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Conference Paper · August 2021

DOI: 10.2514/6.2021-3208

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AIAA AVIATION Forum
August 2-6, 2021, VIRTUAL EVENT
AIAA AVIATION 2021 FORUM

10.2514/6.2021-3208

Assessing the Suitability of Urban Air Mobility Vehicles for a Specific Aerodrome Network

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A wide array of electric vertical takeoff and landing (eVTOL) vehicles are in various stages of development. The addition of these vehicles to the Urban Air Mobility (UAM) market would provide more options for short to medium distance aerial transportation, filling the niche that is currently occupied by helicopters. However, the costs and benefits of adopting these vehicles are reliant on many different factors related to both the aircraft and its operating environment. This paper compares 13 UAM vehicles (12 emerging eVTOL vehicles and one helicopter) using a Direct Operating Cost (DOC) model developed by the authors to compute economic metrics. With the computed DOC values for each vehicle, a computational framework determines, from a set of known passenger trips in the Chicago Metropolitan Area, the number of passenger trips that would use UAM as part of the total trip. These assessments use a specific network of aerodromes in the Chicago Metropolitan Area using existing sites that could support UAM aircraft operations. From the results, we infer important vehicle characteristics and preferable vehicle configurations for the specific aerodrome network that lead to the highest number of passenger trips utilizing UAM.

I. Introduction

Over 450 designs of hybrid and electric Vertical Takeoff and Landing (eVTOL) vehicles currently exist [1], with a wide range of vehicle parameters and performance characteristics. The technical development state of these projects ranges from conceptual designs to production vehicles with thousands of flight hours. As of March 2020, 12 eVTOL aircraft have progressed in the Federal Aviation Administration (FAA) certification process [2]. Once eVTOL vehicles are certified and introduced to the market, transportation service providers, like Uber Technologies Inc. (Uber sold their Elevate division to Joby Aviation in December 2020, but Uber still plans to operate aerial mobility trips using vehicles like Joby's [3]) and BLADE Urban Air Mobility (at the time of this paper, Blade has signed agreements with Beta Technologies and Wisk Aero to operate their vehicles on Blade's networks [4, 5]) intend to purchase vehicles to service Urban Air Mobility (UAM) networks. Thus, there is a need for a selection process to evaluate the growing list of candidate UAM vehicles. Blade's CEO, Rob Wiesenthal, concurred with the need for a selection process by emphasizing the importance of "deploying the most appropriate [electric vertical aircraft] model for each of our specific routes" [4]. For successful implementation, UAM vehicles must be evaluated on metrics such as appropriate range, passenger capacity, cruise speed, efficiency, yearly flight hours, and vehicle lifespan, as well as more detailed characteristics such as frequency and cost of maintenance [6].

In this paper, we study UAM vehicles to assess their suitability for a specific aerodrome network. Aerodromes accommodate vertical takeoff and landing of eVTOL vehicles. We assume aerodromes include existing public infrastructures such as helipads, major airports, and regional airports. Furthermore, we built a database of emerging eVTOL aircraft parameters [7] and developed a Direct Operating Cost (DOC) model to compare the cost of operating these vehicles. Using this DOC model, UAM vehicle parameters, aerodrome network, and passenger demand model for a given metropolitan area, the paper utilizes a computational analysis framework developed by Roy et al. [8] to determine the number of UAM-preferred passenger trips for 13 candidate UAM vehicles. More specifically, this paper studies UAM trips occurring in the Chicago Metropolitan Area between a 10 aerodrome network and identifies the best-suited UAM vehicle, noting key design performance parameters of these vehicles. Vehicle configurations are assessed based on the results of the study. The authors make no claim that one vehicle is superior to another in any case nor claim that the vehicles used in this study have performance values exactly matching the vehicles currently being developed. The purpose of this study is to show the importance of vehicle selection, identify the best-suited aircraft for a specific aerodrome network, and subsequently rank aircraft design parameters.

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The primary question this paper seeks to answer is, *"For a given aerodrome network and passenger demand model, how can we determine the suitability of Urban Air Mobility vehicles from candidate models?"*. A subsequent question is, *"Can we infer, from the selection study, which vehicle characteristics are most important?"*

II. Literature Review

As mentioned earlier, there is a desire by both transportation service providers and vehicle OEMs (Original Equipment Manufacturer) to evaluate and select appropriate aircraft for specific UAM trips. Numerous rankings and comparisons have been developed to compare UAM vehicles. SMG Consulting [9] formulated the Advanced Air Mobility (AAM) Reality Index which ranks OEMs based on "the funding received by the company, the team that leads the company, the technology readiness of their vehicle, the certification progress of their vehicle, and the production readiness towards full scale manufacturing". Silva, et al. sized and compared the performance of notional UAM vehicle designs including a quadrotor, side-by-side helicopter, and lift+cruise VTOL aircraft [10]. Bacchini and Cestino [11] compared the performance of three vehicle configurations, based on emerging UAM vehicles, for three trip lengths.

There exists numerous studies on DOC comparisons for ultralight aircraft, personal air vehicles, thin-haul aircraft, and air taxis [12–15]. Mane and Crossley [12] looked into the feasibility of an air taxi service by comparing several types of aircraft. Stoll and Mikic [13] implemented a DOC model to compare designs of thin-haul aircraft. Justin, et al. [14] investigated the feasibility of operating electric thin-haul aircraft by comparing the vehicle range to a similarly-sized aircraft powered by fossil fuels. Harish, et al. [15] analyze the DOC for thin-haul aircraft operations and compare a notional thin-haul design to a similarly sized twin engine aircraft. They found that a 20% reduction in DOC can be realized by switching a conventional aircraft to a design utilizing distributed electric propulsion (DEP).

