

7. Benchmarking and Cost Estimation

by Dr. James Wang

SNUevtolclass@gmail.com

For students to use in the 2022 eVTOL Design Short Course at SNU,
please do not reproduce or distribute

eVTOL can Perform Multiple Missions

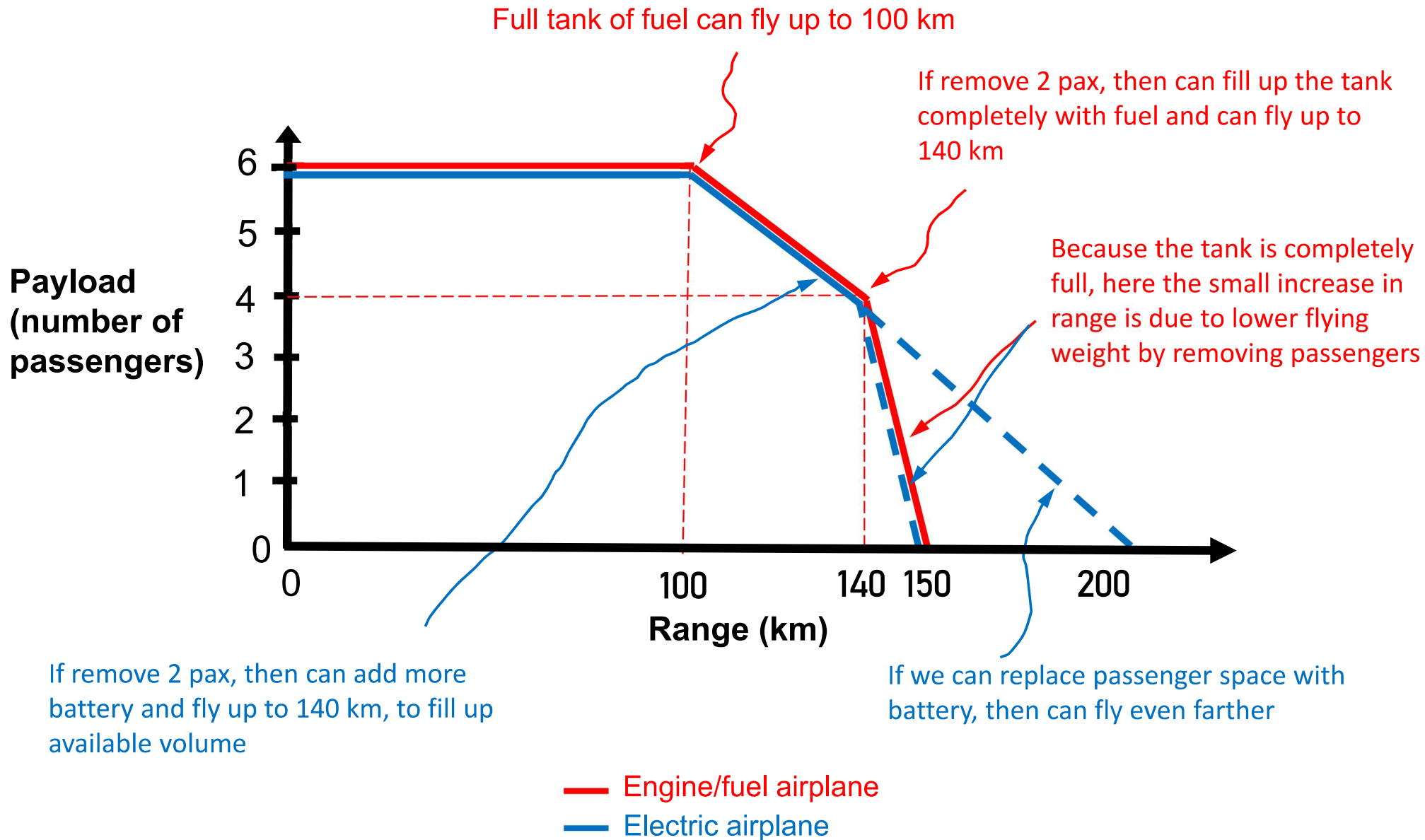
- UAM
- Business travel, VIP transport, luxury Air-taxi
- Private ownership
- EMS (Emergency Medical Service)
- Organ transport
- Cargo delivery
- Disaster relief
- Search and Rescue
- Police, Border patrol
- Logistic, command and control
- Military transport and Commando insertion
- Utility, pipeline surveillance, inspection and repair

Desired Attributes for UAM eVTOL Aircraft

- Electric → Sustainable, lower parts count, lower maintenance, lower manufacturing cost, less noise,
- Recyclability for whole aircraft and batteries
- Configuration takes advantage of distributed electric propulsion & minimize complexity
- >6 lifting rotors, for redundancy, or dual motors per rotor, or dual windings per motor
- Vertical Take-Off & Landing (VTOL) → low infrastructure, no runway
- Possibly allow STOVL (short take-off and vertical landing) → saves power, adds safety
- Efficient cruise → $L/D > 10$ because 90% time will be in cruise, and permits gliding
- Efficient hover → disk loading $< 15 \text{ lb/ft}^2$ if mission require extended hover
- Autonomous capable or later easily upgradable to level 5
- Safety → 10^{-9} , account for cybersecurity, battery fire, electro-magnetic interference
- Noise → external noise at least 15dB $<$ same weight helicopter
- Cabin comfort → vibration $<$ helicopter, permits conversation without headset
- Emergency → ballistic parachute? autorotation? gliding? Rugged crashworthiness.

Payload-Range Curve for Fuel and Electric Plane

A generic example:



Parametric Study for 13 eVTOLs

Volocopter Volocity

EHang 216

Airbus CityAirbus

Beta Technologies Alia

Cora Kitty Hawk

Hyundai Supernal S-A1

Vertical Aerospace VA-X4

Archer 2-Seat Maker

Kitty Hawk Heavyside

Joby S4

Bell Nexus 4EX

Airbus Vahana

Lilium Jet

Parametric Study of 13 Different eVTOLs



Joby S4, USA



Archer Maker, USA



Volocopter Volocity, Germany



Ehang 216, China



Beta Technologies Alia, USA



Hyundai S-A1, Korea



Vertical Aerospace VA-X4, UK



Cora Wisk, USA



Lilium Jet, Germany



Airbus CityAirbus, France



Bell Nexus 4EX, USA



Airbus Vahana, France



Kitty Hawk Heaviside, USA

Volocopter Volocity (multirotor)



EHang 216 (Multirotor)



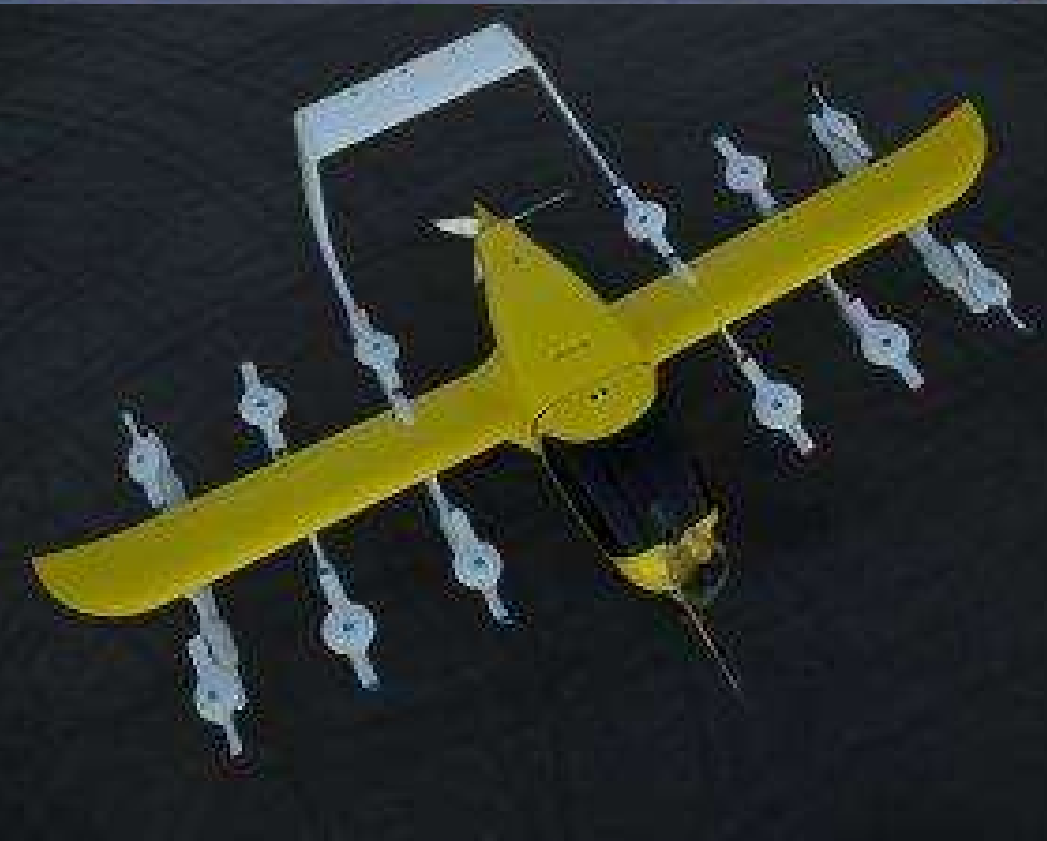
Airbus CityAirbus (quadcopter)



Beta Technology Alia-250C (lift + cruise)



Wisk Cora (lift + cruise)





Hyundai Supernal S-A1 (vector thrust)

Vertical Aerospace VA-X4 (vector thrust)



Archer Aviation Maker 2-Seat Demonstrator



Kitty Hawk Heaviside demonstrator (vectored thrust)



Joby S4 (vectored thrust)





Bell Nexus 4EX (vectored thrust)



Airbus A³ Vahana Tiltwing demonstrator (vectored thrust)



Airbus A³ Vahana Tiltwing demonstrator (vectored thrust)

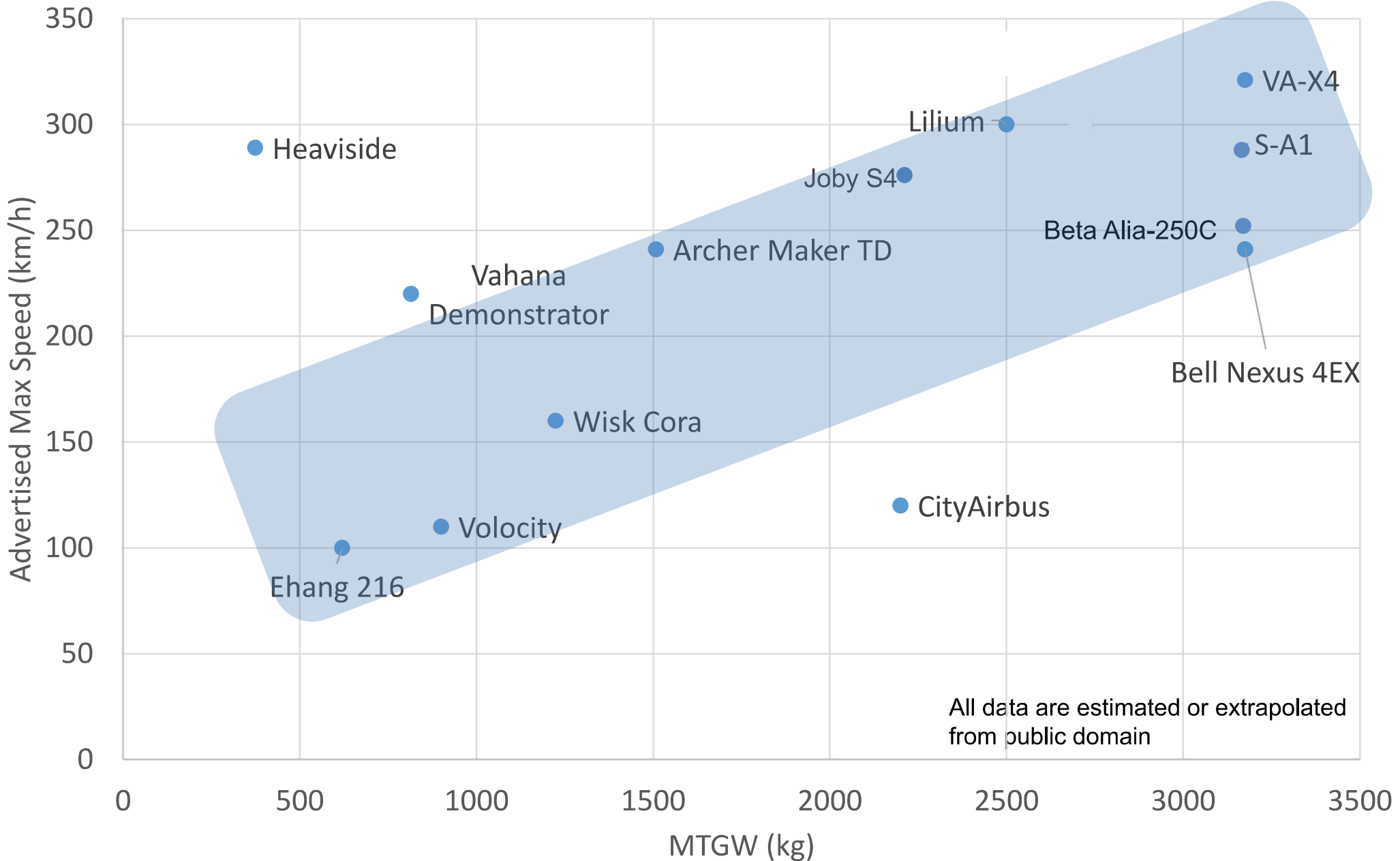
Lilium Jet 5-seat (vectored thrust)



