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Electrification of Airport Shuttle Operations

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Summary

Fleet owners are increasingly looking to adopt electric vehicles, however careful consideration is needed to ensure electric vehicles can perform their duty without impacting operations. This work examines a fleet of 200 Dallas-Fort Worth airport shuttle buses to estimate the opportunity for vehicle electrification. Analysis suggests unique pathways to electrification for each mode of operation, and unique benefits and challenges whether they serve employee lots, rental car lots, remote lots, or aircraft hardstand operations. These analyses include daily energy consumption, charging opportunities; emissions impacts; and charging location potential using hotspot analysis. Results highlight the most promising candidates for electrification and provide pathways for future electrification.

Keywords: bus, electric vehicle, GPS, telematics, BEV

1 Introduction

Public and private fleet owners are increasingly exploring electric vehicles as an alternative to internal combustion for a wide range of commercial vehicles. Transit buses and class 8 tractors are attractive for electrification because multiple manufacturers make these electrified vehicles available for immediate purchase. Reducing climate impacts, lowering operating costs and improving local air quality are the most compelling reasons for fleets to adopt electric vehicles [1], [2]. Further, fleets may also see reduced maintenance costs and a boost in public esteem [3]. Although vouchers and government assistance can lessen the financial risk of purchasing these next-generation vehicles, careful consideration is needed to ensure electric vehicles can still perform their normal operational duties. Specifically, it is critical to identify vehicle range, charging speed and electrical infrastructure required to complete existing operations. By collecting duty cycle information from existing vehicles and using vehicle modeling tools, we can inform the creation of new efficient operating procedures and identify vehicle requirements for a fleet transitioning to electric heavy-duty vehicles [4]. Dallas-Fort Worth (DFW) airport has established itself as North America's first, and the world's largest airport to achieve carbon neutral status and continues to seek new ways to reduce carbon emissions [5], [6]. This study examines four different shuttle services from DFW: employee parking, rental car, aircraft hardstand and remote parking. While these operations appear to be similar, nuances in each service pose unique challenges to, or even eliminate the possibility of, electrification with current battery electric bus (BEB) technology. The forthcoming text details a process to evaluate feasibility, forecast infrastructure needs, and specify vehicle requirements by gathering in-use data, modeling electric vehicle requirements, and comparing to commercially available electric vehicle specifications.

2 Data Collection

When considering electrification, in-use data collection is the first step in understanding vehicle operating requirements, or duty cycles. Modern heavy-duty vehicles utilize a controller area network (CAN) to monitor vehicle performance, detect vehicle faults and control vehicle operation. Specifically, the sensors monitored for data collection use the Society of Automotive Engineers (SAE) J1939 protocol [7] as a common platform for information exchange which can be captured using a CAN-based data logger. Vehicle location data is obtained from a global positioning system (GPS) antenna connected to the logger. A combination of ISAAC Instruments DRU900/908 data loggers and Vector GL2000 data loggers were used to capture vehicle data amounting to 170,000+ miles of shuttle bus operation on four of DFW's shuttle routes. Figure 1 shows the four bus services from which data was collected: A) airport hardstand operation shuttles that are used to transport passengers on-runway from planes to the gates, and can be used in an emergency including plane or terminal evacuations; B) rental car shuttles that transport customers between the terminals and rental car center; C) remote lot shuttles which service the north and south remote parking lots for customers; D) employee shuttles which move between employee parking lots and airport terminals.

Figure 1: DFW shuttles: A) Aircraft Hardstand Operations; B) Rental Car; C) Remote Lot; D) Employee (Images: NREL)

2.1 Daily Duty Cycle

Using the collected in-use data, daily duty cycle statistics were calculated to understand if electric shuttle bus adoption is possible for a given fleet or operation. Daily distance is a good indicator of electrification potential since 40-ft transit buses are not currently available with more than 660 kWh of onboard storage, and typically use around 2 kWh of energy per mile [8]. Stopped time is used to determine if market-available electric buses could maintain daily bus operations and have adequate time to charge. Table 1 provides high-level duty cycle statistics by service type to help frame and compare the extent of the vehicle data collection.

Table 1: Duty cycle statistics by service type

	Aircraft Hardstand	Employee	Remote	Rental Car
Vehicles Logged	4	12	4	14
Miles Logged	676	103,987	20,821	99,840
Active Days Logged	100	412	89	544
Avg. Moving Speed [mph]	12.9	18.7	21.4	20.6
Avg. Daily Distance [miles]	6.8	252.4	233.9	183.5
Max Daily Distance [miles]	28.8	384.9	367.2	306.5
Avg.Fuel Economy [$\mathrm{MPG_{DE}}$]	no data	4.1	4.1	4.3
Avg. Daily Run Time [hrs]	no data	19.5	8.2	14.4
Avg. Daily % Idle	no data	31.8%	46.4%	38.9%
Flywheel Energy [kWh]	no data	641.1	271.4	379.4
Avg. Daily % Energy at Idle	no data	16.2%	19.7%	14.9%

Figure 2 shows distributions of daily average driving speed and distance by service type. The aircraft hardstand operations had the lowest daily average driving speed (2.8mph) and the lowest daily distance (max. 28.8 mi) making this service an excellent candidate for electrification. At 2 kWh/mi a 60-kWh battery can achieve 28.8 mi/day without charging mid-day. The other three operations had higher average speeds (approx. 20 mph) and much longer daily distances. The longest recorded day was 385 miles by an employee shuttle. At 2 kWh/mi this shuttle would need a 770-kWh battery for that day. However, the largest battery size currently available for a 40ft bus is 660 kWh making it necessary to further analyze these duty cycles and identify actual in-use efficiency, opportunities for reducing energy use or mid-day charging opportunities.

