WHERE TO FIRST ELECTRIFY BUS TRANSIT ROUTES: CASE STUDY FOR AUSTIN, TEXAS

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ABSTRACT

Based on a holistic literature review, battery electric buses (BEBs) are the best alternative to harmful diesel buses that a majority of cities use. Hybrid buses are often touted as the stepping stone from diesel to electric, but given the 12-to-18-year lifespan of a public transit bus and the level of maturity that electric bus technology has reached, hybrids are no longer needed. While hydrogen fuel cell buses have the benefit of long range and low net emissions, that technology remains prohibitively expensive and unreliable for long term usage. When compared to on-route BEB charging, overnight or depot-based BEV charging is more feasible and straightforward to implement, resulting in more U.S. Grants to subsidize higher initial costs plus legal agreements that reduce risk for transit agencies transitioning to BEB systems.

The City of Austin, Texas' transit agency, Capital Metro, has announced a rough guideline as to how the city will implement overnight BEBs. Out of the three route types (MetroBus, MetroExpress, and MetroRapid) currently offered in Austin, this study finds that MetroExpress routes for a BEB pilot program to be most reasonable. Metro Routes 10, 982, and 801 were analyzed using GTFS and manually collected GPS data to illuminate how to determine which routes are most cost-effective to electrify. Due to MetroExpress routes having fewer stops and shorter lengths, it is evaluated here as a good option for initial Austin-area BEB implementation, and all seven MetroExpress routes were analyzed.

Keywords: battery electric buses, electrification of transport, transit policy

BACKGROUND

The United States has thousands of diesel-powered buses which generate noise, emissions, and potential long-term health issues for those they serve and those they pass by (Carrilero et al., 2018; Xu et al., 2019). While alternatives to diesel buses are presently uncommon in the U.S. and most other settings, public buses using alternative powertrains are gaining traction around the globe. Leading the charge against diesel-powered internal combustion engines (ICEs) is China, by producing and using a large share of the world's now-available battery electric buses (BEBs). Chinese manufacturer, BYD, has replaced over 420,000 diesel buses with BEBs in major urban cities like Shenzhen. Despite the rest of the world having fewer than 5,000 BEBs combined, numerous countries outside of China (like Brazil, Germany, and Canada) are taking part in innovative pilot programs (Eckhouse, 2019; Du et al., 2019; and Bloomberg, 2018).

Philadelphia currently has the highest number of BEB's at 25, whereas Foothill Transit near Los Angeles has the most structured policy so far (Eudy and Jeffers, 2019). Smaller pilot tests of 4 to 5 buses exist in a dozen cities across the country, from Dallas to Oakland. Although small, these pilot programs could serve to pave the way for a fully electrified bus system in the future.

Current BEB technologies have two standard charging options (Mohamed, 2019). First is the on-route or opportunity system. As the name suggests, the low battery capacity buses are to be charged several times during their normal trips. To enable more efficiency, charging stations are at a high voltage and are incrementally placed along bus routes. Thus, despite the buses having a limited range of only 20 to 40 miles per charge, they're able to fully recharge in only a few minutes (Rogge et al., 2018).

The alternative BEB approach is the overnight or depot-based charging system. These buses boast much larger batteries, with up to nearly 600 kWh storage, so that they can deliver bus riders throughout their daily trips without having to recharge. The overnight or depot-based systems require up to 8 hours to fully charge the larger BEB batteries while using lower-voltage DC (Mohamed, 2019) charging stations. This charging system option can often be used to replace existing diesel buses while making minimal route changes (Deliali, 2018).

In the State of California, several transit authorities are testing fuel-cell electric buses (FCEBs) as an alternative to diesel and natural gas buses (Eudy and Post, 2018). FCEB's use hydrogen cells to charge their batteries, to power their electric motors. Since the only byproduct of the hydrogen cell reaction is water, FCEBs are expected to be the cleanest option in the long term. But it is very energy-intensive to produce hydrogen (H2) these days, so it is not yet a clean option, just like BEB energy can still come from coal and natural gas power plants.

LITERATURE REVIEW

Although other powertrain alternatives to diesel internal combustion engines exist, the electrification option is the most mature. The primary zero-tailpipe-emissions competitor for BEBs is the FCEB. Despite having stellar range when compared to BEB's, the hydrogen fuel cell technology is currently crippled with limitations. Hydrogen used as the bus's fuel must be stored on board, creating a significant hazard in the case of a leak or an accident. Although the bus generates its energy without any harmful byproducts, the hydrogen must be obtained somehow. Currently there are only two options for hydrogen obtainment: by piping it into the bus depots or made on-site with a natural gas reformer. The pipeline-based solution again creates numerous hazards from leaks in the pipeline to the possibility of an outright more catastrophic occurrence. While it is possible to make the hydrogen on-site, the cost of a natural gas reformer is restrictively high, and would require spending a considerable capital investment. The final notable shortcoming for FCEB's is that they have an exorbitantly high maintenance cost. Personnel have to be trained from scratch on every aspect of the process, from refueling the on-board hydrogen tanks to making powertrain repairs (Deliali, 2018).

While promising on a financial and operational scale, hybrid power trains are not the preferred diesel alternative due to their lackluster environmental performance. Unlike the FCEB's or the BEB's, hybrid buses will necessarily produce tailpipe emissions along with whatever electricity demands they have. Because of hybrid buses have a combustion engine, they also run into the maintenance problems associated with diesel buses when compared to BEB's which have no mechanical parts. Although hybrid buses would still be preferred when compared to diesel buses, researchers agree that the implementation of hybrids would merely slow down the transition to a no emissions future (Xylia and Silveira, 2018).

