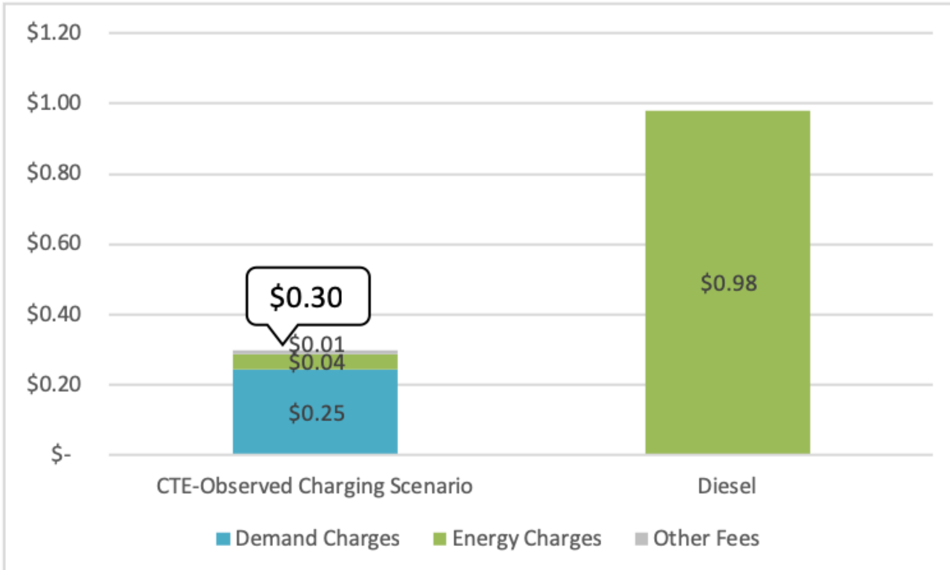

Figure 6: Costs per Mile

Conclusions

ABQ Ride's original deployment plan for the ART BRT service was to operate the delivered BYD K11 buses on all ART blocks using overnight depot charging. At the completion of each block, the bus would return to Daytona and recharge in preparation for service the next day. As a result of our analysis, CTE concludes that this plan will not work with the BYD K11 buses that were delivered to ABQ Ride, regardless if the buses were at full design capacity or at the observed capacity.

BYD has proposed a modified deployment to add on-route charging to the ART service. To be plausible, one to three charging stations are required at each termination point; UTC, CUTC, TRWEN, as well as the Daytona depot. While this operational model may work, there are risks that must be considered. The delivered BYD K11 buses are not equipped with overhead or inductive charging systems. As a result, the buses must be charged on-route using the plug-in charge connector. This would require that these stations be manned or that the driver exit the bus to plug the bus in. Plug-in charging in a public area is not ideal due to potential liability issues as well as staffing requirements.

Consistent charge rates during on-route charge cycles are critical to maintaining service schedules. Additional testing is required to confirm charge rates during various operational and climatic conditions as passively-cooled battery systems are subject to greater variations in charge rate. Batteries, by nature, will heat up when they are charged or discharged. Thermal management systems may purposefully limit vehicle performance or charge rate to protect the batteries. Some thermal management strategies include active liquid-cooling systems that are better at maintaining battery temperature in hot climates, thus minimizing the chance that performance or charge rate is degraded.

Finally, the analysis shows that the proposed BRT service using the proposed BYD K11 buses with both depot and on-route charging cannot be completed as batteries degrade to warranty levels. As a result, ABQ Ride will need to make alterations to the blocks or service over time if this solution is implemented.

If ABQ Ride determines that the original deployment plan or modified deployment plan are unacceptable, there are several zero-emission strategies that may be considered:

1. Modify the block schedule
2. Higher capacity battery electric buses with faster on-route charging.
3. Hydrogen fuel cell electric buses.
4. Combination Strategy

A summary description and consideration for each option is provided below:

Modify the Block Schedule

Shorter blocks are more suitable to the delivered BYD K11 buses. However, shorter blocks may require midday charging in addition to overnight charging. This charging strategy could incur higher electricity costs due to midday demand charges. Alternatively, more buses may be needed to operate the service when shorter blocking strategies are employed.