**All data are estimated or
obtained from public
domain, do not assume
they are all accurate. They
are only used for teaching
purpose in this Short
Course !**

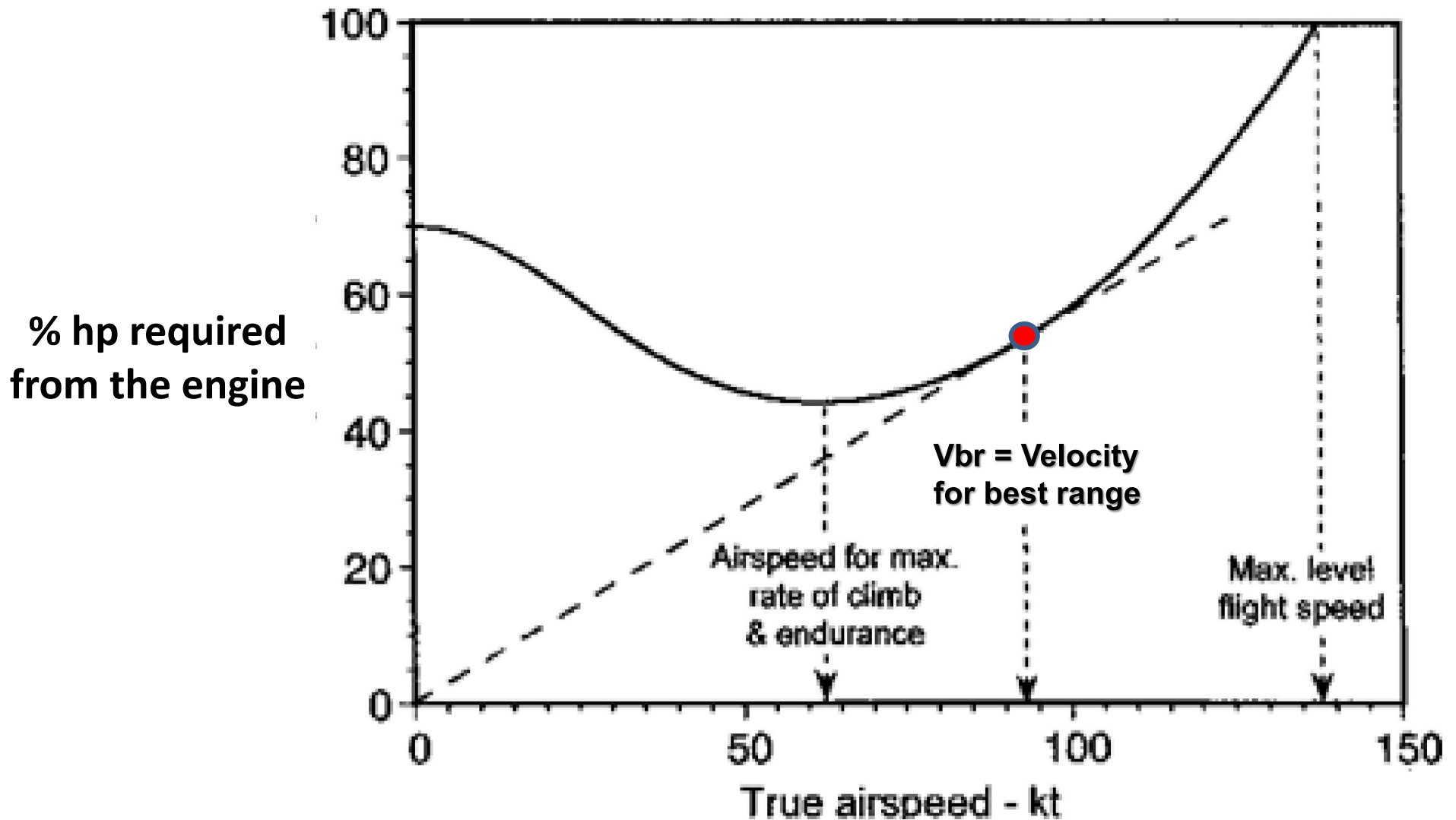
Advertised or Estimated Max Speed vs MTGW

Note, these are max speed, the best range cruise speed should be much lower

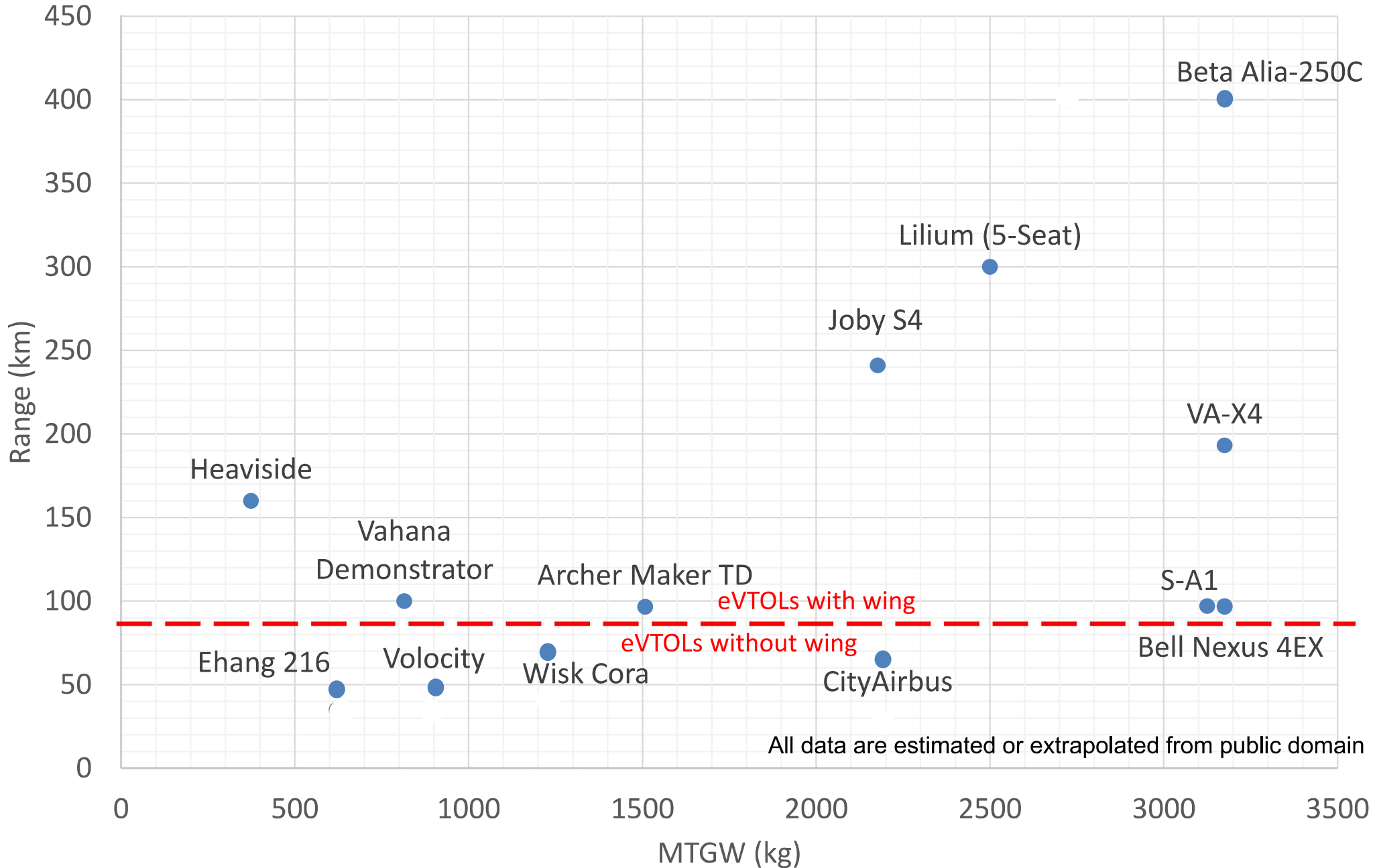


Note, Most Rotorcraft Will Cruise at V_{br}

Typical power required curve shape for helicopters



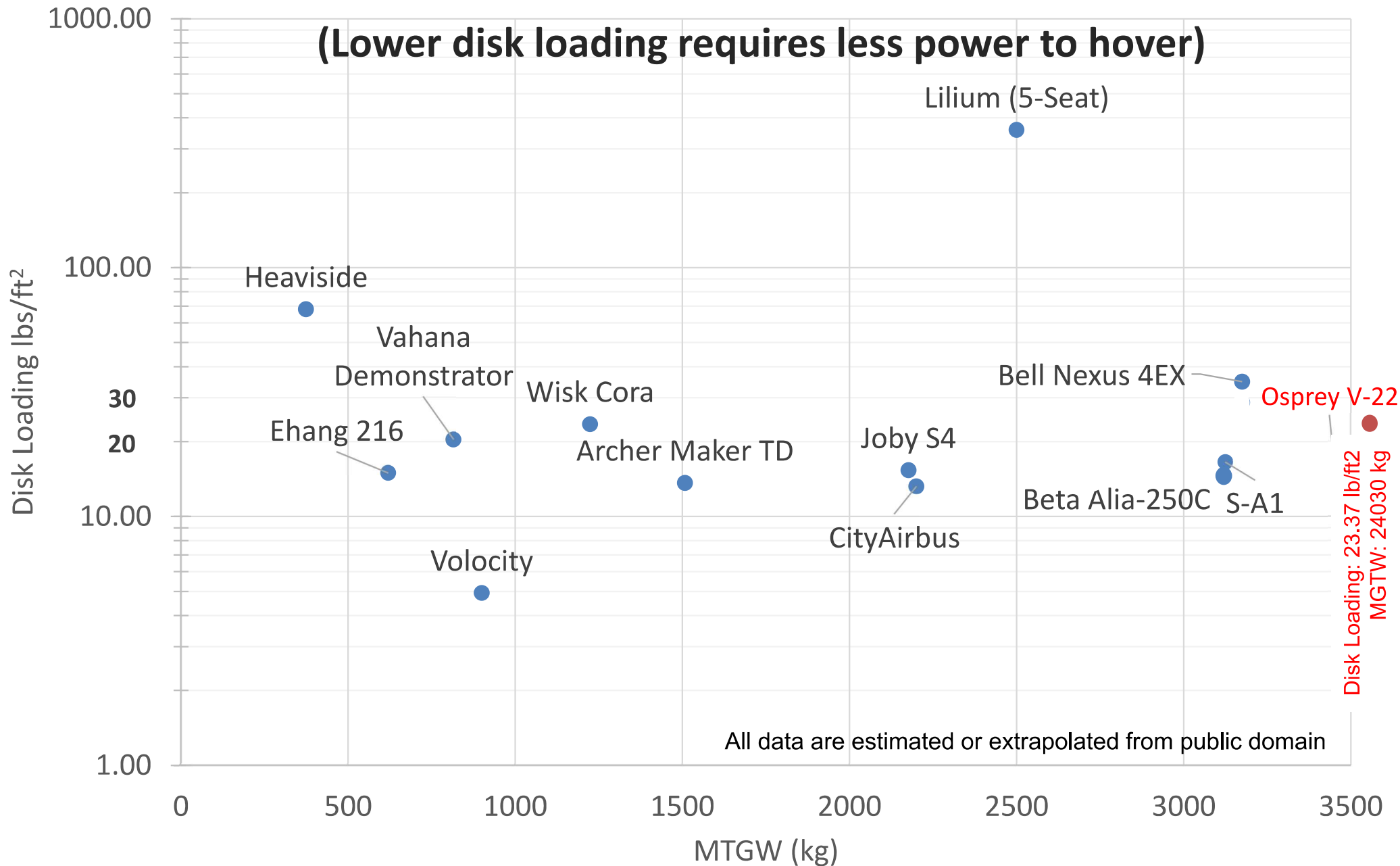
Claimed Range vs MTGW, With What Reserve?



Trend is Multirotor Replaced by Lift+Cruise



Estimated Disk Loading vs Estimated MTGW



What Rotor Diameter and rpm?

Target: We want to keep the disk loading at around 15 to 25 lb/ft². The lower the disk loading the more efficient the aerodynamics and the less power required for hover and cruise, and also quieter. Fullsize helicopters are 4 to 10 lbs/ft².

Target: To keep noise down, we want to keep the blade tip speed at under 556 km/h (about Mach 0.45 because the speed of sound is 1235 km/h).

Exercise Question

Let's say our MTGW is 7000 lbs and we have 6 rotors and our target disk loading is 15 lb/ft², what should be our rotor diameter?

Answer:

Disk loading = thrust per rotor / rotor area

$$15 \text{ lb/ft}^2 = 7000 \text{ lbs} / 6 / (3.1415 \times \text{radius}^2)$$

$$\text{radius} = 4.98 \text{ ft } (1.52 \text{ meter})$$

(By the way, this is roughly the radius of Joby S4, and the S4 has advertised lighter MGTW, too)

What Rotor RPM to Chose for this eVTOL?

Answer: To keep the rotor noise reasonable and stress reasonable, let's keep the blade tipspeed at 556 km/h.