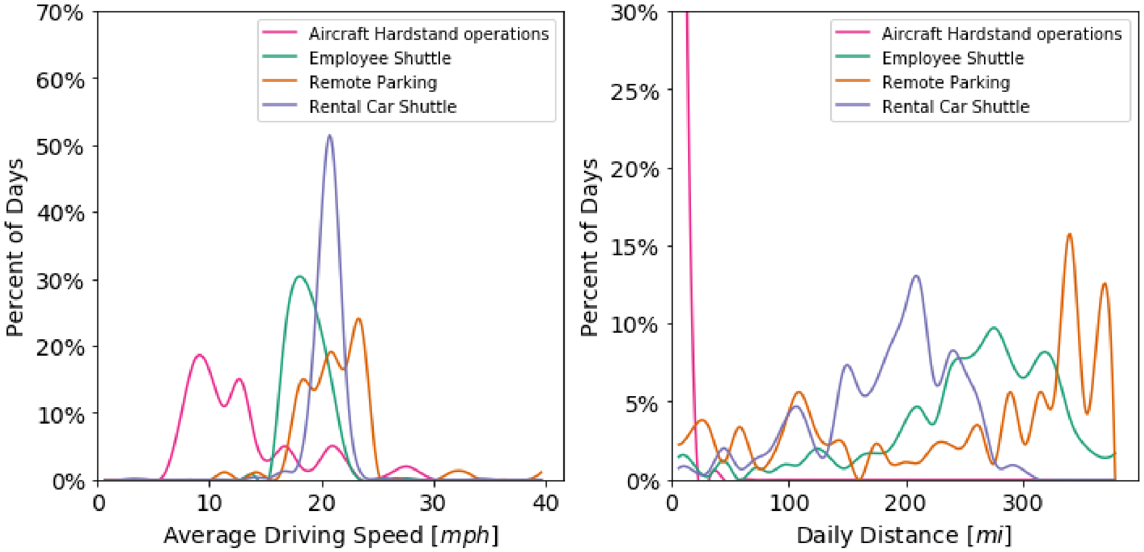

Figure 2: Distribution of daily average driving speed (left) and daily distance (right) by service type

Current DFW shuttles run on compressed natural gas (CNG) aside from the aircraft hardstand shuttles which use diesel. Figure 3 provides a distribution of daily average fuel economy in units of $\mathrm{MPG_{DE}}$ which is the diesel equivalent fuel economy. For this study we assume one liter of diesel has energy equivalent to 0.7634 kilograms of CNG. Based on this assumption the existing shuttles have a daily average fuel of 4.3 MPG_{DE} with most days falling between 3 and 5 MPG_{DE}. The left plot shows the equivalent U.S. gallons per hour with the average around 3 gallons per hour. Unfortunately, the aircraft hardstand shuttles did not report any engine information on the CAN, so they will be excluded for the remainder of this study.

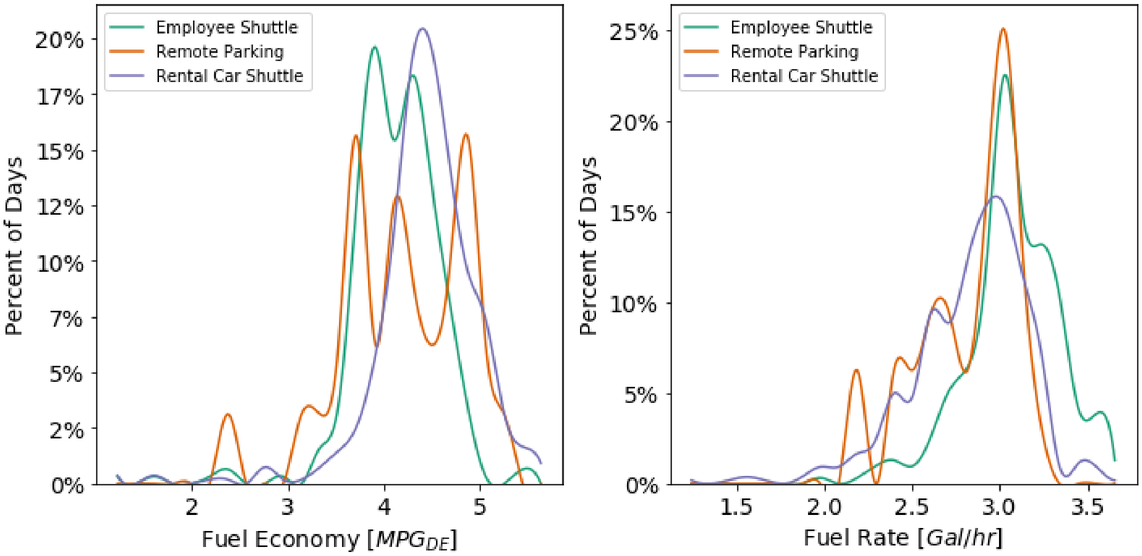

Figure 3: Distribution of daily average diesel equivalent fuel economy (left) and average fuel rate (right) by service type

While it is important to identify the required battery size to complete the daily operation, it is of equal importance to determine if there is enough charge time to replenish the energy used during that day. The left plot of Figure 4 shows the distribution of daily engine run time by service type highlighting that all services operate for a large portion of the day which makes it challenging to find opportunities for charging.

