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# Critique of Battery Powered Flying Cars

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## ABSTRACT

This paper analyzes the performance of two different types of battery powered flying cars. The first is a wingless eight rotor version, similar to a scaled-up drone, and projected to be suitable for use as an intracity air-taxi. The second is a winged twelve-propeller version using a long wing and projected to be suitable for use as an intercity air taxi. In addition to examining the purely battery powered flying cars, a hybrid version is discussed where both electric motors and engines are used as a way to expand utilization beyond that of an air taxi.

## INTRODUCTION

Flying car advocates are very excited about the attention that battery powered drones have brought to the concept of a VTOL capable flying car. However, that vision has remained unfulfilled for decades despite the availability of



engines with twenty times the energy per pound compared with batteries. For a VTOL capable flying car to be utilized outside an air taxi role, it will need to be accessible from a streetside curb. This will require its size to reduce to that of an automobile prior to landing and will limit the swept area of the propellers or rotors. Since power for vertical take-off increases inversely with the square root of the swept area, the power required can become very high as swept area reduces enough to allow flight from the curb. Batteries can produce the high power

(Watts/lb.) required to take off vertically while engines can produce the high energy (Watts/lb.) required for range and speed. This hybrid approach would allow vertical take-off from a streetside curb.

The first design consideration for both winged and wingless air taxis powered only by batteries is minimizing the power required to takeoff vertically by maximizing the propeller or rotor swept area. This can be accomplished with a single large rotor like the helicopter, or with a number of smaller propellers like the Ehang 184 with its eight counterrotating propellers or the Joby S2 with its twelve lifting propellers.

The second design consideration is maximizing range by operating at the speed that results in the maximum lift to drag ratio.

## ANALYSIS

The following equations [1] govern the power required as



a function of aircraft speed:

$$\text{Thrust} = \text{Drag} = \rho A_{\text{eff}} (V_j^2 - V_j V_0)$$

$$\text{Drag} = \left( \frac{C_L^2}{\pi A R_E} + C_{Dw} \frac{A_w}{S} \right) W$$

$$\text{Power} = \text{HP} = \frac{\rho A_{\text{eff}}}{1100\eta} (V_j^3 - V_j V_0^2)$$

Where  $C_L = \frac{W}{0.5\rho V_0^2 S}$   $W$  = Gross weight,  $\rho$  = air density,  $\eta$  = energy conversion efficiency between battery and airstream,  $V_0$  = forward velocity,  $V_j$  = exit velocity either downstream of the propeller or at the ducted fan exit,  $A_{eff}$  = swept area of propellers/2 or ducted fans exit area.

For  $V_0=0$  the above equation reduces to:

$$W = 35.7(\rho A_{eff})^{1/3} (HP\eta)^{2/3}$$

**The total energy available from the battery to the airstream depends on five variables:**

- Battery storage energy (Wh/kg) is a function of the battery chemistry required to tolerate a given discharge rate (W/hr.). Batteries in electric cars use a low average discharge rate of less than 0.5 C and can use NCA lithium batteries with a theoretical energy storage of up to 265 Wh/kg [2]. For a winged air taxi, like the Joby S2, these batteries could be used under the assumption that a short-term 2C discharge during takeoff and landing can be tolerated. For a wingless air taxi, like the Ehang 184, where the continuous discharge rate exceeds 2C, NMC lithium batteries would be needed with a theoretical energy storage of 220 Wh/kg.
- The weight added to cool and package the batteries will significantly lower the net energy stored per kilogram. For example, this added weight in a Tesla automobile reduces its effective stored energy from 265 Wh/kg to 168 Wh/kg. Assuming a similar weight increase with NMC lithium batteries, actual energy storage will reduce to the 140 Wh/kg for the Ehang 184.
- Propeller efficiency can exceed 90% for a winged air taxi as in the Joby S2 where separate motors driving propellers are used to generate thrust. In the wingless Ehang 184, the lift/thrust propellers are operating in crossflow and the efficiency is likely to be closer to 85%.
- The electric motor efficiency for both the winged and wingless air taxis can approach 95% if the motor is designed specifically for the cruising flight conditions. In the case of the Joby S2, this is accomplished by having separate thrust motors/propellers designed to operate at the Joby S2's cruise speed. For the Ehang 184, this suggests that the motors/propellers be designed to operate at a speed where range is maximized, which is close to its specified cruise speed of 62 mph. For the Joby S2, the maximum lift to drag ratio is at 112 mph.
- Prior to reaching cruise speed, both the winged and wingless air taxis will experience a higher discharge rate from the battery. However, if the time to hover, clear the area, and transition to and from cruising

flight and land is less than 2 minutes, the energy consumption for this short high discharge period is included in the average battery discharge efficiency.

Overall energy conversion efficiency between battery and airstream is composed of battery efficiency  $\eta_b$ , motor efficiency  $\eta_m$ , and propeller efficiency  $\eta_p$ .