556 km/h for a 1.52 meter radius means (970 rpm)

Let this rpm provide 1G thrust

Here is the formula: Tipspeed = ΩR

Tipspeed (km/h) = $2 \times 3.1415 \times \text{rpm} \times 60 \times \text{radius (meter)} / 1000$

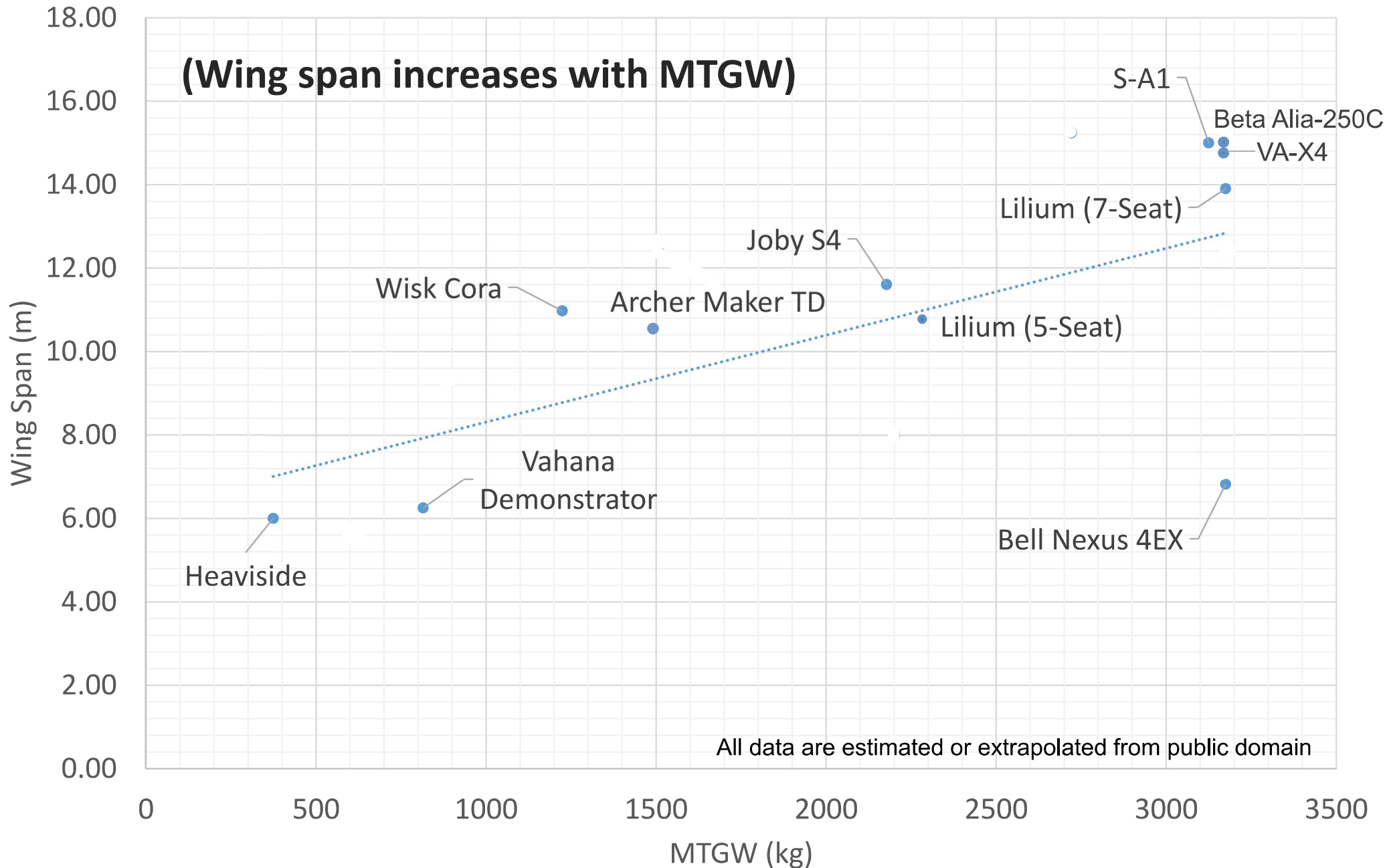
$$\text{rpm} = \frac{\text{Tipspeed (km/h)} \times 1000}{2 \times 3.1415 \times 60 \times \text{radius (meter)}}$$

To improve control response and flight performance, may want to consider raising the tip Mach No. to 0.5 and recalculate rpm. It also depends on using variable pitch or variable rpm for control.

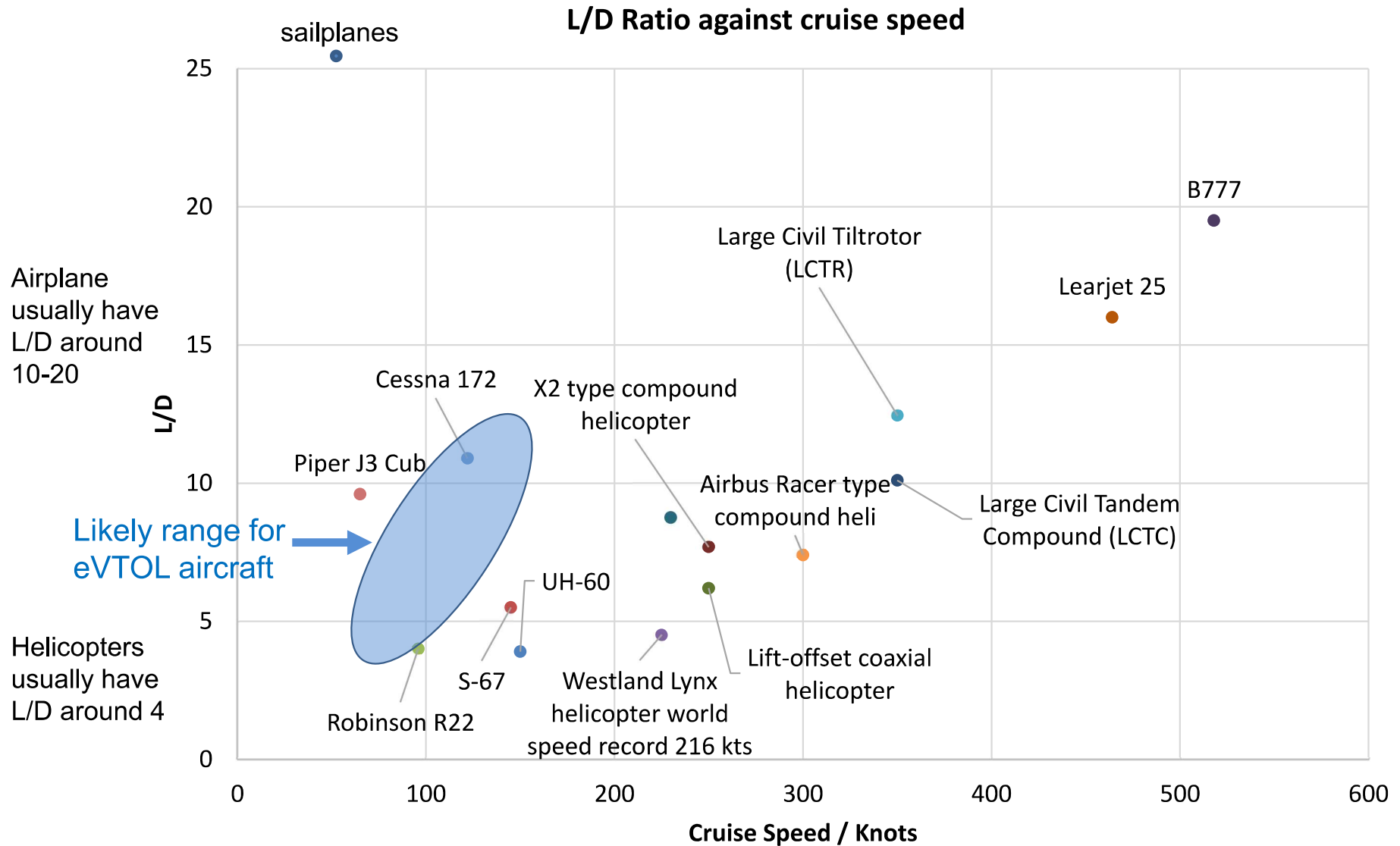
Key design requirements for minimum noise can be summarized as follows:

1. Low disk loading
2. Low tip speed
3. If possible, use more than 2 blades per rotor
4. Minimize interference with rotor flow, both upstream and downstream
5. Minimize what can contribute to high-frequency airload fluctuations