There exists a gap in the literature for comparing UAM vehicles using an effective cost metric that considers both DOC and passenger time, as discussed by Mane and Crossley. As compared to past years, there is now sufficient publicly available information to compare emerging UAM vehicles. In this paper the authors use the computational analysis framework developed by Roy, et al. [8] and further developed by Maheshwari et al. [16, 17] to achieve this comparison.

III. Methodology

The methodology discussion is divided into four sections: 1) overview of the existing computational framework to identify the number of UAM-preferred trips, 2) description of the aerodrome network, 3) selecting notional, candidate aircraft based on existing and in-development UAM vehicles, and 4) development of a detailed Direct Operating Cost (DOC) model for eVTOL vehicles.

A. Overview of the Modular Computational Analysis Framework

Roy et al. [8] developed a modular, multi-modal computational framework for computing the effective costs of automobile, STOL (short takeoff and landing), CTOL (conventional takeoff and landing), and VTOL trips as a function of the vehicle operating costs and each passenger's value of time for the travel time. Taking this network model further, Figure 1 [16] shows possible multi-modal trip configurations from an origin to destination from the point of view of UAM operations. Note that the modes in the network model do not include mass transit options such as trains, buses, etc.

The effective cost of a trip is modeled as a the sum of the used vehicle's operating costs and the total travel time cost. The operating costs for a vehicle are a function of the vehicle's characteristics and its operating environment as well as the total distance traveled using that vehicle. The vehicle DOC derivation is covered much more thoroughly in section III.D. Travel time cost is defined as the product of an individual's value of time and the time that individual spends traveling. To model this value of time more realistically, we have generated a randomized sample of the given metropolitan area's income distribution. This sample is then combined with a randomized set of trips consisting of a set of origin points and destination points as well as a randomized time the trip occurred to better model congestion levels. To determine whether a trip from this set will utilize a given UAM network, we can compare the effective costs for automobile and eVTOL based modes of travel. The mode of transportation with the lowest effective cost will be the preferred mode of transportation for that trip. A trip is said to be UAM-preferred when the effective cost of a trip utilizing an eVTOL vehicle is less than that of a wholly automobile based trip.

To compare UAM vehicles, the number of UAM-preferred trips is determined for each vehicle using the computational framework. Degrees of freedom, like eVTOL vehicle characteristics, passenger demand model, passenger load factor, and aerodrome network, can be altered, affecting the number of UAM-preferred trips. The passenger demand model is based on publicly available commuting trip data for the Chicago Metropolitan Area [17]. For this study, we used a randomized set of 6.2 million commute trips from the Chicago Metropolitan Agency of Planning (CMAP) [18]. CMAP is the authority for the Chicago Metropolitan Area that collects, analysis, and synthesizes travel data for urban development. We assume a load factor of 60% based on OEM expectations and studies with passenger load factors from 57.5% to 75% [19–22]. In this study we perform two case studies: 1) comparing vehicles' economic metrics and 2) analyzing the number of UAM-preferred passenger trips for each vehicle.

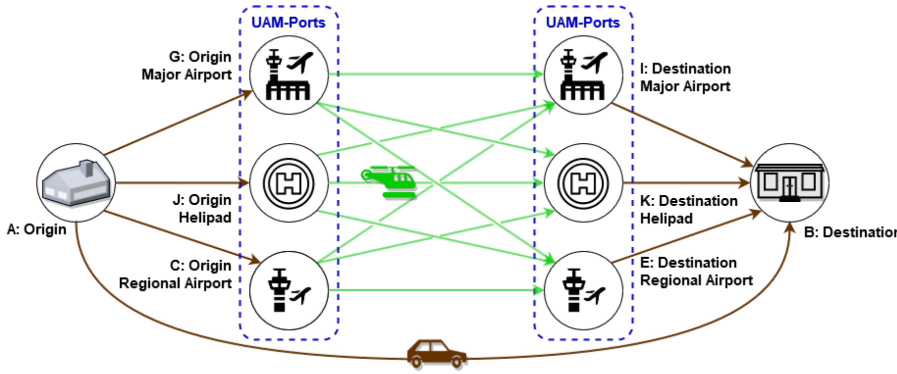

Fig. 1 UAM Network Model of the Modular Computational Framework [16]

$$
\begin{aligned}
Cost_{eff,i} &= Cost_{oper,i} + Cost_{time,i} \\
Cost_{time,i} &= time_{trip,i} * time_{value}
\end{aligned}
$$

where,

$$
\begin{aligned}
&Cost_{eff,i} && \text{– Effective cost for the mode } i \\
&Cost_{oper,i} && \text{– Operating cost of mode } i \\
&Cost_{time,i} && \text{– Cost due to the travel time on mode } i \\
&time_{trip,i} && \text{– Total door-to-door trip time for mode } i \\
&time_{value} && \text{– Value of time of the passenger}
\end{aligned}
\tag{1}
$$

Maheshwari et al. [17], in a sibling paper to this study, details the on-going improvements to the computational framework, aerodrome network model, and the generation of passenger demand data for the Chicago Metropolitan Area. The distribution of trips for a metropolitan area are generated based on the demand data for commute trips.

B. Aerodrome Network Siting

The research conducted to assess the best-suited eVTOL design for UAM operations leverages prior work from the computational analysis framework [8] and current work to perform operational limit analysis for different network sizes [17]. To perform the comparative vehicle analysis, a series of siting decisions were levied to initialize the aerodrome network for this study. The first set of siting decisions pertained to the metropolitan area of interest, number of locations to utilize, and said locations. Given the work done by Maheshwari, Sells, Harrington, et. al. [17] where small-, medium-, and large-sized networks were assessed for the Chicago and Dallas Metropolitan Areas, we selected the medium-sized network of 10 UAM-aerodromes in the Chicago Metropolitan Area to consider. We believe the medium-sized network provides a practical network size for comparing operations of multiple vehicle concepts. Additional work using the computational tool described in [8] and [17] must be leveraged to generate UAM-preferred trips using the network. Using our current work [17, 23], the 10 aerodrome network developed for the Chicago Metropolitan Area contains three international airports (MDW, 1C5, RFD), three regional airports (ENW, PWK, DPA), one municipal airport (IGQ), and three heliports (IL75, 4H1, TF8), shown in Figure 2. The airports are depicted in red and the heliports are depicted in black. The longest distance between aerodromes is 142 miles and the shortest distance is 4.5 miles. The average distance between facilities range from 46 to 70 miles with a network average of 51 miles. The distances are approximated using the great-circle distance formula and the latitude and longitude of the facilities.

