Updated to May 2024

This updated paper increases the pack specific energy to 235 Watt.hrs/Kg. used by the Joby S4 and uses a reserve flight time of 45-minutes.

REVIEW OF SELECTED ADVANCED AIR MOBILITY AIRCRAFT

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Abstract

Enormous interest and investment capital are now being directed to AAM aircraft as a safe and quiet Uber like air taxi alternative to the automobile for intracity and intercity travel.

Morgan Stanley Research [1] predicts that the world market for AAM aircraft will be $9 trillion to $19 trillion annually by the year 2050, which could be more than eighteen times larger than today's entire world aviation industry.

This paper analyzes the performance of five air taxis and briefly reviews the performance of four others. They are differentiated by whether their wings rotate, tilt, or are fixed and whether their energy source is battery, fuel or potentially hybrid. A third differentiator is whether the lift and cruise propulsion systems are separate or combined.

Air taxi performance is evaluated as a measure of the viability of each aircraft design including noise, payload, speed, convenience of use, safety, and range based on the FAA's required 45 minute reserve flight time.

Introduction

The challenge facing air taxi developers is to successfully balance airframe complexity and its associated development and production cost versus performance goals. The legacy aircraft companies like Airbus, Boeing and Embraer have put forward designs that favor airframe simplicity and propeller efficiency over airframe drag and weight. As a result, they use separate lift and propulsion systems. The start-up developers like Joby, Archer, Vertical Aerospace and Lilium use combined lift and cruise propulsion systems that are lighter with lower drag but involve far more articulation of critical components. This could potentially slow FAA certification.

The performance of a VTOL capable air taxis will depend on tradeoffs between speed, range, payload, energy available and mission profile. The most significant variables controlling these tradeoffs are:

- Disc Loading $\left(\frac{\text{Gross Weight}}{\text{Sweep Area}}\right)$: Higher disc loading increases the installed power.
- Wing Loading $\left(\frac{\text{Gross Weight}}{\text{Wing Area}}\right)$: Higher wing loading increases the speed at which maximum $\left(\frac{\text{Lift}}{\text{Drag}}\right)$ ratio occurs.
- Induced Drag: Increases with wing loading and reduces with speed.
- Profile Drag: Reduces with wing loading and increases with speed.
- Maximum Range: Occurs when profile drag equals induced drag.

This analysis makes the following assumptions regarding the FAA's requirements for certification.

- Reserve flight time will remain at 45 minutes.
- Average motor power output is at VTOL level during 90-second transition time to cruise and 60-second from cruise.
- Maximum temporary power will be available for up to two minutes from cold during the 90-second transition to cruise.
- Minimum continuous power is that for VTOL.

EHANG 216-S

Air taxis Being Analyzed

The five air taxis being analyzed were chosen because they represent different credible concepts that have undergone some preliminary flight testing while

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- **President of Moller International and Freedom Motors Inc.**

specifications and projected performance data is available.

- *Ehang 216-S*. Similar to a large wingless drone, uses eight arms supporting sixteen battery powered counter-rotating propellers. It carries two persons.

- *Airbus Vahana* used tandem wings that tilt through 90°. Each wing has four battery powered motor/propellers attached. It carries two persons. This model is now replaced by their NextGen model (see page 9).

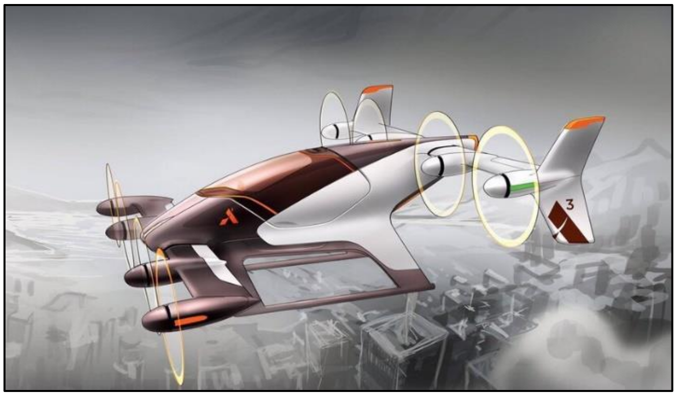
- *Boeing/Wisk Cora* uses twelve propellers/motors for lift that are separated from that for cruise. It carries two persons.

- *Joby S4*. Uses one fixed wing on which four propellers/motors rotate through 90° along with two rotating on the fixed tail. It carries five persons including the pilot.

- *Moller Skycar® 200*. Uses four ducted fans that rotate through 90° that are attached to the fuselage. Each has two counter-rotating engine powered fans. It carries two persons.

Propulsion System Considerations

- In this analysis only the Boeing/Wisk Cora separates the propulsion system for VTOL from that for cruise. This arrangement allows propeller and motor efficiency to be maximized in both operating modes. It also provides an easier conversion to a hybrid configuration .



Airbus VAHANA

- The propeller thrust required during VTOL is over five times that required for cruise. To maintain propeller efficiency during cruise, the number of operating propellers/fans should be reduced. This complication is avoided through the use of separate lift and cruise propulsion systems.

- For combined lift/cruise propulsion, the stopped powerplants can minimize potential drag by folding back their propeller blades. Ducted fans that are imbedded in the airframe can be covered over during cruise.