While battery powered electric buses have their limitations, their advantages are simply far greater than that of the other powertrains discussed. The primary restrictions on electrification are simply economic and operational. Current electric bus and charger options are simply too expensive for a large majority of transit authorities to foot the bill by themselves. Unlike the other alternatives, the total cost of ownership for BEB's is steadily declining. Year after year battery technology and powertrain efficiency improves while at the same time the price of the buses themselves continue to decline. Unlike the fuel cell buses, BEB technology has matured in the commercial space for several years. BYD and Proterra have been producing electric bus models for nearly five years now, and many more companies continue to enter the marketspace. As competition intensifies, bus prices will continue to drop while quality continues to rise. Lastly, since BEB's are a more mature technology, training new maintenance workers is far less complicated than with the comparatively newer hydrogen fuel cell technology.

On-Route BEB Charging

On-route BEB's seem compelling in theory as the number of buses can remain small while still meeting route demands but the on-route option faces significant hurdles before becoming the decisively better option. Due to having to recharge numerous times along a route, on-route BEB's necessarily require a much larger initial expenditure to cover charging station costs. Since the buses will also be charged during peak hours (in the middle of the day), they will face far greater electricity costs than the overnight option.

Despite these significant expenses, Liu et al. (2019) argue that on-route charging is still a more economical choice due to the massive cost of overnight bus batteries. Even after conducting a numerical study on 10 different routes, they found that on-route charging remains more cost effective. Only after a sensitivity analysis that assumed battery costs decreased over time, was overnight more efficient only on a select few routes.

While Liu et al., took into account energy costs, they didn't analyze the grid impacts a high voltage charging system would have during peak hours. The massive power draws from the 200 kW chargers would necessarily cause voltage to drop in the region of the grid around the charging station. If voltage flux is unminimized, charging the on-route buses could cause damaging brownouts. The usage of substation transformers will assist with the voltage changes, but the transformers will face an incredibly low lifetime. The large voltages would increase the temperature of the transformers, and if exceeded 110 degrees Celsius the temperature would cause significant damage to the substation. In hotter climates, like Austin or Phoenix, the likelihood of exceeding that temperature threshold vastly increases. Therefore, because on-route BEB's have a grid impact 5 to 6 times larger than that of overnight BEB's they do not seem to be as preferable.

On-route BEB's also face significant operational problems due to their extreme lack of flexibility. In order to remain functional, the on-route BEB's cannot stray from their designated routes, otherwise they will quickly run out of power. This becomes problematic for transit areas that involve large amounts of interlining, as it would no longer be possible. Certain routes that require long uninterrupted distances on highways could also prove to be problematic due to the bus having fewer chances to recharge in optimal locations.

Overnight BEB Charging

While overnight BEB's are more flexible in that they only have a warehouse charging location, they currently don't have the range required to be a one to one replacement for diesel buses. To match existing route demands, transit agencies will have to purchase spare overnight buses to trade out with the buses that have ran out of battery (Mahmoud, 2016).

As mentioned earlier, a significant cost incurred with the overnight BEB system is the massive batteries needed. It's possible that much of this cost can be recouped from lower night time electricity rates and far fewer needed charging stations. By localizing the BEB charging to one warehouse, grid impacts can be more easily mitigated. In certain municipalities, overnight buses could even help with grid imbalances due to overproduction of energy. Certain renewable energy sources like wind or hydro continue to generate energy at night, when demand is far lower. This excess would be used to charge the BEB's overnight. A similar strategy is used in Montreal as their nuclear powerplants run 24-7 they have a large surplus of energy that is being reinvested into BEB's (Mohamed, 2019 and Ambrose et al., 2017).

Existing Solutions to Problems Outlined

The primary problem any electrification project faces is where to get the capital needed to purchase buses and charging stations. The most straightforward route to acquiring the money needed for BEB's would be through grant qualification. The Federal Transit Administration offers millions in grant monies to pursue demonstration programs for new technologies, which pilot bus electrification projects will likely qualify for. BEB programs might also pay for themselves over time if electricity costs remain lower than diesel costs as projected. Fuel savings will enable transit agencies to recoup infrastructure investments from BEB implementation. The increased health benefits from less smog and fewer airborne particulates will also result in a social surplus from lower healthcare costs (Quarles, 2018).

Another method of overcoming initial funding hurdles would be to use government lending methods. In Taijin, China, the government issued green bonds to finance the BEB's. Similarly, the Brazilian Development Bank (BNDES) provided concessional loans to hybrid bus operators, a system that could be easily emulated for the purpose of investing in BEB's.

Legal arrangements have also enabled certain municipalities to ease the risks involved with bus electrification projects. By setting up a mutually beneficial contract, the cities were able to better distribute the risks involved with purchasing BEB's. All over the world, contractual ways to mitigate risks were matched with an increase in stakeholder support, making legal arrangements an incredibly powerful tool to utilize. In Bogota, the manufacturer for their BEB's provided an all-encompassing 5-year maintenance warranty. This contract included complete maintenance for the buses and vitally included training for workers. Thus, as Bogota was establishing the necessary infrastructure needed to implement the BEB's, the manufacturer provided a "safety net" in case anything went wrong in those preliminary 5 years. Bogota, along with Shenzhen, also provided leasing contracts with battery manufacturers to further reduce the risk the cities took on. Through these leases it was possible for the cities to upgrade their batteries as technological improvements rolled out, greatly diminishing any battery related tech anxiety that policymakers had. In Gothenberg, the utility company agreed to pay for investments in the electricity infrastructure, saving the municipality thousands of dollars for substation adaptation and bus chargers. Similarly, the Foothill utility company supplied a demand surcharge waiver which greatly reduced their electricity costs (Li et al., 2018).