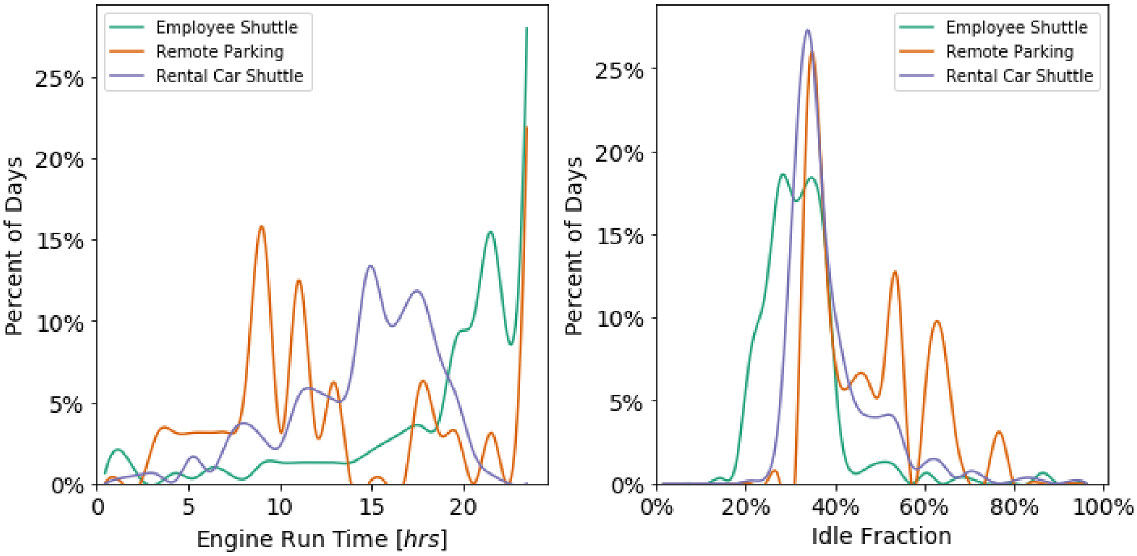

Figure 4: Distribution of daily engine run time in hours (left) and daily idle fraction (right) by service type

Employee shuttles have the longest average daily engine down time at 19.7 hrs followed by the Rental Car shuttles at 14.6 hrs and Remote Lot shuttles at 14 hrs. However, the right plot in Figure 4 indicates that between

15% and 70% of engine run time is spent idling (engine speed > 0 & vehicle speed =0) which provides an opportunity for energy saving since electric buses use very little energy at idle. Research on electrically driven accessories for similarly-sized hybrid electric buses measured electric power steering power around 0.6 kW, electric air compressors around 0.2 kW, and air conditioning between 0 kW for temperatures below 50^{o}F and 2.5 kW at 90^{o}F [9]. At 90^{o}F a bus may use up to 3.3 kW assuming all accessories are active, which would be 0.28 kWh for a 5-minute stop. Further, the times when the bus is idling could be used for instances of short, high-powered "opportunity charging" to sustain the buses battery throughout the day. Figure 5 shows the distribution of daily dwell lengths for all three vehicle service types combined with the individual distributions. The dwell lengths are times when the vehicle engine is off, categorized by charging potential based on dwell length. Dwell instances less than 5 minutes are red and considered too short for any charging. Those periods between 5 minutes and 1 hour in length are orange and are potential periods where a vehicle could be charged using a high-powered fast charger for opportunity charging. While all three service types had notable peaks around 10 minutes and 2 hours, the rental car shuttles had a third peak around 30 minutes which is likely a driver break period that could be good opportunity.

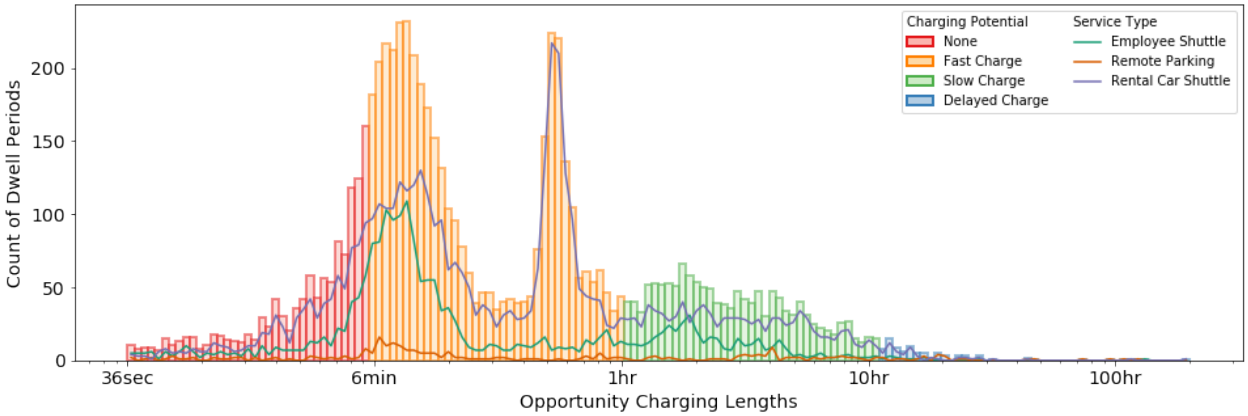

Figure 5: Distributions of dwell periods or periods of bus inactivity.

In electrifying such a challenging duty cycle it is important to get an accurate estimate of required propulsion energy and ensure any electric bus selected for replacement has enough energy storage to complete its operation. Modern engines broadcast instantaneous estimates of power output or flywheel power which can be integrated over the day to give engine "flywheel energy" in kWh that gives a conservative estimate of daily battery energy required. Figure 6 shows the distribution daily flywheel energy on the left and fraction of energy used at idle on the right. Employee shuttles had the highest daily flywheel energy with an average of 650 kWh produced per day and a maximum daily production of 960 kWh. Remote parking shuttles had the second highest flywheel energy production with a 450 kWh average and 875 kWh max followed by the Rental Car shuttles with a 385 kWh average and 640 kWh max.

