# LIFE-CYCLE ANALYSIS OF ELECTRIC VERTICAL TAKE-OFF AND LANDING VEHICLES

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## ABSTRACT

One way to avoid ground congestion is to take to the sky, using vertical take-off and landing craft or 'VTOL'. This study examines opportunities, costs, and energy impacts for an eVTOL (electric VTOL) system across the Austin, Texas region. Using different demand levels and VTOL sizes (4 and 8 seaters), we estimate average minimum costs of $24.84 per person-trip and $0.98 per person-kilometer using 4-seaters, which is less than current ride- hailing costs in U.S. cities. However, ride-hailing is door-to-door, while eVTOLs rely on stations, with non-negligible access and egress costs. We find 4-seaters offer higher energy and greenhouse gas (GHG) savings, based on the Texas power grid's current feedstocks, with eVTOL GHG emissions similar to those of all-electric cars, in operation: about 70 grams per passenger-kilometer. But an eVTOL's lifetime emissions are estimated to be twice those of electric cars (per passenger-kilometer traveled).

## 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 the year 2025 (CBSDFW 2018). Their announced 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) for individuals who want 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 method for recognizing and mitigating emissions and energy effects of new technologies is the 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, 18). While LCAs for similar products can reach somewhat different conclusions (GDRC 2016), such ana- lyses 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.

Although flying over cities as a means of everyday transportation has technological and legislative barriers, Uber’s well-publicized VTOL report (Holden and Goel 2016) claims that on-demand aviation has the potential to radically improve urban mobility,giving back time lost in people’s 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 VTOLs 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 environ- mental 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.

## VTOL Literature Review

Since VTOLs are a relatively new technology that has 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 operationtechnologies 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. However, many cities have hospital and other helipads, as well as underused parcels and open spaces, which may enable limited initial VTOL operations.

In a recent NASA report, Antcliff, Moore, and Goodrich (2016) identified the inside of larger freeway cloverleaf ramps as an ideal location for vertiports and vertistops, recognizing that surrounding freeway noise renders the sound issue rather moot, and inter-changes may enable very ready vehicle access, along with public-ownership of such existing infrastructure by public transportation agencies. Despite all restrictions in such places, the feasibility and practicality of VTOL technology in urban areas can justify its 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 hailing 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 some 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) is a useful 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 (Alonso et al., 2014).

Antcliff, Moore, and Goodrich (2016) claim that for aircraft design studies, VTOL concepts must meet these criteria to be feasible. For feasibility purposes, noise must be reduced by more than 20 dB. Additionally, safety must be comparable to automobile safety, and have a price competitive with the average ride-hailing trip (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. Apart 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.

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/.

Ale-Ahmad et al.'s (2020) recent study considers VTOLs as mass transit for Chicago, competing directly with ride-hailing services. They simulated the performance of on-demand VTOLs using an agent-based framework and assumed the vehicles can land almost anywhere. They used Chicago's travel data for transport network companies which are sometimes called ride-hailing companies. They concluded that 600 such air- craft could serve 0.4 percent of weekday evening peak demand with average wait times under 5 min, but ignored service costs and their effects on demand.

## Life-cycle analysis literature

Bjørn et al. (2018) argue that LCA is critical in analyzing the environmental implications of products, processes and services over all life stages, including design, materials and energy use, transport and 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. However, due to inconsistency of different databases, the results were not similar. Chester (2008) mentions four steps for LCA, 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 relation to scope of study, global or regional; and
- Assess effects of uncertainty, using sensitivity analysis on final results.

Chester (2008) noted how LCA 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). However, many have studied various energy and emissions impacts of vehicle operations. For example, 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).

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 inthe mode's life-cycle, environmental performance was computed and then normalizedper passenger-kilometer traveled (PKT). They showed how each vehicle's powertrain was most important for its lifecycle energy consumption, although non-operational com-ponents for the automobile and bus modes also accounted for a significant lifetime share.They concluded that urban diesel buses consume the most operational energy per PKT served (in the San Francisco Bay Area case study used), at 4 Megajoules per PKT (MJ/ PKT) during non-peak hours.