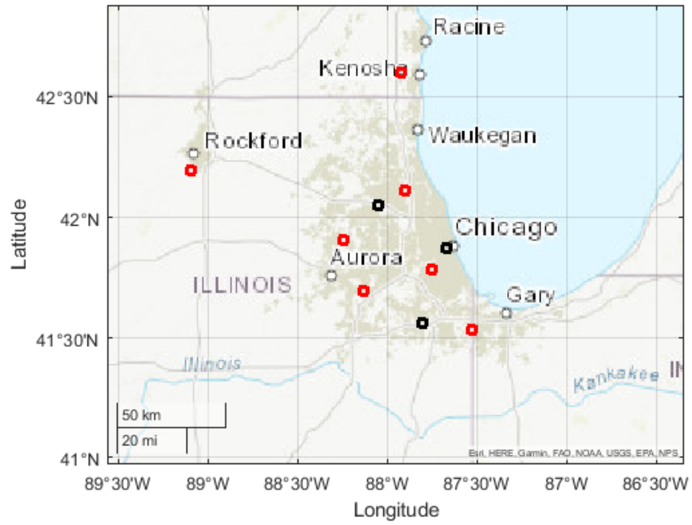

Fig. 2 Notional Aerodrome Network with existing airports (*red*) and heliports (*black*)

C. eVTOL Aircraft Database

The analysis by Roy et al. [8] and Maheshwari et al. [16] included only one composite eVTOL aircraft to estimate the effective cost of trips for any aerodrome network in a metropolitan area. This composite vehicle was based in large part on the findings presented at the Uber Elevate 2018 summit [24], comprising of a max range of 50 nmi (58 mi) and cruise velocity of 130 knots (150 mph) [25]. Maheshwari et al. [16] determined a DOC of $605 per flight hour by multiplying a derived cost per mile from Uber [24] by average speed for a nominal mission. For this analysis, we require a more rigorous DOC method to compare different eVTOL vehicles. A "per mile" cost does not encapsulate the differentiation in vehicle characteristics such as range and cruise speed; we develop a DOC model with these as input variables, building off the work of Kohlman et al. [26]. The DOC model is explained in great detail in section III.D.

This study considers four vehicle configurations: vectored thrust, multicopter, lift+cruise, and helicopter. Figure 3 shows examples of candidate vehicles for each configuration. Vectored thrust vehicles 3(a) use at least one of their motors for both lift and cruise and are most efficient during cruise flight. Multicopters 3(b), most efficient for hover flight, only have motors for lift and no motors for cruise. Lift+cruise configurations 3(c) are a compromise between the two previous configurations with independent motors for lift and cruise. Helicopters 3(d) have horizontally spinning rotor(s) which supply both lift and thrust.

For our case study, we introduce 13 UAM vehicles to use in our computational framework based on emerging eVTOL designs. Candidate emerging UAM vehicles were selected based on their publicly available specifications. Secondary sources and statistical approximations are used when published data is limited. We anticipate that these values will not exactly match the values of real-world vehicles that may or may not operate in the future, but that they are reasonable approximations and can be used to model the differences between notional vehicles. The notional vehicle database, with complete information for the 12 eVTOL vehicles, is available for download [7]. Vehicle parameters shared in the database include passenger capacity, cruise speed (mph), range (miles), lift over drag ratio (L/D), maximum flight time (minutes), vehicle configuration, Maximum Takeoff Weight (MTOW), and vehicle battery capacity (kWh). The database also includes the calculated DOC and DOC per passenger. An abbreviated vehicle database, with the inclusion of the helicopter configuration, is summarized in Table 1. Note that the passenger capacity is not the total number of vehicle seats, but the maximum number of passengers that can be transported at a time with a pilot on-board.

Directly comparing independent, in-development vehicles is very difficult; therefore, several key assumptions were defined. For example, each aircraft manufacturer utilizes a different battery with various battery energy densities, power densities, and lifespans. Battery information is proprietary so we were not able to standardize the vehicle data set for a specific battery energy density. Other battery properties, like power density and lifespan, also vary and are dependent on the vehicle configuration [21, 27, 28]. In addition, it is assumed that each vehicle operates with a pilot on board, although some of these vehicles are being developed with the intent to be fully autonomous. Finally, we assume that all vehicles fly the same mission profile. A description of the mission profile utilized in the computational framework is

(a) Vectored Thrust Configuration Example: Joby S4

(b) Multicopter Configuration Example: EHang 216

(c) Lift+Cruise Configuration Example: Aurora Pegasus

(d) Helicopter Configuration Example: Bell 407 GXi

Fig. 3 Examples of the Four Vehicle Configurations

described by Roy, et al. [8].

D. Modeling of Direct Operating Cost (DOC)

Direct Operating Cost (DOC) is the cost required to operate and maintain a service. For a UAM transportation service, DOC includes vehicle acquisition, crew and avionics, energy, maintenance, and aerodrome costs. On the other hand, Indirect Operating Costs (IOC) include sales, marketing, passenger insurance, and other similar costs. IOC do not vary based on aircraft model, so they can be neglected in this comparison study. Another possible approach is considering revenue generated by each aircraft as a point of comparison, which would be akin to real-world operations. However because of the early technology readiness of the technology and no current passenger operations, it is more straight forward to use DOC.

