Life-cycle Analysis of Electric Vertical Take-Off and Landing Vehicles

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Abstract

Traffic congestion is challenging most world cities, and one way to avoid traffic delays is to take to the sky, using vertical take-off and landing craft or "VTOL". This study examines opportunities, costs, and energy impacts for eVTOL (electrically-powered VTOL) supply and demand across the Austin, Texas region. Using different demand levels and VTOL sizes (4 and 8 seaters - separately and in combination), we estimate per-person CBD trip minimum costs averaging $15.55 using 4-seaters, while a combination of 4 and 8-seaters offering the greatest energy and greenhouse gas savings, based on the Texas power grid's current feedstock.

Keywords: electric vehicles, vertical take-off and landing, air taxis, urban vertiports, short-distance flights, life-cycle analysis, greenhouse gases

1. **Introduction**

Many companies have suggested air taxis as a means to address urban-area congestion and air pollution. For example, Bell Flight is hoping that the U.S.'s first air taxi services will be between the Dallas-Ft Worth airport, the city of Frisco, and Arlington, Texas' baseball and football stadia in year 2025 (CBSDFW, 2018). Their current plan is to have 500 air-taxis, initially with human pilots, so passengers feel more comfortable (rather than autonomously managed aircraft). In collaboration with Uber, they are working on building vertical takeoff and landing aircraft (VTOL) to avoid ground congestion. VTOLs are not a wholly new technology, since helicopters are capable of vertical takeoff and landing, but their intended use in cities, with electrified propulsion (to reduce tailpipe emissions and noise), or eVTOL, is a new concept.

Using technology to solve problems is popular, though not always successful. A "technological fix" using low-cost but inappropriate technology can create more problems than it solves (Rosner, 2013). One way to avoid bad outcomes is to plan ahead, rigorously evaluating new options long before investment begins. One method for recognizing and mitigating emissions and energy effects of new technologies is application of life-cycle assessment/analysis (LCA). LCA is defined as "a tool to assess the potential environmental impacts and resources used throughout a product's life-cycle, i.e. from raw material acquisition, via production and use stages, to waste management". (Bjørn et al., 2018, p. 18). While LCAs for similar products can reach somewhat different conclusions (GDRC, 2016), such analyses are very valuable in identifying important environmental issues and suggesting directions for improvement. Since the 1960s, pollution, energy use, and material scarcity have been major drivers of LCA, with focus evolving from material waste, to pollution, to energy demand and greenhouse gas (GHG) emissions today.

Uber's recent VTOL report (Holden and Goel, 2016) claims that on-demand aviation has the potential to radically improve urban mobility, giving people back time lost in their daily commutes. Based on their proposals and the air taxi services that Bell Labs (CBSDFW, 2018) has proposed, use of VTOLs may be coming soon, to certain cities around the globe. Aside from the travel-time and roadway-congestion advantages that VTOL may offer, reduced tailpipe emissions and energy use may also be feasible, depending on how these vehicles are designed and used. To this end, this research evaluates different eVTOL scenarios' effects on environmental and cost factors, as a function of flight speed, passenger capacity, fuel consumption and weight, assuming a stable demand level between various origin-destination pairs in the Austin, Texas region.

2. **VTOL Literature Review**

Since VTOLs are a relatively new technology that have not been used in urban settings for regular public and personal use, there are few to no evidence-based studies regarding their performance characteristics. The majority of existing publications emphasize the potential for VTOL applications, and their associated requirements. For instance, Holden and Goel's (2016) paper about VTOLs for Uber concludes that current technologies are capable of delivering VTOLs cost-effectively at scale. They recognize that safety, low noise, low emissions, and high vehicle performance are keys for successful deployment. And they believe that distributed electric propulsion and autonomous operation technologies are vital features of such operations.

Holden and Goel (2016) also believe that most cities do not currently have the necessary takeoff and landing sites to readily host VTOL transport. Yet many cities have hospital and other heli-pads, as well as underused parcels and open spaces, which may enable limited initial VTOL operations.

In a recent NASA report, Antcliff et al. (2016) identified the inside of larger freeway cloverleaf ramps as ideal locations for vertiports and vertistops, recognizing that surrounding freeway noise renders the sound issue rather moot, and interchanges may enable very ready vehicle access, along with ready-ownership of such existing infrastructure by public transportation agencies. The feasibility and practicality of VTOL technology in urban areas can justify their infrastructure-intensive demands. Considering inherent infrastructure needs, Holden and Goel (2016) suggest that VTOLs are not meant for door-to-door travel, like driving and ride sharing apps enable. Like most public transit trips, walking or car use will be necessary for the first and last miles (or blocks) of most trips. Of course, walking out of a freeway interchange is simply not feasible, so those settings will probably require car or bus access.

Holden and Goel (2016) also identified VTOL flight altitude/height as an implementation barrier that requires aircraft-specific and setting-specific investigation. A dramatic increase in aerial operational activities is likely if on-demand urban VTOLs succeed. VTOL navigation systems also must be improved, and NASA's unmanned aircraft system traffic management (UTM) can be the beginning. Aside from air traffic issues, weather is another source of VTOL-related performance issues, due to wind and driving rain or snowstorms', which hamper passenger safety and comfort.

Antcliff et al. (2016) claim that for aircraft design studies, VTOL concept must meet these criteria to be feasible. For feasibility purposes, noise must be reduced by more than 20dB. Additionally, safety must be comparable to that of automobile safety, and have a price competitive with the average Uber ride (costing about $2 per mile in the U.S.). Demand studies should consider the current user trends of various transportation modes and demonstrate the VTOLs' market value costs, fleet size, service area, and vehicle utilization rates from hour to hour and day to day. It also is important to anticipate mode choices and connectivity of modes for these inter-modal trips: aside from walk-time and distance-cost penalties, VTOL route choice, and vertiport and (smaller) vertistop capacity constraints must be considered. Aside from all the demand and mode choices, costs of operation, noise, and other challenges, an aerospace study is necessary to show routes and trajectories without conflicts in each region, which may differ from existing studies' evaluations.