Estimated Wing Span vs Estimated MTGW

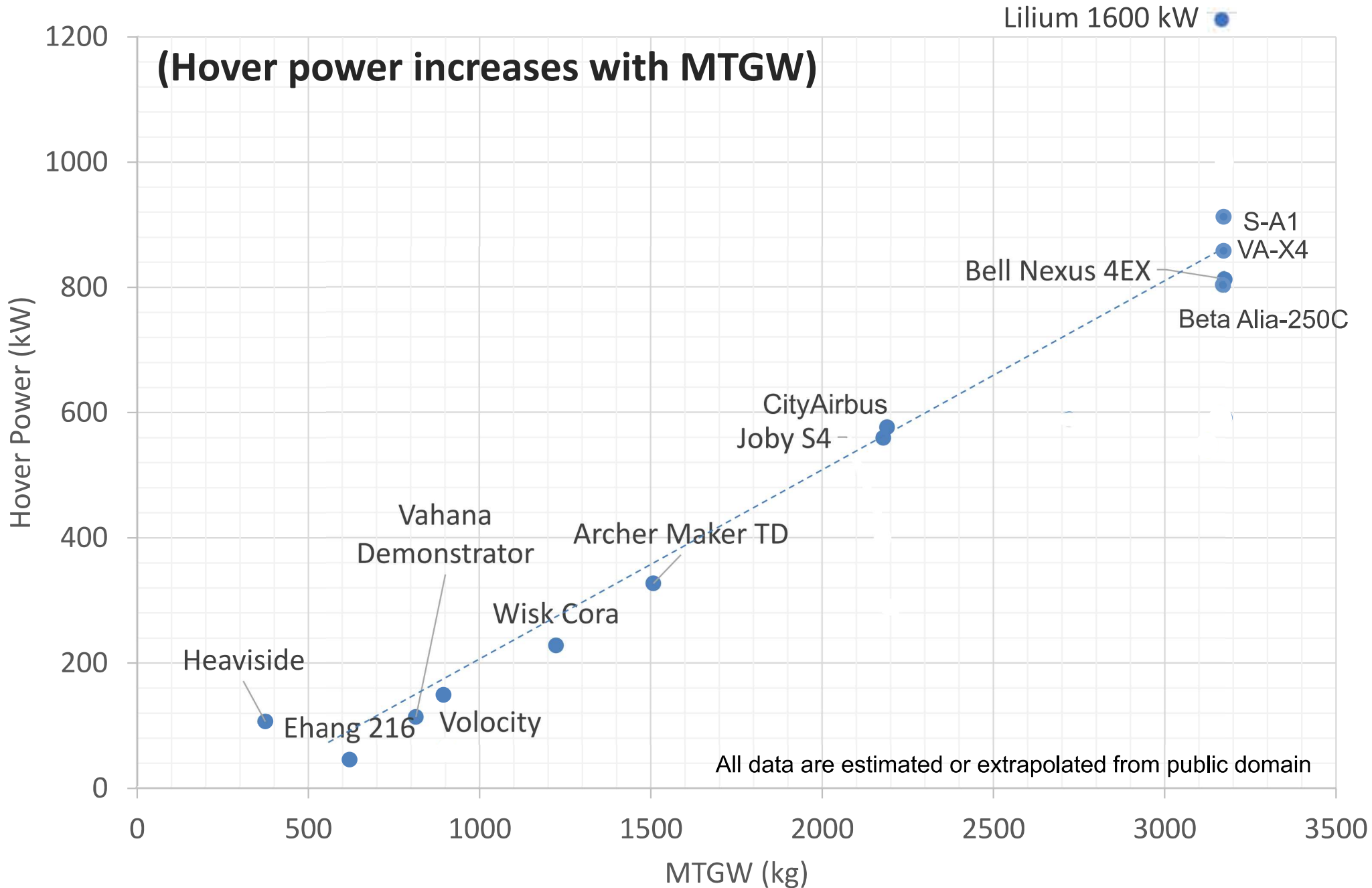


Total Aircraft L/D versus Cruise Speed



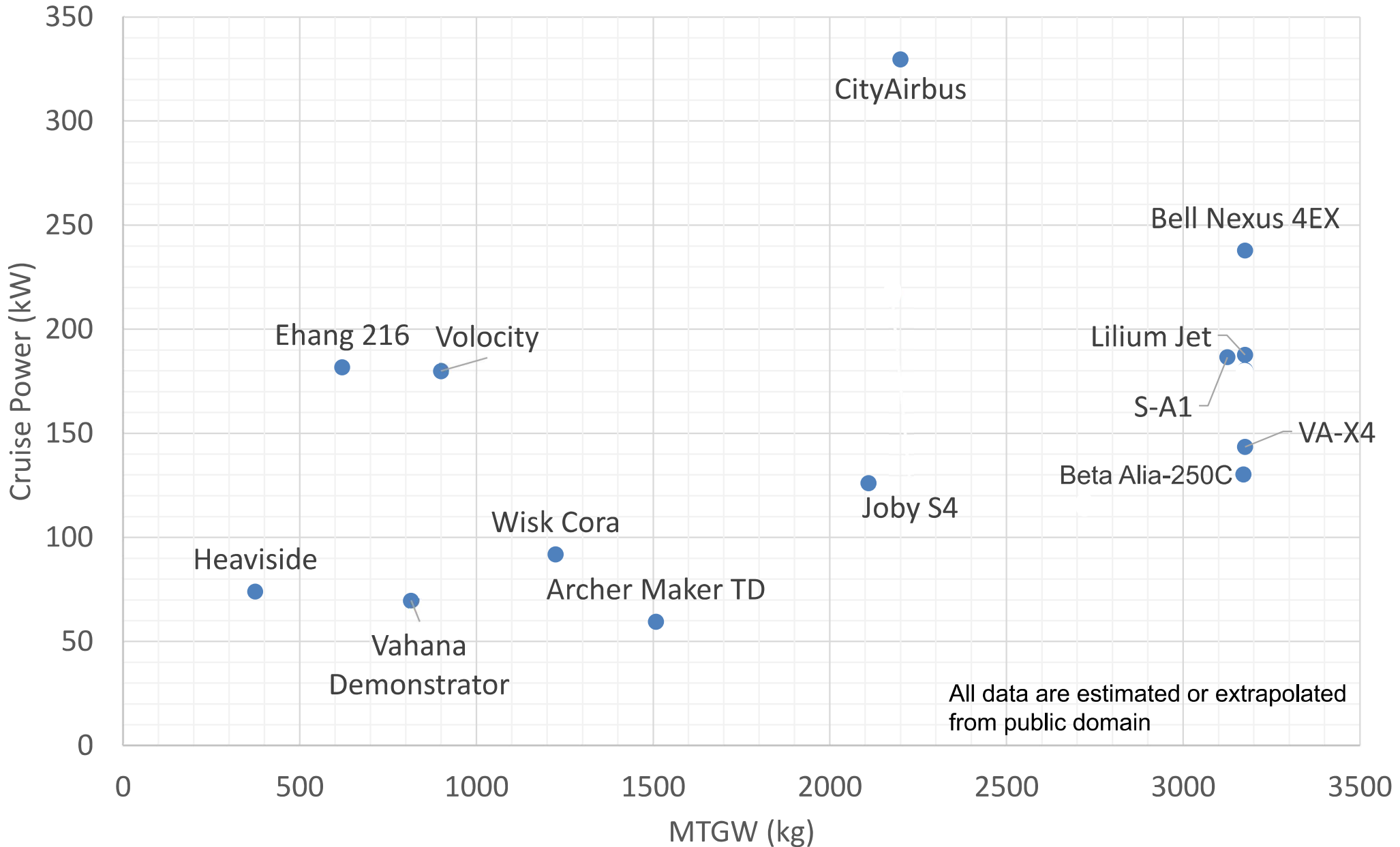
Estimated Hover Power vs MTGW

(Hover power increases with MTGW)

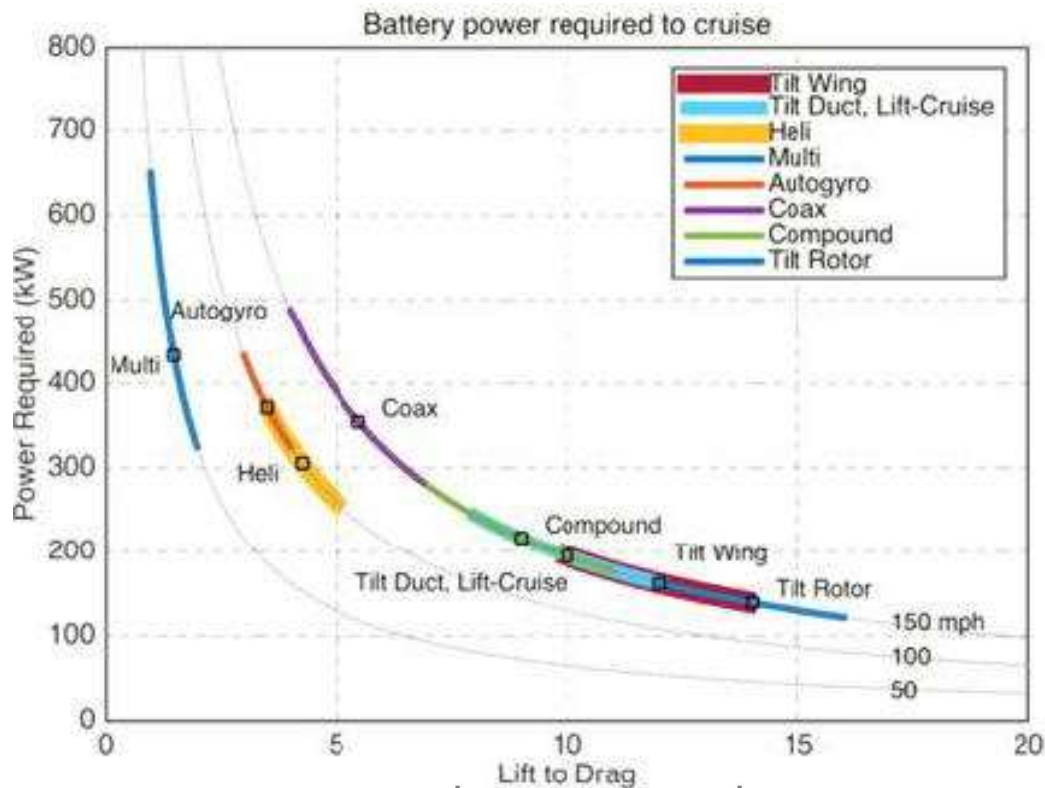


Estimated Cruise Power at V_{br} vs MTGW

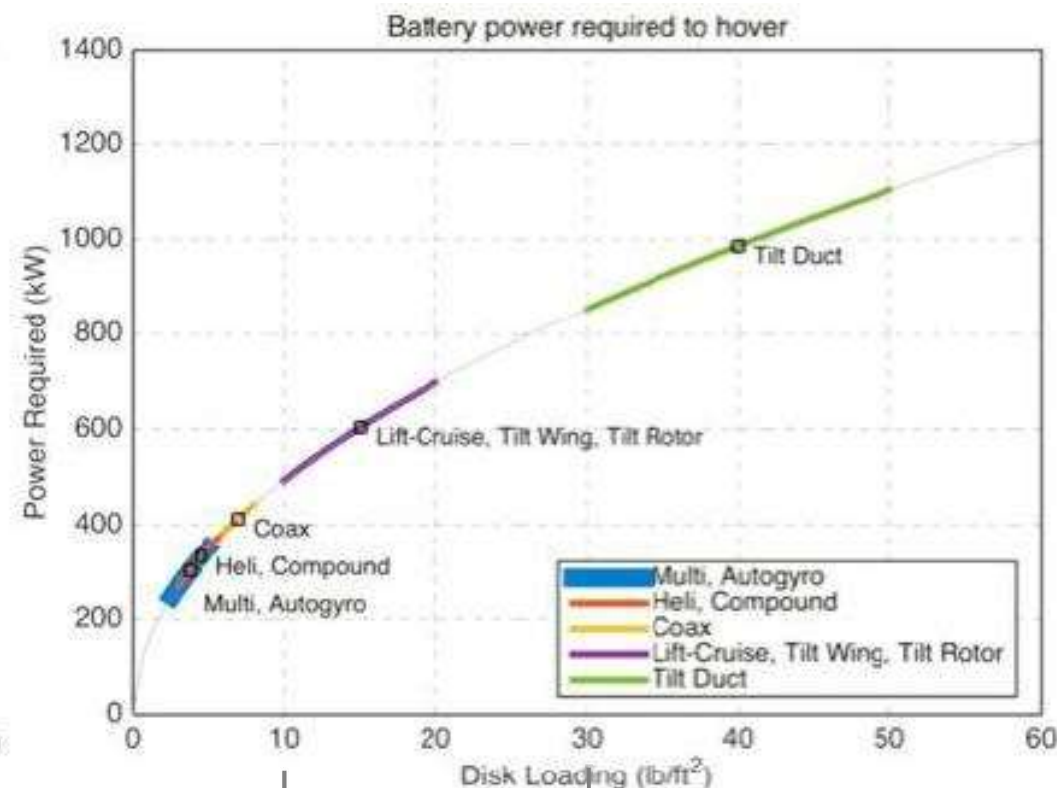
(Lower cruise power = longer range)



Example: Comparing Hover and Cruise Power Required for Different VTOL Designs, (assume all have a MTGW = 5000 pounds)

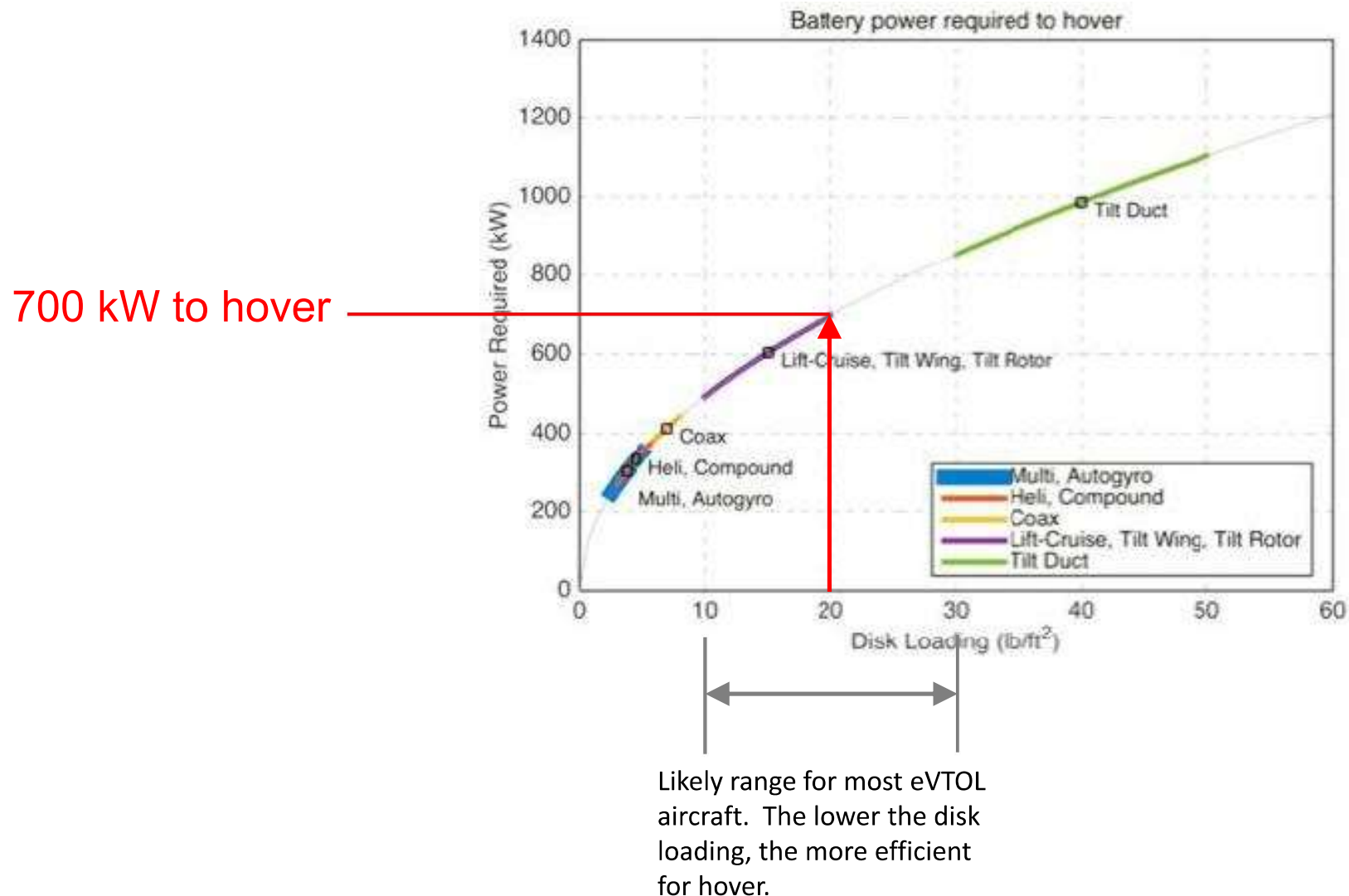


Likely range for most eVTOL aircraft. The higher the L/D, the more efficient for forward flight.