The DOC model leveraged for this study is largely built on the work of Kohlman et al. [26] and Uber Elevate [6]. The DOC model is based on a notional trip respective of each vehicle and is calculated in 2020 US dollars per flight hour. Where possible, we have created statistical models and compared the results to public information to validate the DOC model. The input variables for the DOC model are vehicle MTOW (kg), vehicle battery capacity (kWh), energy (kWh) used for a single trip, and the maximum flight time (minutes) not including energy reserves. The DOC model can only be applied to eVTOL vehicles, other sources are used for determining the helicopter DOC.

1. Acquisition Cost

The UAM vehicle acquisition costs include airframe acquisition, battery acquisition, and insurance rate. The airframe acquisition cost is related to MTOW and manufacturing complexity. We estimate early production rates of eVTOL vehicles at \$300/pound MTOW [6, 26]. The exception is vehicles with a multicopter configuration, which reduces the estimated acquisition cost to \$150/pound MTOW based on published estimates [29, 30].

Instead of using an estimated cost per pound of MTOW, the authors considered using the vehicle unit cost (shared by OEMs in investor presentations) to model the acquisition cost. However, only a handful of companies have shared this information, so for this study we chose to use the statistical estimate and use unit costs as a point of comparison. For

Table 1 Summary Table of Notional eVTOL Vehicles used in study [7]

Vehicle Name	Configuration Type	Passenger Capacity
EHang 216	Multicopter	1
Volocopter VoloCity	Multicopter	1
Aurora Pegasus*	Lift+Cruise	1
Archer Maker*	Vectored Thrust	1
Wisk Cora*‡	Lift+Cruise	1
Lilium Eagle*	Vectored Thrust	1
City Airbus*	Multicopter	3
Joby S4	Vectored Thrust	4
Lilium Phoenix*	Vectored Thrust	4
Archer 5-seater	Vectored Thrust	4
Beta Alia	Lift+Cruise	5
Lilium Jet	Vectored Thrust	6
Bell 407 GXi	Helicopter	6

* indicates that the aircraft is a technical demonstrator
‡ *"Wisk Cora"* refers to the fifth generation vehicle in the Wisk Cora family.

example we calculate the Joby S4-like aircraft to have an airframe acquisition cost of $1.4 million, which aligns closely with Joby's projected unit cost of $1.3 million [19].

We assume that the eVTOL vehicles are capable of 2,000 flight hours per year and have an operational lifespan of 10 years [26]. In the future the authors hope to improve the fidelity of this model by considering the changes in flight cycles per year and total lifespan by vehicle configuration. Some OEMs have published their expected vehicle lifespans and flight cycles per year [19], but more information is needed before this level of detail can be included in a comparison study.

We assume battery acquisition cost to be $400/kWh and that batteries have a 2,000-cycle lifetime for all vehicles [26]. However, battery lifespan is dependent on vehicle and mission profile design and can vary significantly. Recently, Joby announced that their batteries will fly for 10,000 cycles [27]. This is because the Joby S4 has a much larger battery capacity than what is required for an intercity trip, so they do not have to fully charge their battery after every trip. Other vehicles use a majority of their battery capacity for a single trip and will therefore need to swap batteries much more frequently. We calculate the number of battery lifetimes required for 20,000 flight hours based on the nominal trip time to determine the number of times batteries will be replaced. From the lifespan battery kWh over the vehicle's lifespan, we can determine the total battery cost. The insurance rate is 3% of the total airframe and battery acquisition cost per year over the vehicle lifespan [26].

The battery cost methodology used in this DOC model is comparable to Uber Elevate's estimation [6]. Uber Elevate determined a battery cost of $93 per flight hour, including amortizing the batteries and maintenance costs for swapping the batteries. The DOC model used in this study estimates a battery cost between $60-$110 per flight hour, depending on the vehicle design parameters.

2. Crew and Avionics

Crew and avionics costs are grouped together since they are correlated based on the level of vehicle autonomy. In the near-term, UAM vehicles may be remotely-controlled with no pilot on-board, leading to lower crew costs but higher avionics costs. In the long-term, vehicles may be fully autonomous with no manual input. This case study only considers piloted aircraft for the launch scenario. To calculate the cost per flight hour, the costs for crew and avionics are determined for the launch scenario and divide the costs by the pilot yearly flight hours and avionics lifetime flight hours respectively. We assume that there are 50% more pilots than number of eVTOL vehicles in the network to account for shift changes [26]. This assumption leads to pilots flying 1,333 hours per year.

The literature review identified a wide range of values for a pilot's annual salary. Kohlman et al. [26] assumes a pilot salary of $50,000 a year, while a Booz Allen Hamilton market study documented salaries from $60,000 to $90,000 a year [20]. However, salary does not include benefits and training. Therefore, we assume a yearly pilot cost, including salary, benefits, and training, of $110k [6]. We assume the avionics cost is $19,075 [31] for the lifetime of the vehicle. The hourly crew and avionics costs are calculated at $83 for all vehicles.

3. Energy Cost

The energy cost required per flight hour is determined by calculating the energy used by the eVTOL vehicle for a single trip and converting the value to a per flight hour figure. We assume that an eVTOL aircraft will use 60% of its battery charge for a nominal flight and maintain 40% due to capacity fade and FAA mandated reserves [32]. For the Chicago Metropolitan Area, we assume an energy cost of $0.144 per kWh [33]. Using the vehicles' energy usage and trip time for a nominal trip, we estimate the cost per hour for energy.

4. Vehicle Maintenance

Maintenance costs for eVTOL vehicles include inspection and repair of the electrical drive train and rotors /citeMRO. We identified a couple different vehicle maintenance estimates in our literature review and applied a statistical cost estimation approach intended for general aviation aircraft. Kohlman et al. [26] assumes the vehicle maintenance costs at $60 per hour under the notion that each hour of flight time requires one hour of maintenance and upkeep. Uber Elevate estimated $112 per flight hour but the explanation for this derivation is no longer publicly available [6] *.