Chester and Horvath (2009) also estimated commercial aircraft operations to account for 69–79 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, comparablebut lacks the required consistency for comparison between two distinct modes – like pickup trucks and urban buses. Owen (2006) quantified electric-power generation's externalities, which is important when powering electric vehicles, like eVTOLs. And Nichols, Kockelman, and Reiter (2015) compared emissions costs of electric and non- electric passenger vehicles in Texas, with the electric vehicles (EVs) performing better, even with that state's past power grid in place.

Vehicles using substitute fuels are key examples of transportation LCA. Karabasoglu and Michalek (2013) explored driving patterns' impacts on hybrid electric vehicle (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 (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 the latter study, are from sources in 2007 which seem to be pessimistic toward the car industry.

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, Kockelman, and Reiter (2015) evaluated the effects of EV adoption in Texas. They accounted for impacts of battery-charging decisions and power plant energy sources across Texas. They converted plug-in electric vehicle (PEV) demands to emissions over time and space from all the possible sources and compared them to those of conventional passenger vehicles. They concluded that a PEVs' emissions benefits, normalized to 12,000 annual miles of driving, would be lost if more than 25 percent of the power plants were using coal as feedstock. Gawron et al. (2019) later used Austin, Texas, from 2020 to 2050, as a case study for LCA of autonomous taxis (ATs). They argue that thoughtful implementation of ATs should lower energy and greenhouse gas emissions by 60 percent, relative to conventional vehicles, thanks to changes in powertrains.

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. The LCA work of Fagnant, Kockelman, and Bansal (2015) on shared AV (SAV) fleets found dramatic reductions in cold start emissions, though distances traveledrose (unless dynamic ridesharing was 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.

In terms of air travel, Cox, Jemiolo, and Mutel (2018) studied Switzerland's commercial aircraft fleet from 1990 to 2050. They included LCAs of 72 common aircraft types for different flight distances, and multiple scenarios to reflect future aircraft improvements(including fuel efficiency, aerodynamics and emissions). They concluded that relatively more externalities will be due to upstream impacts of kerosene production (aviation fuel) and not direct operation of aircraft, because future aircraft are expected to be 25–50 percent cleaner per passenger kilometer.

# METHODOLOGY

In order to deliver realistic estimates here, we consider the source code and assumptions of a sizing study for Airbus' Vahana A3 (Lovering 2016). The sizing study compared electric helicopters to 8-fan tilt-wing VTOLs. A tilt-wing VTOL has wings capable of 90- degree rotation. The wings remain in the horizontal position while cruising and rotateup for vertical movements. Through the sizing study, Lovering (2016) has provided MATLAB code that is intended to design low-cost, single-passenger electric VTOLs 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 laborcosts (Lovering 2016). We used this code to design our vehicles for 4 and 8 passengers with proper equipment for our intended flying ranges.

There are three major components of LCA for VTOLs: energy consumed, environmental externalities, and operational costs each made of two distinct phases, manufacturing and operational. Based on Lovering (2016), energy consumed in the eVTOL manufacturing phase has already been changed to dollars and entered here as price. The consumed energy in eVTOL and vertiport operation is considered with their monetary values. The remaining parts of LCA are the emission in manufacturing of eVTOLs and their vertiports (the port itself and the required equipment), the operating costs consisting of electricity consumed (same as operation energy), platform rentals, and maintenance labor, the operational emission solely consisting of emissions from powerplants for electricity generation to recharge eVTOL batteries and the ports' energy needs. Note that any assumptions for these conversion values can change over time, due to new technologies and economies of scale in production processes. Therefore, the sensitivity analysis of results based on changes that are more probable in the near future should be considered.

