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Design of a Carbon-Free Urban Air Mobility System

Mohamed Elgendy, Tarek Jarrouje, Andrew Richardson, Asadullah Yousuf, George Donohue

George Mason University

Corresponding author's Emails: aricha@gmu.edu

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Abstract: Urban air mobility refers to a transportation system that will allow growing urban populations to circumvent traditional transportation routes via the use of vertical takeoff and landing vehicles in and around cities. Since this form of transportation has not yet been widely implemented, this study analyzes the trade-offs between how different aircrafts used in a UAM system can achieve flight without increasing the concentration of CO_2 in the atmosphere. This project compares traditional sources of energy with prototype hydrogen fuel-cell and lithium battery-powered vehicle designs. Each design alternative was simulated to determine how the vehicle impacts the financial viability and environmental sustainability of an UAM system and was used to determine possible carbon-free system designs. It was found that of the six potential aircraft designs studied, the most cost-effective net-zero CO_2 UAM system would be comprised of lightweight traditional helicopters paired with the purchasing of carbon credits at $600/ton.

1. Introduction

1.1 Context Analysis

Growing population density increases pressure on transportation systems, creating a demand for alternative methods of transportation. In 2019 Americans in cities lost 99 hours due to congestion, resulting in an $88 billion loss of lost productivity, or an average of $1,377 per person (Inrix, 2020). Since existing ground transportation systems are increasingly congested, the desire to find alternatives to this problem continues to grow. Trial UAM (URBAN AIR MOBILITY) systems like Blade and UberCopter use helicopters to operate at a premium of around $20/passenger per km, about 3x limo, and 20x rideshare app prices. In 2019, $907 million had been invested into the development of the UAM industry, with a speculated market growth of anywhere from 2-20 billion by 2050. According to UAM market analysis by NASA, it was shown that an autonomous UAM public transportation system might become profitable by as early as 2028 with a $900 million return in that year, estimating a trip cost of $50, and 4,100 vehicles available for use (Hader, 2020). Despite this growth potential, Urban air mobility transportation systems have only ever been partially implemented in the form of private helicopter charter services. With the increased awareness of the negative environmental impact of traditional forms of transportation, the desire to transition from hydrocarbon fuels has greatly increased.

1.2 Potential Energy Systems

The vast majority of developers in the UAM industry have looked to lithium battery powered vehicles as a solution both because of their potential for zero direct emissions, as well as the relatively low annual operational cost. However, as shown in Figure 1, the energy density of these batteries is extremely low. This leads to a lower overall power capacity, limiting both payload and range. Another concern is the indirect emissions coming from the energy generation that is used to charge the lithium vehicles. In 2019, close to 60% of US energy was produced by burning coal and methane, which was responsible for 99% of the energy sectors 1.72 billion tons CO_2 emissions. Per kWh this averages to 0.42kg of CO_2, which is close twice as much as the emissions which come from burning jet fuel at 0.24kg of CO_2 / kWh. Therefore if any transition from fossil fuels are made with the purpose of limiting emissions, the generation of the energy from renewables is a key component which must not be ignored. Another fuel alternative with the potential for zero direct emissions is pure hydrogen, through an on board fuel-cell.

While hydrogen is not nearly as volumetricly dense as jet fuel, it is nearly 3 times as dense by weight, as shown in Figure 1. The largest challenge with the use of this fuel comes from containment required to hold the compressed liquid H_2 as well as the limited infrastructure for fueling. Hydrogen itself can be generated without carbon emissions through electrolsys, but today 95% of hydrogen is sourced via methane reformation, a process which releases 0.21kg of CO_2/ kWh.

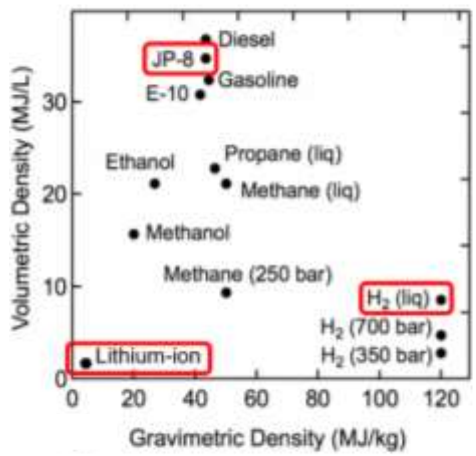

Figure 1. Energy Density of Analyzed alternatives

In our project the differences between the energy systems of lithium batteries, hydrocarbons, hydrogen fuel cells were considered through the comparison of vehicle alternatives for each fuel. The viability of these UAM vehicle designs in system operation were analyzed and compared to determine whether or not the requirements of urban air mobility could be met with a reasonable return on investment, and what trade offs are to be expected with each energy source.