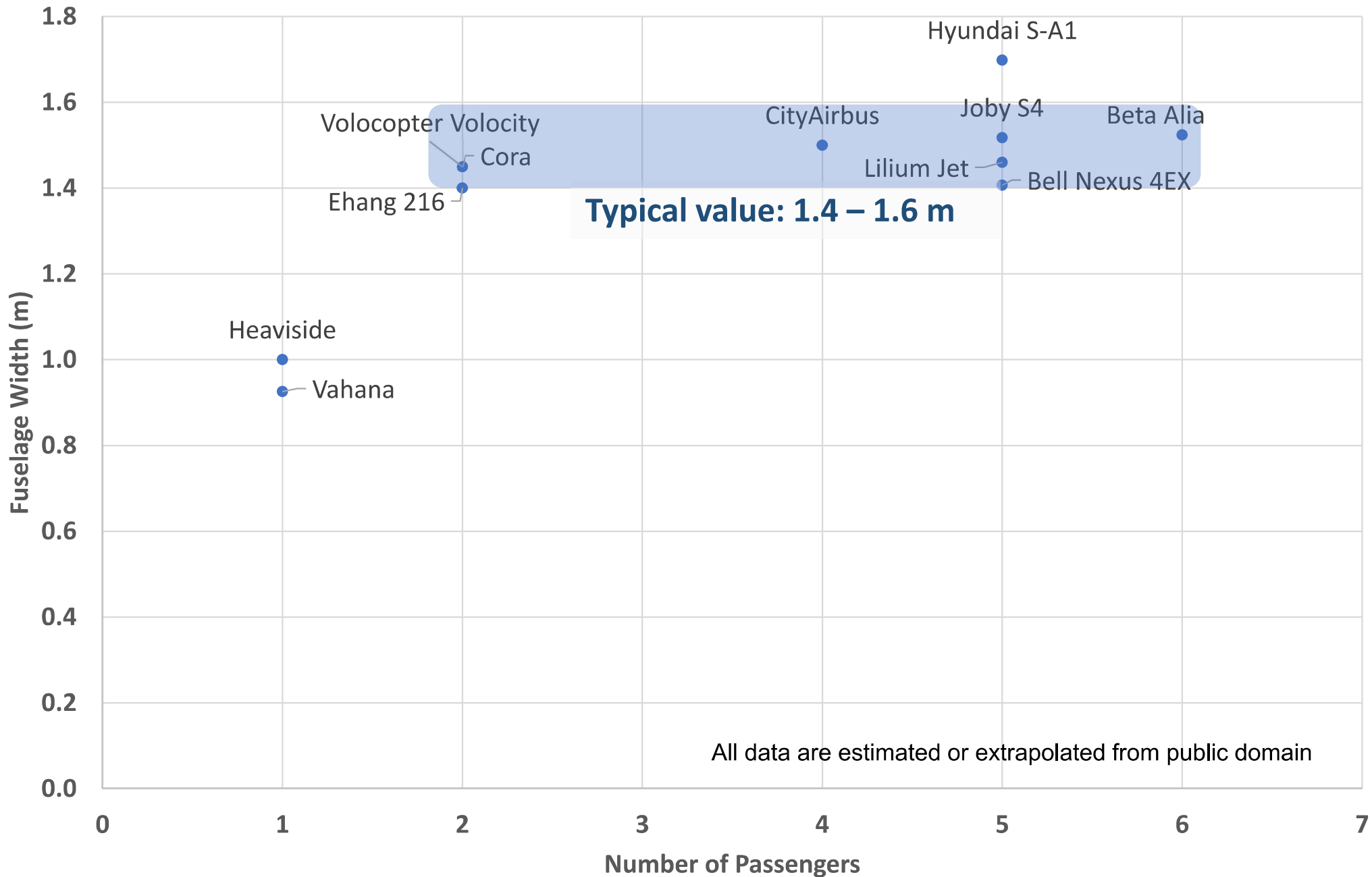


Likely range for most eVTOL aircraft. The lower the disk loading, the more efficient for hover.

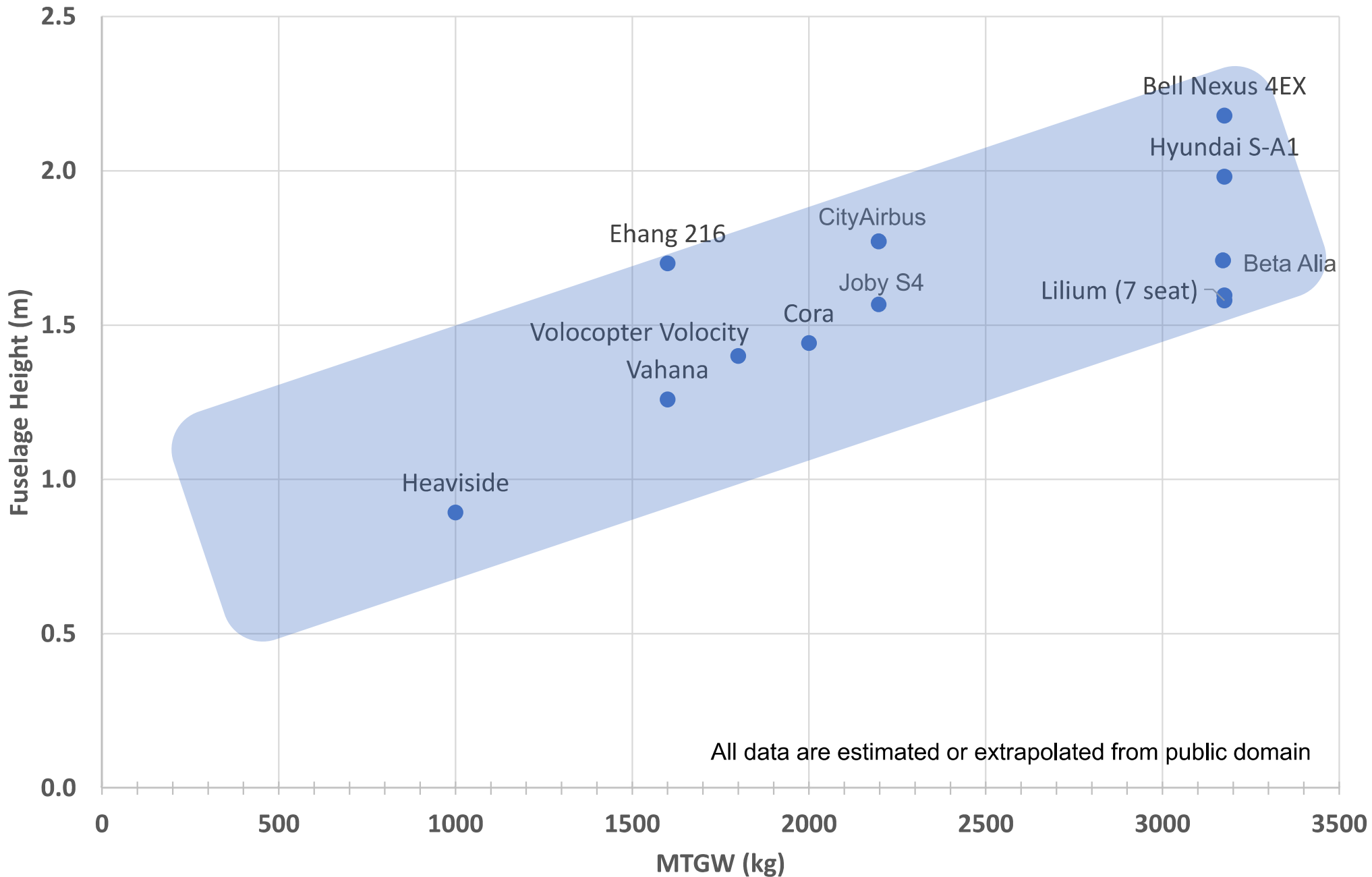
Example: Comparing Hover and Cruise Power Required for Different VTOL Designs, (assume all have a MTGW = 5000 pounds)