## Externality Assumptions

The main parts of the body, aside from the motor and battery, are assumed to be madefrom 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 $140 per kilogram (Reuters 2018). Besides the material cost, tooling cost in this study is assumed to be $10,000 per cubic meter.

Batteries are assumed to be $700 per kilowatt hour they provide, and the battery output is assumed to be 230 watt-hours per each kilogram of its mass. Thus, the battery cost per pound is assumed to be 160 dollars per kilogram. However, Next- battery Corporation (Next-Battery 2019) quotes from Bloomberg New Energy Finance (BloombergNEF) that by 2030 the batteries would cost $300 for each kilowatt hour they provide, which will reduce the battery cost of our eVTOL to $69 per kilogram. The current Tesla Battery Pack costs $260 per each KWh which further reduces the battery cost to $60 per kilogram. The number of cycles in each battery life is assumed to be 2,000. 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. So, the assumed number of cycles appears reasonable.

One very important aspect of using batteries is the time they require to recharge from 20 percent (the reserve value for emergencies during trips). The Opener Blackfly eVTOL has reported four different charging times based on input current and used voltage. It isshown that charging an 8-kWh battery with a voltage of 120 V and input current of 20A would take up to 5.5 h (Opener 2018). That would definitely restrict eVTOL 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 one hour for charging a 100-kWh battery may provide a more reasonable charging time.

The Vahana team suggested $70 per kilogram for propulsion motors. They also added $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 h, 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 the 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 90%, which is optimistic for lithium-ion batteries. The electricity cost is used to evaluate the energy consumed from eVTOL operation.

The facility area required for each eVTOL 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 foot per month. The area then required for operations, passenger access, waiting areas and personnel activities around eVTOLs (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 (Lovering 2016).

Other less important assumptions that do not directly affect cost calculations are the weights of each seat (assumed to be 15 kilograms), avionics (15 kilograms), each servo (just 0.6 kilograms), each wing tilt actuator (4 kilograms), and the ballistic recovery system (15 kilograms) (Lovering 2016). Since landing gear is about 2 percent of a heli- copter'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-based emissions, and manufacturing and maintenance emissions; and these are addressed here. Safety concerns due to hacking, pilot harm, mechanical failure, or even sexual assault of passengers are sometimes mentioned but are not addressed here, due to lack of data. Shaheen, Cohen, and Farrar (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 mainly come from power plant operations and emissions. Nichols, Kockelman, and Reiter (2015) estimated the air quality impacts of using electric vehicles in Texas based on the Electric Reliability Council of Texas (ERCOT) emissions rates of 2012. Texas power plant emissions rates based on the US EPA's year-2016, 2018, and 2021 eGRID data are provided in Table

1. It shows emissions improvements per MWh of coal-generated power, but higher emis- sions from ERCOT's natural gas power plants, per MWh. The eGRID average emissions rate for $CO_2$ equivalent for the State of Texas (ERCOT sub-region of eGRID) in 2016 was 239 kilograms of $CO_{2e}$ per MWh produced, and that number has fallen over time to 223 and 195 kilograms per $CO_{2e}$ per MWh in 2018 and 2021.

Table 1. Average ERCOT (Texas Power grid) Emissions Rates assumed here (Kg/MWh).

| ERCOT Values | Fuel | Pollutants | | | | | |
|---|---|---|---|---|---|---|---|
| | | CO2 | NOx | SO2 | CH4 | N2O | CO2eq |
| Year 2016 | Coal | 1040.34 | 0.58 | 1.70 | 0.24 | 0.03 | 1048.17 |
| | Natural Gas | 195.77 | 0.10 | 0.00 | 0.02 | 0.00 | 195.96 |
| | All | 237.72 | 0.14 | 0.24 | 0.04 | 0.00 | 238.87 |
| Year 2018 | Coal | 1033.57 | 0.61 | 1.80 | 0.23 | 0.03 | 1041.54 |
| | Natural Gas | 200.16 | 0.13 | 0.00 | 0.00 | 0.00 | 200.36 |
| | All | 221.76 | 0.14 | 0.20 | 0.03 | 0.00 | 222.80 |
| Year 2021 | Coal | 528.12 | 0.29 | 0.78 | 0.12 | 0.01 | 532.20 |
| | Natural Gas | 201.76 | 0.13 | 0.00 | 0.00 | 0.00 | 201.96 |
| | All | 193.98 | 0.12 | 0.14 | 0.03 | 0.00 | 194.84 |