- To meet the likely noise ordinance, the tip speed of open propellers may need to be below 400 ft/sec. This could require a gearbox between the motor and the propeller to minimize motor weight, while a high solidity propeller will be needed (propeller planform area divided by swept area). This increases both skin friction drag and rotating inertia.

- One and two person air taxis can achieve pitch and roll control by changing the rotational speed of the propellers or ducted fans if rotational inertia is low enough. This can be improved by using an increased number of smaller propellers.

- Large high solidity propellers will require rapid pitch changes of the blades to provide adequate pitch and roll control.

JOBY S4

- The installed reserve power required to tolerate a motor or engine failure is very dependent on the number of powerplants and how they are arranged. For example, a propulsion system with six motors/propellers will require nearly three times more reserve power than one with twelve motors/propellers.

- Electric motors [2] and high performance engines [3] can achieve a weight to power ratio of 0.6 lbs./Kw. Electric motors have the advantage that they can achieve a temporary 0.3 lbs/Kw. for up to two minutes from cold.

Airframe Considerations

The airframe will need to use composite materials to minimize weight. Fiberglass has been the dominant composite material used in the light plane industry; however, air taxi airframes will need to utilize carbon fiber and Kevlar composites to minimize weight. To help determine the projected weight of the airframe, the weight of several similar class FAA approved airframe (empty weight minus power source) is averaged. From discussions with the designers of the Cessna TTI (Lancair Group) a consensus was reached that using carbon fiber and Kevlar composites could reduce airframe weight by up to 20%. It is estimated that the additional weight of the VTOL airframe and VTOL related components could offset this weight reduction for the surveyed five person airframes which contain little carbon fiber. The two-person airframes cited have a high carbon fiber content and therefore, a 20% weight increase is added to account for added VTOL related component weight. Consequently, the average two-person airframe is projected to weigh 650 lbs. while the five person airframe is projected to weigh 1,784 lbs. [4]. These weights reflect that the two person airframe would be approved under the light sports aviation (LSA) category while the five person airframe would require FAA certification under part 21.

SKYCAR® 200

Performance

The following equations [5] determine the power required during hover and cruise:

Momentum Equation:

$$\text{Thrust} = \text{Drag} = \rho_0 \times \sigma \times A_e \left(V_j^2 - V_j \times V_0\right)$$

Energy Equation:

$$\text{Horsepower} = HP = \frac{\rho_0 \times \sigma \times A_e}{1100 \times \eta} \left(V_j^3 - V_j^2 \times V_0\right)$$

$$\text{Drag} = \left(\frac{C_L}{\pi \times AR \text{ x } \in} + \frac{C_{DW}}{C_L} \times \frac{A_W}{S}\right) \text{ x Lift (W)}$$

Where

$$C_L = \frac{2W}{\rho_0 \times \sigma \times V_0^2 \times S}$$

With drag known, power required for cruise is:

$$HP = \frac{D \text{ x } V_o}{550 \text{ x } \eta}$$

For Vo = 0 momentum and energy equations provide the HP required for the specified gross weight.

$$W = 14.23(\sigma \text{ x } \rho_0 \times A_e)^{1/3} \times (HP \times \eta)^{2/3}$$

This equation only applies to battery powered propulsion. For engine power available, HP in the above equation is multiplied by (1.132σ-.132) to account for the power reduction with altitude.

The above equations show only the installed power needed for VTOL and do not account for the additional power required to maintain stability and control in windy conditions during VTOL and transition. It has been shown [6] that in a 40-mph. wind that the minimum angular acceleration needed about the roll axis is 0.78 rad/sec^2. This translates into a need for approximately 10% additional installed power. In any case, the actual control power required will depend on the location of the ducted fans or propellers and its moment of inertia.

$$L/D \max = \left(\frac{\pi \text{ x } AR \text{ x } \in \text{ x } S}{4 \text{ x } C_{DW} \text{ x } A_w}\right)^{1/2}$$ and occurs when induced drag equals profile drag.

Where,

W = gross weight in lbs.

ρ_0 = standard air density = 0.002378 $\frac{\text{lb sec}^2}{\text{ft.}^4}$

σ = air density ratio $\frac{\rho}{\rho_0}$ = 0.93 (100° F and 5000 ft. altitude)

A_e = $\frac{\text{swept area of propellers}}{2}$ or exit area of ducted fans in ft^2

HP = required horsepower

S = wing area in ft^2

V_0 = air taxis speed in feet per second

V_j = exit air velocity either downstream of propeller or at ducted fan exit in feet per second

AR = aspect ratio

ε = span efficiency factor

A_w = wetted area of entire air taxis except propellers or fans in ft^2

C_{DW} = profile drag coefficient based on wetted area.

η = energy conversion efficiency between energy source and energy in the exiting air stream.

Battery Specific Energy

The NCA and NMC lithium batteries used in most electric cars have a specific energy of over 300 Wh/Kg. but also have a high internal resistance. Even at its relatively low discharge rate of 0.25 c the weight of the battery cooling system lowers the pack specific energy to 165 Wh/Kg. (Tesla). Air taxis have a much higher discharge rate of ~2c during cruise and ~20c during VTOL, which would result in an even heavier cooling system that would further reduce battery pack specific energy. Solid state or lithium polymer (LiPo) batteries have a much lower internal resistance which results in a pack specific energy closer to its specific energy. Joby Aviation uses a pack specific energy of 235 W.hr./Kg., which is consistent with the performance of solid state batteries produced by its investor Toyota Motors. Pack specific energy of 235 W.Hr./Kg.is used throughout this analysis.

