PERFORMANCE EVALUATION OF SELECT PERSONAL AIR VEHICLES

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Abstract

A considerable amount of attention is now being paid to the use of battery powered personal air vehicles (PAVs) with vertical take-off and landing (VTOL) capability as air taxis to improve personal intracity or intercity travel. This paper evaluates the performance of four PAVs that are differentiated by the wing configuration used to achieve VTOL.

- Rotary wing similar to a scaled-up drone.
- Fixed wing with propeller/motors attached that tilt through 90°.
- Fixed wing where attached propeller/motors tilt through 90°.
- Folding wings with hybrid motors/engines detached from the wings.

The performance of all four PAV configurations is unproven. To determine the viability of the various designs, the weight of the power source required to achieve the specified speed, range and payload is first determined. With the gross weight specified, the weight available to accommodate the airframe (empty weight minus power source) is known. This airframe weight can then be compared to that of a state-of-the-art composite and FAA approved airframe. A modest estimated weight is added to account for VTOL related features like articulated wings or tilting propellers. This comparison provides a measure of the likelihood that the PAV will meet its projected performance.

The design requirements to make a PAV deployable directly from one's home or business is also addressed.

Introduction

A viable VTOL capable PAV will undergo tradeoffs between speed, range, payload, and energy consumption based on 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.
- 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.
- Wing Aspect Ratio $\left(\frac{\text{Wing Span}}{\text{Wing Chord}}\right)$. Higher aspect ratio increases the $\left(\frac{\text{Lift}}{\text{Drag}}\right)$ ratio.
- 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.

EHANG 216

Battery/electric motors provide about 5% of the energy per pound of weight compared to engines/fuel. Therefore, for an air taxi to achieve a useful range it needs a state-of-the-art airframe while also minimizing both profile and induced drag.

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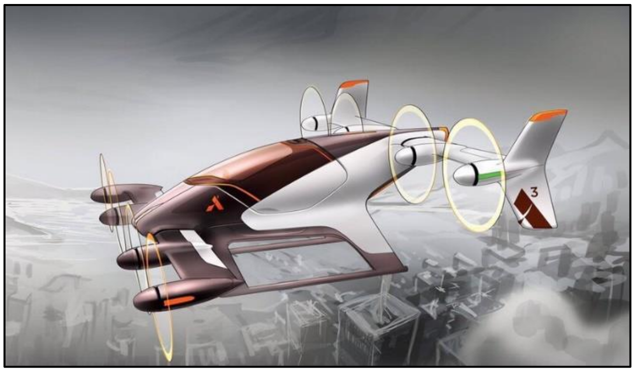


Airbus VAHANA

To minimize profile drag, the total surface area exposed to the airstream should be minimized along with a very aerodynamic design (low profile drag coefficient). Induced drag is minimized by using the largest aspect ratio that stowability and ground footprint will allow.

Propulsion System Considerations

- Ideally the propulsion system used for VTOL is separate from that for cruise. This would allow propeller and motor efficiency to be maximized in both operating modes. The PAVs being evaluated here use the same propulsion components for both VTOL and cruise. As a consequence, the propeller design and its use become significantly more complicated.

- The propeller thrust required during VTOL is over ten times higher than that required for cruise. To reduce this disparity, the number of operating propellers is reduced to two that use variable pitch blades for cruise.

JOBY S4

- The stopped motor/propellers must be able to avoid potential drag. The blades can be folded back like the Joby S4 or if they rotate about the vertical axis like the Kitty Hawk “Cora” the blades can be aligned with the airflow when stopped. For hybrid powerplants the motor/fans can be imbedded in the airframe and covered over during cruise.

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

- PAVs achieve pitch and roll control by changing the rotational speed of the propellers or fans. High solidity fans will increase this response time and reduce stability and control. This can be alleviated by using a large number of smaller propellers. This will also reduce the reserve power required in case of a motor failure.

SKYCAR 200

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 state-of-the-art airframes (empty weight minus power source) [1] 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 weight of the VTOL related components could entirely offset this weight reduction for two person airframes which use very little carbon fiber. The five-person airframes cited already use about a15% carbon fiber content and therefore, a 6% weight is added.