Higher capacity battery electric buses with overhead on-route charging

The ART BRT service can be a showpiece for state-of-the art zero emission bus technology. Fixed routes with dedicated roadways are ideal for battery electric buses. Higher capacity battery electric buses with liquid-cooled batteries can provide greater range with less impact from degradation. Additionally, faster overhead conductive chargers can provide the route energy required in a shorter time, and are also less impacted by degradation.

Hydrogen Fuel Cell Vehicles

Hydrogen fuel cell buses would have the range needed to operate ART's blocks, and they can be refueled in minutes, similar to CNG buses. However, these buses require a source of hydrogen that must be manufactured on-site or delivered. Either option is expensive compared with other fuels. Hydrogen fueling infrastructure is expensive but costs are easily leveraged over a larger fleet. The buses themselves are also more expensive than any other option due to the limited number of vehicles currently produced. CTE expects that both fuel and bus cost to shift downward over time as this option becomes more widely deployed.

Combination Strategies

A combination of the above strategies is also possible. For example, a battery electric bus fleet could be supplemented with a small number of conventional buses to avoid the necessity of on-route charging and provide alternatives to serve longer blocks.

Appendix: BYD-Proposed Scenario

During the course of CTE's analysis, BYD proposed to restore batteries to their full design capacity and reprogram their battery management system to allow for a higher charge rate during on-route charging. Since CTE did not observe these conditions on the delivered BYD K11 buses, we did not analyze those conditions as part of the primary assessment. However, we did analyze these conditions for ABQ Ride in the event that BYD is able to deliver these buses in the future. As with any bus procurement, CTE recommends testing and validation of buses and charging equipment prior to acceptance and placement into passenger service.

CTE repeated its analysis of range and endurance assuming a battery with capacity of 590 kWh. This analysis assumes that BYD will be able to restore the battery to its full design capacity. The resulting range and endurance are presented in Figure 7, Figure 8, Figure 9, and Figure 10 below. It should be noted that the capacity of the degraded battery is unaffected by this change, as the warranted degradation is 70% of the designed capacity regardless of this repair. BYD also contends that the batteries will be able to charge at the full 180 kW power level for 10-minute charges, regardless of the state of charge that the bus begins the charge at. The affect this has on the on-route charging scenario can be seen in Figure 10: Visualization of Endurance Using BYD-Proposed Capacity and Charge Capabilities for Block 12.

Bus	Capacity (kWh)	Service Energy (kWh)
BYD K11 Design Goal	591	532
BYD Estimates after Repair	590	531
Degraded Battery (70% of Design)	414	373