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

Production of a Lithium-ion battery is another source of eVTOL externalities. Romare and

Dahllöf (2017) estimated that the batteries' life cycle generates 17–40 kilograms of $C_{O2e}$ per kilowatt-hour of capacity while the production phase is about 150–200 kilo- grams of $C_{O2e}$. Ellingsen, Hung, and Strømman (2017) estimated a wide range of pro- duction-related emissions: from 38 to 356 kg $C_{O2e}$ per kilowatt-hour of capacity. The variation in values came from assumptions on facets like direct energy demand associated with cell manufacture and/or pack assembly. The 150 kg of $C_{O2e}$ is assumed for battery production phase here.

Note that a 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. In eVTOL manufacturing, carbon fibers or a mixture of carbon fiber and otherlight materials are used in order to make the vehicle lighter. Since there are different procedures to manufacture the carbon fiber and its alloys, different energy intensity for its manufacturing is reported. A company involved in carbon fiber production reportsthat 20 tons of $CO_2$ is emitted per ton of manufactured carbon fiber, and despite thishuge amount of pollution, its usage is justified by the assumption that 22 million tons of $CO_2$ that will be eliminated in car and aircraft life-cycles, thanks to tailpipe emissions reductions (Torayca 2019). A mixture of carbon fiber with resin is assumed for structural parts of eVTOLs. Work of Sunter et al. (2015) suggests that the minimum required energy for manufacturing carbon fiber reinforced polymer is 238 MJ (66.11kWh) per kilogram. If providing the required energy emits a similar amount of pollution to Texas's power plants, the $CO_2$ equivalent emission would be 32.5 kg. This study assumes 35 kg of $CO_2$ equivalent per kilogram of the material used in any structural com- ponents of eVTOLs to account for the material manufacturing, parts shaping, and stamping.

Another important part of eVTOL LCA is motor manufacturing. Unfortunately, there are no sources depicting the emissions in the manufacturing phase of rotor motors thatuse electricity. The work of Nordelof et al. (2019) suggests between 1.45 and 1.77 grams of $C_{O2}$ equivalent per kilometer of movement for the electric vehicle traction motors in their entire lifetime. These motors weigh almost 45 kilograms and their maximum power is 100 kW. The total driving distance is assumed to be 200,000 km. Hence, the $C_O2$ equivalent emission per motor weight and its power is 7.5 and 3.4 kg, respectively. It is obvious that motors in the study of Nordelof et al. (2019) would produce less power (almost 2 kW per each kg weight of motor) than the assumed motors for this study with similar weights (5 kW per each kg weight of motor). Therefore, in this study the worst-case scenario for emission is assumed. We calculate the emission through a motor's lifecycle based on its power.

The emission and energy consumption due to vertiport construction, operation, and maintenance are also the required elements for LCA of eVTOLs. A study by Chester and Hovarth (2012) showed that infrastructure plays a crucial role in the amount of emission and consumed energy in all transportation modes' life cycle analyses. They provided the energy consumption and emission data for each part of the infrastructure construction, operation and maintenance. They suggest the taxiways in air modes required to be built for eVTOLs have 95 MJ (26.4 kWh) and 6.8 kg of GHG $CO_2$ equivalent per square foot, which is different than the GHG emission rates reported in Texas (13 kg of GHG $CO_2$ equivalent per square foot).