Two person PAV airframes are projected to weigh 753 lbs. while the five person PAV airframes are projected to weigh 2,086 lbs.

PAVs Being Analyzed

The four PAVs being analyzed were chosen because they represent different creditable concepts that have undergone some preliminary flight testing while specifications and projected performance 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 each 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 ten counter-rotating ducted fans. Three electric motor/fan sets are imbedded in the airframe and two hybrid fan sets are in the ducts that rotate through 90°. All ducted fans are separate from the folding wings. This allows the PAV to reduce its width to 10 feet or less prior to landing at a street side curb. It carries two persons.

Equations Governing PAV Performance

The following equations [2] 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:

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

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

Where

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

With drag known, power required for cruise is:

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

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

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

This applies to battery only powered propulsion. For hybrid propulsion systems the above equation would apply to each separate or mixed power module. For engines, HP in the above equation would be multiplied by ($1.132\sigma - .132$) to account for power reduction with altitude.

The above equation shows only the installed power needed for VTOL. It does not account for the extra power required to maintain stability and control in windy conditions. 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 [3]. This translates into a need for approximately 10% additional installed power. The actual control power required will depend on the location of the ducted fan or propeller relative to the center of gravity.

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

Where,

W = gross weight

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

HP = required horsepower

S = wing area

V_0 = PAV's speed in feet per second

V_j = exit air velocity either downstream of propeller or at ducted fan exit

AR = aspect ratio

ε = span efficiency factor

A_w = wetted area of entire PAV except propellers or fans

C_{DW} = profile drag coefficient based on wetted area. All three-winged PAVs in this study are assigned a $C_{DW} = 0.0045$. This will be a challenging number to meet and require a clean design utilizing laminar flow airfoil sections.

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 (Whr/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 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 Whr/kg. Packaging, cooling and life related concerns will reduce the net available energy. An energy of 200 Whr/kg is used in this analysis for all four PAVs and may prove to be optimistic. Required discharge rates will determine the energy recovery during the battery's discharge.

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. Since cruise dominates the flight profile, it is assumed that the motors are optimized for cruise.

Propeller and Ducted Fan Efficiency

Unducted propeller efficiency is unlikely to exceed 70% efficiency during VTOL [4], or 90% during cruise. Propeller efficiency for the Ehang during cruise is difficult to estimate due to the complicated crossflow; however, data for light helicopters operating at Ehang 's disc loading show a known power reduction between take-off and cruise. The efficiency of ducted fans with fixed pitch can exceed 90% in VTOL and in cruise as well if duct exit area is reduced.

Overall Energy Conversion Efficiency

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

Ehang 216 during VTOL:
$\eta = 0.98 \times 0.9 \times 0.7 = 0.62$
Vahana during VTOL:
$\eta = 0.98 \times 0.9 \times 0.7 = 0.62$
Vahana during cruise:
$\eta = 1.0 \times 0.95 \times 0.9 = 0.86$
Joby S4 during VTOL:
$\eta = 0.90 \times 0.9 \times 0.7 = 0.57$
Joby S4 during cruise:
$\eta = 1.0 \times 0.95 \times 0.85 = 0.81$
Skycar® 200 on batteries only
$\eta = 0.9 \times 0.95 \times 0.9 = 0.77$
Skycar® 200 electric motors during hybrid VTOL:
$\eta = 0.85 \times 0.9 \times 0.9 = 0.67$
Skycar® 200 engines during cruise and VTOL
$\eta = 0.9$

Analysis of Ehang 216

Specified cruise speed = 81 mph and range = 9.9 miles. [5]

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 [6] where it reduces to ~ 60% of that required for VTOL.

VTOL power = 131 kW (with 10% control power on a 100°F day at 5,000 ft. altitude)

Cruising power = 78.6 kW

L/D= 3.3

Where,
Ae = 85 ft^2 (one half total propeller swept area)
W = 1,271 lbs.

Installed power is 360 kW

Results:

The energy required to cruise at 81 mph. for 9.9 miles is 9.6 kWh. An additional 2.2 kWh is used to operate for one minute (2 x 30 seconds) at VTOL power. Providing a 20% reserve to protect the payload and batteries requires a battery energy of 14.2 kWh. This is substantially less than the specified battery energy of 17.4 kWh.