While grants (cash, land allocations, and tax breaks) are certainly the most common ways to subsidize BEB implementation, there are other strategies municipalities can employ as well. Involvement with utility companies and bus/infrastructure manufacturers can go great lengths to soften experience barriers and charging costs. Through battery leases, one of the largest political hold-ups for BEB implementation, tech anxiety, can be greatly relieved. Thus, transit agencies looking to implement BEB's have numerous options they can pursue to ease the infrastructure, training, and monetary changes that electrification of bus transit necessitates.

BEB's in Austin

In April of 2019, Austin unveiled their plans for initiating a BEB pilot program. Capital Metro, Austin's transportation agency, has purchased four 40-foot Catalyst E-2 buses from BEB manufacturer, Proterra. Along with the buses, Capital Metro purchased four 60 kW Proterra charging systems to be located in a large warehouse in North Austin. The warehouse is said to be able to house over 200 BEB's and will also be the primary charging location. To mitigate risks, Austin has leveraged the state of Georgia's contract to buy the buses. This contract vitally includes a battery leasing agreement so that Capital Metro has to opportunity to modernize their fleet further down the road. Capital Metro aims to test two of the four buses by the end of 2019, but has yet to release what their pilot program will entail (Flores and Norwood, 2019).

The buses purchased from Proterra are overnight charging, long range buses. With an on-board battery capacity of 440 kWh, the buses are rated for a range from 160 to 230 miles on a single charge, depending on various energy consuming factors such as outdoor temperatures, route grade, and number of stops. Austin Energy has only offered to allow Capital Metro to pick between sourcing electricity entirely from renewable energy or if it would rather pay a slightly lower rate by using the utility's grid power. Regardless of which energy rate Capital Metro chooses, the BEB's will still have a far lower greenhouse gas impact than the previous diesel buses due to Austin's relatively high proportion of renewably sourced energy at 26% compared to the national average at 17% (Thornton, 2019 and EIA, 2019).

METHODOLOGY

This section describes the calculations used to determine BEB viability, including background assumptions and equations used. Assumptions made impact the cost effectiveness of BEB's (e.g., range), quantity of buses needed, and energy impacts on the grid. Applications are for 24 hour bus operation on a generic weekday to best simulate demands the BEB's will have to fulfill. Preliminary models for one of each transit type indicate that MetroBus and MetroRapid routes are currently infeasible for BEB implementation. Thus, all seven MetroExpress routes are analyzed to determine the which routes prove to be the most viable as pilot programs and for broader BEB integration for the city of Austin.

Routes Investigated

Capital Metro, Austin's transportation authority, separates bus transit into three different types; MetroBus, MetroExpress, and MetroRapid. MetroBus is the primary public transit option, offering a large number of routes with frequent stops to provide reliable connections for a majority of the city. MetroExpress is the commuter service that runs to and from downtown. Characterized by long stretches of uninterrupted highway transit, this metro type has the fewest number of stops. Lastly, the MetroRapid is a high frequency service with fewer stops than the MetroBus to transport people across Austin along its busy North-South corridors. To develop an accurate depiction of the various bus transit options offered in Austin, one route from each type was selected. The final factor used to consider which routes to analyze was the occurrence of high frequency routes at stops. All three routes selected travel through the transit stops on the higher ridership end.

For the MetroBus and MetroExpress types, routes 10 and 982 were selected due to their average ridership and distance characteristics. The MetroRapid transit type only has two routes and route 801 was selected due to its significantly higher ridership (Capital Metro, 2019). Route information such as stops, lengths, and timings was collected through the publicly available General Transit Feed Specification (GTFS) data and modeled in ArcGIS. The GTFS data indicates ideal conditions and illustrates how the bus routes were planned to act two-dimensionally. Due to this “perfect” estimation, GTFS lacks information on important route characteristics such as road grades, average miles per hour, and only vaguely estimates traffic amounts. Thus, the GTFS data set was supplemented with GPS information obtained while riding certain portions of the bus routes. By also reporting on real world conditions, the range estimates for electrification can be more accurately made.

GTFS data was processed using ArcGIS so that bus stops and transit lines could be precisely visualized by being geographically referenced onto Austin’s streets. After generating and georeferencing GTFS shapes, the model can be used to calculate key route information. Using the BetterBusBuffers tool, the number of trips made on routes 10, 801, and all MetroExpress routes could be calculated. BetterBusBuffers is an ArcGIS plug-in made by ESRI to enable the visualization of transit lines and the stops along them. In order to input GTFS data into ArcGIS, it must first be preprocessed from the text files into an SQL database. This SQL database is then mapped onto the Transit Network Dataset created from a base map of the region to be analyzed. For the purposes of this paper a base map was created from road and geographic information available from Open Street Map, a free to use dataset of geographic information of cities around the world. Using the preprocessed GTFS data and the Transit Network Dataset, BetterBusBuffers is able to project transit access buffers for any route selected. Using the buffers and geographically located stops, BetterBusBuffers calculates the number of trips taken on each route.