In our DOC model we assume $60 per flight hour for maintenance costs for all vehicles. More detail is needed at a subsystem level in order to accurately estimate maintenance costs for eVTOL vehicles, especially for state-of-the-art electric propulsion systems with no prior aerospace history. Refining the vehicle maintenance model is a goal of future work.

5. Infrastructure Costs

Infrastructure costs are the costs of maintaining the aerodromes and are accounted for in takeoff and parking fees for the UAM fleet. These costs are estimated by a statistical model based on existing takeoff and parking fees for helicopters operating within urban centers. We refer to a 1991 analysis of the Wall Street (Manhattan) Helipad [34], one of the busiest helipads in the world. Table 2 lists these takeoff and parking fees, based on MTOW (lbs), adjusted to 2020 USD [35]. As previously mentioned in section III.D.4, we assume one hour of downtime for vehicle maintenance per flight hour, so the hourly parking rate can be directly converted to a one time fee per flight hour [26].

Table 2 Takeoff and Parking fees based on vehicle weight [34]

MTOW [lbs]	Takeoff Fee [$]	Parking Fee [$/hr]
Up to 4,000	50	30
4,001 to 6,000	64	30
6,001 to 8,000	74	30
8,001 to 10,000	90	40

The total infrastructure cost is calculated as the sum of all landing and parking fees accumulated in one flight hour. Note that the total infrastructure cost is an average cost over a large time scale, so the average number of takeoffs per hour, estimated to be two based on our aerodrome network and passenger demand model, is used instead of an integer value. We estimate two takeoffs per hour based on the nodal distances in our network. Joby Aviation [19] plans to operate their vehicle for 40 trips per day for a smaller sized aerodrome network (26 mile versus 42 mile average trip distance). Servicing 40 trips over an 18 hour period (6 a.m. to midnight) is just over two trips an hour.

Other approaches for determining infrastructure fees were investigated, including looking into current takeoff and landing fees and major and regional airports. However, a majority of airports charge no fees for small fixed-wing aircraft

*Since Uber Elevate's merger with Joby Aviation, the talk that the referenced article cites is no longer available on Uber's website.

and helicopters in order to attract pilots to their airport. We predict that regional airports low-to-none fee models are not representative of urban UAM infrastructure, so we disregarded this approach.

IV. Results Summary

We present two case studies to demonstrate the varying suitability between 13 candidate UAM vehicles with a range of aircraft parameters. The first case study compares the vehicles' cost using three different criteria; DOC, DOC per average available passenger-mile (DOC/pax-mile), and Cost per Passenger Seat Mile (CPSM). DOC/pax-mile is similar to Cost per Available Seat Mile (CASM), but here we calculate the mileage as an aggregate node distance instead of the total distance flown by the vehicle in the network. Future efforts will include embedding the CASM calculation within the computational framework analysis as an additional data point for comparing vehicles. The third economic metric analyzed in this study, CPSM, characterizes how the vehicle operates on the aerodrome network and includes an assumed passenger load factor and trip distance.

The second case study compares the vehicles using the UAM-preferred passenger trips metric. These values are calculated using the computational analysis framework with the DOC model and vehicles as inputs for the 10 aerodrome network located in the Chicago Metropolitan Area.

A. Economic Results

1. Direct Operating Cost Results

Using the vehicle parameters from the aircraft selection and the developed DOC model, we can determine the DOC for each of the 12 notional eVTOL vehicles. Figure 4 shows the summation of the DOC sections for each vehicle. As previously mentioned in III.D, the vehicle maintenance and crew and avionics costs are constant across all vehicles at $60 and $83 respectively. Acquisition cost increases as vehicle MTOW increases and for larger battery capacities. Battery capacity storage and energy costs are based on vehicle energy consumption, which is affected by mission profile and the efficiencies of electric propulsion subsystems (vehicle configuration, motor efficiency, battery efficiency, etc.). Infrastructure costs are a function of vehicle MTOW and number of takeoffs per hour, which is held constant at two for all vehicles.

The five vehicles with the lowest DOC have one available passenger seat with a pilot on-board. The DOC for this set of vehicles ranges from $340 to $440. The notional Lilium Phoenix with vectored thrust configuration, has a similar DOC to the notional Volocopter VoloCity multicopter, but the Phoenix seats up to three more passengers. The notional Joby S4 to the notional Lilium Jet, range in DOC from $590 to $650. While the DOC to operate these notional vehicles are similar, the number of available passenger seats varies significantly across these vehicles from one seat for the EHang 216-like multicopter to six for the Lilium Jet-like vectored thrust aircraft.

We can compare these calculated values for emerging eVTOL vehicles to an in-service helicopter. The Bell 407 GXi [36] seats up to six passengers with a fully-burdened range of 337 miles at 153 miles per hour. Blade Aviation currently uses the petroleum-fueled Bell 407 GXi to service UAM trips [37]. Helicopters are not compatible with our DOC model, but Uber Elevate calculated the DOC for the 407 GXi at $1,253 per flight hour [6]. Helicopters have clear disadvantages compared to eVTOL vehicles in terms of noise and emissions, but this study focuses on economic suitability. eVTOL vehicles have a clear economic advantage over helicopters when using the DOC metric, but what if we instead compare the cost per passenger-mile?

2. Direct Operating Cost per Passenger-Mile Results

Figure 5 shows the DOC/(pax-mile) for each notional vehicle with the bar coloring referencing the vehicle configuration. DOC/(pax-mile) is considered in the context of a fully-burdened vehicle operating within the aerodrome network, so the "passenger" value refers to maximum passenger capacity and "mile" is the average distance between aerodromes (51 miles). We exclude vehicles with maximum ranges less than the average network range from the calculation. Figure 5 shows a clear grouping of single and multi-passenger vehicles with respect to cost per passenger mile.