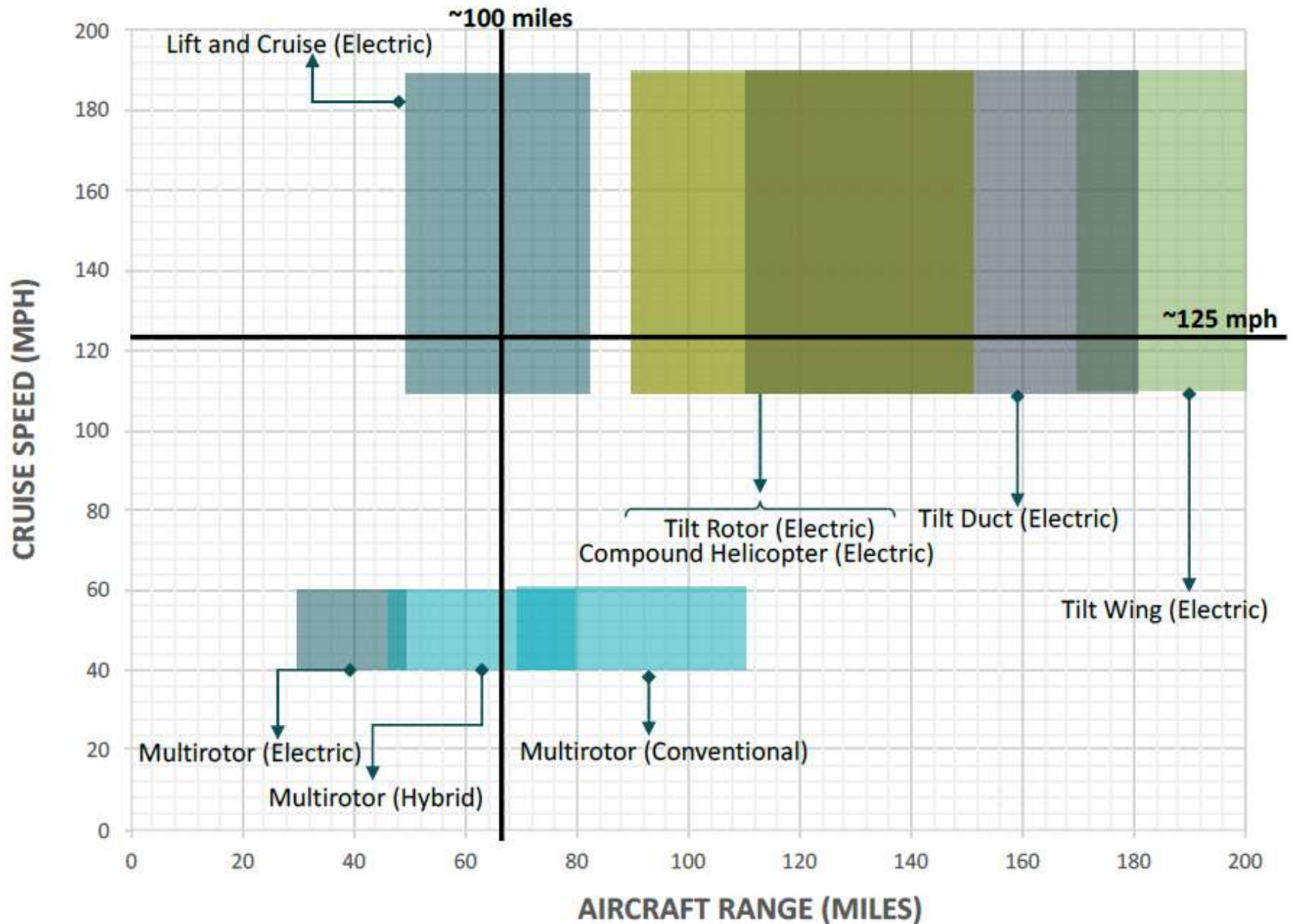
Extrapolated Fuselage Width vs Pax



Extrapolated Fuselage Height vs MTGW

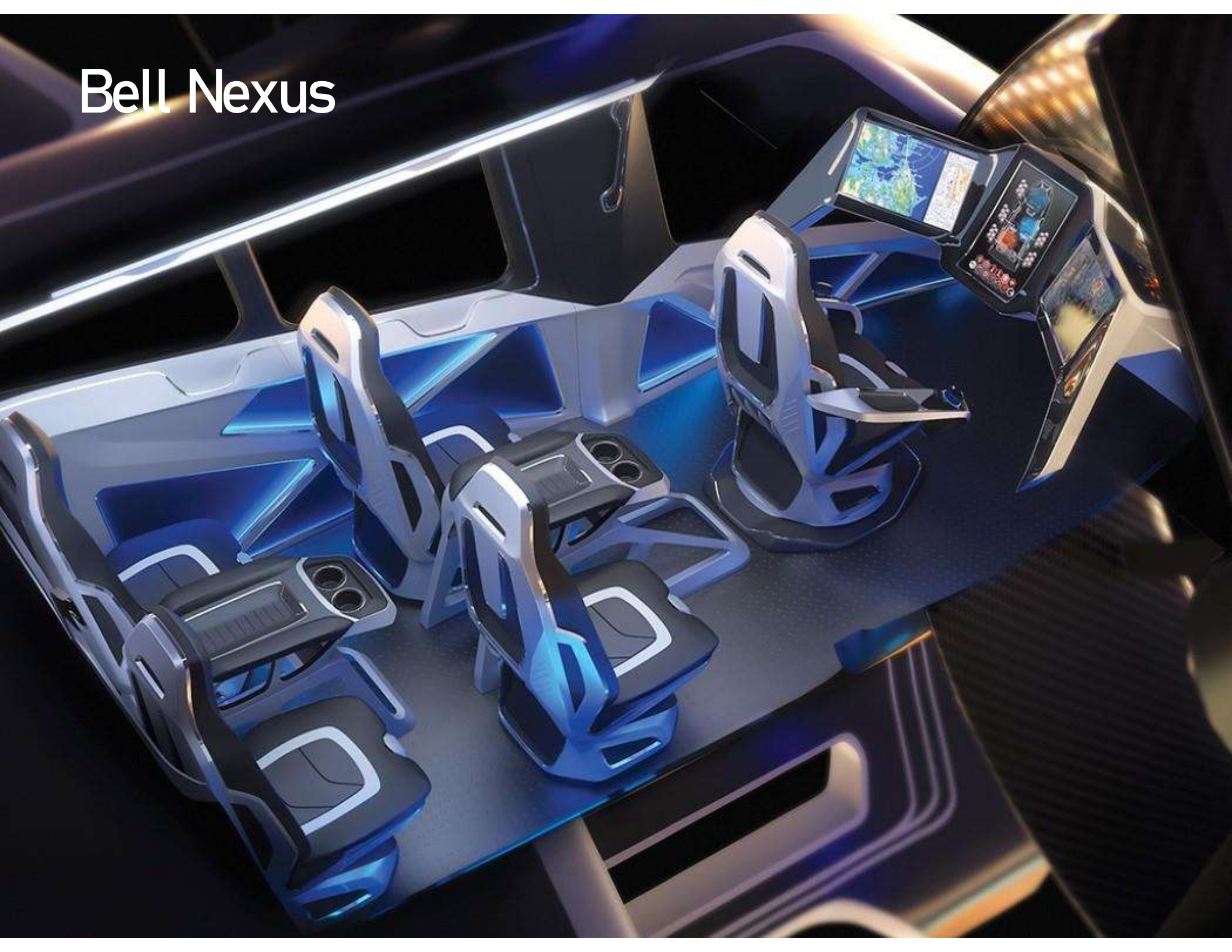


Cruise Speed and Range vs Configuration



Cabin Interior Design

Bell Nexus



Joby S4 Cockpit



Source: Joby brief <https://youtu.be/F49BuJsUH-w>

Vertical VX4 Cabin



450 kg
990 lb

PAYLOAD

VERTICAL

VERTICAL

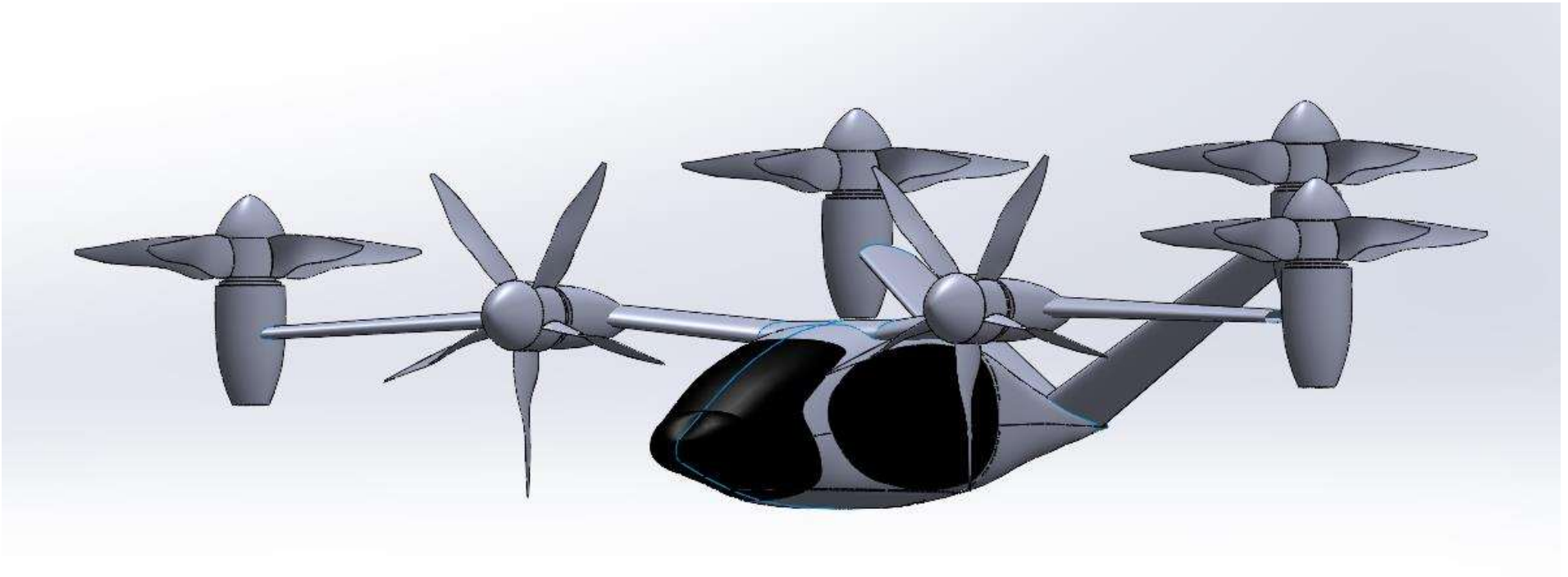
Source:

Vertical VX4 Cabin

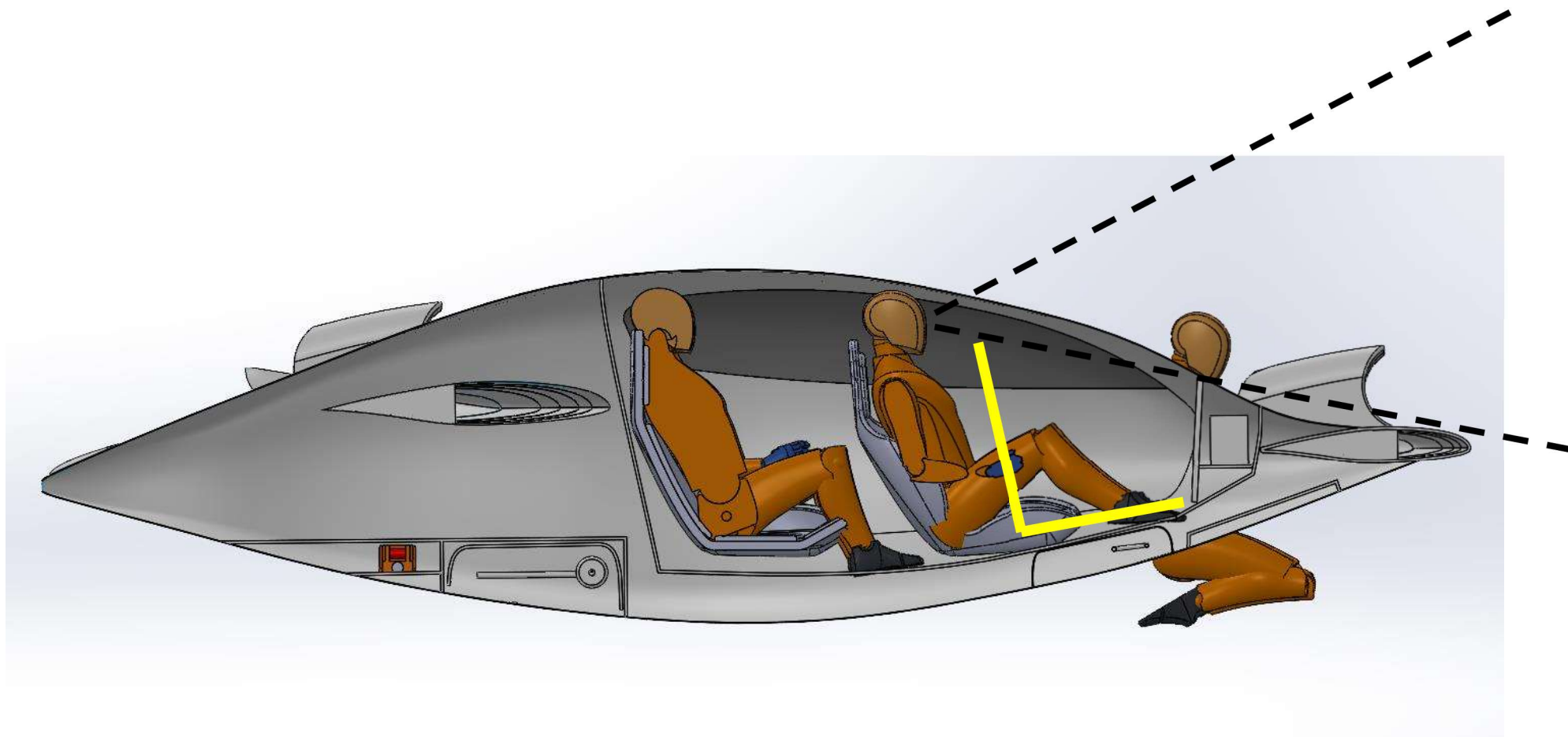


Source:

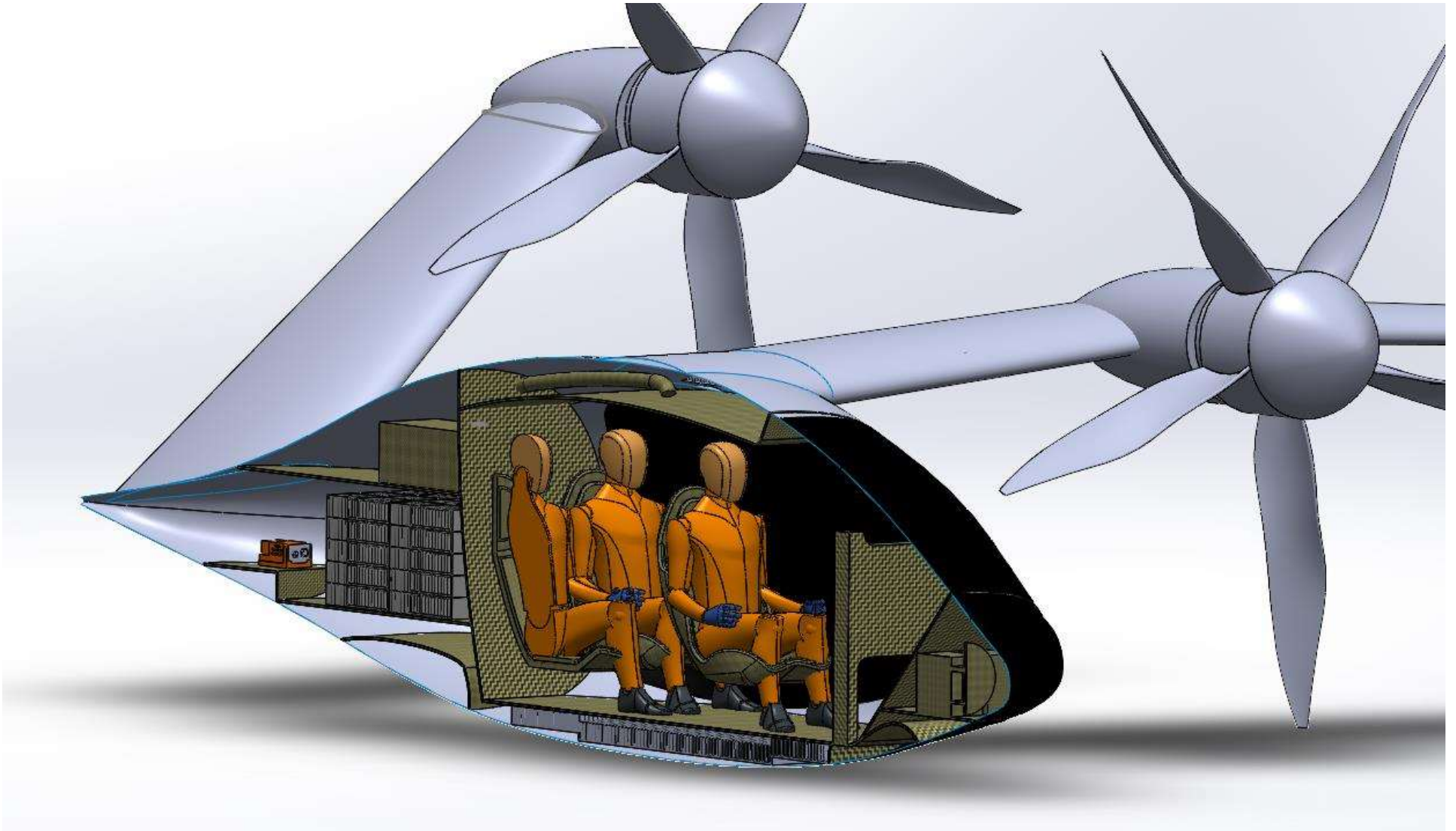
Use glass and doors judiciously, they are heavy