Energy Conversion Efficiency

Conversion efficiency (η) provides a measure of the energy reduction between the energy source (HP or Kw) and the energy available to generate the required lift or thrust during VTOL and cruise. It is a function of battery energy conversion efficiency, motor efficiency and propeller or ducted fan efficiency.

Electric Motor Efficiency

Electric motors can achieve a 95% efficiency for a specific operating condition. However, when used as the power source for both lift and thrust the average efficiency could be significantly less. Ideally, motors utilized in cruise will be designed for cruise, while lift motors will be optimized for VTOL. This requires separate propulsion systems for lift and cruise.

Propeller and Ducted Fan Efficiency

Unducted propeller efficiency is unlikely to exceed 65% efficiency during VTOL [7], or 90% during cruise. The propeller efficiency for the Ehang during cruise is difficult to measure; however, data for light helicopters operating at disc loading similar to the Ehang should see a power reduction of approximately 60% between take-off and cruise. The efficiency of ducted fans with fixed pitch can exceed 90% in VTOL and almost be maintained in cruise if duct exit area is reduced to achieve an internal air velocity that supports fan efficiency.

As in the case of motor efficiency propeller efficiency can be maximized during both cruise and VTOL by using separate propulsion systems for VTOL and cruise.

Overall Energy Conversion Efficiency

$\eta = \eta\text{battery} \times \eta\text{motor} \times \eta\text{propeller}$

Ehang 216-S during VTOL (drone configuration):
$\eta = 0.9 \times 0.95 \times 0.75 = 0.64$
Vahana during VTOL:
$\eta = 0.9 \times 0.85 \times 0.65 = 0.5$
Vahana during cruise (combined propulsion):
$\eta = 0.95 \times 0.85 \times 0.9 = 0.73$
Cora during VTOL (separate propulsion):
$\eta = 0.9 \times 0.95 \times 0.7 = 0.6$
Cora during cruise:
$\eta = 0.95 \times 0.95 \times 0.9 = 0.81$
Joby S4 during VTOL (combined propulsion):
$\eta = 0.9 \times 0.85 \times 0.65 = 0.5$
Joby S4 during cruise:
$\eta = 0.95 \times 0.9 \times 0.85 = 0.73$
Skycar® 200 during VTOL (combined propulsion):
$\eta = 0.9$
Skycar® 200 during cruise
$\eta = 0.85$

Battery Energy Reserve

A portion of the battery energy is held in reserve to provide the FAA’s forty five minute reserve flight time in case of unexpected circumstances during landing. This reserve also ensures that battery energy is never depleted to less than 20% capacity during normal operations.

The reserve flight speed is determined at maximum L/D rather than minimum power where the speed can be close to stall due to the high wing loading of VTOL capable air taxis.

Ehang 216-S

The design range is 20 miles at 60 mph [8]

VTOL power = 121.5 Kw (with 10% control power on a 100°F Day at 5,000 ft. altitude).

The propulsion system uses sixteen motor/propellers which require a 16% increase in installed power to tolerate an engine failure for a total of 140.9 Kw.

Data for light helicopters with a disc loading $\left(\frac{\text{Gross Weight}}{\text{Sweep Area}}\right)$ similar to the Ehang 216-S show that minimum power occurs near 60 mph [9] where it reduces to ~ 40% of that required for VTOL. A 45 minute reserve flight time would require 36.8 Kwh.

Cruising power = 48.6 Kw

Where,

A_e = 85 ft^2 (one half total propeller swept area)
W = 1,271 lbs.
Installed battery energy = 17.4 Kwh

Results:

Operating for 150 seconds at VTOL power during transition requires 2.53 Kwh which leaves 11.4 Kwh. This would provide a range of 21.5 miles at 60 mph with no reserve flight time.

A^3 Vahana (Beta)

The design range is 60 miles.[9]

VTOL power = 279.4 Kw (with 10% control power on a 100°F Day at 5,000 ft. altitude).

The Vahana uses eight motor/propellers that are evenly distributed. To tolerate a motor failure requires a 54% increase in installed power to 430 Kw.

L/D max = 14.1 @ 130.3 mph.

Cruising power = 45.4 Kw @130.3 mph.

At maximum L/D a 45 minute reserve flight time requires 34 Kwh.

Where,
S ~ 75 ft^2
Aw ~ 350 ft^2
C_{DW} ~ 0.0055 (best case)
AR ~ 7.3
ε ~ 0.9 (tandem wings)
W = 1,800 lbs.
A_e = 76 ft^2 (one half total propeller swept area)

Results:

With gross weight at 1,800 lbs.; payload at 450 lbs; airframe at 650 lbs; and propulsion system at 168 lbs. (0.6 lbs./Kw.) the battery weight is 532 lbs. with a specific energy of 56.8 Kwh.

With 11.6 Kwh for 150 seconds at VTOL power and 34 Kwh for 45 minutes reserve flight time, the range is 32.6 miles at 130.3 mph.

Boeing/Wisk Cora

The design range is 62 miles at 110 mph. [10]

VTOL power = 451.5 Kw (with 10% control power on a 100°F Day at 5,000 ft. altitude).

The Cora uses twelve lift motor/propellers that are evenly distributed. To tolerate a motor failure requires a 31% increase in installed power to 591.4 Kw.

L/D max = 13.3 @ 89.6 mph.