2. Stakeholder Analysis, Problem and Need Statements

2.1 Stakeholders

The stakeholders of a carbon-free urban air mobility system are categorized into primary stakeholders and secondary stakeholders. These include, UAM Passengers, Pilots, UAM Fleet Operators, Vertiport Operators, Original Equipment Manufacturers (OEMs), Residential Communities. Secondary stakeholders include the Federal Government (FAA and U.S. Department of Transportation), State and Local Government, Insurance Companies, Real Estate Developers, and any Competitors.

2.2 Problem and Need Statement

Existing UAM systems can only operate via the use of hydrocarbon fuels, with each vehicle releasing hundreds of pounds of CO_2 per hour. It is anticipated that increased regulation of carbon emissions will limit the operation of these UAM systems in the future. There is a need for an Urban Air Mobility system that can operate without carbon emissions. It is imperative to determine an acceptable carbon-free aircraft design that can satisfy the needs of a UAM system.

3. Concept of Operations

The proposed concept of operations for the design of a carbon free UAM system will operate and transport passengers or cargo at altitudes within urban areas. The system was assumed to have the capability to transport at least 50,000 people per year while utilizing existing helicopter infrastructure such as routes, helipads, and Air Traffic Control (ATC) services. The UAM system and vehicles were assumed to operate within the operational requirements under FAA 14 CFR 135 operations in which certificate holders can conduct on-demand operations with UAM vehicles (FAA, 2020). The system was required to utilize a net zero carbon system, either via the use of zero emission vehicles and energy generation, or capture technology to capture carbon dioxide emissions from carbon emitting vehicles to produce a net-zero carbon emissions.

To achieve measurable results, a simulation tool in python was developed to evaluate various vehicle design characteristics and monitor how they impact overall system outputs, costs, and to determine which of the vehicle designs best fits the constraints of our systems objective function. In the UAM transportation simulation (shown in figure 2) each proposed design alternative underwent 25,000 flights of normally distributed distances for roughly 8 hours per day for a year, transporting over 50,000 passengers. With the specific information about each vehicle entered, realistc projections of total cost, total emissions, and minimum fleet size to meet system demand were created and will be discussed further in our conclusion.

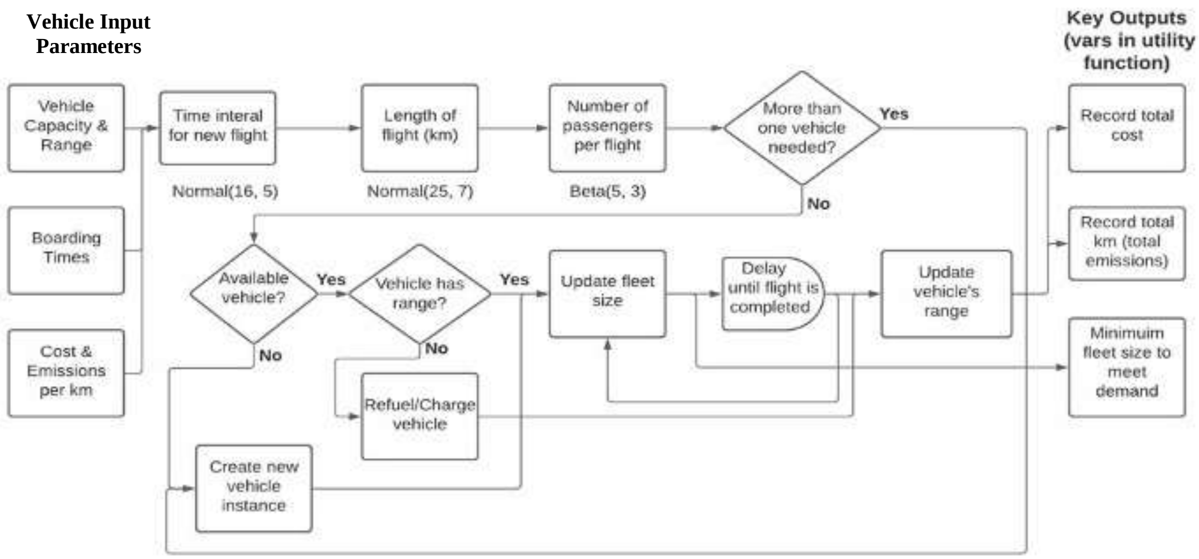

Figure 2. Operational Transportation Simulation used to compute Fleet size, Costs and Emissions

These alternatives and their propulsion systems were also compared through a NASA rotorcraft design tool (NDARC) to verify the individual parameters used in the UAM system simulation such as operational cost, fuel consumption rate, energy effiecncy, and the emissions of each design (Johnson, n.d.). In the NASA rotorcraft design tool, individual flight paths were modeled to verify the accuracy of the larger UAM system model results, as shown in Figure 3. From the python system model's results, a case can be made for the most cost-effective business plan for a UAM system which is capable of net zero-emission transportation on a large scale.