Of the three services, the rental car shuttles were the only buses with average and max daily flywheel energies below the largest available BEB battery size of 660 kWh suggesting that much of the rental car shuttle service can be electrified. Average daily flywheel energy for the remote parking shuttles was also below the 660 kWh available battery size, but a large portion of those days were above that battery size meaning electrification may be challenging with existing operations and BEB technology. Finally, the employee shuttles had the highest daily flywheel energy with most days above the maximum available battery size making it very challenging to electrify these buses. Despite these high energy days, the right plot in Figure 6 shows that on average almost 18% of the daily energy produced comes from idling, which would be significantly reduced if these vehicles were electrified.

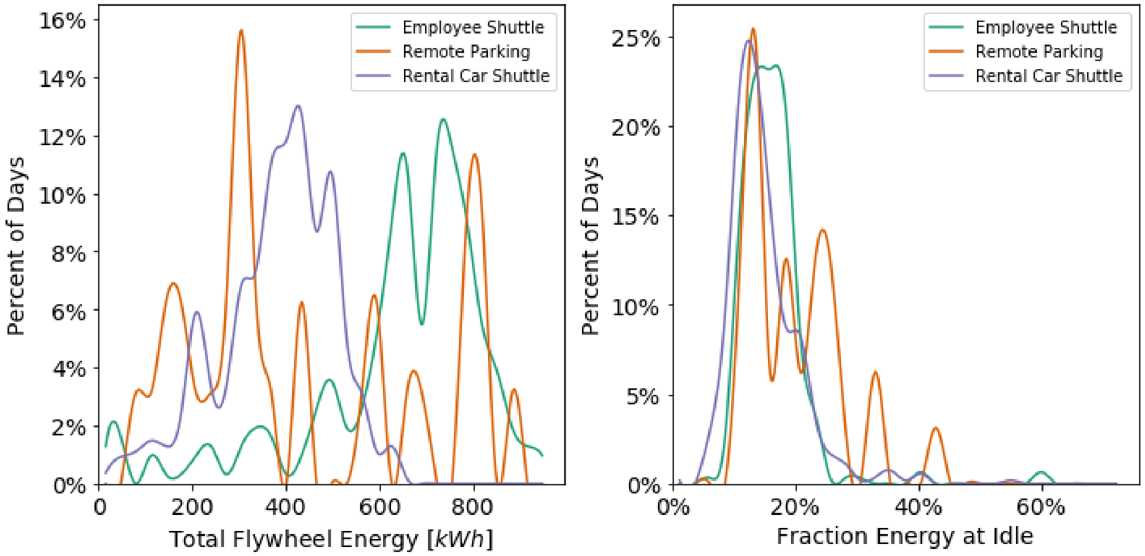

Figure 6: Distributions of daily engine flywheel energy (left) and fraction of energy produced at idle (right)

3 Modeling and Analysis

Rental car shuttles appear to be the best candidates for electrification based on the distribution of daily operating hours shown in Figure 4 and the energy distributions from Figure 6. However, those analyses do not consider the full use-dwell-use cycle to evaluate whether the daily energy consumed can be replenished before the next day's work. For instance, if there is no dwell between two days where 660kWh of energy is used, a bus would have a state of charge (SOC) violation meaning the buses battery would drop to 0% SOC.

3.1 Vehicle Model

To ensure that electric vehicles can meet daily demands, NREL developed a simplified electric powertrain model using data collected on the conventional buses to estimate BEB energy requirements. Figure 7 shows a diagram of the simplified model which works by taking the conventional vehicle power produced by the engine and assuming that is the power the BEB would use to complete the same drive cycles. For instance, if the engine produced 50 kW of power to move the conventional bus, we assume the BEB would also need 50kW of power. Next, we assume a 90% efficiency of the power electronics between the battery and the motor so that 50kW of propulsion power from the motor would equate to 55.5kW from the battery.

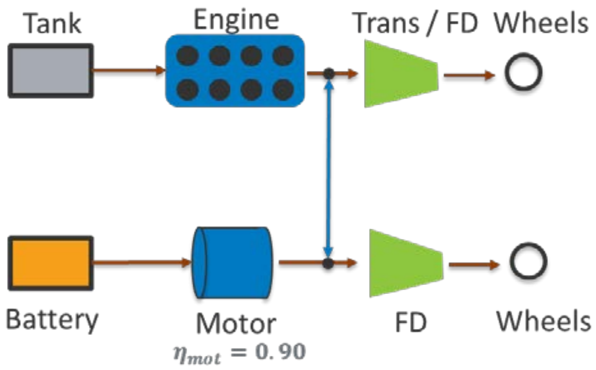

Figure 7: Simplified vehicle model diagram

This model also assumes that the BEB does not use energy when it stops since the equivalent electrical accessory loads are unknown. Another limitation of this model is that it does not account for energy recapture through regenerative braking resulting in a conservative estimate of net energy consumption by an electric bus. When the vehicle engine is stopped for longer than a specified time, the battery can be charged. Battery size and charge rate of the modeled BEB are then varied to identify battery and charger size combinations that enable electrification under that charging assumption. While the model is simple, it can make coarse approximations of battery size and charging power levels relative to commercially available options. For example, one bus manufacturer offers battery pack options of 220 kWh, 440 kWh, or 660 kWh. Figure 8 shows an example of the charge and discharge profile of a modeled electric vehicle over the entire data collection period. By looking at the vehicle's SOC verses time we can see instances where the SOC drops below 0% indicating a SOC violation. In other words, the bus required more energy than was available from the battery and alternative strategies may be needed to make this bus work.

