REVIEW OF SELECTED PERSONAL AIR VEHICLES

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Abstract

Considerable attention is being directed to personal air vehicles (PAVs) with vertical take-off and landing (VTOL) capability as air taxis to improve personal intracity or intercity travel. This paper reviews the operability of four PAVs that are differentiated by their wing configuration and power source.

- Rotary wing using battery power similar to a scaled-up drone.
- Tilt wings that rotate through 90° with battery powered propeller/motors attached.
- Fixed wing where attached battery powered propeller/motors rotate through 90°.
- Folding wings where rotatable ducted engine/fans are separate from the wings.

The performance of a battery powered PAV depends on how the FAA rules on a number of issues.

- Can the present 20-minute reserve flight time for helicopters be lowered or eliminated?
- Will the motors be allowed to be temporarily overpowered during transition from VTOL to cruise or following a motor failure?
- What is a safe minimum battery charge level?
- How repeatedly discharging the battery at 3 c or more will affect its reliability?

This analysis estimates the maximum range with no reserve flight time and a 10-minute reserve. It assumes the motors can be overpowered as necessary to complete transition to cruise in 30 seconds from vertical take-off and that enough continuous power is available to safely execute a vertical landing following a motor failure.

Introduction

The viability of a VTOL capable PAV will be determined by tradeoffs between speed, range, payload, energy available and its 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.

Battery/electric motors provide about 6% of the energy per pound of weight compared to engines/methanol. For an air taxi to achieve a useful range using battery power, it will need a state-of-the-art light weight airframe that minimizes profile and induced drag.

To minimize profile drag, the total surface area exposed to the airstream should be minimized while the shape should be as aerodynamic as possible. Induced drag is minimized by using the largest aspect ratio that stowability and ground footprint will allow.

EHANG 216

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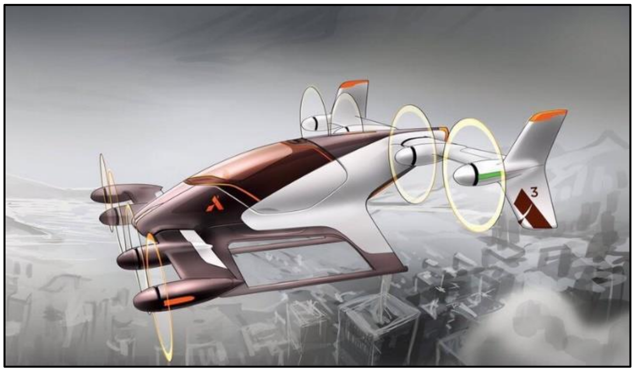
Propulsion System Considerations

- Missing from this analysis due to lack of data is the Wisk “Cora” PAV, which has a propulsion system for VTOL that is separate from that for cruise. This propulsion system arrangement could allow propeller and motor efficiency to be maximized in both operating modes. It also could provide an easy hybrid option.



Airbus VAHANA

- The PAVs in this study use the same propulsion components for both VTOL and cruise and as a consequence, optimizing the propeller/motor or engine/fan design is significantly more complicated.

- The propeller thrust required during VTOL is up to ten times higher than that required for cruise. To accommodate this disparity, the number of operating powerplants is reduced during cruise.

- The stopped powerplants can minimize potential drag by folding the blades back like the Joby S4 or rotate the propellers about the vertical axis like the “Cora” where the blades are aligned with the airflow when stopped. Ducted fans that are imbedded in the airframe can be covered over during cruise.

If the PAV is to meet a noise ordinance, the tip speed of the open propellers may need to be below 400 ft/sec. This could require a gearbox between the motor and the propeller to minimize the motor weight, while the propeller will need a high solidity (propeller planform area divided by swept area) which increases the skin friction drag and could lower propeller efficiency.

- PAVs can achieve pitch and roll control by changing the rotational speed of the propellers or fans if their rotational inertia is low enough. This can be achieved by using a large number of smaller propellers, which will also reduce the reserve power required in case of a motor failure.

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

JOBY S4

- The weight of the propulsion system required to tolerate a motor or engine failure is dependent on the number of powerplants and how they are arranged.