For the operation phase in air modes, runway lighting is required. Although eVTOLs do not need any runways, there should be proper lighting to make their operation safe. Chesterand Hovarth (2012) suggest 471 GWh per year to light runways, but this is more than what is required for a helipad to operate safely. It is assumed that the takeoff and landing pad in each vertiport requires 30 omnidirectional perimeter LED lights with 15 Watts of power in its perimeter. At least two surface LED Light Projectors having 100W of power, one Homing Beacon LED with 150W of power and one approach path indicator that has 200W of power, are required. For lighting regular areas of a vertiport, like waiting areas, at night, 30 LED lights with 100 Watts of power are assumed to be sufficient (FAA 2016).

The vertiports also need to have charging stations. A study by Lucas, Silva, and Neto (2012) with the assumption of a 150,000 km lifetime of electric vehicles concluded 3.7– 8.5 g carbon dioxide equivalent per kilometer and 0.06–0.17 megajoules of energy are required for manufacturing charging points in the Portugal electricity grid. A more recent study conducted in China by Zhang et al. (2019) concluded that each charging point would emit 94.06 grams of $CO_2$ equivalent per each delivered kWh through its life- time. Each charging station for commercial use has different costs, but one can buy a level two charger for $700 from Amazon. The national average price for a home electric vehicle charging station in the U.S. is $1200, but a level three charger costs between $12,000 to $35,000 (https://www.fixr.com/costs/home-electric-vehicle-charging- station). While most existing stations are not yet capable of charging a 100-kWh battery in an hour, Tesla superchargers can do so, at a cost of roughly $270,000 (Tasha 2016) depending on the number of cords or stalls and site modifications needed. Since the charging station is used regularly, 50 percent of its value is assumed to be the price for yearly maintenance.

## Life-cycle analysis

Here, demand for eVTOLs is assumed to be two or five percent of the Austin area's per- sonal vehicle trips between each vertiport. U.S. walk mode shares are routinely under 10%, and bike shares are just 1% of U.S. person-trips. Thanks to economies of density in service, system efficiency is expected to rise for higher mode splits, with costs per passenger-mile served falling at higher use levels. High start-up costs and lack of familiarity will keep mode splits low at first, but eventually, they may get to 10% or higher for markets/ zone-pairs served. For this reason, the low and middle values of 2% and 5% are examined specifically here, which are less than the 12% mode split found by Fu, Rothfeld, and Antoniou (2019) in their stated preference surveys of residents of Munich, Germany. Their finding is not used here since they showed a significant change in the share of public transit that would result from eVTOL introduction, which is unlikely.

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. Figure1's proposed vertiport locations are based on important destination choices, current trip pat- terns, and physical possibility of building a vertiport. As previously discussed, vertiports can beplaced on top of tall buildings or in large parking lots. Vertiports are not restricted to emergency uses like hospital helipads and must be on a place accessible to the public.

There are three different buffer radii used in Figure 1: 0.8, 3.2 and 8 kilometers, and they are believed to be adequate for those walking and biking, busing, and/or driving to the vertiports, respectively. Those with a 0.8-kilometer radius are used for Austin's downtown locations, with scarce parking but high trip-origin and – destination densities that motivate people to walk, bike or e-scooter to these vertiports. The 8-kilometer buffer is used only for the Georgetown City station, far from the regional core, where population and job densities are relatively low and parking is much less expensive and/or more readily available. The remaining vertiports are assumed to serve people from a 3.2-kilometer radius. There is