In an earlier NASA report, Alonso et al. (2014) demonstrated a mid-term solution for vertical takeoff and landing called Hoppers. Hoppers may be feasible with electric motors for regional or metropolitan aerial transportation systems. This study was conducted to evaluate a possible aerial transport network across the San Francisco Bay Area, served by three vehicle sizes (6-, 15- and 30-passenger vehicles), of which the latest design was a tandem helicopter with electric propulsion. Phase 1 of this study focused on design of battery-powered helicopters capable of carrying up to 30 passengers for 65 nautical miles. In Phase 2, tandem helicopters with different propulsion systems were examined, by evaluating tradeoffs between power and energy (Alonso et al., 2014).

Airbus, Boeing, and other corporations are devoting money and time to design and operate VTOLs. For instance, Airbus' Vahana A^3 made its first unmanned flight at the Oregon regional airport in 2018. The Opener Blackfly (manufactured in Palo Alto, California) and many other prototypes had their first manned flights in 2018 and earlier, as described at http://evtol.news/evtol-timeline/.

2.1. Life-cycle Analysis Literature

Bjørn et al. (2018) argue that life-cycle analysis has become a vital systematic method to analyze the environmental implications associated with products, processes and services through different stages of a product's life including design, materials and energy usage, transportation, construction, operation, maintenance and salvation. Since 1990 there has been an ambitious effort to quantify all the impacts imposed on the environment by products under study. The efforts culminated in the development of multiple databases adequate for life-cycle inventory. Although, due to inconsistency of different data bases, the results were not similar. The newest database which is used for life-cycle analysis and quantifying impacts on environment is "ecoinvent" which is a not-for-profit association founded by several institutes of the ETH domain and is aimed for consistent data standards and quality (Ecoinvent, 2019). The previously mentioned data base was process based which means to account for material and energy, emission, pollution and solid waste consumed and generated in the life-cycle of a product. There is another approach which is a top – down procedure to inventory the effects based on national statistics of trade between sectors leading to environmental input/output analysis. Although there are multiple standards and ISOs for LCA analysis, Chester (2008) claims four main LCA stages can be assumed, as follows:

- Define goals and scope to define boundaries and obstacles;
- Inventory analysis involving data collection and calculation of environmental burden;
- Assess human health effects in relative to scope of study, global or regional; and
- Assess effects of uncertainty, using sensitivity analysis on final results.

Chester (2008) notes how lifecycle analysis has been neglected in many areas of transportation research, design, and operations. For example, before his 2008 publication, there were no formal comparisons of passenger transportation modes (car, bus, high-speed rail, light-rail, and air travel). Although due to inclination toward personal vehicles there are many studies assessing its impacts. As an illustration, MacLean and Lave (2003) studied light vehicle duties in contexts of three sustainability axioms based on Anastas and Zimmerman (2003)'s 12 green design principles. They determined that despite some advancement toward greener LVDs but there is a tradeoff between acceptance of vehicles by people and getting greener. Lave et al. (2000) examined the economic and environmental consequences of the fuels and propulsion technologies that will be available for powering a large portion of the light-duty fleet (cars, vans, SUVs, and light trucks). Lave and MacLean (2002) compared the second generation of the first commercial hybrid electric vehicle (HEV), the Toyota Prius, to Toyota's conventional (internal combustion engine) Corolla. They concluded that for Prius to be financially attractive for US consumers the gasoline must be at least three times more expensive than now. Spatari et al. (2005) developed an LCA model to estimate the environmental implications of the production and use of ethanol in automobiles in Ontario, Canada.

LCAs of personal and commercial vehicles will continue, with Chester and Horvath (2009) using 79 distinct components to estimate the life-cycle energy and emissions impacts of different transportation modes. Their vehicle-based components can be separated into two operational and non-operational subcategories. For each component in the mode's life-cycle, environmental performance was computed and then normalized per passenger-kilometer traveled (PKT). The energy and emissions occurring over each component's lifetime were annualized or discounted to a present value for consistent comparisons. They showed how each vehicle's powertrain was most important for its lifecycle energy consumption, although non-operational components for the automobile and bus modes also accounted for a significant lifetime share, due to use of power and steel during production and manufacture. They concluded that Urban Diesel buses consume the most operational energy per PKT served (in the San Francisco Bay Area case study they used), at 4 Megajoules per PKT during non-peak hours. The second most-consuming mode in operational activities was the conventional gasoline pickup truck, using 3.5 MJ/PKT.

Chester and Horvath (2009) also estimated commercial aircraft operations to account for 69 to 79 percent of their life-cycle energy demands, making them the transportation mode with the highest ratio of operational to (total) life-cycle energy demand (for typical California-focused usage levels). While aviation had the biggest share, energy estimates for small, midsize and large aircraft were estimated to be just 1.8, 1.5, and 1.4 MJ/PKT, respectively. They also estimated airlines to exhibit the lowest sensitivity in energy use (per PKT) across typical passenger loads.

Note that the previously mentioned normalization makes similar transportation modes in different situations, like urban bus in off-peak and peak hours, comparable but lacks the required consistency for comparison between two distinct modes - like pickup trucks and urban buses. Since the pickup truck is not intended to move people, it is better to normalize its energy consumption by the amount of freight it moves or the total traveled distance of the vehicle not including the passengers. Sen et al. (2017) compared substitute truck fuels' emission externalities across the truck's life-cycle, by monetizing emissions damages in dollars. Owen (2006) quantified electric-power generation's externalities, which is important when powering electric vehicles, like eVTOL. And Nichols et al. (2015) compared emissions costs of electric and non-electric passenger vehicles in Texas, with the EVs performing better, even with that state's past power grid in place.