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)

At the specified cruise speed of 140 mph. the range is 62 miles. [7]

VTOL power = 254 kW (with motor failed plus 10% control power on a 100°F day at 5,000 ft. altitude).

L/D = 11.7 L/D max 11.7 @ 140 mph.

Cruising power = 49.8 kW @140 mph.

Where,
S = 50 ft^2 (estimated)
Aw = 350 ft^2 (estimated)
C_{DW} = 0.0045 (clean design)
AR = 5.8
ε = 0.9 (tantem wings)
W = 1,797 lbs.
A_e = 76 ft^2 (one half total propeller swept area)

Installed electric motor power = 360 kW.

Results:

The battery energy required to cruise at 140 mph for 62 miles is 22 kWh. To operate for one minute (2 x 30 seconds) at VTOL power, 4.33 kWh is required. With 20% reserve energy to protect payload and battery the total installed energy required is 31.7 kWh and weighs 349 lbs. At 1.5 kW/lb. the motors weigh 240 lbs., payload is 450 lbs., and airframe is 753lbs. for a gross weight of 1,792 lbs. The Vahana range is maximized by cruising at its maximum lift to drag ratio.

Analysis of Joby S4

At the maximum payload the specified range is 181 miles or, with a cruise speed of 200 mph., the range is 150 miles at a reduced payload [9].

VTOL power = 642 kW (motor failed plus 10% control power on a 100°F day at 5,000 ft. altitude)

Cruising power = 174 kW @ 200 mph.

L/D= 11.3 L/D max = 15.1 @ 136 mph.

Cruise power required at L/D max is 88.6 kW.

Where,
S = 137 ft^2
A_w = 762 ft^2
CD_W = 0.0045 (clean design)
AR = 6.5
ε = 0.95
A_e = 210 ft^2 (one half propeller sweep area)
W = 4,000 lbs.

The cruise propellers generate a 212 lb. down force on the wing during VTOL, which results in the need to generate 4,212 lbs. of up force during VTOL.

Installed electric motor power = 417 kW.

This is adequate to achieve VTOL with 4 persons on a 59°C day at sea level without provision for engine failure or control power.

Results:

To determine range at maximum payload, the weight available for the battery is obtained by subtracting the 840 lb. payload, 428 lb. motors, and 2,086 lb. airframe from the 4,000 lb. gross weight. The battery weighs 646 lbs. with an installed energy of 58.7 kWh. With 20 % reserved battery energy and 10.7 kWh for one minute at VTOL power, the useful energy is 37.8 kWh. This is sufficient for a 53-mile range at 136 mph or 42 miles at 200 mph.

Analysis of Skycar 200

Specified range is 500 miles at a cruise speed of 200 mph. or 725 miles at 133 mph.

VTOL power = 408 kW (186 kW from engines and 222 kW from electric motors. This includes 10% control power on a 100°F day at 5,000 ft. altitude.

Cruising power = 78 kW @ 200 mph.

L/D= 10.2 L/D max = 14.4 @ 133 mph.

Cruise power required @ L/D max on engines is 36.8 kW or 40.9 kW on batteries.

Where,
S = 58 ft^2
A_w = 350 ft^2
CD_W = 0.0045 (clean design)
AR = 8 (lifting tail and canard)
ε = 0.9 (Swept back wing)
W = 1,800 lbs.
A_e = 17 ft^2

Installed battery/motor power =450 kW
Installed engine power = 186 kW

Using 1.35 kW/lb. [10] for engines and 3.5 kW/lb. [8] for motors (a few minutes from cold) the weight of the power source is 286 lbs. To provide VTOL electric motor power for one minute with 100 % reserve, the battery will need to provide 7.4 kWh and weigh 82 lbs. while undergoing a 25C discharge rate.

Results:

To determine the range at the specified cruise speed, the weight of the various components is used to provide the weight available for the fuel. Airframe weight is 753 lbs., engines and motors weigh 286 lbs., two persons weigh 450 lbs. and the battery weighs 82 lbs. This provides 229 lbs. for fuel. With a SFC of 0.8 lb./HP.hr. (methanol) and 15-minute reserve, the range is 527 miles at 200 mph. or 737 miles at 133 mph.

If the Skycar® was only engine powered, it would have a range of 225 miles at 200 mph.