Cruising power = 62.1 Kw @110 mph.

At maximum L/D a 45 minute reserve flight time requires 34.7 Kwh.

Where,
S ~ 114 ft^2
Aw ~ 550 ft^2
C_{DW} ~ 0.01 (best case)
AR ~ 11.4
ε ~ 0.95 (tandem wings)
W = 2,800 lbs.
A_e ~ 75 ft^2 (one half total propeller swept area)

Results:

The Cora's high gross weight suggests that separating lift propulsion from cruise substantially increased airframe weight. Using an increased ratio of empty weight to gross weight (EWF) of .60 (see Addendum).

With gross weight at 2,800 lbs., empty weight at 1680lbs.; payload at 400 lbs; the battery weight is 720 lbs. with an energy capacity of 76.9 Kwh, at 235 Wh/Kg.

With 18.8 Kwh for 150 seconds at VTOL power and 34.7 Kwh for 45 minute reserve flight time, the range is 41.5 miles at 110 mph.

Joby S4

The design range is 100 miles [12].

The wing tip propellers generate 280 lb. down force on the wing during VTOL, which results in the need to generate 5,580 lbs. of lift during VTOL.

VTOL power = 911 Kw (10% control power on a 100°F Day at 5,000 ft. altitude)

The Joby uses six motors/propellers that are evenly distributed. To tolerate a motor failure requires an 84% percent increase in installed power to 1,676 Kw.

L/D max = 12.6 @ 150 mph.

Cruise power required at L/D max= 180.8 Kw.

At maximum L/D a 45 minute reserve flight time would require 135.6 Kwh.

Where,
S ~ 137 ft^2
A_w ~ 762 ft^2
C_{DW} ~ 0.0055 (best case)
AR ~ 6.5
ε ~ 0.95
A_e = 210 ft^2 (one half propeller sweep area)
W = 5,300 lbs.

Results:

With weight at 5,300 lbs; payload at 1,000 lbs.; airframe at 1,784 lbs; propulsion system at 547 lbs. (0.6 lb./Kw), the battery weighs 1,969 lbs. and provides a battery specific energy of 210.6 Kwh. 30.8 Kwh is used for 150 seconds at VTOL power and 135.7 Kwh for 45 minute reserve flight time. The range is 36.8 miles at 150 mph.

Skycar 200

The design range is 500 miles at 200 mph.

VTOL power = 320 Kw. This includes 10% control power on a 100°F Day at 5,000 ft. altitude.

Providing for an engine failure requires an installed power increase of 36% for a total of 435 Kw.

L/D @ 200 mph = 6.32.

L/D max = 11.4 at 116 mph

Cruise power =122.3 Kw at 200 mph

Where,
$S = 58\ ft^2$
$A_w = 450\ ft^2$
$C_{DW} \sim 0.0055$ (best case)
$AR \sim 7$
$\varepsilon \sim 0.9$ (Swept back wing)
$W = 1{,}650$ lbs.
$A_e = 16\ ft^2$

Results:

With gross weight at 1,650 lbs., payload at 450 lbs., airframe at 650 lbs. propulsion system at 261 lbs. and reserve fuel at 28 lbs., the fuel weight available for flight is 281 lbs. With SFC of 0.75 lb./Hp.hr (methanol) the maximum range is 501 miles at 200 mph with a 45-minute reserve flight time at maximum L/D.

Factors Determining Air taxis Deployability

FAA Certification

The FAA has proposed an initiative called “Modernization of Special Airworthiness Certification (Mosaic)”. Specifically, Mosaic could allow two person air taxis to be certified under the light sport aircraft (LSA) category. In this case a FAA accepted consensus standard would serve as the means of compliance. This approval process is far less demanding than that for larger air-taxis which must meet the FAA part 21 standard for powered lift aircraft. The final detailed approval process is expected to take effect in mid-2024.

Convenience

Uber has been promoting the concept where it would operate from a large Skyport located near the city center to provide service. The practicality of this approach was highly criticized in an article published by Curbed magazine (link) [13] where the author makes a credible argument that a single centrally located Skyport will not work for a number of logistical reasons. In particular, getting to a large Skyport would still involve congested ground travel or alternatively numerous large Skyports throughout a city to be useable.

To make air taxis accessible to the commuter at or near one’s home or business, it should be able to land almost anywhere including a city curb or small parking lot. It must also meet the local ordinance for noise. These two requirements will have a major impact on the design. To land at the curb the air taxis will need to be able to reduce their width to 10 feet or less prior to landing. This will require the wings to fold and the propulsion system to be separated from the wings. Disc loading will increase, which increases installed power and could make using batteries alone less viable.

Noise

The noise generated by the air taxis will need to meet certain standards depending on where it operates from. The primary sources of noise are the propellers or ducted fans and engine exhaust. Ducted fans can be much quieter than propellers for the same disc loading and tip speed due to the absence of tip vortex related noise. The maximum noise that is allowed in a residential area varies from city to city. In many cities a maximum short-term noise of 88 dBA at 25 feet is allowed, while somewhat longer-term noise cannot exceed 80 dBA [14].

- The Airbus Vahana, Boeing/Wisk Cora and Ehang 216-S use open propellers that operate at higher tip speeds and may not meet the 88-dBA limit when operating from the top of a high building, a noise level above 88 dBA may be acceptable.