Vehicles using substitute fuels are key example transportation LCA. Samaras and Meisterling (2008) estimated life-cycle GHG emissions from plug-in hybrid electric vehicles (PHEVs), using a combination of economic input-output models and process-based LCA methods. They concluded that PHEVs may or may not enjoy lower GHG emissions than HEVs, over their life-cycles, depending on where the vehicle gets its power and how long it is used for (before crashing or being otherwise scrapped). Karabasoglu and Michalek's (2013) related work explored driving patterns' impacts on HEV and plug-in EV life-cycle costs and emissions. Instead of using US federal test cycle efficiency estimates, they recommend real-world driving cycles for better cost and emissions estimates. They used the New York City or NYC driving cycles to better reflect low-speed urban driving conditions, with frequent stops, and this lowered their HEV's life-cycle costs by up to 20 percent and its GHG emissions by up to 60 percent. Using highway-driving engine loads (with speeds up to 60 mph) suggested that more conventional vehicles offer lower life-cycle costs and GHG emissions. Note that the life-cycle GHG emissions for a vehicle, used in latter study, are from sources in 2007 which seems to be pessimistic toward the car industry.

Hawkins et al. (2013) estimated a 10 to 24 percent decrease in GHG emissions via battery-only electric vehicles based on the EU's power plant electricity mix, thanks to much more efficient drivetrains and motors. They note that electric vehicles may also cause a significant increase in freshwater eco-toxicity, freshwater eutrophication, and metal depletion, due to battery and vehicle manufacture processes and inputs. Efforts made to capture the sensitivity of these results show more variation for electric vehicles with respect to lifetime. Assuming an electric vehicle lifetime of 200,000 km increases the potential toward decrease of global warming to 27 and 17 percent for gasoline and diesel vehicles, respectively. The environmental benefit relative to diesel vehicles would be indistinguishable assuming a lifetime of 100,000 km for electric vehicles.

Furthermore, Tessum et al. (2014) demonstrated that the lifetime air quality impacts of electric vehicles on human health are not always lower than those of conventional vehicles or those with substitute biofuels. Considering the source of energy, electric vehicles with coal as their main energy supply (electricity plants powered by coal) is the worst case. Similarly, the vehicles operating on corn ethanol are the second worst vehicles regarding this metric. Similar concerns were investigated by Messagie et al. (2014) developing a range-based modeling system that enables a more robust interpretation of the LCA results. After assuming a possible range for weight, fuel consumption and different values of emission, a Monte Carlo simulation is used to evaluate the life-cycle effects and costs of different car technologies. The analyzed components are the effects on climate change, respiratory effects, acidification, and mineral resource depletion considering them for driving 230,500 km in 13.7 years. Although the previously mentioned manuscript is unable to provide any insight on the effects of their decision based on one-point estimation, it provides a variation of results for different vehicles with different fuels.

To eliminate the variation of possible differences due to location and condition of implementing new technologies and their effects and costs through their lifetime, Nichols et al. (2015) evaluated the effects of electric vehicle adaptation in Texas. They take into account the impacts of battery-charging decisions and power plant energy sources across Texas. They convert a plug-in electric vehicle (PEV) demands to emissions over time and space from all the possible sources related to PEVs. The emissions impacts are evaluated relative to conventional passenger vehicles (CVs). They concluded that PEV's emission benefits, normalized to 12,000 annual miles of driving, would be lost if more than 25 percent of the power plants use coal as their fuel.

As new technologies continue to emerge, and connected autonomous vehicles (CAVs) are introduced, the potential to decrease transportation externalities has led to additional LCA research. Gawron et al. (2018) estimated that passenger vehicle primary energy use and GHG emissions could rise by 3 to 20 percent due to more power consumption from added weight, drag, and data transmission needs on CAVs, versus human-driven vehicles. But CAVs' potential operational benefits, including eco-driving, platooning, and intersection capacity improvements may more than address such issues – in the near to long terms. Sharing right-sized electric AVs (rather than relying on the typical utility vehicle many Americans buy, for example) and sharing rides together (to fill seats) offers even greater benefits. The LCA work of Fagnant et al. (2015) on shared AV (SAV) fleets found dramatic reductions in cold start emissions, though distances traveled rose (unless dynamic ride-sharing is heavily used), due to empty-vehicle driving between travelers. Lee and Kockelman's (2019) evaluations of CAVs' various energy impacts (which reflect the added demand that comes with making "driving" easier) note how critical CAV drivetrain electrification will be, to offset such added demands for motorized travel.

3. **Methodology**

There are three major components of LCA for VTOLs: energy consumed, environmental externalities, and operational costs. The energy consumed has two distinct phases, the first from manufacturing VTOLs and the second from operation. The environmental externalities, including pollution emission, also has similar distinct phases in which the operational phase's environmental costs, due to electricity usage, are assumed to be solely due to recharging batteries as there is no tailpipe emission.

In order to deliver realistic estimates here, we consider the source code and assumptions of a sizing study for Airbus' Vahana A3 (Lovering, 2016). That study compared electric helicopters to 8-fan tilt-wing VTOLs. The code was used to design low-cost, single-passenger electric VTOL capable of serving many people (Lovering, 2016) and was adjusted here to allow for more seats and more flying weight.

Vahana's open-source code is capable of calculating design values based on maximum takeoff weight, size and cruise speed by optimizing the operating cost, which includes acquisition, insurance, facility, energy, battery and motor replacement, servomechanism or "servo" (an on-board computer) replacement, and labor costs (Lovering, 2016). Based on that study, energy consumed in the eVTOL and vertiport infrastructure manufacturing phase has already been changed to dollars and enters here as price, so there is no need for further elaboration in this regard. Additionally, operating costs consisting of electricity consumed, platform rentals, and maintenance labor have been converted to US dollars ($). Note that these assumptions and values can change over time, due to new technologies and economies of scale in production processes. Therefore, the sensitivity analysis of results based on some changes that are more probable in near future should be considered.

3.1. Externality Assumptions

The main parts of the body, aside from the motor and battery, are assumed to be made from a material a little heavier than carbon fiber. Since carbon fiber is used in vehicle industries for many nonstructural parts, it makes sense to compare the elements surface unit weights with carbon fiber. Lovering's (2016) Vahana trade study assumes material plus assembly cost for each pound to be $100. This may be a conservative assumption considering a 2014 Reuters study reported the average cost of light-weight carbon fiber parts to be $64 per lb (Reuters, 2018). Besides the material cost, in this study tooling cost is assumed $300 per cubic feet.