The DOC/(pax-mile) results align closely with figures presented by OEMs. Joby Aviation predicts their fully-burdened CASM at $0.86 [19] for a load factor of 57.5% and average trip length of 24 miles. We back-calculated their CASM value into terms of DOC/(pax-mile) at $1.41. This is similar to our calculation of $2.50 based on our DOC model, network, and load factor of 60%.

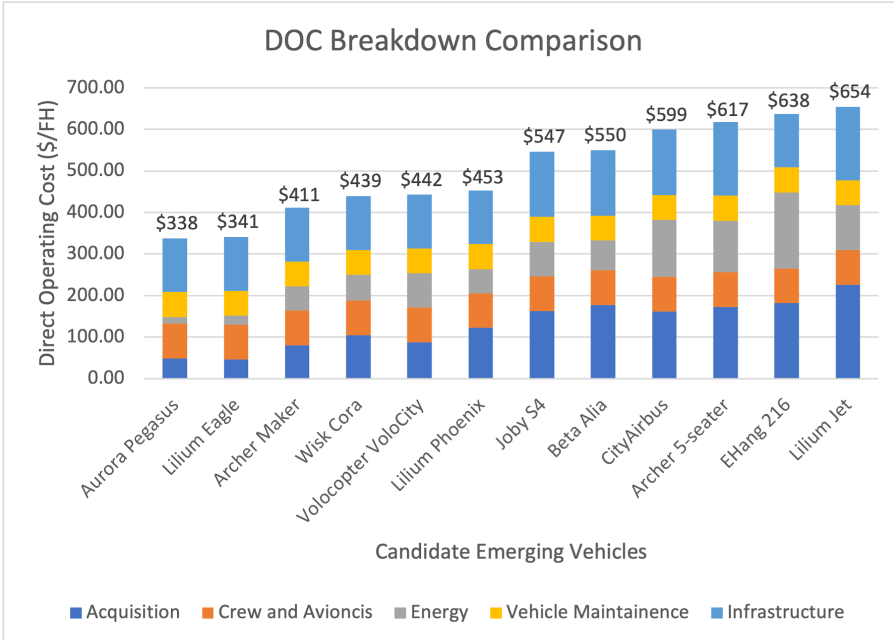

Fig. 4 DOC Breakdown by Section for each Vehicle

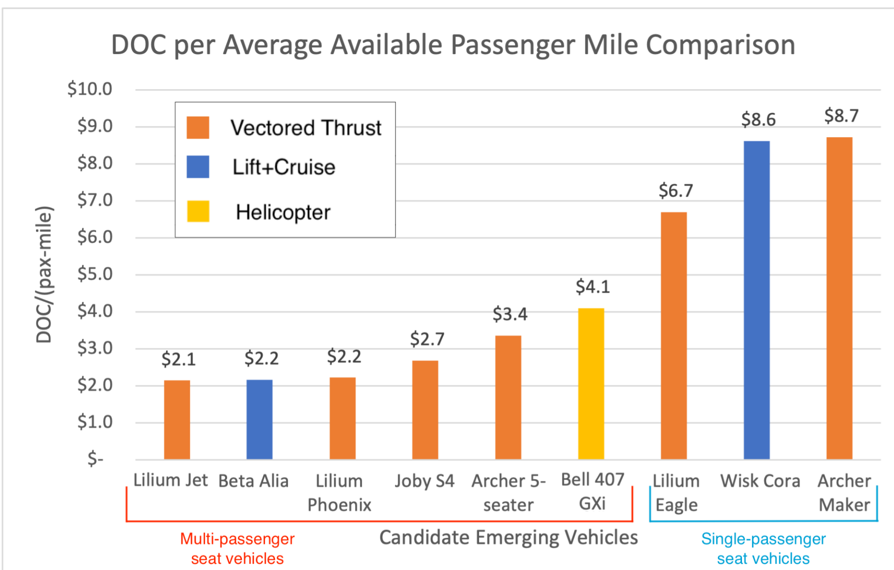

Fig. 5 DOC per Passenger-Mile for each Vehicle

As before, we compare the economic metric to a reference helicopter. The DOC/(pax-mile) for the Bell 407 GXi is \$3.90, the most costly of the multi-passenger eVTOL vehicles but better than the single passenger seat vehicles. In the next section we calculate CPSM, which includes passenger load factor.

3. Cost per Passenger Seat Mile Results

To calculate CPSM, we assumed a passenger load factor of 60% as described in Section III.A for multi-passenger vehicles and assumed full passenger capacity for the single-passenger vehicles. We again use the aggregated average distance between aerodromes, 51 miles, as previously noted in Section III.B. We exclude vehicles with maximum ranges less than the average network range from the CPSM calculation.

The CPSM values follow a similar trend as DOC/(pax-mile), but there is a smaller difference in the highest and lowest costs. The single seat vehicles' costs do not change between DOC/(pax-mile) and CPSM because we assume they operate with 100% load factor. As expected, the costs for the multi-passenger seat vehicles increases. Bell 407 GXi's CPSM is $6.50, which is similar to the four single passenger vehicles. However, it costs almost twice as much as the three best performing eVTOL vehicles.

As a reference point, Archer Aviation shared in their investor presentation a CPSM of $3.30 for their production aircraft [38] for a network with 25 mile average trip distances and unknown load factor. We calculated $5.60 using our DOC model, network, and 60% load factor.