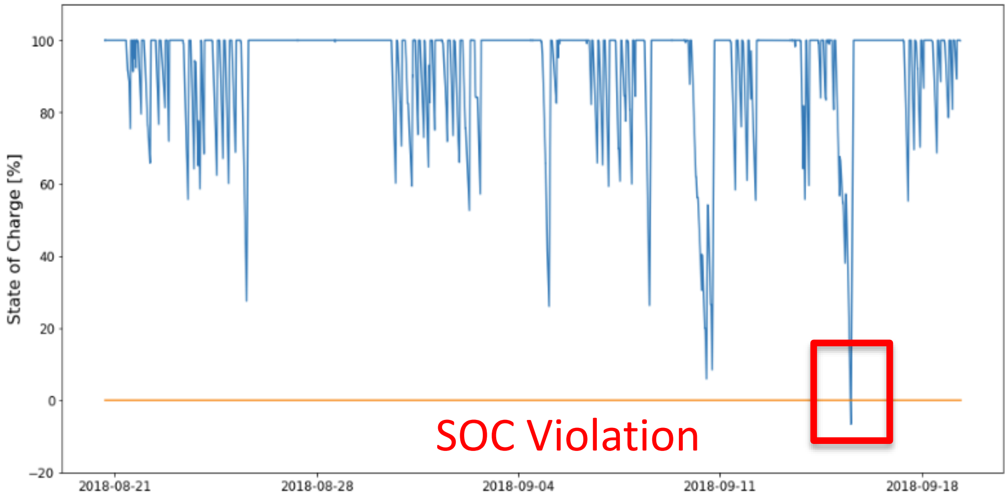

Figure 8: Example of charge and discharge output for 200kWh battery and 100kW charging highlighting a SOC violation

We ran the collected data from each bus through the model for two charging scenarios: 1) Charging during dwell times greater than 50 minutes. Most charging occurs in the bus depot, overnight or during driver changes. 2) Charging during dwell times greater than 5 minutes to assess on-route opportunity charging such as at a shuttle stops. Figure 9, Figure 10 and Figure 11 show a sweep of battery sizes and charge rates for the 50 minute or longer stop scenario. Brighter colors indicate more SOC violations, and darker colors indicate less along with two points showing plug-in and fast charge technology.

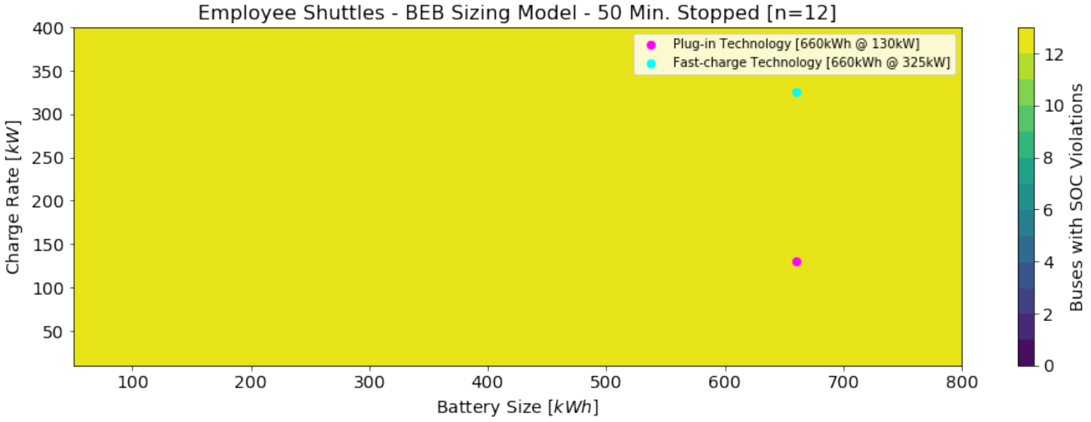

Figure 9: Employee shuttle model results for charging when the buses is stopped for 50 minutes or longer

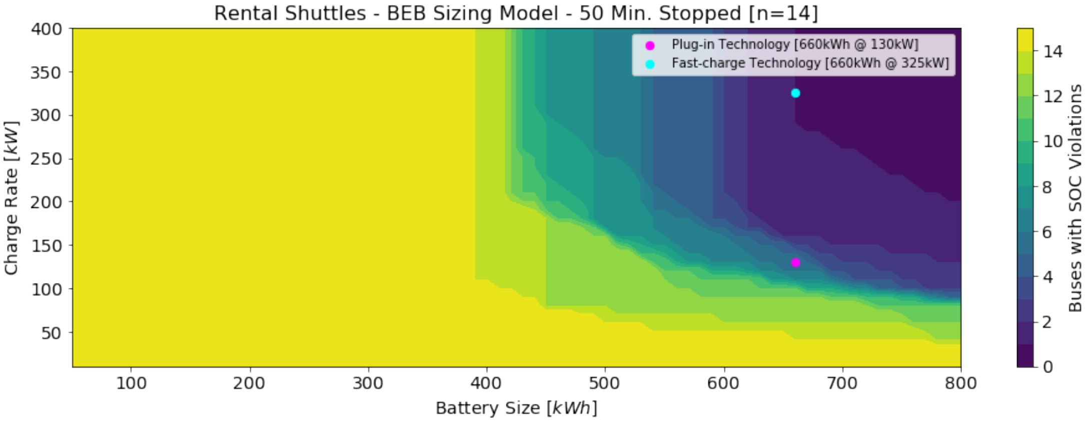

Figure 10: Rental car shuttle model results for charging when the buses is stopped for 50 minutes or longer