- State-of-the-art electric motors [1] can double their power output when temporarily overpowered (2 minutes from cold). For high performance engines [2] or motors rated for continuous operation, the powerplant weight is about 0.6 lb./Kw. It is estimated that the weight of the remaining propulsion related components will range between 0.1 lb./Kw and 0.2 lb./Kw. A propulsion system weight of 0.75 lb./Kw is used in this analysis but could differ significantly between PAVs.

Airframe Considerations

The airframe of a PAV will need to use composite materials to minimize weight. Fiberglass is the dominant composite material used in the light plane industry due to the high cost of carbon fiber and Kevlar composites. To help determine the projected weight of a PAV airframe, the weight of several similar class FAA approved airframes (empty weight minus power source) [3] is averaged. Since minimum weight is so critical with the low energy available from batteries, it is assumed that as much carbon fiber composite will be used as is effective in lowering airframe weight. From discussions with the designers of the Cessna TTI (Lancair Group) a consensus was reached that up to 50% carbon fiber composite by weight 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 five person airframes which contain very little carbon fiber. The two-person airframes cited have a high carbon fiber content and therefore, a 20% weight increase is added.

The two person PAV airframe is projected to weigh 650 lbs. while the five person PAV airframe is projected to weigh 1,784 lbs.

SKYCAR® 200

PAVs Being Analyzed

The four PAVs being analyzed were chosen because they represent different credible concepts that have undergone some preliminary flight testing while specifications and projected performance data have been made available.

- Ehang 216. Similar to a large wingless drone, uses eight arms supporting sixteen battery powered counter-rotating propellers. It carries two persons.
- A^3 Vahana (beta). Uses tandem wings that tilt through 90°. Each wing has four battery powered motor/propellers. It carries two persons.
- Joby S4. Uses one fixed wing on which four propellers tilt through 90° along with two tilting propellers on the fixed tail. It carries five persons.
- Skycar® 200. Uses six thrust generating ducts. Four rotate and are attached to the fuselage. Each has two counter rotating Rotapower® engine powered fans. Two ducts are imbedded in the airframe and each has a single engine/fan. It carries two persons.

Equations Governing PAV Performance

The following equations [4] 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 Equations:

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

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

Where

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

With drag known, power required for cruise is:

$$HP = \frac{D \times Vo}{550 \times \eta}$$

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

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

This equation only applies to battery powered propulsion. For engine powered propulsion 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 that in a 40-mph. wind that the minimum angular acceleration needed about the roll axis is 0.78 rad/sec^2 [5]. This translates into a need for approximately 10% additional installed power. The actual control power required will depend on the location of the ducted fans or propellers relative to the center of gravity.

$$L/D\ max = \left(\frac{\pi \times AR \times \in \times S}{4 \times C_{DW} \times A_W}\right)^{1/2}$$

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 ft²
HP = required horsepower
S = wing area in ft²
V_0 = PAV's 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 PAV except propellers or fans in ft²
C_{DW} = profile drag coefficient based on wetted area.
η = energy conversion efficiency between energy source and energy in the exiting air stream.

Energy Conversion Efficiency

Conversion efficiency (η) provides a measure of the energy reduction between the energy source (HP) and the energy available to generate the required lift or thrust during VTOL and cruise. It is a function of battery efficiency, electric motor efficiency and propeller or ducted fan efficiency. This evaluation uses the best case for many of the estimated efficiencies.

Battery Efficiency

Battery chemistry determines energy storage (Wh/kg), power output (W/kg), and internal resistance. The NMC battery used in the Joby S4 has a proven battery cycle life and can operate at discharge rates required for battery powered PAVs. The Vahana, Ehang and Skycar® use a LiPo battery where its low internal resistance would appear to make it a better choice once its reliability in this application is established. LiPo and NMC batteries can have an energy of up to 250 Wh/kg. However, packaging, cooling and life related concerns will reduce the net available energy. The NCA batteries in the Tesla electric car have a theoretical energy approaching 300 Wh/kg; however, due to packaging and cooling requirements the energy available is only 156 Wh/kg. Battery cooling requirements for a PAV will be much higher, because of the very rapid discharge rate. An energy of 150 Wh/kg is used in this analysis for all battery powered PAVs and likely to be optimistic.