Table 10: Battery Capacity for Estimates with BYD's Proposed repair

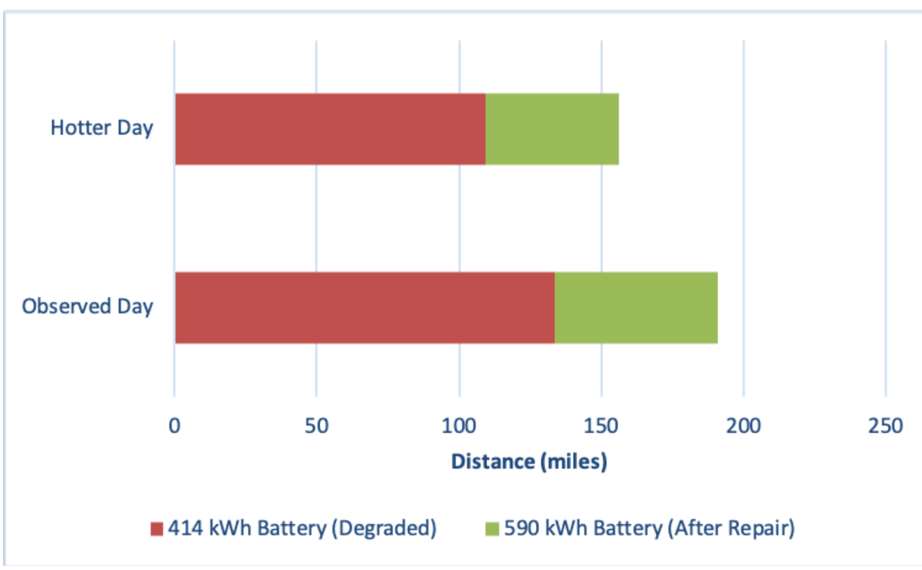

Figure 7: Projected Range with BYD's Proposed Battery Capacity Repair

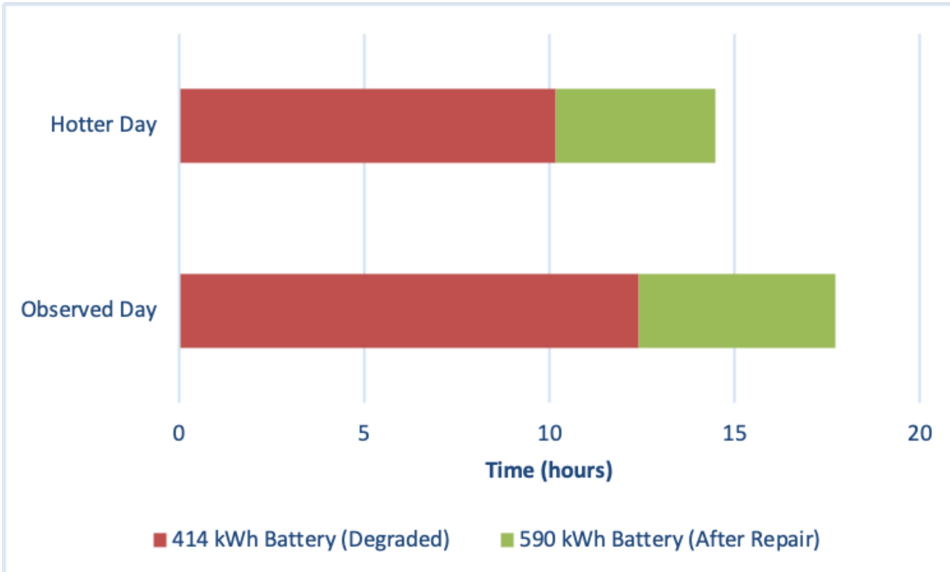

Figure 8: Projected Endurance with BYD's Proposed Battery Capacity Repair

Figure 6 shows that even with the repaired batteries, additional energy is needed to complete the blocks as they currently stand. This conclusion can be confirmed by comparing the energy required for the blocks as listed in the table above to the service energy available in the repaired battery.