By geographically referencing the transit routes onto the WGS 1984 World Mercator Projected Coordinate System, the model could be used to compute all route lengths needed. Since the GTFS data also includes route timings, the model was used to calculate the average headway for each of the routes. Lastly, ArcGIS was utilized to determine the deadheads for both the Northbound and Southbound trips for all bus routes. By adding the Capital Metro electric bus warehouse, into the GTFS data as a “final stop” the route deadhead is calculated through the line length function.

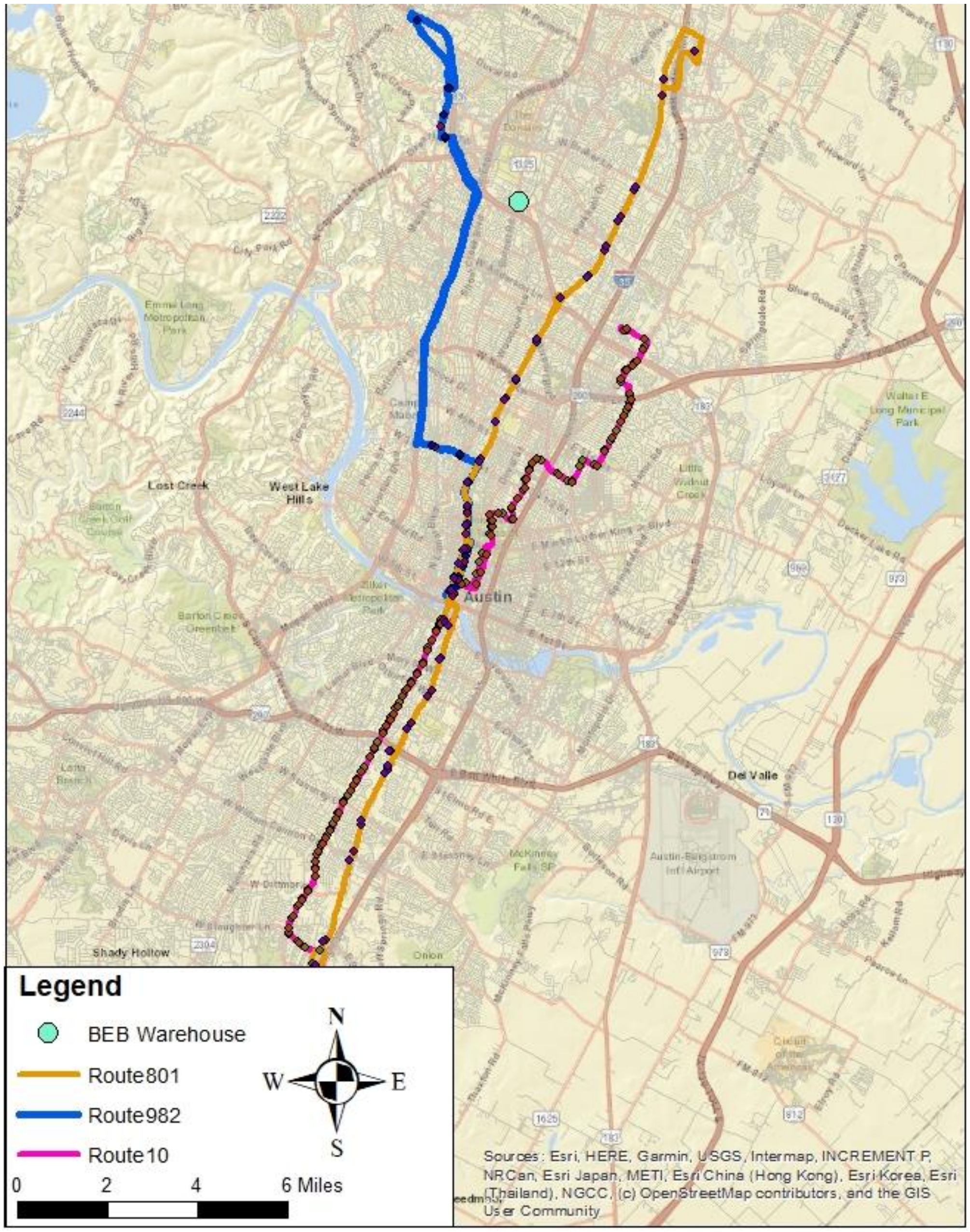

Fig. 1. Routes 801, 982, and 10 visualized using ArcGIS.

Range Considerations

When calculating energy consumption and range of the BEB's on the selected routes the primary consideration was route length. Using battery power to engage the powertrain and move the bus consumes the most energy out of all other bus operations. Due to Austin's generally hot climate throughout the year, a 25 kW (Gohlich et al., 2018) is assumed to be consumed simply for running the on board air conditioning system in the bus. Due to Austin's heavy traffic and the high frequency of stops, all three of the bus transit types had a low mile per hour average when running their routes, with only Route 982's average breaking 25 miles per hour. Slower trips necessitate a longer time that the bus is running, thereby further resulting in battery power losses (Mahmoud, 2016).