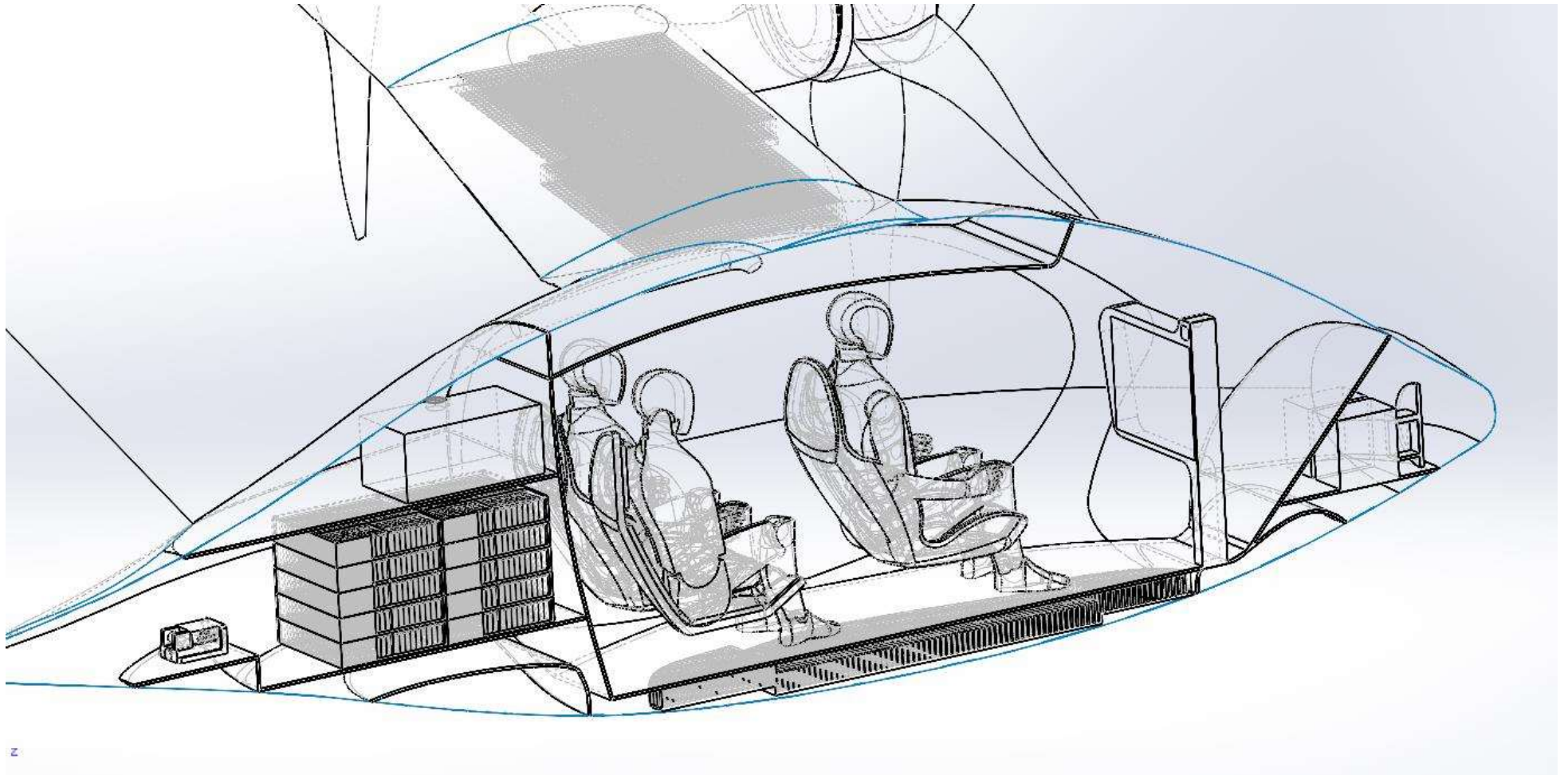
Check Visibility for Pilot



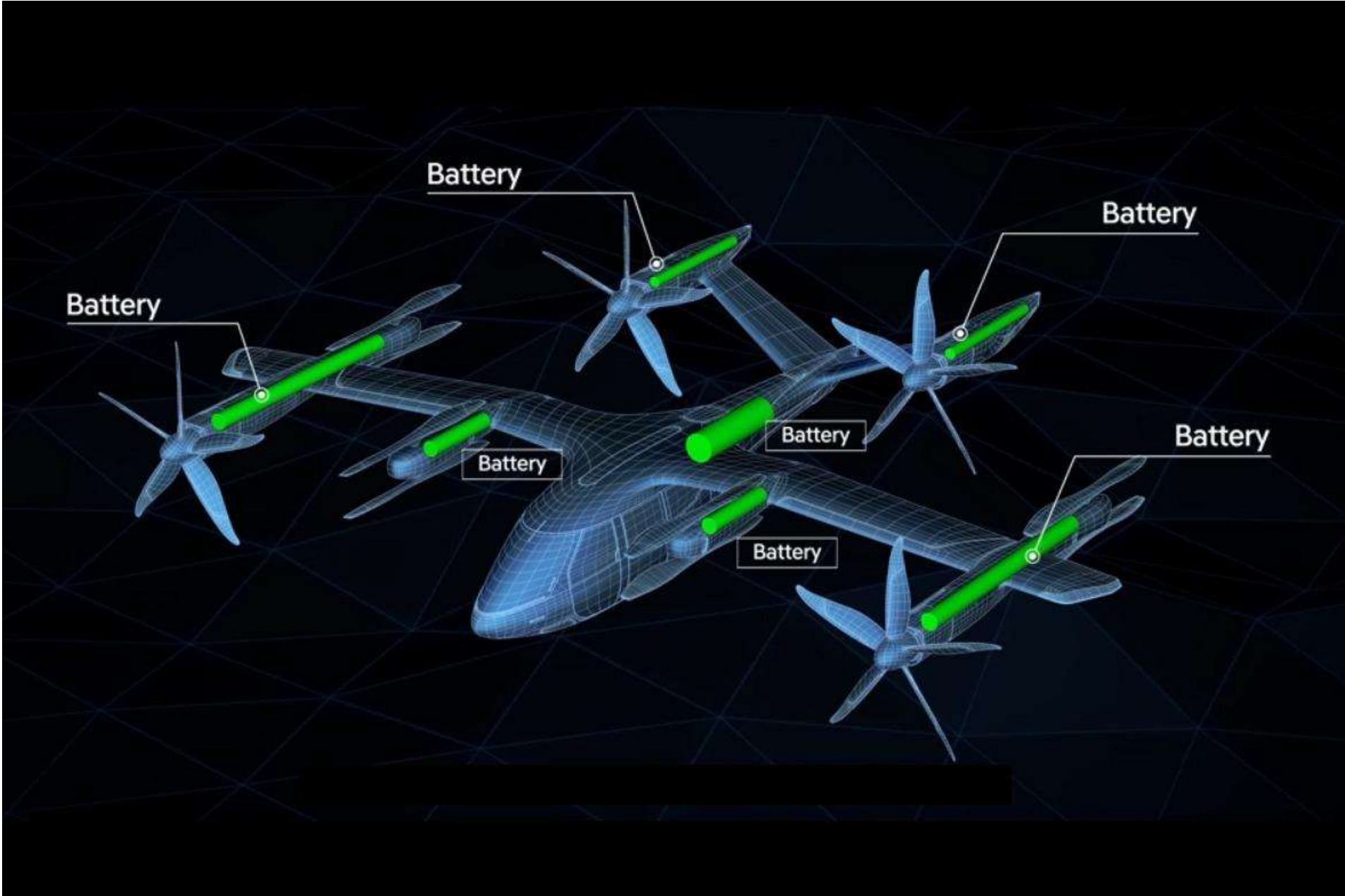
Make Sure Passengers are Comfortable



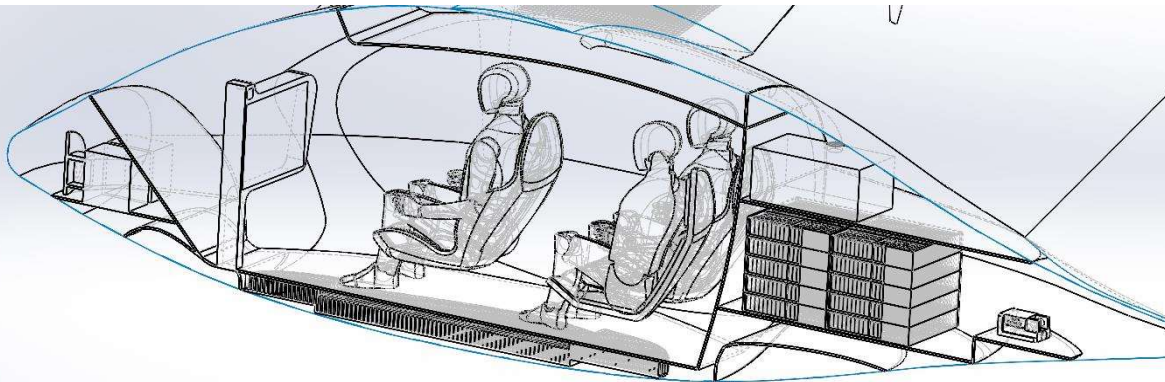
Packaging



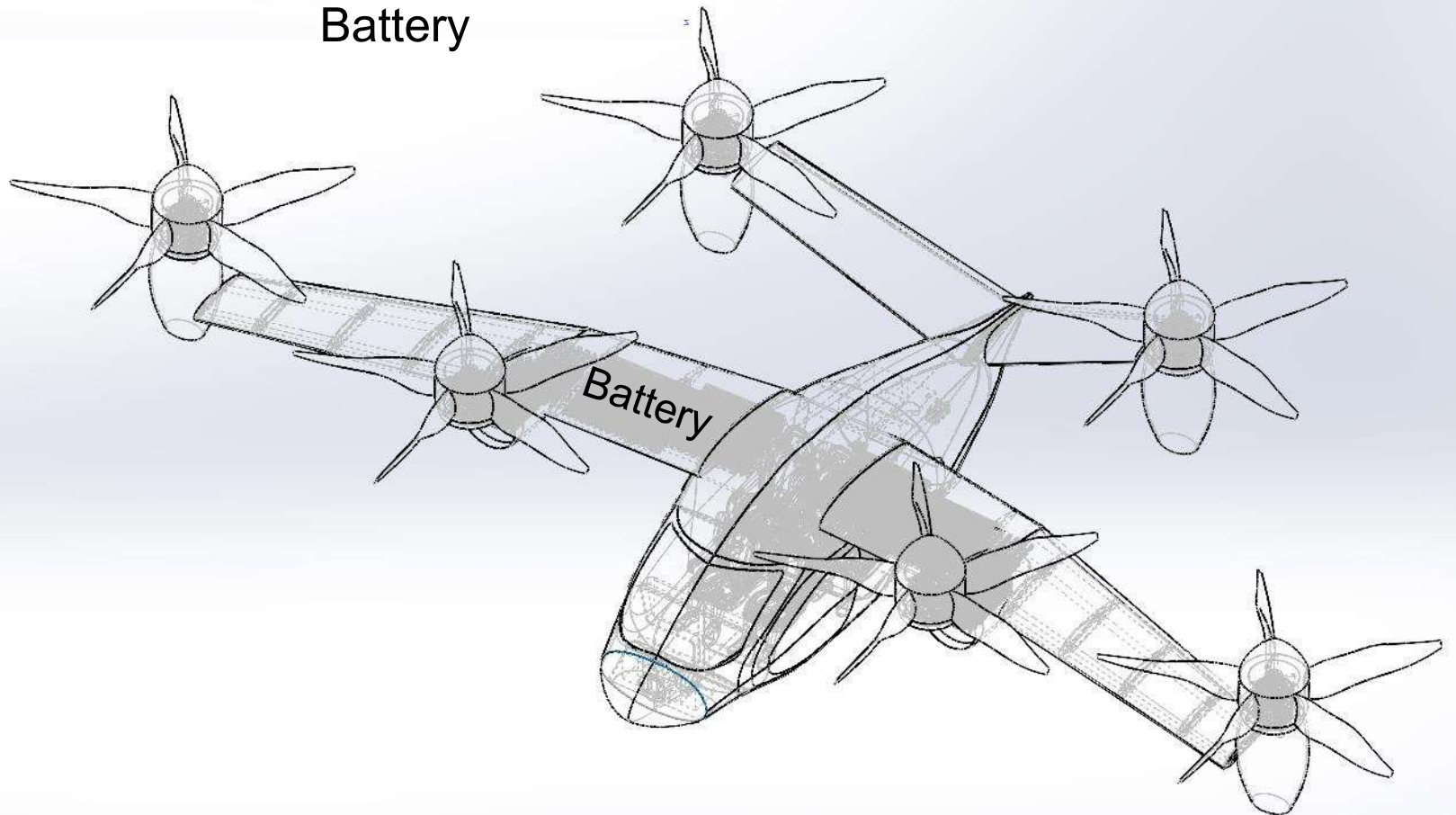
Think about Battery Placement



Put Battery in Fuselage or in Wing?