Batteries are assumed to be $700 per kilowatt hour they produce, and the battery output is assumed to be 104 watt-hours per each pound of its mass. Thus, the battery cost per pound is assumed to be 74 dollars per pound. Although Next-battery Corporation (Next-Battery, 2019) quotes from Bloomberg new energy finance that by 2030 the batteries would cost $300 for each kilowatt hour they provide, which will reduce the battery cost of our VTOL to $32 per pounds. The current Tesla Battery Pack is $260 per each KWH which further reduces the battery cost to 30 dollars per pound. The number of cycles in battery life are assumed to be 2000. Although the regular lithium ion batteries' number of cycles throughout their lifetime is between 400 and 1200, Tesla's Battery pack has 7,500 cycles. Therefore, the assumed cycles in a battery life is reasonable.

One really important aspect of using batteries is the time it requires to recharge from 20 percent (the reserve value for emergency during mission). The Opener Blackfly eVTOL has reported four different charging times based on input current and used voltage. It is shown that charging an 8 kWh battery with a voltage of 120V and input current of 20A would take up to 5.5 hours (Opener, 2018). That would definitely restrict VTOL usage and dramatically increase costs. Tesla's Superchargers are able to charge a 100 kWh battery (model S of Tesla cars) in half an hour from 20 to 80 percent of capacity, as charging slows down to protect the battery after passing 80 percent of capacity (PodPoint, 2019). Therefore, assuming this amount of time for charging 100 kWh of battery may provide a more reasonable charging time. The fact that batteries would not be completely discharged after each eVTOL flight will help to reduce the time required to prepare each eVTOL for its next destination.

The Vahana team suggests $70 per kilogram for propulsion motor. They also add $800 for each servo and $30,000 for avionics costs on each eVTOL. 14 servos are required for an 8-fan tilt wing eVTOL, as used here.The motors are assumed to be capable of generating 5 kW per kilogram. The motor and servo lifetimes are assumed to be 6,000 hours, which enables estimation of motor and servo replacement costs. Labor required for maintenance and battery swap inspection is assumed to be 0.1 person-hours per flight-hour (Lovering, 2016).

The average electricity cost in US is 12 cents per kWh but the value for Texas is less than 11 cents per kWh (ComparePower, 2018). Due to losses during charge, the charge efficiency is assumed to be 0.9 which is optimistic regarding lithium ion batteries. The electricity cost is used to evaluate the energy consumed from VTOL operation.

The facility rental cost is assumed to be 20% larger than the vehicle footprint, which equals (8 x rotor radius + 1) * (4 x rotor radius + 3), in order to enable maintenance access. The Vahana code's base platform-rental cost assumption is $2 per square feet per month. The area then required for operations, passenger access, waiting areas and personnel activities around VTOL (for maintenance and such) is assumed to be 10 times greater. Insurance costs per year are assumed to be 6.5 percent of the value of product or total acquisition cost. Other, less important assumptions, that do not directly affect cost calculations, are the weights of each seat (assumed to be 30 pounds), avionics (30 pounds), each servo (just 1.3 pounds), each wing tilt actuator (8 pounds), and the ballistic recovery system (32 pounds). Since landing gear is about 2 percent of a helicopter's maximum takeoff weight (Lovering, 2016), a similar assumption is made here for each eVTOL. Such assumptions help with estimation of VTOL manufacturing and operating costs.

Environmental externalities from eVTOL use include battery and vehicle parts disposal, noise, power and manufacture and maintenance emissions; and these are addressed here. Safety concerns due to hacking or pilot harm or even sexual assault of passengers are sometimes mentioned but are not addressed here, due to lack of data. Shaheen et al. (2018) also note that VTOL passengers generally cannot stand up in or even change their seats in these small aircraft.

Environmental externalities due to recharging batteries come mainly from power plant operations and emissions. Nichols et al. (2015) estimated the air quality impacts of using electric vehicles in Texas based on the Electric Reliability Council of Texas (ERCOT) emissions rates, as shown in the first part of Table 1. More recent Texas power plant emission rates based on the US EPA's (2016) eGRID data, provided in Table 1's second half, show emissions improvements per MWH of coal-generated power, but higher emissions from ERCOT's natural gas power plants, per MWH. Aside from that, the eGRID average emission rate for CO_2 equivalent for the State of Texas (ERCOT sub region of eGRID) is 1054.6 pounds of CO_{2e} per MWH produced.

Production of a Lithium-ion battery is another source of eVTOL externalities. Romare and Dahllöf (2017) estimated that the batteries' production process generates 37 to 87 pounds of CO_{2equiv} per kilowatt-hour of capacity.

TABLE 1. AVERAGE ERCOT (TEXAS POWER GRID) EMISSIONS RATES (LB/MWH)

	Fuel	*NOx*	*SO2*	*CH4*	*N2O*	*CO2eq*	*PM2.5*	*CO*	*VOC*
Values of 2012	Coal	4.04	19.2	284.7	422.3	6,537.5	0.11	2.97	0.03
	Natural Gas	0.28	0.006	52.6	5.4	671.8	0.04	0.12	0.02
	Other	0.11	1.8	28.1	41.2	641.6	-	-	-
	Biomass	2.06E-4	1.41E-5	0.276	0.037	0.004	-	-	-
ERCOT Values of 2016	*Fuel*	*NOx*	*SO2*	*CH4*	*N2O*	*CO2eq*	-	*CO2*	-
	Coal	1.19	2.95	0.27	0.04	2,330.5	-	2312.74	-
	Natural Gas	0.45	0.01	0.02	0.00	865.17	-	864.37	-

Note: PM2.5 is particulate matter less than 2.5 microns in effective diameter and VOC is volatile organic compounds. Powerplant SO2 regularly forms PM2.5 downwind. Nuclear reactors, wind and solar sources also exist for power generation but offer no operating emissions, so they are not shown here.

Note that high concentration of SO_2 gasses can produce multiple health and environmental issues because they are a major precursor of $PM_{2.5}$. SO_2 gasses are formed when fuel containing sulfur, like coal, is burned (EPA, 2018).