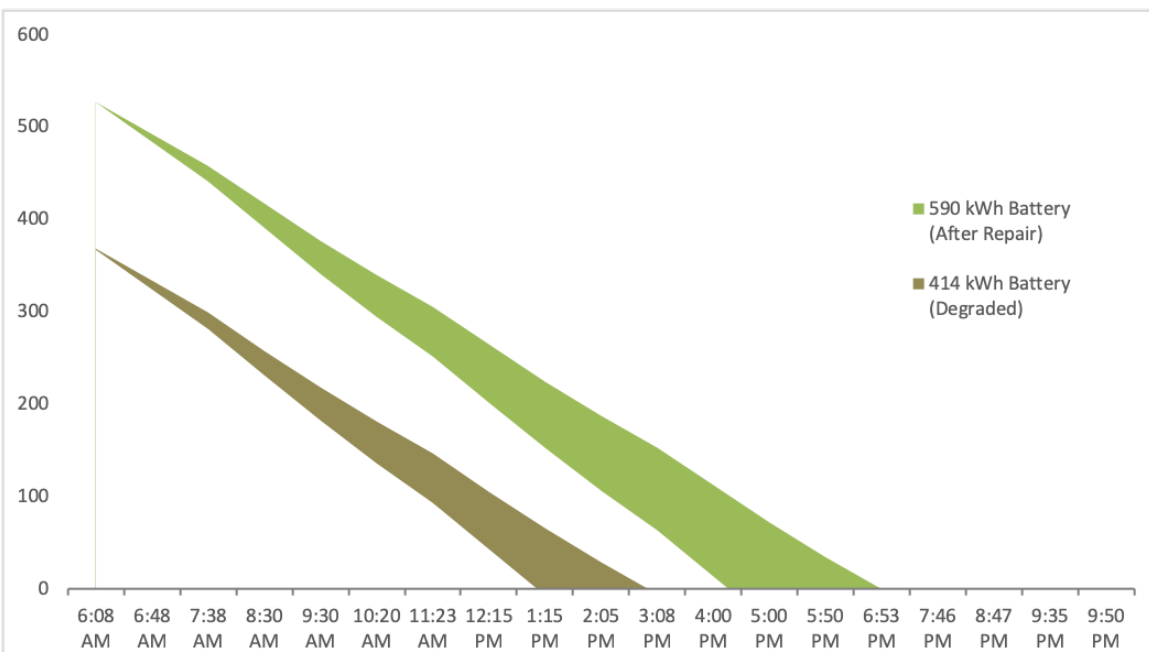

Figure 9:Visualization of Endurance Using BYD's Proposed Repaired Capacity for Block 12

When the battery has been repaired, as BYD has proposed, and when BYD makes changes that allows for consistent 180 kW on-route charging over a 10-minute period, the resulting endurance is shown in Figure 10. While a few of the charge windows are longer than this 10-minute limit and the subsequent change in charge power after the 10-minute limit is exceeded is not included in the model, this is not expected to have a significant effect on the results because these lower-power charge windows are infrequent and brief.

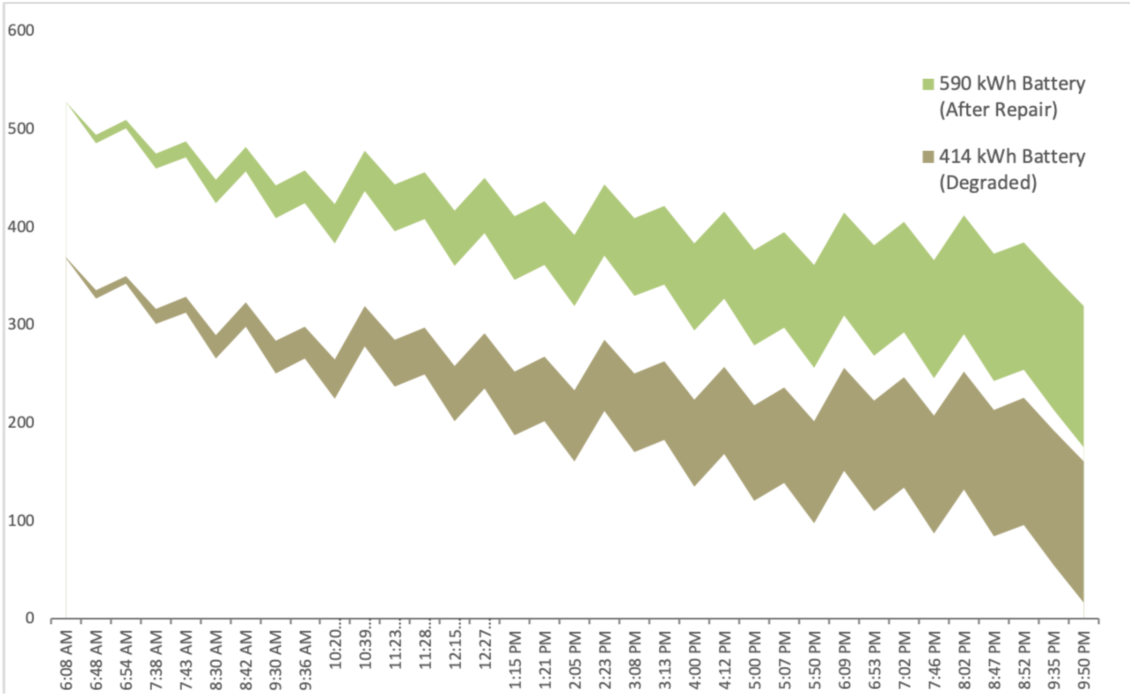

Figure 10: Visualization of Endurance Using BYD-Proposed Capacity and Charge Capabilities for Block 12