For wingless flying car  $\eta = \eta_b \cdot \eta_m \cdot \eta_p = 0.93 \cdot 0.95 \cdot 0.85 = 0.75$

For winged flying car  $\eta = 0.95 \cdot 0.95 \cdot 0.92 = 0.83$

### ANALYSIS OF WINGLESS EHANG 184 FLYING CAR

Specified cruise speed = 62 mph (for maximum lift to drag ratio), Specified range = 26 miles [3].

Data for light helicopters [4] with a disc loading (gross weight / swept area) similar to the Ehang 184 show that minimum power occurs near 60 mph where it drops to 60% of that required to hover.

Hover power = 57.8 kW for two minutes

Cruising power = 34.7 kW at 62 mph

Where  $\eta = 0.75$ ,  $\rho = 0.0627 \text{ lb./ft}^3$  (100°F day @ 5,000 ft. altitude),  $A_{eff} = 43.3 \text{ ft}^2$ ,  $W = 748 \text{ lbs}$ . Specified energy consumption = 14.4 kWh. With the 20% reserve required to protect the batteries and 220 lb. payload, the battery pack will weigh 272 lbs. This would leave 256 lbs for airframe, powerplants, and ergonomics.

### ANALYSIS OF THE WINGED JOBY S2 FLYING CAR

Cruise speed used = 112 mph (for maximum lift to drag ratio), Specified range = 200 miles [5].

Hover Power = 181 kW for two minutes.

Cruising power at 112 mph = 21 kW.

Where  $S = 56.3 \text{ ft}^2$ ,  $A_w = 340 \text{ ft}^2$ ,  $C_{DW} = 0.004$ ,  $A_{RE} = 16.3$ ,  $\eta = 0.83$ ,  $W = 2,000 \text{ lbs}$ ,  $\rho = 0.0627 \text{ lb./ft}^3$  (100°F day @ 5,000 ft. altitude),  $A_{eff} = 68.75 \text{ ft}^2$  (motor failed).

If minimum retained battery energy is 20% for protection of batteries and payload is 390 lbs., the battery energy capacity required is 45 kWh. With a battery energy of 168 Wh/kg, the battery pack would weigh 589 lbs. This would leave 1,021 lbs. for airframe, powerplants, and ergonomics.

### HYBRID APPROACH EXPANDS FLYING CAR PERFORMANCE AND UTILITY

For the foreseeable future, a VTOL capable flying car with sufficient capability to personalize versus commercialize airborne transportation engines will be needed for aerodynamic flight supplemented by battery power during VTOL flight. This hybrid approach could make the following performance possible:

- Intercity range over 500 miles.

- Cruise speed over 250 mph.
- Expanded payload capability.
- Can land curbside while wings are folded and with the size and stowability of a large automobile.
- Fuel economy exceeding 100 passenger miles per gallon.

Analysis shows that to meet these objectives [6], a hybrid flying car would derive most of its power during vertical takeoff from batteries. To be landable at the curb it must reduce its size prior to landing. This will limit the size of the propulsion system's sweep area and increase the

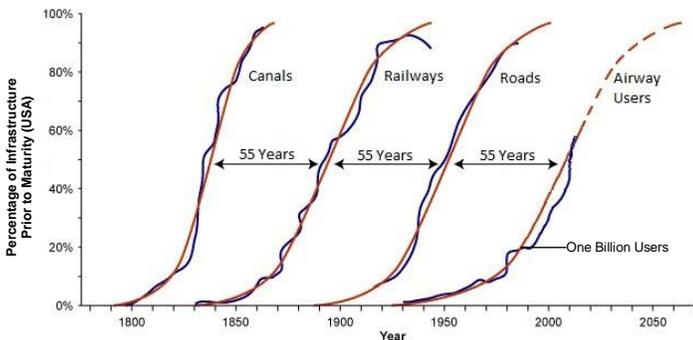


Skycar® 200 (hybrid)

short-term power required (watts/lb.) to take off vertically. Consequently, the discharge rate from the batteries will be high (~50 C) requiring the use of a LFP lithium type battery where the energy storage per kilogram is significantly lower than that used in an air taxi application. The VTOL flight time including transition to aerodynamic flight will need to be measured in seconds to minimize battery weight and maximize its life.