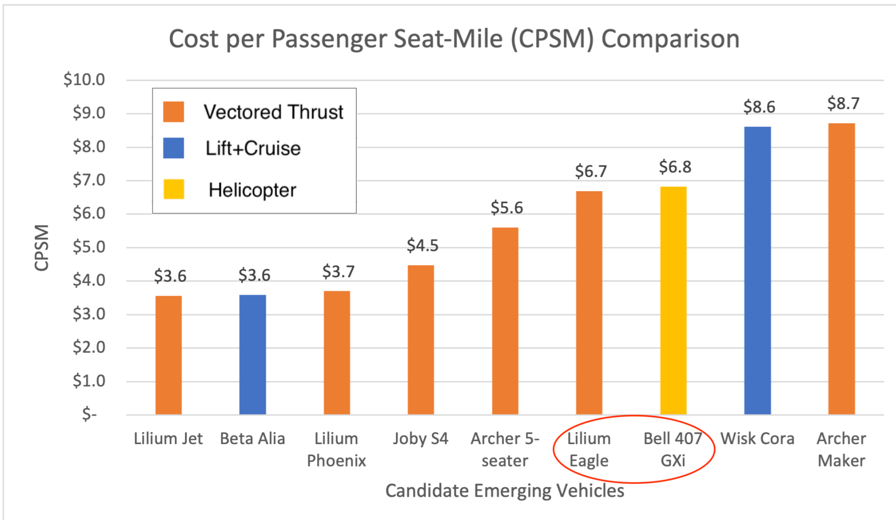

Fig. 6 Cost per Passenger Seat Mile for each Vehicle

B. UAM-Preferred Passenger Trips Results

Figure 7 shows the number of UAM-preferred passenger trips for each eVTOL vehicle and Bell helicopter. Vehicles with single passenger seats operate at 100% passenger load factor, and vehicles capable of ride sharing operate at 60% load factor. There are significant differences in trip counts, where some vehicles are suitable for zero trips while others have over 30,000. As expected, the passenger trip results closely align with the CPSM results IV.A.3, with the least costly vehicles generating the highest number of trips and vice versa. Lilium Phoenix and Jet are the best-suited vehicles for the aerodrome network because of their low costs and high cruise speeds, 186 and 175, respectively. Joby S4 compares less favorably for passenger trips relative to CPSM because of a lower cruise speed (165 mph). Bell 407 GXi helicopter, even with a high DOC, generates more trips than any single-passenger eVTOL vehicle.

C. Important Parameters for UAM Vehicle Design

From the economic analysis and trip simulation, we compared 12 eVTOL vehicles and one helicopter. We identified best-suited vehicles and described some of their desirable characteristics. In this section, we define and rank vehicle characteristics.

First, to understand why eVTOL vehicles are promising technologies, we look at the suitability of the Bell 407 GXi helicopter. For the economic metrics, the 407 is comparable to the worst performing eVTOL vehicles. In terms of UAM-preferred passenger trips, the 407 outperforms almost all of the single passenger seat vehicles. However, the best-suited eVTOL vehicles generate an order of magnitude more trips than the helicopter. This clearly shows that eVTOL vehicles are better suited for UAM than helicopters.

But not all eVTOL vehicle configurations are comparably well-suited. Given our specific aerodrome network, multicopter configurations performed poorly because of low range, low passenger capacity, low cruise speed, and high DOC. Vectored thrust configurations performed the best in terms of CPSM and UAM-preferred passenger trips. Beta Alia's lift+cruise configuration also performed well, ranking third place for both lowest CPSM and highest number of trips.

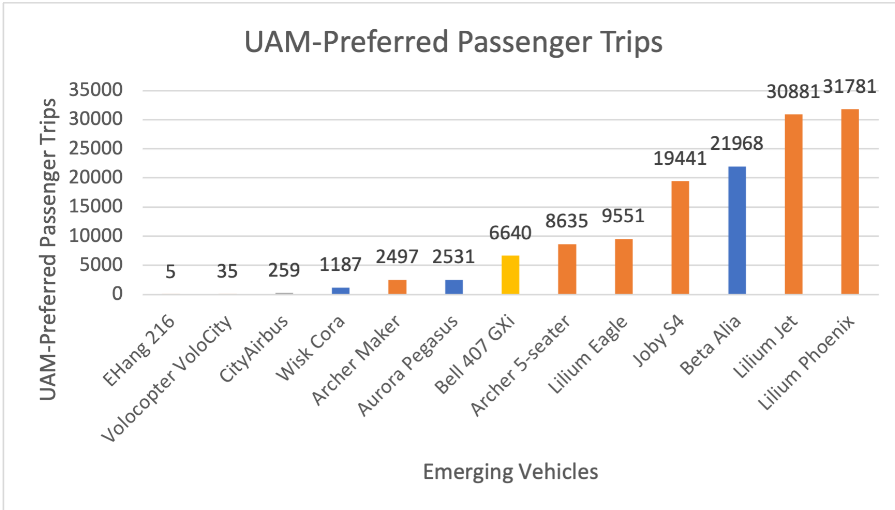

Fig. 7 UAM-Preferred Passenger Trips Comparison

Ride sharing[†] is a key enabler for UAM by lowering the per passenger cost of operations. Knowing that ride sharing is important, what can be said about the preferable vehicle passenger capacity? From the CPSM and trip results, the top three best-suited vehicles have between four and six passenger seats. Lilium Phoenix (four passenger seats) edged out Lilium Jet (six passenger seats) in CPSM and number of trips because of lower cost and slightly higher cruise speed.

In future work we would like to evaluate vehicles with two, three, and five passenger seats. CityAirbus, a multicopter configuration vehicle, has three passenger seats, but did not compare well because of limited range and low cruise speed.

"Low range" has repeatedly been noted as a reason for poor vehicle suitability. Given that, what are appropriate range bounds for eVTOL vehicles for the specified aerodrome network? Consider the Archer 5-seater, which carries the same number of passengers and is similar in terms of CPSM and cruise speed to Joby S4, but Archer has a third of Joby's trips. The difference between the vehicles is range, where Archer 5-seater can travel up to 60 miles, Joby S4 can travel a much higher range of 150 miles. Vehicle range requirements must be evaluated in the context of the aerodrome network. For this study, the aerodrome network III.B has an average range of 51 miles with distances between aerodromes as far as 142 miles. Archer 5-seater is missing out on potential trips because of its limited range. On the other hand, Lilium Eagle is the best-performing single passenger seat vehicle because of its long range (186 miles) and high cruise speed (186 mph), much higher than any other single passenger vehicle.