Pollution emitted during manufacture and construction is another important feature of LCA. Sullivan et al.'s (2010) detailed life-cycle energy and CO_2 results for a generic 3,370-pound passenger car are considered here. For instance, the amount of emitted CO_2 during stamping is estimated to be between 0.06 and 0.88 pounds for each kilogram of stamped material. In many cases CO_2 is calculated from listed energy assumed to be natural gas and grid electricity; for example, energy for stamping is 5.1 mega Joules, which is converted to the emitted CO_2.

These VTOL calculations use carbon fibers (or a mixture of carbon fiber and other light materials), with an estimate of 20 tons of CO_2 emitted per ton of carbon fiber manufactured. This is justified by the assumption that 22 million tons of CO_2 will be eliminated in car and aircraft life-cycles thanks to tailpipe emissions reductions (Torayca, 2019).

Considering the amount of GHG emissions, the only part that can be changed is the Material Transformation. Based on de Beer et al.'s (2003) work, production of one ton of Iron results in 0.6 to 2.2 tons of CO_2 using manufacturing technologies of that era. Assuming the prototype weight of the Vahana VTOL used in flight and the comments Zach (Lovering, 2018) made on the proportion of carbon fiber used in their design to be 400 pound, the carbon fiber percentage would be 37% of empty weight. Although these calculation and assumptions seem rational, we won't consider these emissions in our calculations because of increasing industry efficiency and the age of assumed values.

3.2. Life-cycle Analysis

Here, demand for eVTOLs is assumed to be two and five percent of the Austin area's personal vehicle trips between each vertiport. Assuming the eVTOL's main purpose is to bypass congestion, a notional network is assumed to connect all vertiports directly – with Euclidean routing or straight lines. Figure 1's proposed vertiport locations are based on important destination choices, current trip patterns and physical possibility of building a vertiport. As previously discussed, vertiports can be placed on top of tall buildings or in large parking lots and are not restricted to emergency uses like hospital helipads.

There are three different buffer radii used in Figure 1: these are 0.5, 2 and 5 miles, and believed to be adequate for those walking and biking, busing, and/or driving to the vertiports, respectively. Those with 0.5-mile radius are used for Austin's downtown locations, with scarce parking but high trip-origin and –destination densities that motivate people to walk or bike or e-scooter to these vertiports. The 5-mile buffer is used only for the Georgetown City station, far from the regional core, where population and jobs densities are relatively low and parking much less expensive or freely available. The remaining vertiports are assumed to serve people from a 2-mile radius. There is only one vertiport for which the demand is assumed to be derived from people living in the San Antonio CBD; this is outside the 6-county Austin regional boundary, but can capture many trips between the two cities and those at the southern edge of Austin. The maximum distance between this network's OD pairs is 62.3 miles (between Georgetown and San Antonio's CBD). The minimum is 1.33 miles, between the University of Texas campus and Austin Convention Center. The average distance is 22 miles and there are 81 OD pairs considered.