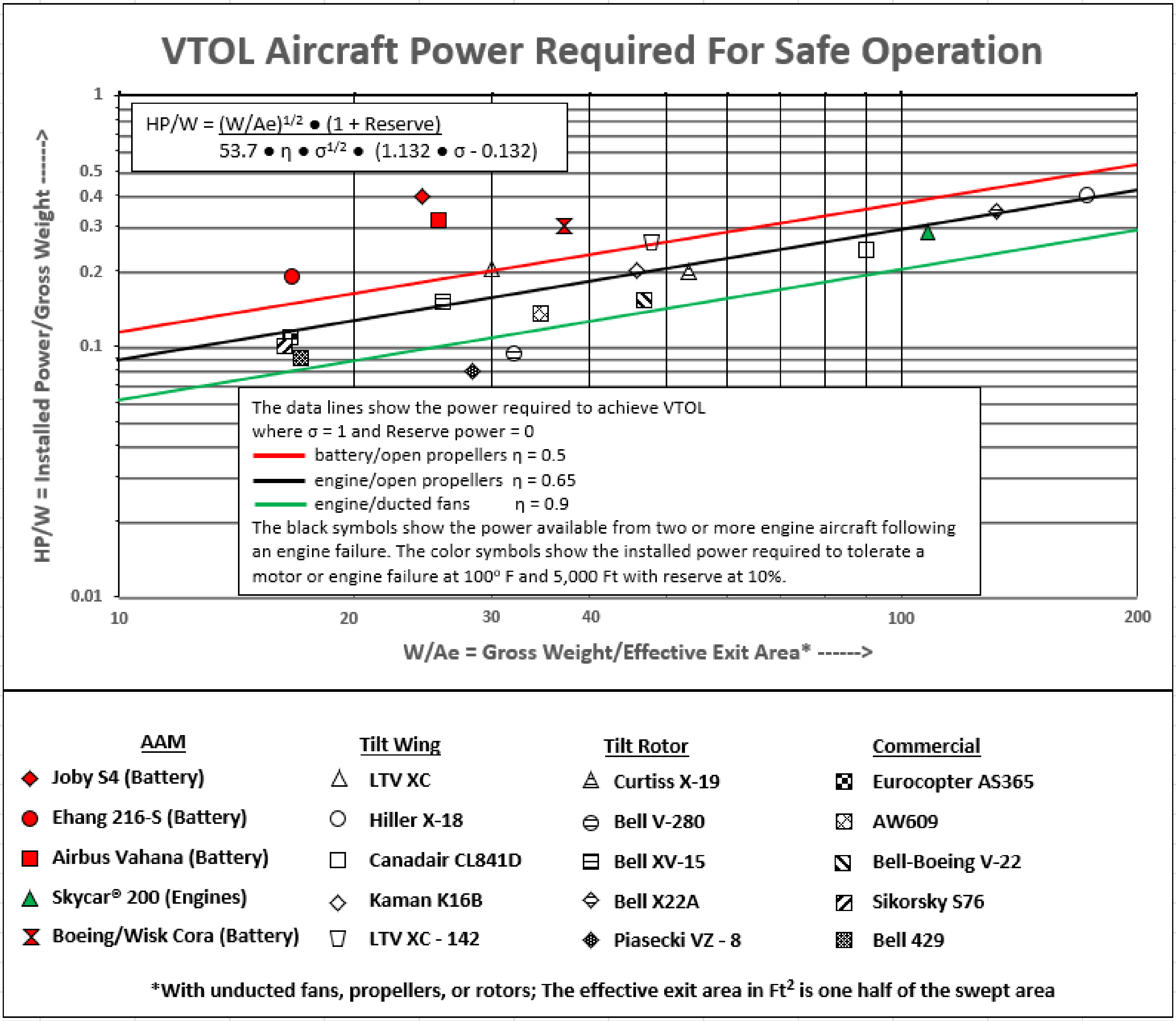
- The Joby S4 recorded 65 dBA at 330 feet distance during take-off. This translates into 88 dBA at 25 feet and is probably the quietest air taxis presently under development.

- The Skycar® 200 must address both ducted fan and engine exhaust noise. Its low solidity fans use a higher tip speed to avoid gearboxes and to minimize rotating inertia. Because the fans are enclosed, they are amenable to active noise control where the noise could potentially be reduced by over 30 dBA at the dominant frequency [15]. Exhaust noise is reduced by using a compound 5-stroke engine [3]. Its additional expansion cycle reduces the exiting exhaust to nearer atmospheric pressure and consequently, a lower noise level. Modest additional silencing may meet the 88-dBA noise limit.

Safety

The consequence of a powerplant failure during VTOL or transition to cruise is the dominant safety concern. From 1950 through the 1970’s over fifty different VTOL aircraft were demonstrated. Most had a single engine while some had two engines. Many lives were lost due to engine or critical component failure. Inherent in any VTOL capable aircraft is the need to have many powerplants producing a surplus of power, which when evenly distributed will allow a safe powerplant failure on a hot day at altitude.