If only battery powered, it would have a range of 60 miles at 133 mph.

Personal Air Vehicle Accessibility

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 creditable argument that a single centrally located Skyport will not work for a number of logistical reasons. In particular, getting to a gigantic Skyport would still involve congested ground travel or need numerous large Skyports within a city to be useable.

To have a PAV accessible to the commuter at or near one's home or business, it must 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 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. The disc loading will need to increase which will increase installed power. This makes the use of batteries alone less viable.

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. However, 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].

To avoid gearboxes, propeller and fan tip speeds are usually higher and result in noise levels well above the 88-dBA limit. Minimum rotating inertia is important to maximize propeller or ducted fan response to needed changes in rpm as required to achieve pitch and roll stability and control. This is helped by minimizing solidity (planform divided by swept area) and using as many smaller propellers as possible.

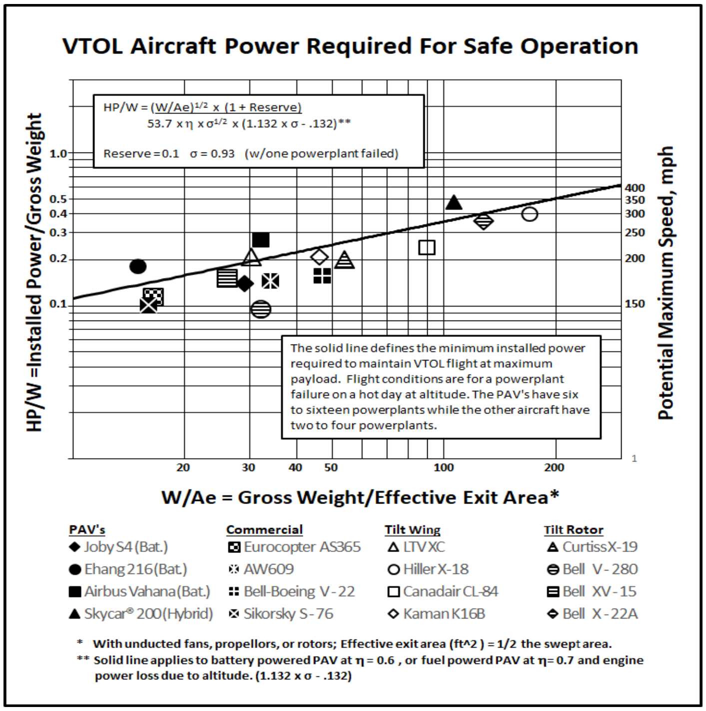
- The Airbus Vahana and Ehang 216 use low solidity propellers, which operate at higher tip speed to create the required thrust and are unlikely to meet the 88-dBA limit. As an air taxi operating from the top of a high building, a noise level above 88 dBA may be acceptable.

- The Joby S4 uses a low tip speed which should meet the 88-dBA limit. However, its high solidity and large diameter propellers will have a high rotating inertia and could slow the response time to control inputs. Gearboxes will also be required to minimize motor weight.

- 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 [10]. Its double expansion cycle results in an exiting exhaust at nearer atmospheric pressure and consequently at a low noise level. Modest additional silencing is projected to meet the 88-dBA noise limit.

Safe Flight Considerations

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 distributed will allow a powerplant failure on a hot day at altitude. In the following figure the solid line indicates the minimum power necessary to VTOL safely following an engine/motor failure. Only PAVs (solid symbols) with eight or more powerplants are able to operate substantially above this line for the specified flight conditions. VTOL aircraft with W/Ae greater than 15 will not be able to autorotate in case of a powerplant failure.



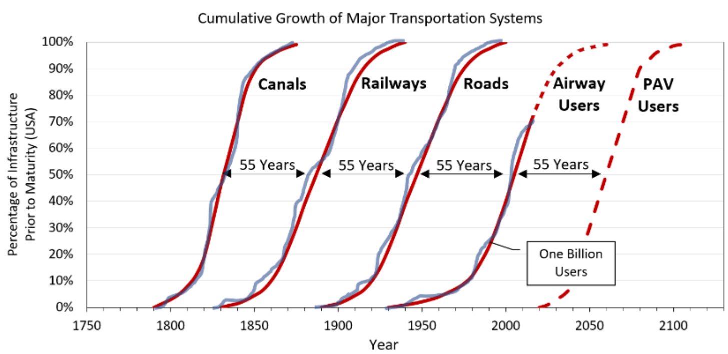
Achieving fool-proof redundancy for both powerplants and flight control systems will be the key to establishing public confidence in pilotless personal air vehicles.