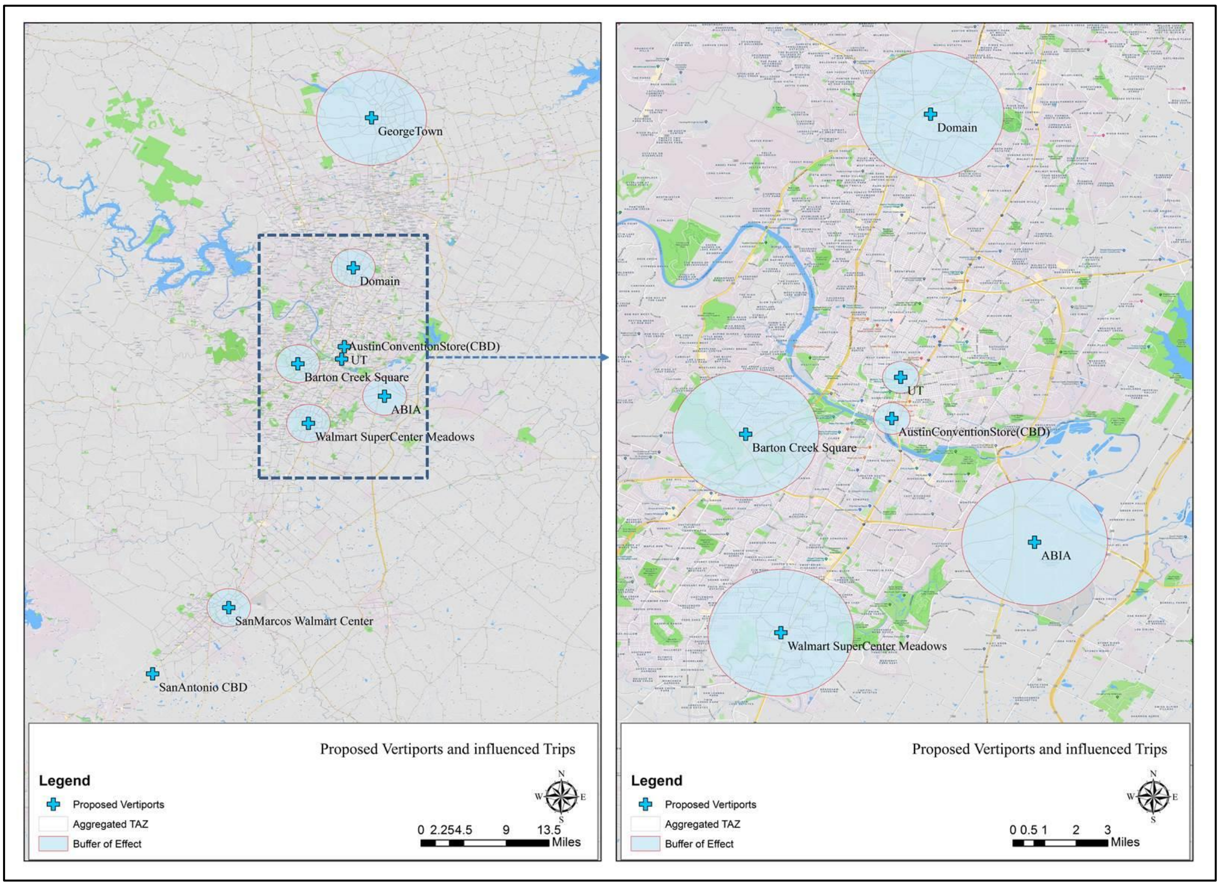

FIGURE 1. PROPOSED VERTIPORT LOCATIONS AND AFFECTED TAZs

4. **Results**

The required number of eVTOLs and each traveler's trip time is calculated for afternoon-peak-period service after assuming that demand is uniform during afternoon peak hours, cruise speed is at least 125 mile/hr (200 km/hr), each takeoff and landing or "hover transition" takes 3 minutes, and boarding of and alighting from eVTOLs take 1 and 2 minutes, respectively, for 4- and 8-passenger eVTOLs. Demand varies across 3 other broad times of day (AM peak, mid-day, and overnight periods, during a typical Austin-region weekday), and those are computed as well, for a 24-hour "typical day" LCA.

Two methods for flight scheduling are used here, with both methods having the same system layout and demands, but different vehicle configurations. VTOL flights are scheduled only for scenarios that with sufficient demand to ensure 50 percent or higher eVTOL occupancy levels. The first method uses just one vehicle design or configuration, in terms of passenger capacity, and is tested for 4-seater and then 8-seater aircrafts separately. The second method uses more efficient (and cost-effective) combinations of 4- and 8-seater eVTOL to schedule flights between various origins and destinations. Method one is labeled “single eVTOL service” while Method two is called “Multiple eVTOL service”.

Since eVTOL craft’s range has significant effects on usability and costs (Table 2), different types of eVTOLs are assigned to different OD pairs routes to keep costs low. eVTOL ranges rise with battery and motor size, so Table 2’s data are for the distances of the Austin system evaluated here.

Assuming 10 years for each eVTOL’s life-cycle and demand change pattern for trips throughout the year, similar to Hallenbeck et al. (1997) findings, Table 3 presents total passenger-mile covered by eVTOLs using both scheduling methods. Table 3 shows how eVTOLs suitable for mid-distance flights (31.25 to 50 miles) carry the most PMT. Due to fact that motor, servo and battery life-cycles are shorter than an eVTOL’s life-cycle, their usage is calculated separately, with replacement costs included. Table 4 presents the estimated numbers of required batteries, motors and servos, based on the externality assumptions discussed above, using Vahana Airbus source code.

TABLE 2. VTOL TYPES USED AND CHARACTERSITICS FOR EACH OD PAIR

# Passengers	*Payload (lb)**	*Range (miles)*	*Maximum Takeoff Weight (lb)*	*Acquisition Cost ($US)*	*Station Costs ($US) per Year*	*Energy Used per Flight (kWh)*	*Energy Costs ($US) per Flight*
4 pax.	*1000 lb*	6.25 mi	2,609 lb	$146,843	$ 324,900	10.2 kWh	$1.40
		12.50 mi	2,713lb	$ 153,753	$ 316,571	11.1 kWh	$1.48
		18.75 mi	2,823 lb	$ 161,167	$ 315,099	11.6 kWh	$1.55
		25.00mi	2,937 lb	$ 168,927	$ 317,820	12.2 kWh	$1.63
		31.25 mi	3,054 lb	$ 176,969	$ 323,333	12.7 kWh	$1.70
		37.50 mi	3,177 lb	$ 185,273	$ 330,897	13.3 kWh	$1.77
		43.75 mi	3,300 lb	$ 193,840	$ 340,148	13.8 kWh	$1.84
		50.00 mi	3,428 lb	$ 202,675	$ 350,793	14.4 kWh	$1.91
		56.25 mi	3,560 lb	$ 211,796	$ 362,727	14.9 kWh	$1.98
		62.50 mi	3,696 lb	$ 221,219	$ 375,839	15.4 kWh	$2.06
8 pax.	*2000 lb*	6.25 mi	4,717 lb	$ 221,767	$ 520,659	19.0 kWh	$2.53
		12.50 mi	4,875 lb	$ 232,232	$ 507,165	19.9 kWh	$2.65
		18.75 mi	5,047 lb	$ 243,779	$ 503,937	20.8 kWh	$2.77
		25.00 mi	5,227 lb	$ 256,084	$ 507,118	21.6 kWh	$2.89
		31.25 mi	5,416 lb	$ 269,010	$ 514,656	22.5 kWh	$3.00
		37.50 mi	5,612 lb	$ 282,512	$ 525,534	23.4 kWh	$3.12
		43.75 mi	5,817 lb	$ 296,584	$ 539,067	24.3 kWh	$3.24
		50.00 mi	6,028 lb	$ 311,233	$ 554,903	25.2 kWh	$3.36
		56.25 mi	6,248 lb	$ 326,498	$ 572,881	26.1 kWh	$3.48
		62.50 mi	6,477 lb	$ 342,420	$ 592,832	27.0 kWh	$3.60

* Each passenger with his/her associated luggage is assumed to weight 250 lb (114 kg).

TABLE 3. VTOL TOTAL PASSENGER MILES OVER LIFTIME (M PAX-MI)