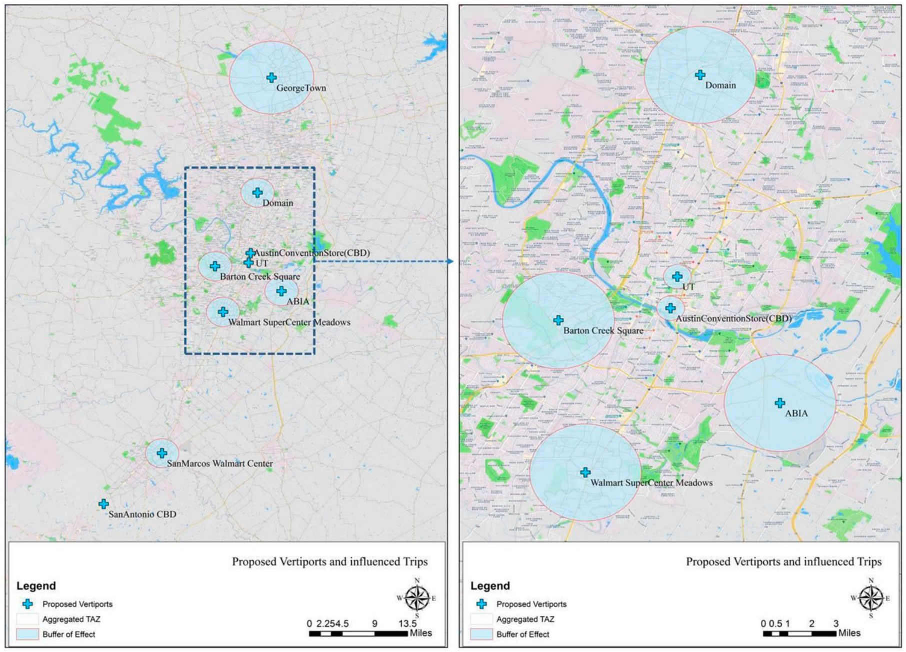


Figure 1. Proposed Vertiport locations and affected TAZs.

only one vertiport for which the demand is assumed to be derived from people living in theSan Antonio CBD; this is outside the 6-county Austin regional boundary, but can capture many trips between the two cities, including those from Austin's southern edge to down- town San Antonio. The maximum distance between this network's OD pairs is 100 kilo- meters (between Georgetown and San Antonio's CBD). The minimum is 2.12 kilometers, between the University of Texas campus and the Austin Convention Center. The average distance is 35 kilometers and there are 81 OD pairs considered.

## 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,each takeoff and landing or 'hover transition' takes 3 min, and boarding of and alightingfrom eVTOLs takes 1 and 2 min, 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.

VTOL flights are scheduled only for scenarios with sufficient demand to ensure 50 percent or higher eVTOL occupancy levels. Just one vehicle configuration, in terms of passenger capacity, is tested for 4-seater and then 8-seater aircrafts separately.

Since an 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. The acquisition costs are in the same range as reported prices by Uber, Mitsu, and the price of Volocopter: between $200,000 and $600,000 (Kinjo 2018).

Table 2. VTOL types used and characteristics for each OD pair.