### FUTURE OF PERSONALIZED AIRBORNE TRANSPORTATION

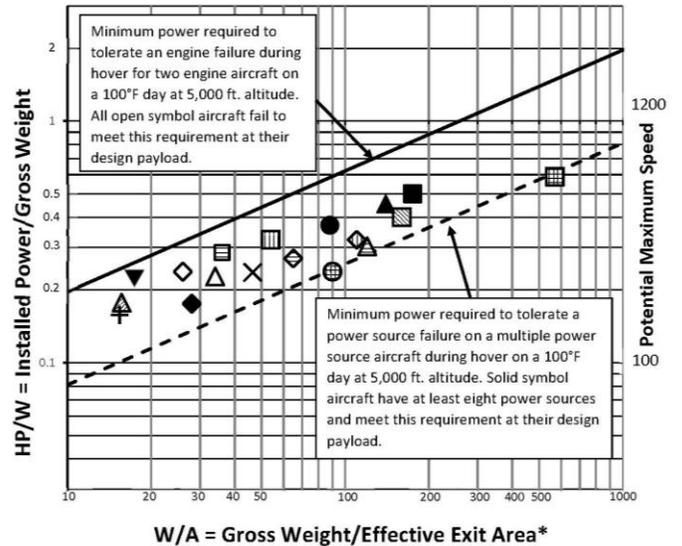
If all the cars on the road in the US were airborne and evenly spaced, they would be over two miles apart. This benign environment will make pilotless flying cars far easier to implement than the ground-based driverless cars currently under development. The following figure shows a future where personal travel could be done mostly by air utilizing the relatively unused airspace above US.



The status of airway infrastructure is not qualifiable like canals, railways, and highways. However, passenger usage has historically followed the infrastructure status of the other transportation modes. For that reason, passenger usage is used as a surrogate for airway infrastructure status. Airborne private travel could demand far more performance than can be provided by flying cars powered by batteries unless an unexpected breakthrough in battery chemistry occurs.

From 1950 through the 1970's over fifty different VTOL aircraft were demonstrated. Most had a single engine while none had more than two engines. Many lives were lost due to engine or the failure of a critical component. Inherent in any VTOL capable aircraft is the need to have enough total installed power, which when distributed will allow a powerplant failure on a hot day at altitude. The following figure shows that all two-engine prototype and production VTOL aircraft are unable to hover at altitude on a hot day while carrying their design payload. This requires operating above the solid line. VTOL aircraft with eight or more powerplants operate safely above the dotted line.

VTOL Aircraft Power Required for Safe Operation



- ◇ Aerospatiale N500    △ AW609    × Bell-Boeing V-22
- ◇ Bell XV-15    △ Bell X22A    ● Canadair CL84 1D
- Curtiss X-19    ◇ Doak VZ4    ▼ Ehang 184 (electric)
- △ Eurocopter AS365    □ Hiller X-18    ◆ Joby S2 (electric)
- Neuera 200    □ Piasecki VZ-8P    □ Ryan XV5A
- + Sikorsky S76    ■ Skycar® 400 (hybrid)    ▲ Skycar® 200 (hybrid)

\*With unducted fans, propellers, or rotors the effective exit area in ft<sup>2</sup> is one half the swept area.

Achieving fool-proof redundancy for powerplants, onboard flight systems, and the flight control network will be key to establishing public confidence in a pilotless alternative to the automobile.

## CONCLUSIONS

The winged Joby S2 and wingless Ehang 184 are most suitable for use as air taxis, primarily because their size and/or configuration limits their ability to operate from a streetside curb.

- Analysis of the winged Joby S2 shows that it could fly for 200 miles at 112 mph and at a higher speed if the weight of its airframe, propulsion system and ergonomics to make it commercially viable can be reduced below 1,000 lbs. However, to achieve its specified cruise speed of 200 mph, the above components would have to weigh 452 lbs, which would be extremely challenging, if even possible.
- Analysis of the wingless Ehang 184 shows that it could fly for 26 miles at its specified cruise speed of 62 mph. However, the airframe, propulsion system, and ergonomics to make it commercially viable could weigh no more than 256 lbs. This would be extremely challenging if even possible to achieve.
- The winged air-taxi similar to the Joby S2 would be the best choice for intracity trips of up to 25 miles. In a typical flight the battery would use only 20% of its battery energy storage capacity. The time to recharge the battery would be reduced, as would turn around time while battery life would improve. For this mission, the maximum lift drag ratio is less important. Consequently, the wing can be shortened, resulting in a size near that of the wingless air-taxi. Having a wing provides the ability to glide, which is a further attribute.
- If the growth of airway infrastructure follows the historic path of canals, railroads, and roads, air-taxis will make up a very small portion of future airborne trips by the public. To achieve this personal use growth, the flying car will need to be able to land at a street curb. This will require that the flying car reduce its size to that of a large automobile prior to landing and that all propellers be ducted.
- Until the energy storage capacity of batteries increases by an order of magnitude, curbside operations will make it necessary for the flying car to operate in a hybrid mode where during takeoff and landing most of the power is derived from batteries while engines provide the power during cruise.

## Definitions, Acronyms, Abbreviations

**NCA:** Lithium Nickel Cobalt Aluminum Oxide

**NMC:** Lithium Nickel Manganese Cobalt Oxide

**LFP:** Lithium Iron Phosphate

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