The following figure shows the increase in installed power required to maintain safe flight following the failure of a single powerplant during VTOL. This is shown as a difference between the color symbols and the corresponding color lines. It ranges from 84% for the six powerplant Joby S4 down to 16% for the sixteen-powerplant Ehang 216-S. Historically, very few of the many experimental VTOL aircraft had sufficient power to operate above the minimum power black line. Air taxis achieve fail-safe operation by replacing the helicopter's single rotor and complex powertrain by a number of propellers each powered by a motor or engine. The smaller propellers have a lower rotating inertia thereby, letting powerplant speed provide pitch and roll control.



$$HP/W = \frac{(W/Ae)^{1/2} \bullet (1 + \text{Reserve})}{53.7 \bullet \eta \bullet \sigma^{1/2} \bullet (1.132 \bullet \sigma - 0.132)}$$

The data lines show the power required to achieve VTOL where σ = 1 and Reserve power = 0

🟥 battery/open propellers $\eta = 0.5$

⬛ engine/open propellers $\eta = 0.65$

🟩 engine/ducted fans $\eta = 0.9$

The black symbols show the power available from two or more engine aircraft following an engine failure. The color symbols show the installed power required to tolerate a motor or engine failure at 100° F and 5,000 Ft with reserve at 10%.

*With unducted fans, propellers, or rotors; The effective exit area in Ft^2 is one half of the swept area

Consequently, the helicopter's large number of critical components is replaced by a highly redundant software driven flight control system that can tolerate a powerplant or flight control component failure.

Depleting the battery energy or fuel supply would be catastrophic because making a dead stick landing would be very difficult due to the air taxi's high stall speed. In recent years 443 lives have been saved by airframe parachutes which should be mandatory on all air taxis.

Achieving fool-proof redundancy for both powerplants and flight control systems will be the key to establishing public confidence in pilotless air taxis.

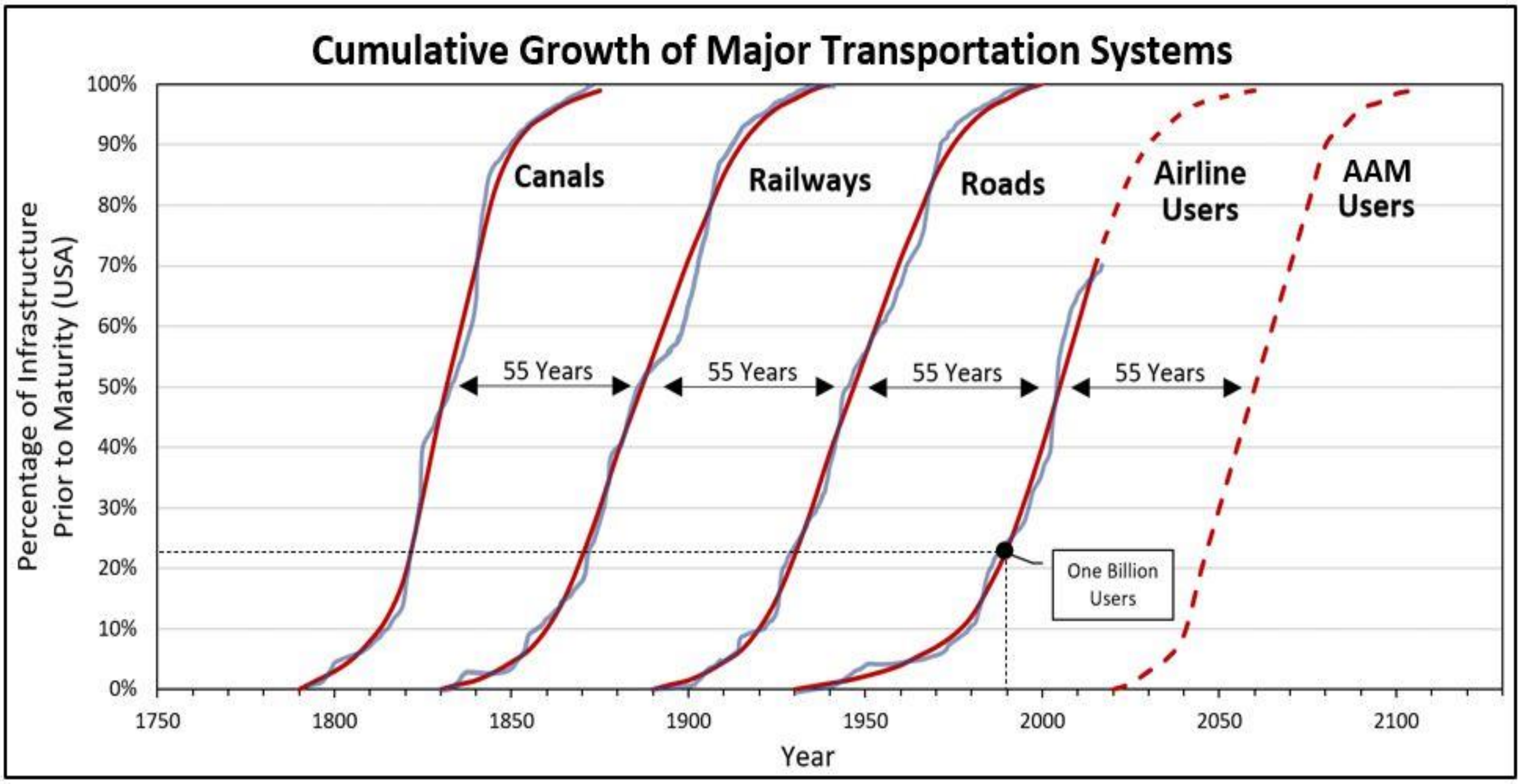
Payload

If the primary goal for air taxi use is to provide a much more convenient way to get to work or go shopping directly from home, a single person air taxi would suffice for the vast majority of trips. Getting couples to a restaurant or to an entertainment center could be covered by a lesser number of two passenger air taxis. For longer trips and/or higher payloads, it would need to be available in a hybrid or engine only version.