| # Passengers | Payload (kg)* | Range (km) | Maximum Takeoff Weight (kg) | Acquisition Cost ($US) | Battery Mass (kg) | Motors Mass (kg) | Energy Used per Flight (kWh) | Energy Costs ($US) per Flight |
|---|---|---|---|---|---|---|---|---|
| 4 pax. | 460 kg | 10 km | 1,335 | $166,670 | 207 | 87.1 | 15.6 | $1.71 |
| | | 20 km | 1,381 | $127,090 | 231 | 89.6 | 20.2 | $2.22 |
| | | 30 km | 1,420 | $ 178,010 | 257 | 92.3 | 24.9 | $2.74 |
| | | 40 km | 1,461 | $ 184,340 | 282 | 95.1 | 29.8 | $3.28 |
| | | 50 km | 1,505 | $ 191,050 | 310 | 98.0 | 35.0 | $3.85 |
| | | 60 km | 1,552 | $ 198,120 | 338 | 101.1 | 40.3 | $4.43 |
| | | 70 km | 1,601 | $ 205,550 | 367 | 104.2 | 45.8 | $5.04 |
| | | 80 km | 1,652 | $ 213,340 | 396 | 107.6 | 51.5 | $5.67 |
| | | 90 km | 1,705 | $ 221,510 | 428 | 110.9 | 57.4 | $6.32 |
| | | 100 km | 1,760 | $ 230,070 | 460 | 114.6 | 63.6 | $6.99 |
| 8 pax. | 920 kg | 10 km | 2,564 | $ 273,940 | 374 | 169.7 | 29.4 | $3.23 |
| | | 20 km | 2,639 | $ 284,630 | 419 | 175.1 | 37.4 | $4.11 |
| | | 30 km | 2,715 | $ 296,090 | 467 | 181.1 | 45.9 | $5.05 |
| | | 40 km | 2,798 | $ 308,470 | 519 | 187.5 | 55.0 | $6.05 |
| | | 50 km | 2,888 | $ 321,920 | 575 | 194.6 | 64.8 | $7.13 |
| | | 60 km | 2,986 | $ 336,680 | 636 | 202.6 | 75.5 | $8.31 |
| | | 70 km | 3,095 | $ 353,030 | 703 | 211.6 | 87.2 | $9.59 |
| | | 80 km | 3,217 | $ 371,390 | 778 | 221.8 | 100.2 | $11.02 |
| | | 90 km | 3,357 | $ 392,350 | 864 | 233.8 | 114.7 | $12.62 |
| | | 100 km | 3,520 | $ 418,810 | 964 | 248.1 | 131.5 | $14.46 |

* Each passenger with his/her associated luggage is assumed to weight 115 kg (250 lb).

Assuming 10 years for each eVTOL's life-cycle and demand change pattern for trips throughout the year, similar to the findings of Hallenbeck et al. (1997), Table 3 presents total passenger-kilometers covered by eVTOLs. It shows that eVTOLs suitable for mid- distance flights (50–80 kilometers) carry the most passenger kilometer (PK).

Table 4 provides recent GHG ($CO_2$ equivalent) emissions per kWh powered by plants in Texas's ERCOT power grid. Checking the emissions results shows how the lifetime emissions of 4-seaters are lower than 8- seaters per passenger kilometer traveled (PKT), for both demand scenarios. It is strange that using smaller vehicles would result in lower emissions, but since the demand is not great enough, the regular aggregation will not have lower emissions. As Table 4 shows, increasing demand from 2 to 5 percent would decrease the difference in emission values. Considering only the operational emissions of eVTOLs shows lower GHG emission can be achieved with larger eVTOLs with greater demand. Lower demand service frequency (aided by more, smaller aircraft) is often preferred by passengers (Pax) too.

In order to estimate GHG emissions for battery-only and plug-in hybrid electric vehicles versus conventional passenger cars, the US EPA's (2019) online emissions website is used here. The EPA estimates $CO_2$e emissions rates of 75 grams per vehicle kilometer traveled (g/VKT) for the Chevrolet Spark BEV, 81.3 g/VKT for Ford's Focus BEV, and 81.3 for Tesla's Model X Long Range Plus produced in 2020. The emission rates of these vehicles depend on their production year too which is considered in the EPA online calculator. The emissions rates

estimates are
100 g/VKT in the Chevrolet Volt PHEV and 131.3 g/VKT in the Ford Fusion. Average emissions of $CO_2e$ per VKT for regular passenger vehicles with internal combustion engines (ICEs) are 256 g/VKT (EPA 2019). Assuming an average vehicle occupancy of 1.5 persons per VMT, these emissions rates all fall by 33 percent, suggesting that eVTOL GHG emissions is as good as the hybrid vehicles and not plug-in EVs at this time. Comparing these results with similar ones, like work of Stolaroff et al. (2018) on drones capable of delivering packages, shows different conclusions. Note that the previously mentioned study has just included battery production, electricity usage and warehousing. The emission due to operation is dependent on the emission rates of powerplants presented in Table 1. Hence, the values reported in Table 4 for the emission due to operation are lower than corresponding values of emission based on 2018s rates. The total cost of eVTOL operation for each demand scenario is also presented in Table 4. It shows that an increase in demand would lead to lower average prices. Using larger eVTOLs will not lower cost.