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. Motors utilized in cruise will be designed for cruise, while the other motors will be optimized for VTOL.

Propeller and Ducted Fan Efficiency

Unducted propeller efficiency is unlikely to exceed 65% efficiency during VTOL [6], or 90% during cruise. Propeller efficiency for the Ehang during cruise is difficult to estimate; however, data for light helicopters operating at disc loading similar to the Ehang, undergo a known power reduction between take-off and cruise. The efficiency of ducted fans with fixed pitch can exceed 90% in VTOL and be almost maintained in cruise if duct exit area is reduced to achieve an internal air velocity that supports fan efficiency.

Overall Energy Conversion Efficiency

η = ηbattery × ηmotor × ηpropeller

Ehang 216 during VTOL:
η = 0.9 × 0.85 × 0.65=0.5
Vahana during VTOL:
η = 0.9 × 0.85 × 0.65=0.5
Vahana during cruise:
η = 0.95 × 0.9 × 0.9=0.77
Joby S4 during VTOL:
η = 0.90 × 0.85 × 0.65=0.5
Joby S4 during cruise:
η = 0.95 × 0.9× 0.9=0.77
Skycar® 200 during VTOL:
η = 0.9
Skycar® 200 during cruise
η= 0.85

Analysis of Ehang 216

The flight-tested maximum range is 9.9 miles at 81 mph [7]

VTOL power = 155.7 Kw (with 10% control power on a 100°F day at 5,000 ft. altitude).

The propulsion system uses sixteen motor/propellers which requires a 16% increase in installed power to tolerate an engine failure for a total of 180.6 Kw.

Data for light helicopters with a disc loading $\left(\frac{\text{Gross Weight}}{\text{Sweep Area}}\right)$ similar to the Ehang 216 show that minimum power occurs near 80 mph [8] where it reduces to ~ 60% of that required for VTOL.

Cruising power = 93.4 Kw

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

Results:

The energy required to cruise at 81 mph. for 9.9 miles is 11.4 Kwh, providing a 20% reserve to protect the payload and batteries and 2.7 Kwh to operate for one minute (2 x 30 seconds) at VTOL power requires a battery energy of 16.9 Kwh. This agrees with the Ehang installed battery energy. The Ehang's very short range is a consequence of its limited battery capacity and the low lift/drag ratio of rotary wing aircraft.

Analysis of the A^3 Vahana (beta)

The maximum range design goal is 60 miles at 144 mph [9]

VTOL power = 277 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. If a motor fails the remaining six operating motors would need to produce 320.4 Kw for a total installed power of 427 Kw.

L/D 13.1@ 144 mph. L/D max 14.1 @ 124 mph.

Cruising power = 51.2 Kw @144 mph.

Where,
S = 75 ft^2
Aw = 350 ft^2
C_{DW} = 0.0055 (very clean design)
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 320 lbs. (0.75 lbs./Kw.) the battery weight is 380 lbs.

Battery specific energy = 25.9 Kwh at 150Wh/kg. With 20% reserve to protect payload and battery and 4.6 Kwh for one minute (2x30 sec) at VTOL power, the energy available is 16.1 Kwh. This would provide a maximum range of 45.3 miles at 144 mph with no reserve flight time. With 10-minute reserve at maximum L/D the range would reduce to 26.3 miles.

Analysis of Joby S4

The maximum range design goal is 150 miles [10].

The wing tip propellers generate a 254 lb. down force on the wing during VTOL, which results in the need to generate 5,054 lbs. of lift during VTOL.

VTOL power = 785 Kw (10% control power on a 100°F day at 5,000 ft. altitude)

The Joby uses six motors/propellers that are evenly distributed. If a motor fails, the remaining four operating motors need to produce 962 Kw for a total installed power of 1443 Kw.

L/D max = 13.2 @ 139 mph.