The GPS data collected indicated that several battery draining functions were not included in the GTFS data and therefore not modeled in the ArcGIS visualization. Austin's topography contributes to another loss of range, as grade changes (up to a 13% incline on Route 801) can significantly impact power consumption (Kontou and Miles, 2015). Thus, another 5 kW is assumed to be lost due to route elevation changes, based on average grade of 10% multiplied by an additional 0.5 kW consumed. The number of stops was the final range determining variable considered due to its large impact on battery power consumption (Mohamed et al. 2016). This loss was calculated as an increase in mileage due to the consequential power losses from the time waiting at the stop and the power required to start the bus from its stopped position. Each stop is assumed to take two minutes, based on GTFS stop timing defaults. Capital Metro currently provides a bus schedule that indicates how many buses are running on each route and when they go into the garage for refueling or maintenance.

Thus, the range required by a bus (R_{Total}), in miles, can be determined as a function of total miles traveled per trip (*m*), number of daily trips (*n*), energy consumed while stopped (*S*), energy consumed for heating and cooling of the bus cabin (*h*), miles traveled as deadhead (*d*), and energy consumed due to differences in grade (*g*). Due to differences in route characteristics between Southbound and Northbound trips (notably with deadhead and numbers of trips), they are calculated separately in Eq (1):

$$R_{total} = \big((m + S) \times n\big) + h + d + g \tag{1}$$

where *s* is determined based on the average time spent at each stop (*t*), the number of stops per trip (n_{stops}), and the average bus speed (*v*). Using this function, the time spent stopped is effectively converted as an expression of mileage for easier use with the rest of the variables. Based on Austin's route characteristics, the average time spent at each stop is 2 minutes and the average velocity of the MetroBus and MetroRapid buses are 20 miles per hour, while the MetroExpress buses are slightly faster, with an average of 25 miles per hour.

$$S = \frac{(t \times n_{stops})}{60} \times v \tag{2}$$

The energy consumed for the heating or cooling of the bus cabin is also converted to be an expression of lost mileage by dividing the energy consumed (25 kW) by the Proterra Catalyst E-2's kWh/mile efficiency. Thus, all variables are expressed in effective mileage so the range required by the BEB's can be precisely estimated regardless of route or direction.

Energy Considerations

Using the total required range as calculated in Eq 1, the number of BEB's is determined by dividing R_{total} by the range of the BEB in question. However, in some of the modeled routes the optimized number of BEB's was fewer than the amount that are currently in use, so in those instances the current amount of buses overrode the optimized amount. For the purposes of our calculations, the 190-mile range of the Proterra Catalyst E-2 is used. With that information, the number of needed kilowatts is calculated by multiplying the number of BEB's used by the size of its battery. To calculate the daily energy costs for the BEB's, the previously calculated kilowatt value is multiplied by the commercial cost of high demand electricity. Lastly, the amount of chargers needed is the same as the number of active buses because BEB's must fulfill route requirements from the start of each day. This will be sufficient to ensure that on routes where the BEB's must be swapped, an equal number of buses will always be ready to transport passengers.

Results

Table 1: Total Daily Range Required, Primary Routes

Route	Direction	One-way Distance (miles)	Range Loss from Stops (miles)	Number of Daily Trips	Deadhead (miles)	Total Daily Range Required (miles)
10	Northbound	21.0	52.0	66	4.7	4,853
	Southbound	21.0	52.0	67	18.9	4,940
982	Northbound	15.4	11.7	25	5.2	712
	Southbound	15.4	11.7	28	10.2	798
801	Northbound	25.2	20.7	94	8.3	4,350
	Southbound	25.2	20.7	94	18.9	4,360

The number of BEBs needed is determined based on the estimation of bus range after the various assumptions made above are taken into consideration. The bus being implemented by Capital Metro, the Proterra 40-foot Catalyst E2, has an estimated range from 161 to 230 miles. After estimated losses from Austin's high average temperature and significant grade changes, available range is likely to be around 190 miles per single charge. Due to the BEB's shorter range than that of the diesel bus, Capital Metro's fleet must expand to retain existing capacity. Thus, the minimum number of BEB's required to electrify Route 10 is 23 and 801 requires the most at 59.

However, Route 982 defies this trend by not requiring any additional buses. This is because of the incredibly low total mileage on the route. Even for the Southbound route, a single bus would not have to travel more than 150 miles per day, which is well within the range of the Proterra Catalyst E-2. Thus, the distinct characteristics for MetroExpress routes makes them more applicable to potential electrification.

Table 2: Total Daily Range Required, MetroExpress Routes

Route	Direction	One-way Distance (miles)	Range Loss from Stops (miles)	Number of Daily Trips	Deadhead (miles)	Total Daily Range Required (miles)
935	Northbound	17.4	11.7	9	6.3	298
	Southbound	17.4	11.7	9	12	304
980	Northbound	47.1	10.0	10	12.1	613
	Southbound	47.1	10.0	10	8.2	609
981	Northbound	17.8	8.3	2	8.2	90
	Southbound	17.8	10.0	2	5.2	91
982	Northbound	15.4	11.7	25	5.2	712
	Southbound	15.4	11.7	28	10.2	798
985	Northbound	42.4	10.0	24	19.9	1,308
	Southbound	42.4	10.0	27	8.3	1,453
987	Northbound	41.5	13.3	9	19.9	543
	Southbound	41.5	13.3	9	10.3	534
990	Westbound	32.3	10.0	3	9.8	167
	Eastbound	32.29	11.7	3	24	186

Table 3: Minimum Number of Buses Needed by Route on Weekdays

Route #	10	801	935	980	981	982	985	987	990
# of BEB's	52	46	7	12	4	13	16	12	4
# of Diesel Buses	15	40	7	12	4	13	16	12	4

Based solely on a range perspective, route 985 exists as an outlier for MetroExpress Routes. Thus, it would not be an optimal choice for electrification when compared to routes with lower range requirements. Despite this, range is not the only important criterion. Due to the number of times each route is run per day, optimal range calculations cannot apply so the number of buses must be increased so that the route is still functional for passengers. Thus, extremely low range routes such as 981 and 990, are not optimal due to the high cost of BEB purchasing massively outweighing the savings in electricity costs.