Table 3. VTOL total passenger kilometers over 10-year lifetime (Million pax-kM).

| Demand Scenario | | 2% of nearby trips | | 5% of nearby trips | |
|---|---|---|---|---|---|
| # Passengers | Range (km) | 4 pax | 8 pax | 4 pax | 8 pax |
| VTOL Range (kilometers) | 10 | 12.57 | 12.19 | 30.51 | 30.52 |
| | 20 | 27.86 | 27.52 | 66.78 | 66.78 |
| | 30 | 12.76 | 11.04 | 30.68 | 30.53 |
| | 40 | 6.33 | 2.61 | 14.67 | 14.22 |
| | 50 | 44.72 | 34.84 | 114.82 | 102.12 |
| | 60 | 38.01 | 38.01 | 94.37 | 92.07 |
| | 70 | 32.60 | 32.21 | 80.23 | 80.23 |
| | 80 | 14.28 | 13.81 | 34.63 | 34.63 |
| | 90 | 0.00 | 0.00 | 0.00 | 0.00 |
| | 100 | 0.00 | 0.00 | 0.00 | 0.00 |
| Sum | – | 188.95 | 172.22 | 466.72 | 451.09 |

Table 4. $CO_{2e}$ emissions using ERCOT 2021 rates eVTOL life-cycles (gr) and average flight costs

| Externalities | Emissions | | | | Costs | | | |
|---|---|---|---|---|---|---|---|---|
| | Operation Only through life time | | All emissions through life time | | Cost per Passenger Flight ($) | | Cost per Passenger-kilometer ($) | |
| *Demand Scenarios* | *2% of nearby trips* | *5% of nearby trips* | *2% of nearby trips* | *5% of nearby trips* | *2% of nearby trips* | *5% of nearby trips* | *2% of nearby trips* | *5% of nearby trips* |
| 4-Pax eVTOL | 83.59 g/PKT | 77.96 g/PKT | 160.38 g/PKT | 126.82 g/PKT | $52.31 | $24.84 | $2.08 | $0.98 |
| 8-Pax eVTOL | 85.63 g/PKT | 76.26 g/PKT | 186.67 g/PKT | 131.69 g/PKT | $74.61 | $32.80 | $3.05 | $1.31 |

# CONCLUSION

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 and infrastructure emissions are calculated separately based on the Texas ERCOT power grid's average emissions rates and previous studies. Two demand scenarios are considered in a notional network with 9 vertiport locations, each absorbing passenger within a radius of 0.8–3.2 or 8 miles, depending on location. At least 50 percent of VTOL seat capacity is used to provide passenger service, with different aircraft sizing assumptions. Comparing cost and emissions estimates suggests that eVTOLs would have many more emissions, even considering only operational emissions, in comparison to EVs. eVTOL service appears to be a costly solution, with minimum CBD flight cost of nearly $12.16 per passenger flight (and zero profit). The demand serving policy (to only provide service for a demand that is at least 50 percent of eVTOL capacity) prevents us from serving the most distant vertiports that are more than 50 miles apart. 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 of this paper, the eVTOL must be cheap enough to be an alternative for ground transportation, and $1.25 per kilometer ($2 per mile) was mentioned as the average rate using Uber. Regarding our analysis, the maximum average cost per kilometer using each type of eVTOL and each scheduling method would be $3.60, while the lowest would be just $0.98 per PKT, neglecting access and egress costs to vertiports for those travelers.

Regarding emissions, this study recommends using smaller (4-passenger) eVTOLs, in either demand scenario (i.e. when serving just 2% of relevant trips for that O-D pair or 5% of those trips), although the amount of emissions is high in comparison to EV's. Because, with the assumed demands, in both demand scenarios 4-passenger eVTOLs had less emissions than the other alternative, i.e. 8-passenger. 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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