Cruise power required at L/D max=130.9 Kw

Where,
S = 137 ft^2
A_w = 762 ft^2
CD_W = 0.005 (very clean design)
AR = 6.5
ε = 0.95
A_e = 210 ft^2 (one half propeller sweep area)
W = 4,800 lbs.

Results:

With gross weight at 4,800 lbs; payload at 840 lbs.; airframe at 1,784 lbs; propulsion system at 1,082 lbs. (0.75 lb./Kw), the battery weighs 1,109.4 lbs. with a battery specific energy of 75 Kwh. Providing a 20% reserve and 12.1 Kwh for one-minute VTOL, the energy available is 48 Kwh and would provide a maximum range of 51 miles at 139 mph with no reserve. With 10-minute reserve at maximum L/D, the range reduces to 24 miles.

Analysis of Skycar 200

The maximum range design goal is 500 miles at 200 mph.

VTOL power = 267 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 22% for a total of 326 Kw.

L/D @ 200 mph =7.5.

Cruise power =100 Kw.

Where,
S = 58 ft^2
A_w = 400 ft^2
CD_W = 0.005 (very clean design)
AR = 7
ε = 0.9 (Swept back wing)
W = 1,600 lbs.
A_e = 21 ft^2

Results:

With gross weight at 1,600 lbs., payload at 450, airframe at 650 lbs. propulsion system at 244 lbs. The weight available for fuel is 256 lbs. With SFC of 0.8 lb./Hp.hr (methanol) the maximum range is 521 miles at 200 mph with no reserve, or 510 miles with a 10-minute reserve at maximum L/D.

Factors Determining PAV Deployability

Convenience

Uber has been promoting the concept where air taxis would operate from a large Skyport located near the city center to provide air taxi service. The practicality of this approach was highly criticized in an article published by Curbed magazine (link) [11] 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 Skyports throughout a city to be useable.

To make a PAV 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 PAV will need to be able to reduce its width to 10 feet or less prior to landing. This will require the wings to fold and the propulsion system to be separate from the wings. Disc loading will increase, which increases installed power and make using batteries more difficult.

Noise

The noise generated by the PAV must 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 [12].

- The Airbus Vahana and Ehang 216 use open propellers that operate at higher tip speeds and may not meet the 88-dBA limit. As an air taxi operating from the top of a high building, a noise level above 88 dBA is probably acceptable. In this case PAV size is also less critical.

- The Joby S4 uses a low tip speed propeller which could meet the 88-dBA limit.

- The Skycar® 200 must address both ducted fan and engine exhaust noise. Its low solidity fans use a relatively high tip speed to avoid gearboxes and to minimize rotating inertia. Because the fans are enclosed, they are very amenable to active noise control where the noise could potentially be reduced by over 30 dBA at the dominant frequency [13]. Exhaust noise is reduced by using a compound form of the Rotapower® engines [2]. Its double expansion cycle results in an exiting exhaust at nearer atmospheric pressure and consequently at a lower noise level. Modest additional silencing is projected to meet the 88-dBA noise limit.

Payload

If the primary goal is to provide a much more convenient way to get to work or go shopping directly from home, a single person battery powered PAV 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 PAVs. For longer trips and/or higher payloads, the PAV could be available in a hybrid or engine only version.

The increased complexity of larger PAVs carrying higher payloads could lead to a lengthy and costly FAA certification process. For example, the BA-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 far exceeding one billion dollars.