Capital Metro has opted to use the MC060KW charging station to charge their Catalyst E-2 buses, which have an onboard 440 kWh battery. Due to the charging station's 60 kW per hour rate an individual bus will have a full recharge time of over 7 hours. Consequently, the bus fleet would have to be expanded past the minimum range requirements since it will take almost a full night to charge the bus when compared to a diesel bus's short refueling time. Therefore, due to long trip lengths and high frequency on Routes 10 and 801, spare buses will be needed to replace the buses that will have drained batteries part-way through the day.

Capital Metro will be charged high voltage electricity costs 24-7 to keep their routes running fully functionally. Assuming current commercial rates, it will cost $0.152/kW of charging (Loeb, 2016) or $0.35/mile. Whereas diesel-powered buses with a miles per gallon of 3.25 (USEIA, 2019) are more expensive due to the comparatively higher price of diesel at $3 per gallon (AFDC, 2019), costing $0.92/mile. Lastly, cost per passenger mile is calculated assuming ridership of 8 passenger-miles per bus mile.

Table 4: BEB Total Cost of Ownership (12-year Lifecycle)

Route	# of BEBs	kWh used daily	Electricity Costs ($)	# Chargers Needed	Cost of Chargers ($)	Maint. Costs ($)	Total ($) Cost over 12 yrs	Total ($) Cost per Passenger Mile
10	52	9,880	$6.58 M	15	$0.68 M	$2.68 M	$46.77 M	$0.27
801	46	8,740	$5.83 M	40	$1.80 M	$2.37 M	$42.57 M	$0.28
935	7	1,330	$0.89 M	7	$0.32 M	$0.16 M	$6.32 M	$0.59
980	12	2,280	$1.52 M	12	$0.54 M	$0.33 M	$10.89 M	$0.51
981	4	760	$0.51 M	4	$0.18 M	$0.05 M	$3.57 M	$1.12
982	13	2,470	$1.64 M	13	$0.59 M	$0.43 M	$11.87 M	$0.42
985	16	3,040	$2.02 M	16	$0.72 M	$0.79 M	$14.87 M	$0.29
987	12	2,280	$1.52 M	12	$0.54 M	$0.29 M	$10.85	$0.58

The current cost of a Proterra Catalyst E-2 is around $700,000 (Proterra, 2019) which is significantly more than that of the current Gillig Diesel Buses, which cost $536,761 each (Thornton, 2019). The total initial cost of fully electrifying Route 10 or 801 is estimated to be triple the cost of the primary diesel competition and double the cost for Route 982.

While considerably more expensive at the initial investment, other factors contribute to the potential cost effectiveness of BEB's when compared to traditional diesel buses. First, maintenance costs are significantly lower for BEB's due to their lack of mechanical parts. This results in savings of over 8 thousand dollars each year (Bloomberg, 2018). Therefore, the annual costs for BEB operation will be significantly lower than that of diesel buses due to the lower maintenance costs with BEB's at $0.124 per mile and diesel buses at $0.236 per mile (Mahmoud et al., 2016). Due to expected price drops in battery technology, the net cost difference could soon be in favor of BEB's. In the status quo, Proterra's E2 batteries sell for $250 per kWh (Ambrose et al., 2017), meaning the 440 kWh batteries currently cost around $110,000 but due to expected battery technology advancements per kWh costs could drop to $200 by 2025 resulting in the 440 kWh batteries costing only $880,000.

Table 5: TCO Comparison

Route	Diesel	BEB Control ($)	% Cost Diff.	Battery Leasing Costs ($)	% Cost Diff.	Electricity Deal ($)	% Cost Diff.	Combined Savings ($)	% Cost Diff.
10	33,130,087	46,774,196	+41%	41,782,196	+26%	44,610,476	+35%	39,618,476	-15.3%
801	43,607,469	42,574,929	-2%	38,158,929	-12%	40,660,869	-7%	36,244,869	-14.9%
935	5,298,630	6,324,385	+19%	5,652,385	+7%	6,033,115	+14%	5,361,115	-15.2%
980	9,532,369	10,889,838	+14%	9,737,838	+2%	1,0390,518	+9%	9,238,518	-15.2%
981	2,607,709	3,568,993	+37%	3,184,993	+22%	3,402,553	+30%	3,018,553	-15.4%
982	11,029,483	11,872,505	+8%	10,624,505	-4%	11,331,575	+3%	10,083,575	-15.1%

While TCO for a standard BEB purchase from Proterra is not optimistic, Austin could follow the lead of several other cities to make its electrification strategy cost effective. The first policy option that could save significant amounts of money would be to participate in Proterra's battery leasing program. The program would save Capital Metro around $8,000 per bus due to discounted battery upgrade options and maintenance savings (Blanco, 2019). While not revolutionary, this considerably straightforward implementation decision would result in route 982 becoming net cheaper over the 12-year lifespan of the buses. An additional benefit would be that Capital Metro has the opportunity to decrease battery risks which might persuade additional stakeholders to participate in the pilot project.