Larger air taxis carrying higher payloads could lead to a lengthy and costly FAA certification process. For example, the WA-609 VTOL aircraft, which is a commercial version of the proven military XV15, has been in development and certification for 25 years at a cost exceeding billions of dollars.

Other Air taxis that were Briefly Reviewed

Joby S2 is a very well thought out design with a range that surpasses any other two-person battery powered air taxis where performance specifications were available. The 103-mile projected range at 98 mph is a result of its high aspect ratio wing, clean design and ability to fold back propeller blades from stopped motors. The use of twelve well distributed motors allows it to tolerate a motor failure with a modest increase of installed power.



Future Personal Air Travel

The US population makes 1.1 billion vehicle trips per day with an average duration of 55 minutes [16]. This means that 42 million vehicles are in operation at the same time. If this many air taxis were evenly spaced up to a 10,000 feet altitude, they would be two thirds of a mile apart. This benign environment will make pilotless air taxis far easier to implement than the ground-based driverless cars currently under development. The figure at the bottom adapted from [17] suggests a future where personal intercity travel may be done mostly by air taxis utilizing the relatively unused airspace above us.

The status of airway infrastructure is not quantifiable like canals, railways, and highways. However, passenger use has historically followed the infrastructure status of the various transportation systems. For that reason, passenger usage is chosen as a surrogate for airway infrastructure status.

Archer Maker. This two-passenger air taxi is a mix between Joby S4 and Cora designs. It uses six lifting propeller/motors and six that transition between hover and cruise. The use of twelve propellers significantly reduces the installed power necessary to tolerate a propeller/motor failure. The Maker claims a modest 60 mile range. It and the Cora project a gross weight higher than other two passenger air taxis as a consequence of using separate lift and cruise propellers/motors.

Airbus NextGen. Airbus abandoned the Vahana design in favor of their NextGen version that eliminates articulation of any components. It uses eight propellers/motors where six are used for lift only while two are somewhat tilted in order to provide thrust for cruise and lift. During hover the NextGen operates in a nose up attitude to offset thrust from the tilted propeller/motors. All propellers/motors continue to function during cruise. In effect the Airbus NextGen is a combination of the airplane and the helicopter in a very simplified configuration.

These four passenger air taxis claim a range of 50 miles at 75 mph. This goal is realistic while the simplicity of the design should reduce both development and production costs. Most importantly, FAA certification should be easier to obtain.

Lilium cannot be considered a credible design for a number of reasons, including its unrealistically low gross weight, very high disc loading, large-wetted area, and high profile drag coefficient. The Lilium's disc loading is ten times higher than other air taxis and will require three times more power to take-off. During cruise many of its ducted fans will need to be stopped and feathered while the fan exit area will need to be reduced to maintain fan efficiency. The exposed ducts and feathered fans will have a large wetted area, while the feathered fans and non-functioning ducts will generate high drag. Despite these performance limiters, Lilium claims its two person air taxi has an outrageously longer range and higher speed than other far more credible designs. Its five-person version has even less chance of success.

Conclusions

- The Ehang 216-S design range of 20 miles is achievable but would provide no reserve flight time with its small 17.4 Kwh battery. Like all rotating wing aircraft, the low lift to drag ratio shortens its range. The Ehang design is very tolerant of a motor failure.

- The Airbus Vahana range is 32.6 miles with a 45 minute reserve flight time. After extensive flight testing by Airbus has discontinued development of Vahana and replaced it with its Airbus NextGen version. This is consistent with other legacy developers that separate life propellers/motors from cruise propulsion, thereby reducing the articulation of many VTOL related components.

- The Boeing/Wisk Cora range is 41.5 miles with 45 minute reserve flight time. Its airframe weight and profile drag are higher in return for reduced complexity and a potentially easier path to FAA certification.

- The Joby S4 is a flight tested design that is relatively quiet during its operation. Its range is 36.8 miles at 150 mph with a reserve flight time of 45 minutes.

- The Skycar® 200 has a range that is substantially longer than a battery powered air taxi at the same cruise speed. This is a consequence of more useful energy being available at the same weight from methanol fueled engines compared to battery powered motors .

- Despite using a best case pack specific energy of 235 watt hours per kilogram, the viability of battery powered air taxis is problematic unless the FAA reduces its 45 minute reserve flight time.

- Over 80% of today's automotive trips transport one person, Therefore, one person autonomous air taxis will likely dominate the air taxi market. Broad utilization will require most air taxis to land very near one's destination. This will require reducing its width to ten feet or less during VTOL.in order to utilize city curb access.

- Air taxis that have separate lift and cruise propulsion systems can most easily become a hybrid to increase range.

- To achieve convenient widespread personal intracity use, air taxis must be quiet (below 88 dBA at 25 ft.) to land almost anywhere. This requirement will have a major impact on the overall design.

- If larger multi-passenger air taxis cannot reduce their width prior to VTOL, they will need to operate from a large centralized Vertiport/Heliport/Skyport as advocated at the Uber Elevate Summit [18]. This will greatly reduce their convenience for personal use.

- Air taxis should use as many powerplants as possible to provide redundancy. This will also minimize the installed power required to accommodate a motor or engine failure. Achieving FAA approved battery reliability in this critical application will be particularly challenging and could make an airframe parachute mandatory.