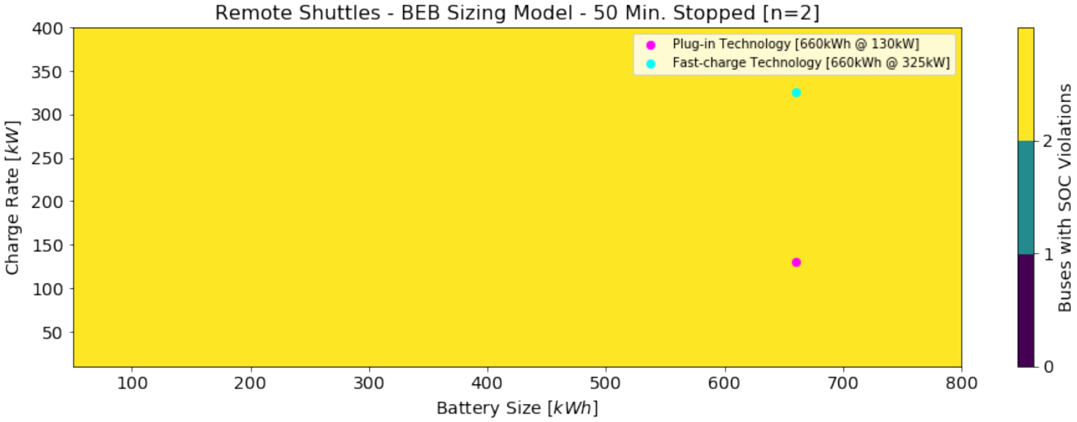

Figure 11: Remote lot shuttle model results for charging when the buses is stopped for 50 minutes or longer

With the current battery size of 660 kWh and charge rate of 130 kW as well as fast-charge rate of 325 kW, Figure 9 and Figure 11 indicate that the employee parking and remote parking shuttles were not able to complete the full suite of measured duty cycles over a month of operation without SOC violations using either plug in technology or fast-charge technology. In other words, those vehicles were not able to complete their existing work without dropping to 0% SOC. However, Figure 10 indicates that 9 out of the 14 rental car shuttle buses could be electrified with existing plug-in technology, and all rental car shuttles could be electrified if they used fast charge technology and charged when stopped longer than 50 minutes. It should be noted that only two of the remote shuttles had engine power data available, so the analysis is limited.

On-route fast charging is a commercially available option that can enable bus electrification by charging the bus during each pass of a loop thereby reducing battery size which would result in a cheaper bus and overall cost of the bus. Figure 12, Figure 13 and Figure 14 examine the potential for on-route fast charging to enable electrification by looking at battery sizes and charge rates that would enable electrification if the vehicle charged when it was stopped for 5 minutes or longer. Results indicate that employee shuttles are still unable to complete the full suite of driving without a significant number of SOC violations under this charging scenario. This means that changes to the operation, more buses or changes in BEB technology are needed to enable electrification for the employee shuttle operation. This analysis does not take into consideration the location of charging. Figure 13 and Figure 14 show that all remote parking and rental car shuttles can be electrified with existing technology assuming these vehicles charge when they are stopped for 5 minutes or longer at 130 kW and carry a battery 660 kWh or smaller. While this charging scenario is aggressive and likely to be cost prohibitive due to the increase in required charging infrastructure, the analysis should serve as an example of how a robust charging network can enable electrification.

Figure 12: Employee shuttle model results for charging when the buses is stopped for 5 minutes or longer

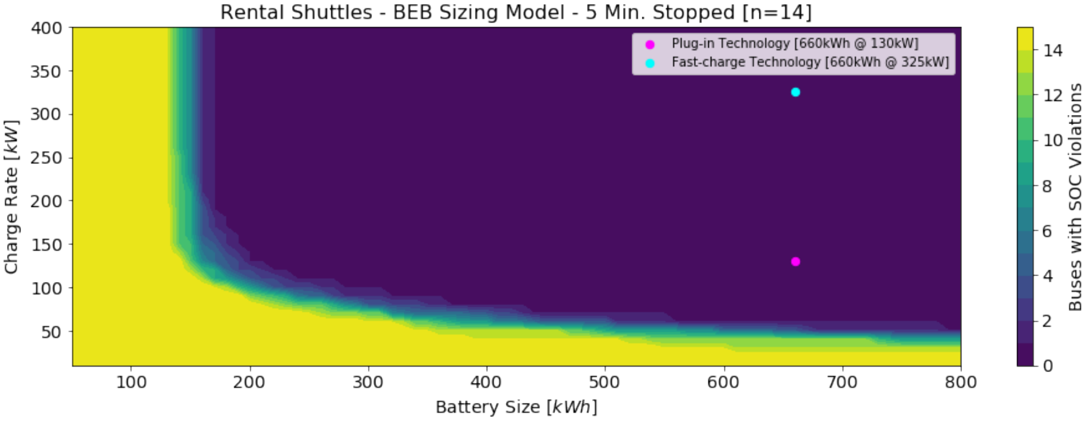

Figure 13: Rental car shuttle model results for charging when the buses is stopped for 5 minutes or longer