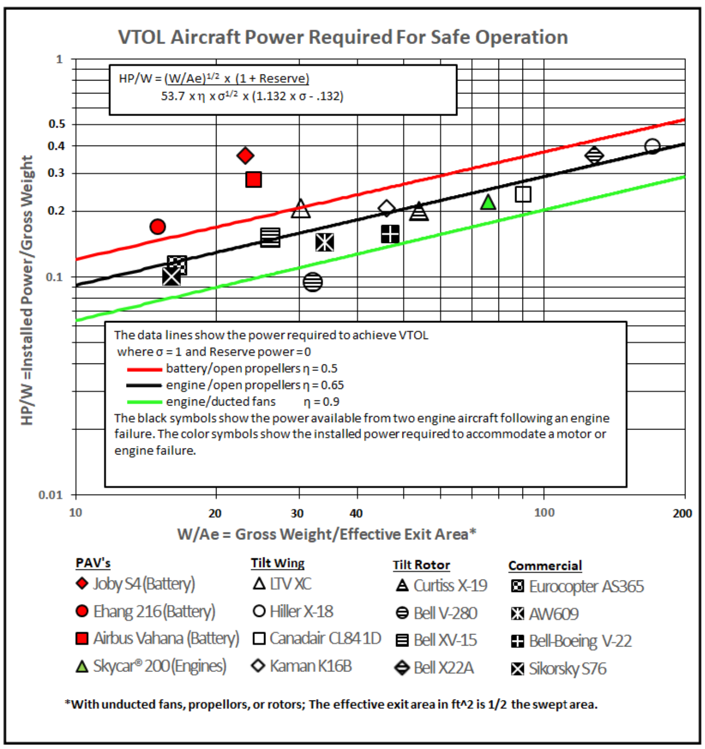
A one person PAV weighing 1430 lbs. or less may meet one of the FAA requirements to be classified as light sport with its simpler certification process. FAA certification may be easier for a hybrid version because it would put less emphasis on the uncertainty surrounding battery power, which will be challenging when seeking FAA approval for the following reasons:

- Difficulty in knowing the battery's condition.
- If and how much can the motors be the overpowered?
- What is the minimum level of battery charge that is allowed?
- How much reserve flight time is required?

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 figure below 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. Historically, very few of the many experimental VTOL aircraft shown could operate safety above the minimum power black line.



Drones benefit from their small size centered around the use of many smaller propellers in place of a larger one. This results in propellers with a lower rotational inertia allowing the propeller rpm to be changed quick enough to provide pitch and roll control. As a result, software replaces hardware. A PAV with larger propellers like the helicopter with its large rotor, needs complicated blade pitch control and numerous gear boxes. This leads to many critical moving parts, increasing cost and reducing reliability.

Depleting the battery energy or fuel supply would be catastrophic because making a dead stick landing would be very difficult due to the PAV's high stall speed. In recent years dozens of lives have been saved by an airframe parachute. This should be mandatory on all PAVs.

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

Other PAVs that were Reviewed

Joby S2 is a very well thought out design with a range that surpasses any other two-person battery powered PAV where specifications were available, The Joby's 103-mile range at 98 mph is a result of its high aspect ratio wing and clean design. The use of twelve well distributed motors allows it to tolerate a motor failure with a small increase of installed power.

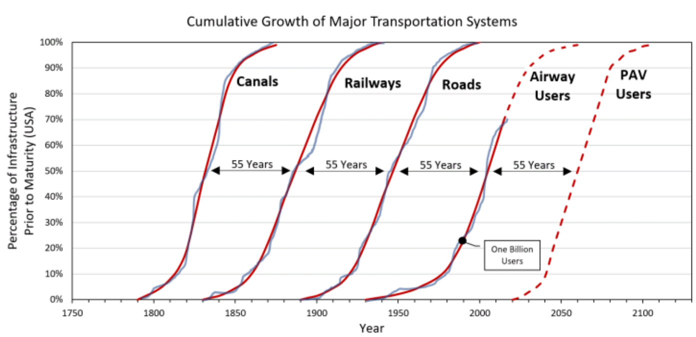
Wisk Cora is a very credible design. It uses separate lift and propulsion systems. As a result, transition from VTOL to cruise is simplified by the use of fixed position lifting propellers. Consequently, maximum propulsion efficiency is able to be achieved during both take-off and cruise. The Cora is advanced in its path towards FAA certification and therefore it is notable that this two-person PAV has a much higher gross weight than that predicted for the Vahana. This could be due, in part, to the Cora's higher profile drag, provision for a 10-minute reserve flight time and separate motor for cruise thrust. The Cora specifies a modest range of 62 miles at 110 mph., which adds to its credibility.