Method		***Single eVTOL Service***				***Multiple eVTOL Service***			
Demand Scenario		*2% of nearby trips*		*5% of nearby trips*		*2% of nearby trips*		*5% of nearby trips*	
Number of Passengers		*4 pax*	*8 pax*	*4 pax*	*8 pax*	*4 pax*	*8 pax*	*4 pax*	*8 pax*
VTOL Range (miles)	*6.25 mi*	7.81 M pax-mi	7.62M pax-mi	19.07M pax-mi	19.03M pax-mi	0.19 M pax-mi.	7.62M pax-mi	0.54M pax-mi	19.03M pax-mi
	12.50 mi	17.30M pax-mi	16.77 M pax-mi	41.74 M pax-mi	41.74 M pax-mi	0.54 M pax-mi	16.77 M pax-mi	1.25 M pax-mi	41.74 M pax-mi
	18.75 mi	7.74 M pax-mi	5.85 M pax-mi	19.18M pax-mi	18.97M pax-mi	1.89M pax-mi	5.85M pax-mi	5.03M pax-mi	18.97M pax-mi
	25.00 mi	3.40M pax-mi	0.22M pax-mi	9.17M pax-mi	8.38M pax-mi	3.18M pax-mi	0.22M pax-mi	8.69M pax-mi	8.38M pax-mi
	31.25 mi	22.47M pax-mi	20.17M pax-mi	64.52M pax-mi	58.10M pax-mi	2.30M pax-mi	21.77M pax-mi	14.72M pax-mi	62.22M pax-mi
	37.50 mi	22.28M pax-mi	21.91M pax-mi	53.77M pax-mi	53.77M pax-mi	0.30M pax-mi	23.46M pax-mi	0.74M pax-mi	57.55M pax-mi
	43.75 mi	21.18M pax-mi	20.08M pax-mi	52.24M pax-mi	52.24M pax-mi	1.05M pax-mi	19.32M pax-mi	2.51M pax-mi	50.14M pax-mi
	50.00 mi	7.51M pax-mi	6.39M pax-mi	18.38M pax-mi	18.38M pax-mi	1.27M pax-mi	7.65M pax-mi	3.02M pax-mi	21.65M pax-mi
	56.25 mi	7.81M pax-mi	7.62M pax-mi	19.07M pax-mi	19.03M pax-mi	0.00	0.00	0.00	0.00
	62.5 mi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sum		112.94M pax-mi	102.25M pax-mi	286.10M pax-mi	278.64M pax-mi	10.72M pax-mi	102.66M pax-mi	36.51M pax-mi	279.66M pax-mi
Total						113.39M pax-mi		316.17M pax-mi	

TABLE 4. VTOL MOTOR, SERVO, AND BATTERY REPLACEMENT COST DURING LIFETIME

# Pax.	*Payload (lb)*	*Range (mile)*	*Battery Mass (lb)*	*Motor Mass (lb)*	*# Flights before Recharging*	***Single eVTOL service***				***Multiple eVTOL service***			
						#Required Motors & Servo Package		*#Required Batteries*		*#Required Motors & Servo Package*		*#Required Batteries*	
						2%	*5%*	*2%*	*5%*	*2%*	*5%*	*2%*	*5%*
4 pax	1000 lb	6.25	448.8	173.8	3	11	23	112	253	0	1	3	6
		12.50	521.4	182.6	3	13	30	100	225	0	1	3	8
		18.75	596.2	193.6	4	5	11	20	43	1	3	5	13
		25.00	671	202.4	4	2	5	6	15	2	5	6	15
		31.25	745.8	211.2	4	10	31	26	77	1	9	4	24
		37.50	822.8	220	5	2	23	18	40	0	0	1	1
		43.75	902	228.8	5	2	22	16	37	0	1	1	2
		50	981.2	237.6	5	0	8	5	11	1	1	1	2
		56.25	1062.6	246.4	5	2	0	0	0	0	0	0	0
		62.5	1146.2	255.2	6	0	3	2	3	0	0	0	0
8 pax	2000 lb	6.25	732.6	314.6	3	7	15	60	133	7	15	60	133
		12.50	844.8	330	3	8	18	56	122	8	18	56	122
		18.75	957.0	343.2	3	2	6	11	32	2	6	11	32
		25.00	1073.6	358.6	4	0	3	1	8	0	3	1	8
		31.25	1190.2	371.8	4	5	15	12	35	5	16	13	37
		37.50	1311.2	387.2	4	6	13	13	26	6	14	13	28
		43.75	1432.2	402.6	4	5	13	10	25	5	12	10	24
		50	1557.6	415.8	5	2	5	3	7	2	6	3	8
		56.25	1687.4	431.2	5	0	0	0	0	0	0	0	0
		62.5	1819.4	446.6	5	1	2	1	2	0	0	0	0

The numbers of charging cycles are calculated based on number of trips (i.e. number of flights) required to cover demand. Table 6**Error! Reference source not found. Error! Reference source not found.**provides recent GHG (CO2 equivalent) emissions per kWh by powered plants in Texas's ERCOT power grid for both methods. Checking the emission results for single and multiple eVTOL service show the weighted average of total emissions for multiple eVTOL service is lower than single eVTOL service, per PMT, for both the 4- and 8-seater configurations. Weighted averages for total emissions rates do not vary much, so it should be better to use larger eVTOL aircraft in order to have lower GHG emissions, assuming demand warrants it. But service frequency (aided by more, smaller aircraft) may be preferred by passengers.

In order to estimate GHG emission for battery-only, plug-in hybrid electric vehicles and conventional cars the US EPA (2019) online emissions website is used here. EPA estimates for Chevrolet's Spark EV, Ford's Focus Electric EV and Tesla's Model X AWD are 140,160 and 200 grams of CO_2e per traveled mile in Austin CBD for the year 2016. Checking for the emission of PEHVs, the emission rate of CO_2e per traveled mile in Austin CBD for Chevrolet's Volt PEHV and Ford's fusion energy PEHV are 180 and 240 respectively. The reported ICE average emission rate of CO2e per traveled mile of the EPA online emission website is 410.Assuming average vehicle occupancy of 1.5 persons, CO2e emissions rates are 93.3, 106.7 and 133.3 grams per PMT for mentioned EVs, 120 and 160 for PEHVs respectively. Therefore, eVTOL neither helps nor makes the environment polluted with respect to current EVs.