The second route for considerable savings would be for Capital Metro to strike a deal with Austin Energy in order to get discounted rates. Following the model of transit organizations like Foothill, Austin Energy could provide a 5 cent discount on each kW of energy used by the chargers. This would improve the affordability of electrification on its own, but when combined with the battery leasing option it's possible for Austin to save money on electrifying all routes that were modeled.

In addition to the quantifiable monetary impacts, BEBs produce zero tailpipe emissions (He et al., 2019 and Bakker and Konings, 2018) resulting in a reduction of nitrogen oxides (NOx) and volatile organic compounds (VOC) by 60% to 80% and up to a 40% reduction in fine particulate matter ($PM_{2.5}$). This decreasing of pollutants will result in thousands of dollars saved in social costs from lower medical bills (Xylia et al., 2019).

CONCLUSIONS

Although the upfront costs of BEBs are high, the cost of purchasing the buses and their infrastructure fails to tell the entire economic story. The existing contract that the pilot is based off of also indicates that Proterra will provide training services and heavy discounts for the 60 kWh charging stations used by the buses. The assumed price of electricity used in the monthly electricity cost calculations also remains extremely conservative as Capital Metro is already seeking to establish a discounted rate for their charging stations (Thornton, 2019). Lastly, Capital Metro could qualify for a sizeable grant from the Federal Transit Administration which would help to offset the large initial cost for BEB's.

Regardless of how Capital Metro seeks to minimize the Total Cost of Ownership for BEB's, their pilot program should begin with MetroExpress routes. Due to the comparatively lower amount of stops and daily trips along the route, the MetroExpress routes could be electrified in the near future. Routes 982, 981, and 985 also benefit from having a relatively smaller deadhead given the North Austin location of the BEB warehouse. A MetroExpress pilot program would help prepare Austin's infrastructure to handle a higher load of BEB's as the infrastructure could be phased in while BEB/battery/charger prices continue to drop.

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REFERENCES

AFDC. (2018) Maps and Data - Average Fuel Economy of Major Vehicle Categories. Average Fuel Economy of Major Vehicle Categories. December 2018. https://afdc.energy.gov/data/10310

Ambrose, H., Pappas, N., and Kendall, A. (2017) Exploring the Costs of Electrification for California's Transit Agencies. 2017. The University of California Institute of Transportation Studies. https://doi.org/10.7922/G2PZ570Z

Austin Energy. (2019) Corporate Reports and Data Library. January 11, 2019. https://austinenergy.com/ae/about/reports-and-data-library/data-library/data-library

Bakker, S. and Konings, R. (2018) The transition to zero-emission buses in public transport – The need for institutional innovation. October 2018. *Transportation Research Part D: Transport and Environment* Volume 64, October 2018, Pages 204-215. https://doi.org/10.1016/j.trd.2017.08.023

Blanco, S. (2019) Proterra Ready For Electric Bus Battery Leasing With $200-Million Credit Facility. Forbes. April 18, 2019. https://www.forbes.com/sites/sebastianblanco/2019/04/18/proterra-ready-for-electric-bus-battery-leasing-with-200-million-credit-facility/#2ad1691a2314

Bloomberg. (2018). Electric Buses in Cities: Driving Towards Cleaner Air and Lower CO2. March 29, 2018. Bloomberg New Energy Finance. https://data.bloomberglp.com/bnef/sites/14/2018/05/Electric-Buses-in-Cities-Report-BNEF-C40-Citi.pdf

Blynn, K. and Attanucci, J. (2019) Accelerating Bus Electrification: A Mixed Methods Analysis of Barriers and Drivers to Scaling Transit Fleet Electrification. May 1, 2019. *Journal of the Transportation Research Board.* https://doi.org/10.1177/0361198119842117

CapMetro. (2019) Ridership. May 51, 2019. https://capmetro.org/ridership-stats/

Carrilero, I., Gonzalez, M., Ansean, D., Viera, J., Chacon, J., Pereirinha, P. (2018) Redesigning European Public Transport: Impact of New Battery Technologies in the Design of Electric Bus Fleets. *Transportation Research Procedia*, Volume 33, 2018, Pages 195-202. https://doi.org/10.1016/j.trpro.2018.10.092

Deliali, A. (2018) Zero-Emission Transit Bus and Refueling Technologies and Deployment Status: A Review Across U.S. Transit Agencies. UMass at Amherst. April 5, 2018. https://doi.org/10.7275/78av-7x59

Du, J., Li, F., Li, J., Wu, X., Song, Z., Zou, Y., and Ouyang, M. (2019) Evaluating the technological evolution of battery electric buses: China as a case. *Energy*, Volume 176, 1 June 2019, Pages 309-319. https://doi.org/10.1016/j.energy.2019.03.084

Eckhouse, B. (2019) The U.S. Has a Fleet of 300 Electric Buses. China Has 421,000. Bloomberg. May 15, 2019. https://www.bloomberg.com/news/articles/2019-05-15/in-shift-to-electric-bus-it-s-china-ahead-of-u-s-421-000-to-300

El-Taweel, N., Mohamed, M., and Farag, H. (2017) Optimal Design of Charging Stations for Electrified Transit Networks. 2017 IEEE Transportation Electrification Conference and Expo (ITEC) 2017. DOI: 10.1109/ITEC.2017.7993369

Eudy, L. and Post, M. (2018) Fuel Cell Buses in U.S. Transit Fleets: Current Status 2018. National Renewable Energy Laboratory. 2018. TP-5400-72208

Eudy, L., and Jeffers, M. (2017) Foothill Transit Battery Electric Bus Demonstration Results: Second Report. National Renewable Energy Laboratory. 2017. TP-5400-67698

Federal Transit Administration. (2018) FTA Annual Report on Public Transportation Innovation Research Projects for FY 2017. Federal Transit Administration Report No. 0120, February 2018.