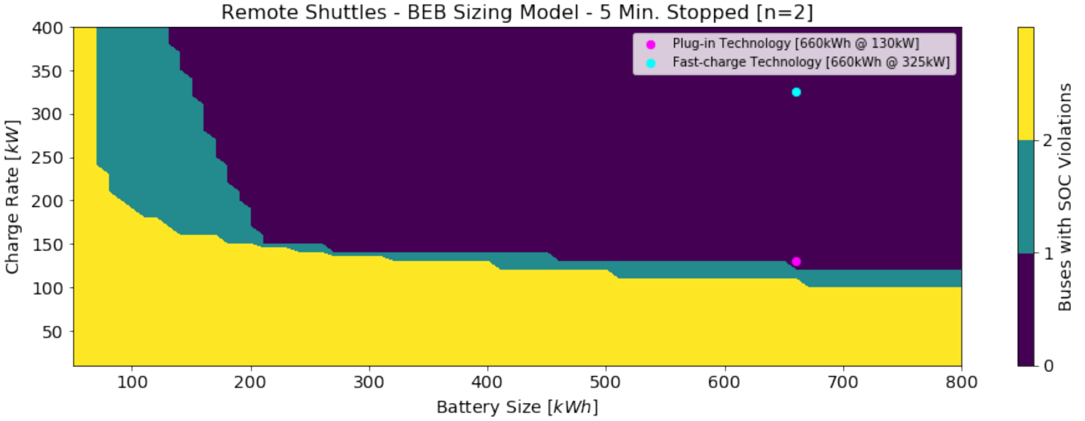

Figure 14: Remote lot shuttle model results for charging when the buses is stopped for 5 minutes or longer

Charging location is an important consideration in vehicle electrification, with slow charging typically happening at a depot and fast charging on route. To help identify potential charging locations, NREL performed a hotspot analysis of frequent stop locations which is shown in Figure 15.

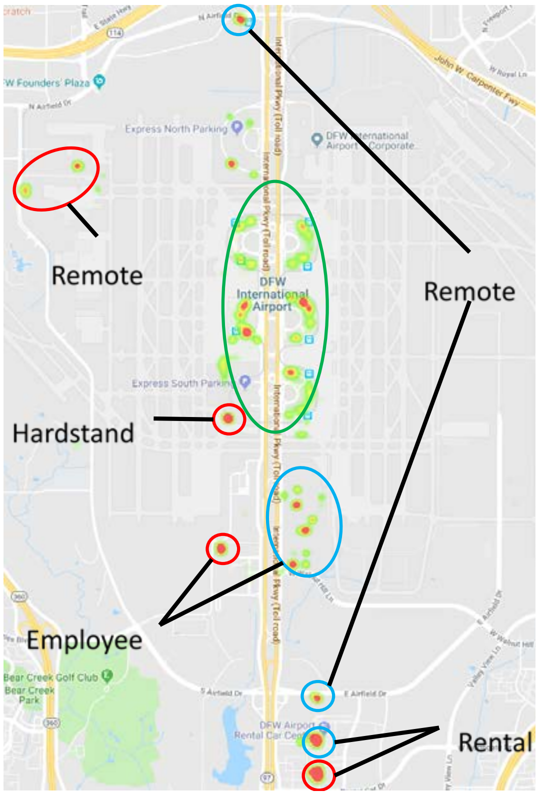

Figure 15: Hotspot analysis of stop location. Red Circles – stops greater than 50 min; Blue Circles – stops greater than 5 minutes; Green Circles – stops greater than 5 minutes within the terminal area. (base map: Google)

Hotspot analysis works by clustering geographic areas with more frequent stops as dark red and areas of less frequently stopping as lighter green. Further, Figure 15 has additional differentiation based on service type and stop duration. Red circled hotspots indicate stop locations of 50 minutes or longer for a single service type which are potential locations for overnight chargers. Blue circles highlight stop locations of 5 minutes or longer for a single service type, which could be used for fast charging. Installing fast chargers in blue circled locations would only service a single bus type, potentially resulting in the installation of redundant chargers. The green circled location outlines the airport terminals which has multiple stop locations co-located with the remote parking, employee lot and rental car shuttle service types. A charger placed at the terminal could be utilized by multiple service types thus reducing the total charging infrastructure cost.

3.2 Emissions

Energy use and estimated emissions were developed for the modeled BEBs and measured CNG vehicle information to allow the fleet owners to quantify the emissions impacts of electrification. As part of its efforts to achieve carbon neutrality, DFW purchases 100% wind energy meaning vehicle electrification fully eliminates tailpipe and production emissions usually associated with electricity generation. Production emissions for CNG were developed using Argonne National Laboratory's 2017 GREET model with production of CNG producing 420 $gCO_{2/}$kgCNG, 1.99g SO_X/kgCNG and 0.77g NO_X/kgCNG [10]. Tailpipe emissions were estimated based on vehicle reported fueling rate with the assumption that was composed of 95.7% Methane and 4.3% Ethane [11], and that 2.752 $kgCO_2$ were produced per kg of CNG by assuming all carbon is converted to CO_2 since all vehicles had catalytic converters. Figure 16 shows emissions from the existing CNG vehicles broken into fuel production and tailpipe emissions in the left plot and combined emissions in the right plot. It should be noted that CO2 is scaled by 1000g to show all emissions on the same plot. This analysis shows that electrification of the employee, remote parking and rental car shuttle services will eliminate nearly 18,000 tons of CO_2 emissions per year.