TABLE 5. CO_{2E} EMISSIONS USING ERCOT 2016 RATES EVTOL LIFE-CYCLES (OZ)

Methods	***Single eVTOL Service***		***Multiple eVTOL Service***	
Demand Scenarios	*2% of nearby trips*	*5% of nearby trips*	*2% of nearby trips*	*5% of nearby trips*
4-Pax eVTOL	4.30 OZ (121.84 gr)	3.99 OZ (113.22 gr)	3.33 OZ (94.33 gr)	3.46 OZ (98.21 gr)
8-Pax eVTOL	4.15 OZ (117.75 gr)	3.68 OZ (104.38 gr)	4.17 OZ (118.09 gr)	3.69 OZ (104.61 gr)
Total (ounces per traveled Passenger Mile)			4.09 OZ (115.85 gr)	3.66 OZ (103.87 gr)

The total cost of eVTOLs operation and used energy for both scheduling methods per passenger flight, per mile and per passenger mile are presented in Tables 6 and 7, for each demand scenario. Costs do not include the costs due to emissions. Table 6 shows increase in demand would lead to lower average prices for scheduling methods. Using multiple eVTOL service will not lower cost. Beside that the average cost using 4-seater eVTOLs would be lower than 8-seater eVTOLs in all demand scenarios considered here for single eVTOL Service method. An interesting finding based on the average costs of different eVTOLs is the significant difference between eVTOL with 25 mile range of fly and others' average cost per passenger flight. The only possible reason for this significant difference can be because of the form of network.

TABLE 6. VTOL AVERAGE COST PER PASSENGER FLIGHTS OVER LIFTIME ($)

Methods		***Single eVTOL Service***				***Multiple eVTOL Service***					
Demand Scenario		*2% of nearby trips*		*5% of nearby trips*		*2% of nearby trips*			*5% of nearby trips*		
# Pax		*4 pax*	*8 pax*	*4 pax*	*8 pax*	*4 pax*	*8 pax*	*Combo*	*4 pax*	*8 pax*	*Combo*
VTOL Range (miles)	*6.25 mi*	$27.76	$34.75	$15.55	$18.96	$368.65	$33.42	$38.72	$159.89	$15.16	$22.06
	12.50 mi	$37.44	$39.95	$20.28	$27.68	$120.67	$37.44	$39.76	$135.15	$17.00	$30.18
	18.75 mi	$42.10	$86.02	$23.19	$37.38	$114.12	$84.74	$91.78	$190.21	$29.85	$49.51
	25.00 mi	$90.64	$2054.12	$34.68	$59.43	$98.09	$2054.12	$232.06	$234.03	$61.13	$86.79
	31.25 mi	$87.08	$123.70	$37.30	$54.90	$254.20	$118.48	$132.69	$90.71	$45.24	$73.24
	37.50 mi	$34.36	$53.79	$36.68	$31.79	$45.39	$50.37	$50.31	0	$23.14	$45.89
	43.75 mi	$43.79	$71.12	$40.32	$38.91	$282.03	$67.62	$78.47	$146.65	$29.46	$52.95
	50.00 mi	$42.09	$74.64	$34.55	$29.93	$282.48	$74.64	$104.17	$146.89	$29.74	$43.98
	56.25 mi	0	0	0	0	0	0	0	0	0	0
	62.5 mi	0	0	0	0	0	0	0	0	0	0
Total Average		$42.55	$48.55	$25.15	$31.28	170.41	$56.46	$64.31	$165.87	$35.19	$40.00

TABLE 7. FLIGHT COSTS

Methods		Single eVTOL Service		Multiple eVTOL service	
Demand Scenarios (%)		2% of nearby trips	5% of nearby trips	2% of nearby trips	5% of nearby trips
Cost per Passenger Flight ($)	4-passenger VTOL	$42.55	$25.15	$170.41	$165.87
	8-passenger VTOL	$48.55	$31.28	$56.64	$35.19
Average Cost Per Passenger Flight ($)				$64.31	$40.00
Cost per Flight-Mile ($)	4-passenger VTOL	$9.72	$5.95	$27.19	$22.89
	8-Passenger VTOL	$20.98	$13.98	$24.36	$15.81
Average Cost per Mile of flight ($)				$24.83	$11.78
Cost per Passenger-Mile ($)	4-passenger VTOL	$2.74	$1.60	$8.01	$7.13
	8-Passenger VTOL	$3.22	$2.01	$3.74	$2.25
Average Cost per Passenger-Mile of flight ($)				$4.15	$1.79

5. **Conclusions**

This paper estimates eVTOL implementation costs for application across the Austin, Texas region. Airbus' Vahana A^3 group eVTOL-sizing programs are used, and costs reflect energy consumed, materials, electricity and vertiport facilities required. Operational emissions are calculated separately based on the Texas ERCOT power grid's current average emission rates, and two demand scenarios are considered in a notional network with 9 vertiport locations, each absorbing passengers with a radius of 0.5 to 2 or 5 miles, depending on location.

At least 50 percent of VTOL seat capacity is used to provide passenger service, with different aircraft sizing assumptions. One method uses only 4- or 8-seater VTOLs, while the other uses a mixture to better reflect demand. Comparing cost and emissions estimates does not suggest a clear winner between driving and flying the inter-vertiport distances. eVTOL service appears to be a costly solution, with minimum CBD flight cost (and zero profit) of nearly $15.55 per passenger. The longest possible considered trip with eVTOL lowest cost per passenger is about $29.93 which is not covering the longest assumed fly in the notional network. The demand serving policy (to only provide service for a demand that is at least 50 percent of eVTOL capacity) prevents us to serve the most distant vetriports, those that are more than 50 miles apart. The lowest case of average cost for scheduling methods' provided service per passenger is $42.55 for absorbing just 2 percent of nearby trips and $25.15 for absorbing 5 percent of the demand. The both cases are the cost of 4-seaters in single eVTOL service. As a point of comparison, The Uber Copter (a private flight service) from Manhattan to JFK Airport charges passengers $200 to $250, while providing ground transport at each end of the flight (Curley, 2019). Aside from that, as was mentioned in literature review part the eVTOL must be cheap enough to be an alternative for ground transportation, and a $2 per mile was mentioned as the average price using Uber. Regarding our analysis, the maximum average cost per mile using each type of eVTOL and each scheduling method would be $4.15 while the lowest is $1.60 which both is comparable to previously mentioned Uber cost. Note that using eVTOL: in most cases requires ground transportation in both ends which would impose more costs

Regarding emissions the best-case emissions scenario recommends use of combination of larger (8-passenger) eVTOLs together with 4-seaters for both demand scenarios. Much more detailed looks at different markets, and production and supply costs, with survey data on consumer willingness to pay for specific port locations and allow for eVTOL aircraft flying overhead, will be needed to better anticipate the introduction of this new mode in real settings.

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