- With the future goal of eliminating the use of petroleum-based fuels in transportation, hybrid or engine powered air taxis will need to use a carbon neutral fuel like renewable methanol, which can be created by combining CO_2 and hydrogen. Renewable methanol is essentially as green as battery or hydrogen energy created from renewable sources [19]. Methanol has a number of other advantages as a fuel for air taxis [20].

- Projecting the airway infrastructure growth using the number of infrastructure users suggests that air taxi utilization for personal airborne mobility could dominate by 2050. This is consistent with a recent paper by Morgan Stanley Research, predicting that the world market for AAM aircraft (air taxis, drones, etc.) could be between $9 and $18.9 trillion per year by then.[21]

Definitions, Acronyms, Abbreviations

NMC: Lithium Nickel Manganese Cobalt Oxide

LiPo: Lithium-Ion Polymer

NCA: Lithium Nickel Cobalt Aluminum Oxide**.**

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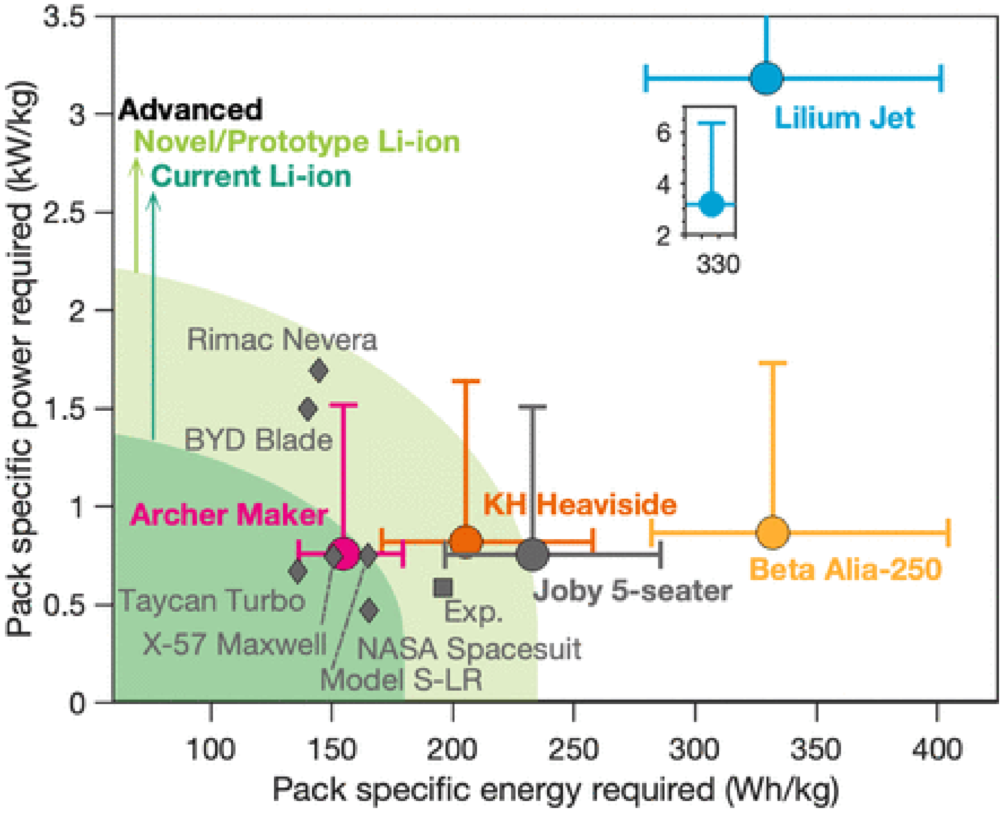
Addendum

A recent article by battery experts at Carnegie Melon University attempted to quantify battery performance as it relates to air taxis performance. Their results are presented in the figure below followed by their explanation of its presentation. (Reference: “The promise of energy-efficient battery-powered urban aircraft” at: https://www.pnas.org/content/118/45/e2111164118).



Pack specific energy and specific power (discharge) requirements for the aircraft analyzed at an EWF of 0.5, where the abscissa error bars indicate estimates at an EWF of 0.45 and 0.55. Cruising speed for maximum range with 30-min reserves is assumed for battery sizing. The ordinate error bars show the landing power requirement where half the battery pack has failed. Battery packs that have been developed, to date, are shown and labeled as gray diamonds. “Current Li-ion” represents batteries manufactured at large scale; “Novel/prototype Li-ion” indicates chemistries and designs developed recently or for high-performance applications; “Advanced” indicates nascent pack designs that are not yet commercially available. The gray square labeled “Exp.” shows the only experimental EVTOL battery reported in literature, reported by Yang et al. *Inset* shows the zoomed in pack specific power and pack specific energy for the Lilium Jet.

Comments on the Above Battery Performance Figure

This figure shows the significance of the empty weight divided by gross weight called empty weight fraction (EWF). A survey of existing two-passenger to six-passenger aircraft showed EMF ranging from .55 to .66. The use of carbon fiber could offset some of the expected VTOL related weight gain; however, it is unlikely that the EWF of battery powered air taxis can fall below .55. In the preceding analysis, the defunct Vahana EMF was .43, the Joby S4 is .43, the Ehang 216-S is .52, the Skycar® 200 is .55 and the Cora is .6. According to this battery performance figure, the Lilium and the Beta Alia-250 will require batteries that are probably decades away.