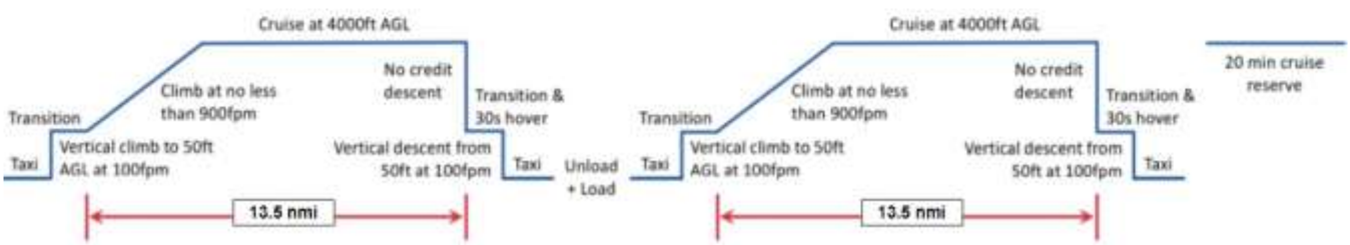

Figure 3. NDARC Flight Profile

4. Requirements

4.1 Mission Requirements

The systems mission requirements are as follows:

MR.1 The system shall provide on-demand air transportation between a set of predetermined urban locations.
MR.2 The system shall operate with a net-zero emission of CO_2 into the atmosphere.
MR.3 The system shall be capable of transporting at least 50,000 people per year. (roughly 1% of New York city's first-class passenger volume.)
MR.4 The system shall meet the operational requirements of the FAA UAM operations under 14 CFR Part 135.
MR.5 The system shall determine and operate with the most cost-effective vehicle which meets these requirements in a set of alternatives.

These requirements were evaluated and verified via Analysis, Inspection, and Testing, to determine system viability. For each requirement, a validation plan has been created to ensure the system stakeholders' goals are met.

5. Design

To satisfy the mission and design requirements as stated in our scope statement, 6 design alternatives were identified and are shown in Table 1. (Colors represent certainty within 1%, 10%, and 50%, for green, yellow, and orange respectively.) Figure 4 shows examples of several of the selected designs (Helis, 2016), (R44 Robinson, 2021), (Airbus, n.d.), (Skai, n.d.).

Table 1. Design Alternatives

Vehicle Alternatives		Energy Source	CO_2 (kg/km)	Range (km)	Speed (km/hr)	Passenger Capacity	Initial Cost	Annual Cost	Noise (dB)
R44		HC	0.89	550	202	3	$515k	$160k	81
R66		HC	2.25	650	222	3	$880k	$210k	83
Airbus H130		HC	4.18	606	235	7	$3.45m	$350k	82
Prototype Designs	**E-R44**	Li	1.1	54	148	3	$800k	$125k	82
	CityAirbus	Li	0.99	95	120	3	$1.25m	$140k	78
	Skai	H_2	1.13	600	185	4	$500k	$170k	78

Figure 4. Airbus H130, E-R44, CityAirbus, and Skai

6. Utility Function

The Utility Function used to evaluate the proposed alternatives is was calculated with the following metric weights:

W_E = Weight of CO_2 emissions = 0.40
W_{TRL} = Weight of Technology Readiness Level = 0.10
W_S = Weight of vehicle speed = 0.10
W_R = Weight of vehicle range = 0.25
W_C = Weight of comfort = 0.10
W_N = Weight of vehicle noise = 0.05

Using the swing weights method this provides equation (1) as well as the results shown below (Table 3).

Table 3. Overall Utility Scores

Vehicle Alternatives (Weight)		Emissions (0.4)	Range (0.25)	TRL (0.10)	Comfort (0.10)	Speed (0.10)	Noise (0.05)	Utility Score
R44		0.41	0.83	1	0.33	0.68	0.87	0.62
R66		0.1	1	1	0.35	0.81	0.83	0.55
Airbus H130		0.02	0.93	1	0.46	0.9	0.81	0.51
Prototype Designs	E-R44	0.33	0.01	0.7	0.33	0.32	0.85	0.31
	CityAirbus	0.37	0.07	0.7	0.4	0.13	0.93	0.34
	Skai	0.32	0.92	0.6	0.4	0.57	0.93	0.56

7. Results and Conclusion

The initial cost of a UAM system using each alternative, in combination with the annual operational cost was used in combination with an optimistic set ticket price of $10/passenger per km to find the NPV (3% discount rate; equation 2) and break even point for each potential zero emission UAM system, shown in Figure 5.