Flores, R. and Norwood, K. (2019) CapMetro unveils plan to bring electrical buses to Austin this year. KVUE. April 22, 2019. https://www.kvue.com/article/news/local/capmetro-unveils-plan-to-bring-electrical-buses-to-austin-this-year/269-e26b00a6-6266-4fc5-9d26-75c11c9b8e6a

Gallet, M., Massier, T., and Hamacher, T. (2018) Estimation of the energy demand of electric buses based on real-world data for large-scale public transport networks. *Applied Energy*, Volume 230, 15 November 2018, Pages 344-356. https://doi.org/10.1016/j.apenergy.2018.08.086

Gohlich, D., Fay, T., Jefferies, D., Lauth, E., Kunith, A., and Zhang, Xudong. (2018) Design of urban electric bus systems. *Design Science*, 4, E15. doi:10.1017/dsj.2018.10

Hao, H., Ou, X., Du, J., Wang, H., and Ouyang, M. (2014) China's electric vehicle subsidy scheme: Rationale and impacts. *Energy Policy Volume 73*, October 2014, Pages 722-732.

He, X., Zhang, S., Ke, W., Zheng, Y., Zhou, B., Liang, X., and Wu, Y. (2018) Energy consumption and well-to-wheels air pollutant emissions of battery electric buses under complex operating conditions and implications on fleet electrification. *Journal of Cleaner Production*, Volume 171, 10 January 2018, Pages 714-722. https://doi.org/10.1016/j.jclepro.2017.10.017

Li, X., Castellanos, S., and Maassen, A. (2018) Emerging trends and innovations for electric bus adoption—a comparative case study of contracting and financing of 22 cities in the Americas, Asia-Pacific, and Europe. *Research in Transportation Economics*, Volume 69, September 2018, Pages 470-481

Mahmoud, M., Garnett, R., Ferguson, M., and Kanaroglou, P. (2016) Electric buses: A review of alternative powertrains. 2016. https://doi.org/10.1016/j.rser.2016.05.019

Mohamed, M., Farag, H., El-Taweel, N., and Ferguson, M. (2017) Simulation of electric buses on a full transit network: Operational feasibility and grid impact analysis. 2017. https://doi.org/10.1016/j.epsr.2016.09.032

Mohamed, M., Ferguson, M., and Kanaroglou, P. (2018) What hinders adoption of the electric bus in Canadian transit? Perspectives of transit providers. 2018. https://doi.org/10.1016/j.trd.2017.09.019

Proterra. (2019) CapMetro to purchase four Proterra electric buses and battery charging systems. Mass Transit. April 24, 2019. https://www.masstransitmag.com/bus/vehicles/hybrid-hydrogen-electric-vehicles/press-release/21077603/proterra-capmetro-to-purchase-four-proterra-electric-buses-and-battery-charging-systems

Proterra. (2019) CATALYST® : 40 FOOT BUS PERFORMANCE SPECIFICATIONS. https://www.proterra.com/wp-content/uploads/2019/05/Proterra-Catalyst-40-ft-Spec-Sheet.pdf

Quarles, N. and Kockelman, K. (2018) Costs and Benefits of Electrifying and Automating U.S. Bus Fleets. *Transportation Research Record*. 2018. Under review for publication in *Public Transport*.

Rogge, M., van der Hurk, E., Larsen, A., and Sauer, D. (2018) Electric bus fleet size and mix problem with optimization of charging infrastructure. February 1, 2018. *Applied Energy*, vol. 211, 1 February 2018, Pages 282-295. https://doi.org/10.1016/j.apenergy.2017.11.051

Thornton, R. (2019) Capital Metro to buy last wave of diesel, first electric buses. April 23, 2019. Austin Monitor. https://www.austinmonitor.com/stories/2019/04/capital-metro-to-buy-last-wave-of-diesel-first-electric-buses/

USEIA. (2019) Gasoline and Diesel Fuel Update. July 8, 2019. https://www.eia.gov/petroleum/gasdiesel/

Xu, X., Lv, X., and Han, L. (2019) Carbon Asset of Electrification: Valuing the Transition from Fossil Fuel-Powered Buses to Battery Electric Buses in Beijing. May 14, 2019. *Sustainability* vol. 11, issue 10. https://doi.org/10.3390/su11102749

Xylia, M. and Silveira, S. (2018) The role of charging technologies in upscaling the use of electric buses in public transport: Experiences from demonstration projects. December 2018. *Transportation Research Part A: Policy and Practice*, vol. 118, December 2018, Pages 399-415. https://doi.org/10.1016/j.tra.2018.09.011

Xylia, M., Leduc, S., Laurent, A., Patrizio, P., van der Meer, Y., Kraxner, F., and Silveira, S. (2019) Impact of bus electrification on carbon emissions: The case of Stockholm. February 1, 2019. *Journal of Cleaner Production*, vol. 2019, 1 February 2019, Pages 74-87. https://doi.org/10.1016/j.jclepro.2018.10.085

EIA (2019). US Energy Information Administration. Short-term Energy Outlook. July 9, 2019. https://www.eia.gov/outlooks/steo/report/electricity.php