		UTC		CUTC		TRWEN		Garage
	Weather Conditions	On-Peak Energy (kWh)	Off-Peak Energy (kWh)	On-Peak Energy (kWh)	Off-Peak Energy (kWh)	On-Peak Energy (kWh)	Off-Peak Energy (kWh)	Off-Peak Energy (kWh)
BYD-Proposed Charging	Observed Day	153	19	94	24	97	24	299
	Hotter Day	169	19	100	25	106	24	424

Table 11: Estimates of Average Facility Energy Usage Per Block Under BYD-Proposed Scenario

The annual costs at the three on-route charging facilities are projected to be higher under the BYD-proposed charging scenario than the CTE-observed scenario from Figure 5, while the costs at the Daytona facility are lower. Due to the higher charging power available throughout the whole day, more energy is replaced during the on-route charges that result in less energy needing to be replaced overnight. Since the increased daytime energy usage occurs during the on-peak rates, the charges at the three on-route facilities rise disproportionately more than the Daytona facility charges fall when comparing the CTE-observed scenario to the BYD-proposed. However, this change does not have a large effect on per-mile costs, as the cost per-mile under this scenario is estimated to be $0.32, as opposed to the $0.30 under the CTE-observed charging scenario.

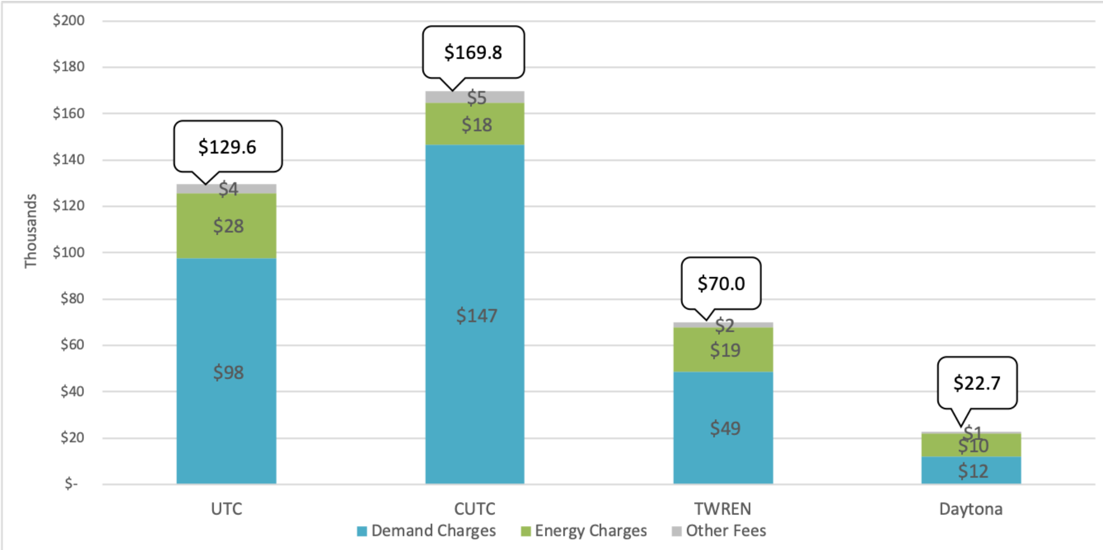

Figure 11: Annual Costs with BYD-Proposed Capacity and Charge Rate

While these results make on-route charging with these vehicles on these blocks more feasible, they are reliant on BYD's ability to realize the claimed improvements.