Even though the battery electric prototype vehicles had cheaper individual vehicle opperational costs, the minimum fleet sizes (shown in parenthesis of Figure 6) needed to meet the system requirements were more than double that of other alternatives, due to the limited power capacity, range, and slower speeds. These lithium powered vehicles have the potential for zero emissions, but not without the development of a renewable energy power source, which was estamted to increase the energy price by 50% (ROM, rough order of magnitiude). The prototype Skai hydrogen fuel-celled aircraft also has the potential for zero direct emissions, but here also it is necessary to account for the indirect emissions in hydrogen production. The process of sourcing zero emission hydrogen requires on site generation through electrosis increasing the cost by about 200%. While this alternative has the energy density required for long-range flight, major infrastrure development is required if these vehicles are to be used in the implementation of a UAM system. In order for the hydrocarbon fuels to achieve carbon neutrality, an external direct air capture technology would need to be used to remove the CO_2 that is released by the system. Today there are 17 DAC carbon capture facilities in operation, with another 20 under development, and a speculated cost per ton removed of $600 was included in the overall system cost. This removal cost was included in the annual operation of each helicopter releasing CO_2 to compare the costs of each alternative in a carbon free UAM system.

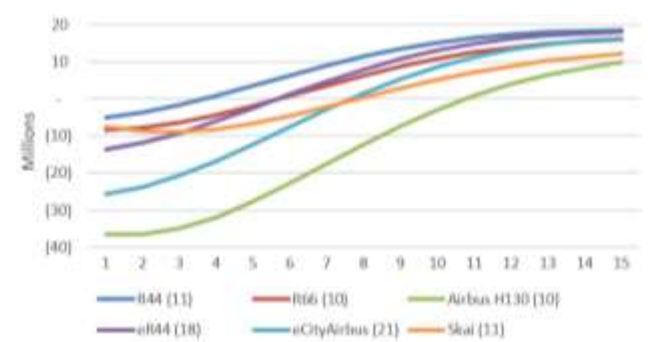

Figure 5. NPV over 15 years (fleet size)

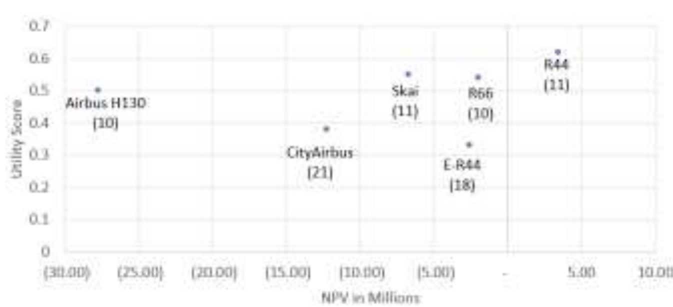

Figure 6. Utility vs 5 year NPV

Ultimately, a fleet of 11 Robinson R44 helicopters was shown to be both the most cost-effective and greatest utility score for a system capable of meeting all requirements. Using the python system simulation's outputs, the break-even point was found for this fleet to be between year three and four, using a ticket price of $250 gives an average of $10/passenger km.

This price estimates include the acquisition, operation, maintance, insurance, and energy costs for each vehicle to be used in a UAM system, but it is important to note that the ticket price and NPV calculations do not reflect the cost of infrastructure development, advertising, lobbing, or vertiport operations.

Additionally, three possible operational scenarios were considered with varied total flight distances, averaging 25km, 50km, and 100km. In order to accurately compare the lithium electric vehicles with design alternatives capable of longer ranges, the 25km mean distance was used for the outputs and calculations shown until this point, and every vehicle completed all flights in this range. In the 50km use case, the lithium vehicles could only complete 80% of the flights, and at 100km, could only meet 25% of the demand. In both cases the minimum fleet sizes for all vehicles increased by 15% and 40% respectively, as well as increased operational costs of 30% and 100%. Due to the extreme limitations of a low energy density power source in aircraft design, it is unlikely that the battery powered vehicles, often seen as the face of UAM, will operate with any large payload capacity at range. Instead, carbon neutral UAM systems will be composed of vehicles utilizing hydrocarbon fuels in combination with carbon capture technologies.

$$U(Alternative) = 0.4V_E(X_E) + 0.25V_R(X_R) + 0.10V_{TRL}(X_{TRL}) + 0.10V_C(X_C) + 0.10W_SV_S(X_S) + 0.05V_N(X_N) \tag{1}$$

$$\frac{R_t}{(1+i)^t} = \frac{ticket\ price * demand_t - \ annual\ cost_t \ - \ inital\ cost_t}{(1.03)^t} \tag{2}$$

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