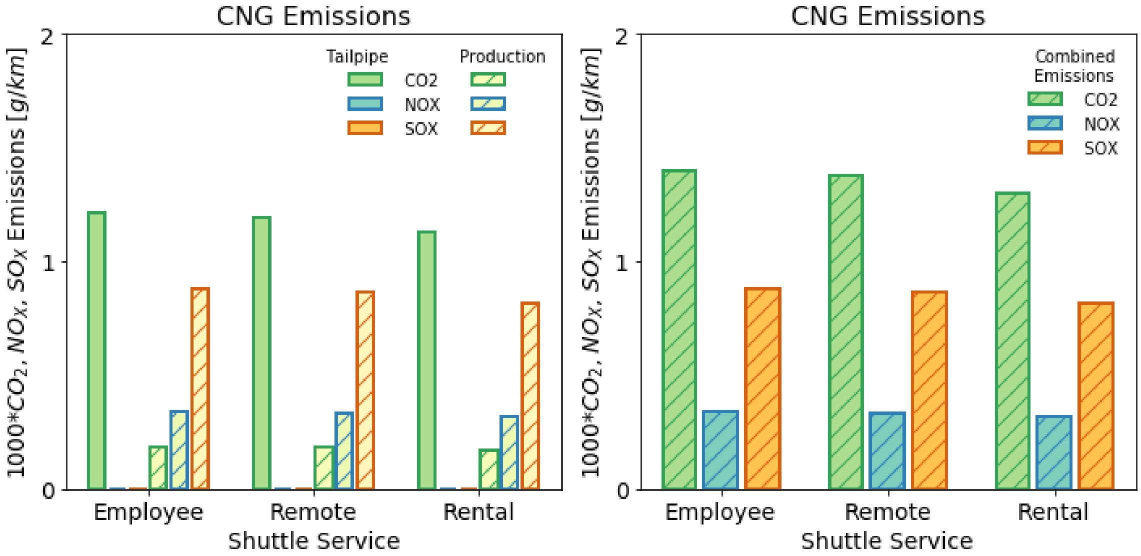

Figure 16: Emissions by source (left) and combined emissions (right).

4 Conclusion

This work outlines a process for heavy vehicle electrification by highlighting four airport shuttle services with varying electrification potentials. We examined existing operations by collecting data from in-service vehicles and developed a simplified vehicle model to estimate the benefits of, and requirements for, vehicle electrification. Results indicate that electrification is possible for rental car and aircraft hardstand airport shuttle services with little modification to existing operation. Remote parking and employee shuttles will need technological improvements, significant charging infrastructure, or changes to their operation to accommodate battery electric buses. Finally, with DFW purchasing 100% renewable energy, transition to a fully electric fleet would eliminate 18,000 tons of CO_2 per year, including tailpipe and energy production emissions. Results of his study are feeding airport decision making along with the U.S. Department of Energy collaborative Athena project that looks at improving transportation efficiency through high performance computing. Future work for this area should examine novel bus routing and optimization to help enable high penetration of BEBs along with developing higher fidelity vehicle models to better assess remote parking and employee shuttle operations. Further, in service testing of a BEB is recommended to understand climate impacts on HVAC loads.

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References

[1] H. Cai and M. Xu, “Greenhouse Gas Implications of Fleet Electrification Based on Big Data-Informed Individual Travel Patterns,” *Environ. Sci. Technol.*, vol. 47, pp. 9035–9043, 2013.

[2] D. Y. D.-Y. Lee, A. Elgowainy, A. Kotz, R. Vijayagopal, and J. Marcinkoski, “Life-cycle implications of hydrogen fuel cell electric vehicle technology for medium- and heavy-duty trucks,” *J. Power Sources*, vol. 393, no. April, pp. 217–229, 2018.

[3] M. Singer, “Consumer Views on Plug-in Electric Vehicles – National Benchmark Report,” no. January, p. 38, 2016.

[4] M. Thornton *et al.*, “Data Collection , Testing , and Analysis of Hybrid Electric Trucks and Buses Operating in California Fleets Final Report Data Collection , Testing , and Analysis of Hybrid Electric Trucks and Buses Operating in California Fleets Final Report,” 2015.

[5] Dallas Fort Worth Airport, “DFW Airport Achieves Carbon Neutral Accreditation for Third Year,” 2016. [Online]. Available: http://dfwairport.mediaroom.com/181108-DFW-Achieves-Carbon-Neutral-Accreditation-for-Third-Year.

[6] Dallas Fort Worth Airport, “Dallas Fort Worth International Airport: Carbon Footprint,” Fort Worth, TX, 2018.

[7] Society of Automotive Engineers, “J1939-71 Vehicle Application layer,” *SAE Int.*, vol. J1939-71, 2012.

[8] L. Eudy and M. Jeffers, “Foothill Transit Battery Electric Bus Demonstration Results: Second Report,” 2017.

[9] A. J. Kotz, “DATA DRIVEN APPROACH TO VEHICLE EMISSIONS REDUCTION,” University of Minnesota, 2016, p. 101.

[10] M. Wang *et al.*, “Summary of Expansions and Updates in GREET,” 2018.

[11] Enbridge, “Chemical Composition of Natural Gas - Union Gas.” [Online]. Available: https://www.uniongas.com/about-us/about-natural-gas/chemical-composition-of-natural-gas. [Accessed: 19-Mar-2020].

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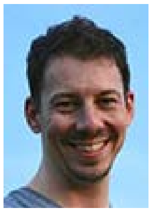
Kenneth has over 25 years of transportation research experience at NREL where he currently manages NREL’s Commercial Vehicle Technologies team partnering with government and industry to develop advanced vehicle technologies for medium- and heavy-duty applications. While at NREL, Ken has managed and conducted research in a wide array of advanced vehicle and transportation technologies. He holds M.S. and B.S. degrees in Mechanical Engineering from Ohio University. He may be reached at Kenneth.kelly@nrel.gov

Karen Ficenec received her bachelor’s and master’s degrees, in physics and business analytics respectively, from the College of William & Mary. Working as a data scientist at the National Renewable Energy Lab, Karen uses machine learning, optimization and data visualization to advance technology in the transportation sector. Her work includes optimizing component sizes for heavy duty vehicle specifications, helping inform emissions policy decisions by reporting on vehicle data, and running models to reduce congestion, increase mobility and aid in future design of transportation systems. She may be reached at Karen.Ficenec@nrel.gov



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