The Kitty Hawk design team developed the Cora prior to its acquisition by Wisk. The team seems to have realized how sensitive PAV performance is to payload and have chosen to concentrate on their single person Heaviside. While the performance of the Heaviside has yet to be verified, a range of 55 miles at 220 mph or 100 miles at 180 mph has appeared in the press.

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 drag coefficient. The Lilium disc loading is ten times higher than other PAVs 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 remaining fans will need variable pitch to maintain propulsion 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's two person PAV claims an outrageously longer range and higher speed than other far more credible designs. Its five-person version is even less credible since battery powered PAVs become less viable as they scale up.

Future Personal Air Travel

The US population makes 1.1 billion vehicle trips per day with an average duration of 55 minutes [14]. This means that 40 million vehicles are in operation at the same time. If evenly spaced up to a 10,000 feet altitude, they would be over one-half mile apart. This benign environment will make pilotless PAVs far easier to implement than the ground-based driverless cars currently under development. The following figure adapted from [15] suggests a future where personal intercity travel may be done mostly by PAVs 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.

Conclusions

- The Ehang's maximum claimed range (no reserve flight time) is borne out in this analysis. Like all rotating wing aircraft its low lift to drag ratio accounts for its very short range. The Ehang design is very tolerant of a motor failure.

- The Vahana at its specified gross weight of 1800 lbs. could not meet its designed range (no reserve flight time). However, at a gross weight of 1925 lbs. it could. To provide a 10-minute reserve flight time the gross weight would have to increase to 2350 lbs.

- The Joby S4 is an elegant design that would be relatively quiet during its operation. To meet its specified maximum range, while tolerating a motor failure, could require a battery with a specific energy that is 2.5 times higher than any that currently exists. In a hybrid configuration the Joby should be able to achieve a 500-mile range with a 10-minute reserve flight time and full payload.

- The Skycar® achieves its longer range by using methanol as an energy source with 43 times more useful energy per pound than a battery. Key to its performance is the methanol fueled Rotapower® engine that can produce three horsepower per pound and 200 Hp per cubic foot. The Skycar® propulsion system is mounted on the fuselage, which allows VTOL with folded wings. This makes curbside operations from one's home or business possible.

- The battery powered PAV that is most likely to dominate personal airborne mobility is a one-person version with a range approaching 100 miles. It should be able to land at the curb near one's home or business and may include hybrid propulsion to eliminate battery charging downtime and improve range.

- It should be straight forward to convert a battery powered PAV to a hybrid configuration. For a version like the Cora, the single thrust motor would be replaced by an engine. For others where the motors provide both thrust and lift like the Vahana and Joby, two of the motors would be replaced by engines.

- To achieve convenient widespread personal use, the PAV should be quiet (below 88 dBA at 25 ft.) and able to land almost anywhere. To do so, it will need to reduce its width to 10 feet or less prior to landing. This may require folding wings and a propulsion system that is separate from the wings. This could result in a higher disc loading and make it more difficult to operate on batteries alone.

- If the PAV cannot reduce its width prior to VTOL, it may need to operate from a large centralized Vertiport/ Heliport/Skyport as advocated at the Uber Elevate Summit [16]. Consequently, getting to or from this centralized location by ground will greatly reduce the potential use of PAVs.

- PAVs should use as many powerplant/propellers 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 make an airframe parachute mandatory.

- With the future goal of eliminating the use of petroleum-based fuels in transportation, hybrid or engine powered PAVs should use a carbon neutral fuel like renewable methanol, which can be created by combining CO_2 and hydrogen [17]. Renewable methanol is essentially as green as batteries charged by a renewable source and greener than hydrogen. It is shown to have a number of other advantages as a fuel for PAVs [18].

- Projecting the airway infrastructure growth using the number of infrastructure users suggests that PAV use for personal travel could be dominant by 2050. This is consistent with a recent paper by Morgan Stanley Research, predicting that the world market for autonomous aircraft (UAV and PAV) could be between $1.5 trillion to $2.9 trillion per year by 2040 [19].

Definitions, Acronyms, Abbreviations

NMC: Lithium Nickel Manganese Cobalt Oxide

LiPo: Lithium-Ion Polymer

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

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