Other PAVs that were Reviewed

Kitty Hawk Cora uses separate lift and propulsion systems. As a result, transition from VTOL to cruise is simplified by eliminating the need for variable pitch on some propellers and folding back of the propeller blades on others. Consequently, maximum propulsion efficiency is able to be achieved during both take-off and cruise. This PAV is more advanced in its path towards FAA certification than others and therefore, it is meaningful that it has a much higher gross weight than predicted for the Airbus Vahana. This suggests that battery weight and perhaps airframe weight have been underestimated for the Vahana, Joby S4, and hybrid Skycar. The Cora specifies a modest range of 62 miles at 110 mph., which adds to its credibility. The Cora design team appears to have recognized how sensitive gross weight is to payload for battery powered PAVs, having recently demonstrated a one person PAV called Heaviside with a range of 100 miles at 220 mph.

Lilium cannot be considered a creditable design for a number of reasons, including an 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 be the source of the large wetted area, while the feathered fan and non-functioning ducts will generate the high drag coefficient. Despite these performance limiters, Lilium claims an outrageously longer range and higher speed than other far more creditable designs. Its five-person version is even less creditable since battery powered PAVs do not realistically scale up.

Future Personal Air Travel



If all the cars on the road in the US were airborne and evenly spaced up to 10,000 ft. altitude, they would be over two miles apart [14]. 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 could be done mostly by air 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

- Using batteries as the only power source is likely to require the PAV to operate from an elevated Skyport as advocated at the Uber Elevate

Summit [16]. The reasons for this include propeller noise, PAV size, and battery charging or replacement.

- A battery-powered PAV with VTOL capability will find it very challenging to carry more than two persons at speeds above 140 mph. and range of over 75 miles. As gross weight increases, the weight of the electrical propulsion system increases much faster. This together with the very low specific energy of batteries further limits range and payload. This performance limiter cannot be overcome by reducing the disc loading because the required propeller swept area would need to be unrealistically large.

- The performance of the Ehang 216 exceeds its specified speed, range, and payload; however, like all rotating wing aircraft its low lift to drag ratio accounts for its very short range.

- The Vahana can meet its specified cruise speed at its specified range with an airframe that utilizes a 50% carbon fiber composite content. The Vahana is the only winged PAV in the analysis that cruises at a speed that maximizes its lift to drag ratio and hence its range.

- The Joby S4 is a state-of-the-art design, however, to meet its specified range at maximum payload it would appear to need a battery with an specific energy far higher than any known to be commercially available or expected. The S4 achieves a low noise level by operating its propellers at a low tip speed. As a consequence, its large high solidity propellers will have a high rotational inertia. This could reduce its stability and control response in an adverse environment.

- The Skycar®'s use of a hybrid power source gives it an enormous performance advantage. Despite using a low energy carbon neutral fuel (methanol) the rotary engine/fuel power source provides ten times more energy than a battery/motor power source. This much higher power to weight ratio allows the power source to be separated from the wing and is key to making the Skycar® accessible from a city curb or small parking lot.

- Without a 50% carbon fiber composite content in the airframes, the Vahana range would reduce to 30 miles, the Joby S4 to 10 miles, and the Skycar® 200 to 134 miles.

- 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 battery reliability in this critical application will be particularly challenging.

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

- In view of the goal of eliminating the use of petroleum-based fuels, hybrid versions should use a carbon neutral fuel like renewable methanol. This can be created by combining CO_2 and hydrogen [17]. The majority of electrical energy produced to charge batteries is not carbon neutral and unlikely to be so in the near future [18].

- Projecting the airway infrastructure growth using the number of infrastructure users indicates that PAV use for personal travel could be very significant by 2050.

Definitions, Acronyms, Abbreviations

NMC: Lithium Nickel Manganese Cobalt Oxide

LiPo: Lithium Ion Polymer

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