From this study, we are not able to appropriately evaluate the desired upper range bound. Generally, vehicles that are "over-designed" for this network performed better than "under-designed" vehicles. For example, Lilium Phoenix, the best-suited vehicle in terms of CPSM and trips, has a range of 186 miles, which far exceeds the aerodrome network range. By only carrying enough energy, and therefore battery weight, given a specified a network a vehicle could minimize costs while not missing out on potential trips. However, other considerations, like battery redundancy and battery health, are vital requirements.

Cruise speed is another important vehicle design parameter. The best-suited vehicles have cruise speeds between 165 and 190 mph. Wisk Cora and Archer Maker are both single passenger seat aircraft with about 60 mile ranges and similar CPSM. But Archer Maker has twice as many trips. The difference is cruise speed, where Archer flies at 150 mph while Wisk Cora travels at only 110 mph.

Another vehicle of note is the Lilium Eagle, a single passenger seat, vectored thrust vehicle with high cost, range, and cruise speed. Even without ride sharing capability it generates the fifth highest number of trips, out-pacing four vehicles with ride sharing capability. This demonstrates the importance of the range and cruise speed design parameters.

The Uber Elevate White Paper [21], published in 2018, laid out requirements for UAM vehicles. They imagined aerodrome networks in Los Angeles and London of similar distances as our Chicago network. They reasoned a vehicle should have two to four passenger seats, cruise speed between 150-200 mph, L/D above 10, and a range over 50 miles. Generally, our analysis concurs with Uber's. The nodal distances in our aerodrome network are larger, and thus our range requirement is higher. Uber's findings for L/D and cruise speed match the results of this study. More analysis is

[†]See our sibling paper, Maheshwari et al. [17] for more details on the ride sharing.

needed to evaluate vehicles with other passenger capacities.

Our second research question focused on identifying the most important aircraft characteristics. Based on the results from the economic metrics and trip simulations, we rank three of the design characteristics in order of importance.

1) Range. Vehicles with range limitations relative to the aerodrome network lost out on potential trips.
2) Cruise Speed. A key differentiation between vehicles with similar costs is cruise speed. Saving minutes on UAM trips has a significant impact on the trip's total effective cost.
3) Cost per Passenger - Vehicle MTOW is a key variable in determining airframe, battery, energy, and infrastructure costs. There is an important trade-off in the passenger capacity and the aircraft weight. Single passenger vehicles generally performed poorly in both the economic metrics and trip simulations.

A final note is in order to again state that there is significant uncertainty in most aspects of the vehicle database and the mission assumptions. In section IV.A.1 we compared the calculated CPSM results to industry and showed close comparisons. However, even values presented by industry should not be taken as ground truth representing eVTOL UAM operation. There are many variables and factors at play. Any values shared by academia or industry should be considered tentative and predictive until real world, passenger carrying flights are operating. That said, we can still model DOC, compare vehicles, and assess candidate vehicles and vehicle configurations under a well-defined set of assumptions.

V. Conclusion and Future Work

This paper compared candidate UAM vehicles using economic metrics and number of UAM-preferred passenger trips for a specific aerodrome network. We developed a DOC model, identified notional parameters of emerging eVTOL aircraft, and simulated trips for each vehicle using the computational framework with passenger demand data and a specified aerodrome network as inputs. To demonstrate the methodology, we analyze the data for the Chicago Metropolitan Area in this paper but the methodology is applicable to any other region provided the required data is available. Other eVTOL vehicles can also be analyzed if the DOC or vehicle design parameters are known. Such a tool could be employed by vehicle designers during the conceptual design phase or UAM operators comparing vehicles for a specific network.

We can clearly see that vehicles which are poorly-suited for the network impose an operational limit on the success of UAM. For example, we showed that the multicopter configuration is poorly suited for the specified network due to low passenger capacity, low range, and low cruise speeds. The Bell 407 GXi helicopter is currently used to service UAM operations and was employed as a comparison to emerging eVTOL vehicles. The helicopter performs similarly to single passenger eVTOL vehicles in terms of CPSM and generates significantly more UAM trips. But, the best-suited eVTOL vehicles generate an order of magnitude more trips than the Bell 407 GXi.

We analyzed the results to infer desirable vehicle design parameters. A range greater than 60 miles is preferred in order to service all of the potential trips for the aerodrome network. A cruise speed between 150 and 190 mph saves passengers' time and decreases the trip effective cost. Vehicles with relatively high passenger capacities capable of leveraging ride sharing are best-suited.

The next step in this research is to compare the UAM vehicles using alternate aerodrome network configurations. Interesting questions arise, such as "Is there such an aerodrome network configuration where multicopters are the best-suited vehicle?" "What if the aerodrome network increases from 10 aerodromes to 50 aerodromes?"

This study focused on near-term operations, thus in future work we would like to see how vehicle selection studies change with respect to time and further technological improvements such as battery energy density. In addition, there are more details and research needed to further refine the DOC model. Comparing economic metrics within the computational framework, such as CASM, is a point of interest. Another interesting problem is the design of best-suited aircraft fleets for a particular network, investigating various fleet options (combinations of vehicles) and their efficacy for a defined network. This network could encompass Advanced Air Mobility more broadly, including both urban and regional trips.

Acknowledgments

This work is partially funded by National Institute of Aerospace under the contract number NNL13AA08B. The authors would like to thank our technical monitor Michael Patterson at NASA LaRC for his valuable feedback during the course of this project.

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