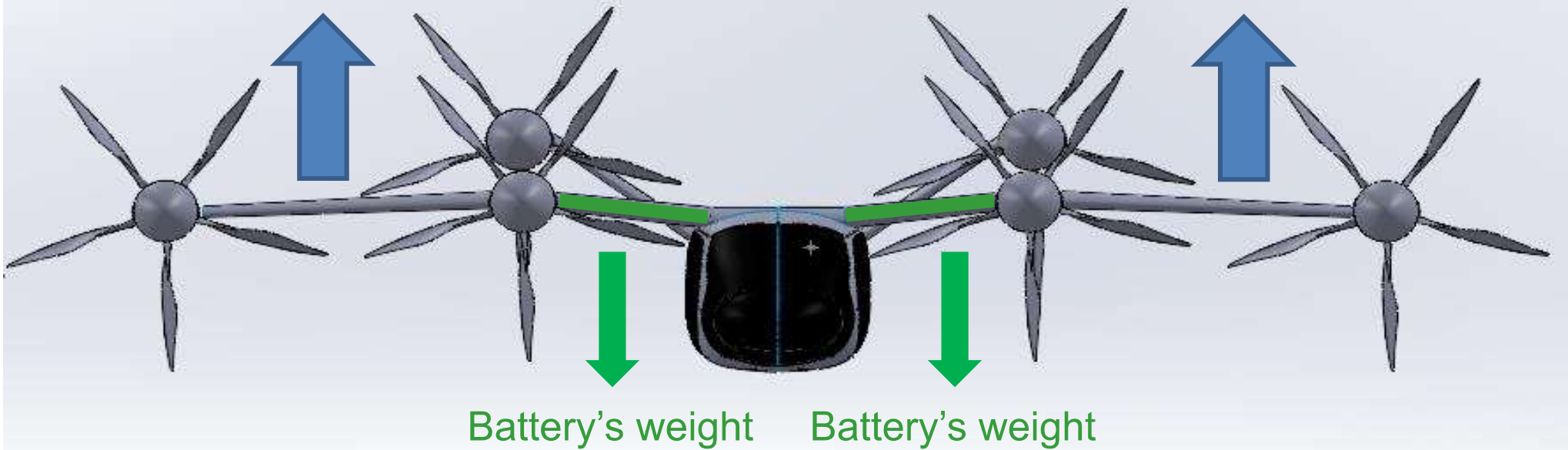
Battery



Consider Bending Moment in Wing

Wing's lift in forward flight
Rotors' lift in hover

Wing's lift in forward flight
Rotors' lift in hover



Joby S4 Uses 4 Battery Packs in Wing Only

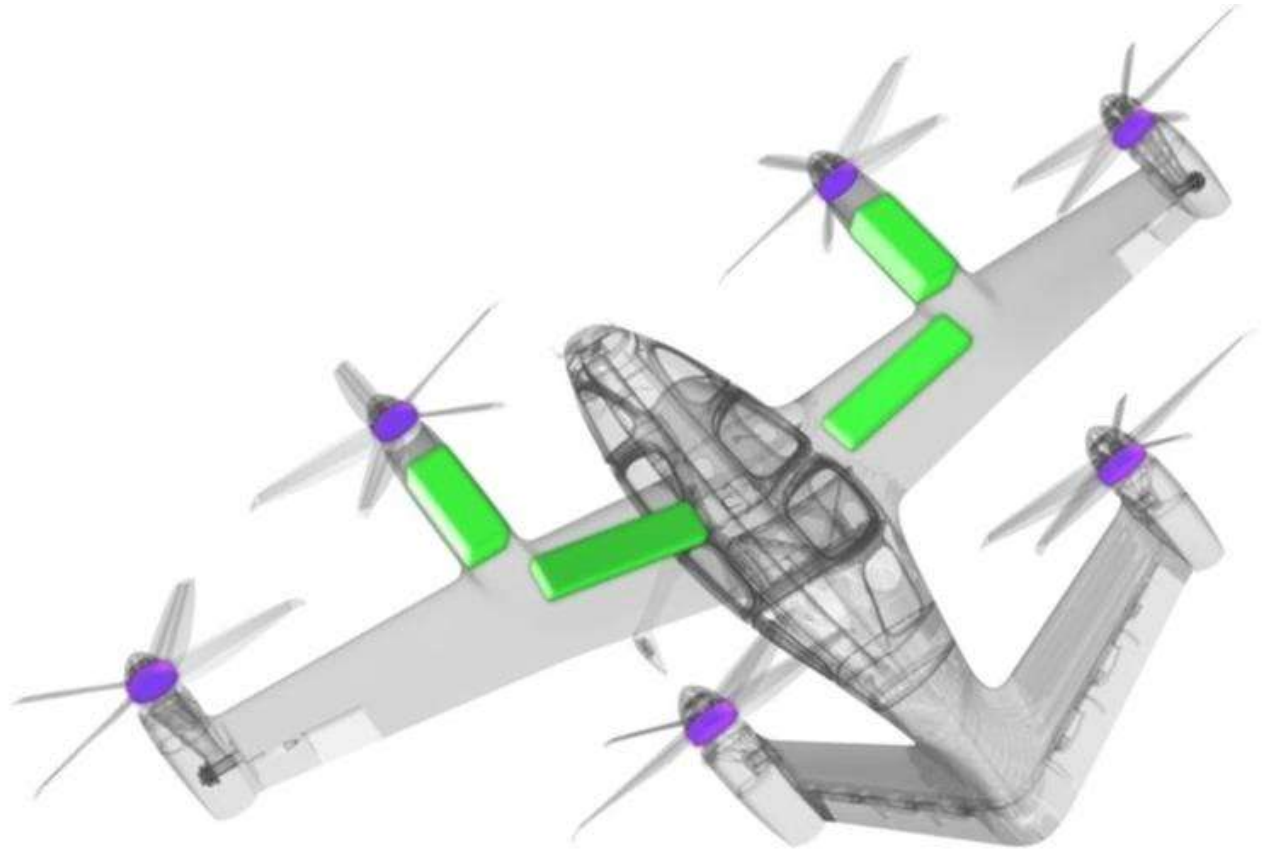
6 propellers – can fly safely with the loss of any one propeller

Each motor is redundant and powered by two separate inverters

Each inverter is wired to a separate battery pack

4 isolated and redundant battery packs on board

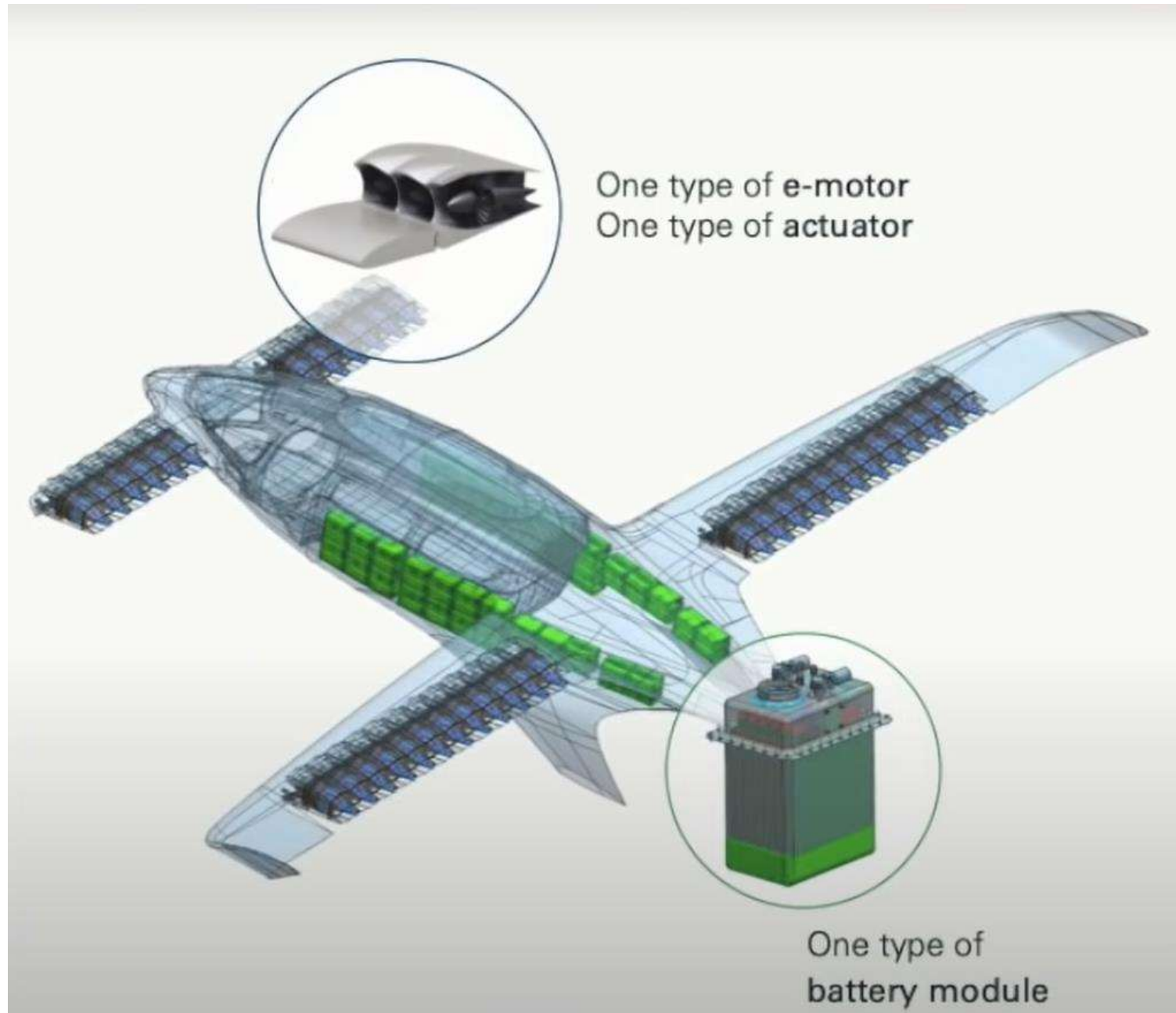
Motor continues to function if an inverter or pack fails



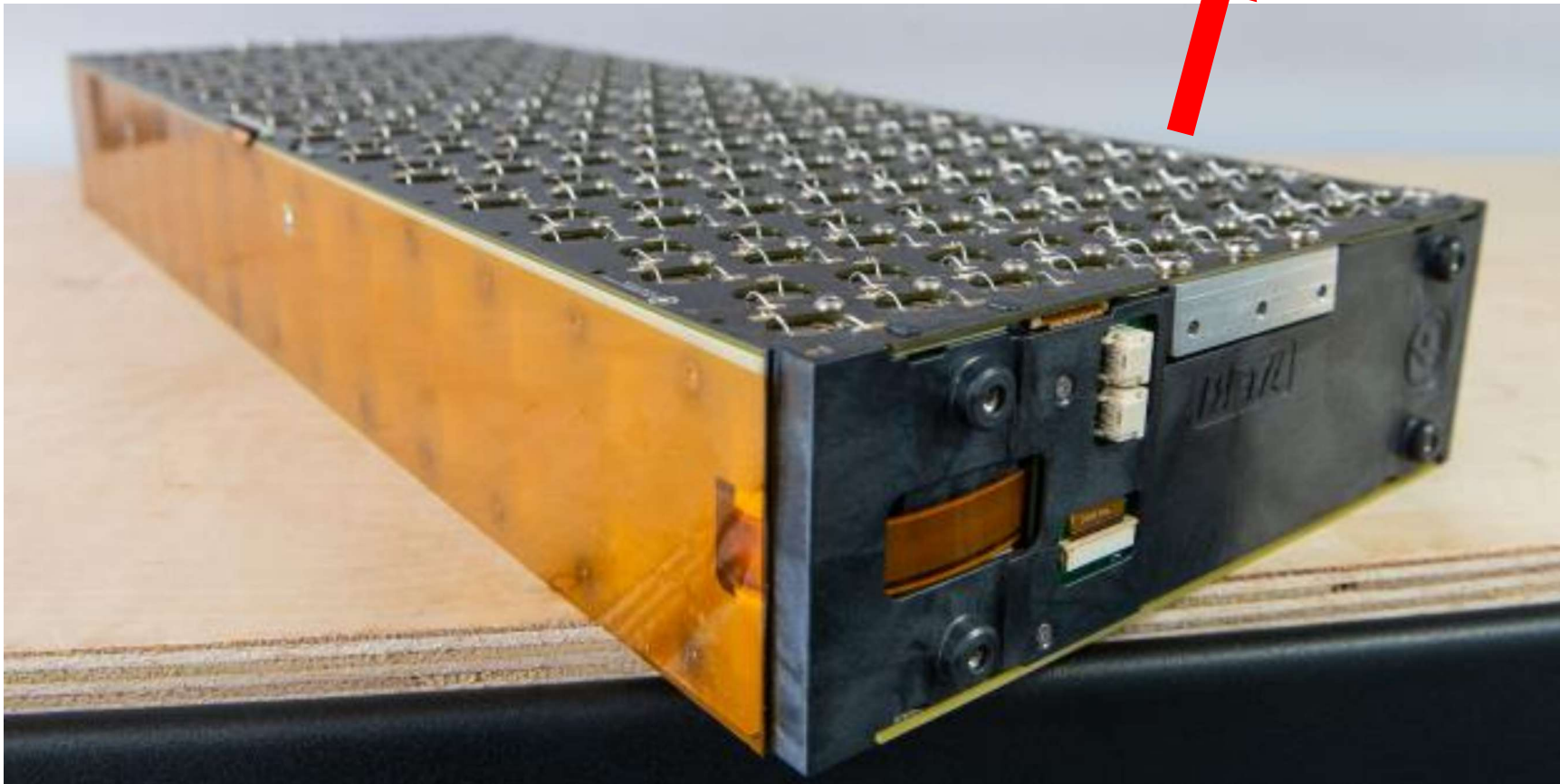
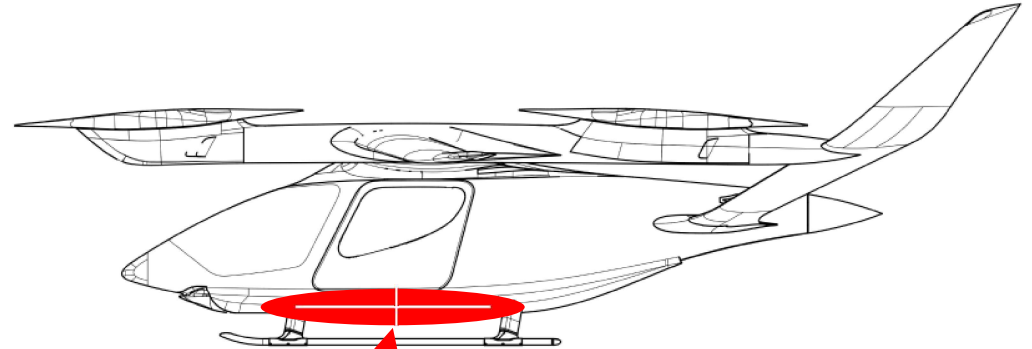
Joby S4 Uses 4 Battery Packs in Wing Only



Battery on Sides of Fuselage



Think about Battery Placement



Batteries Are Placed in the Belly for Eviation

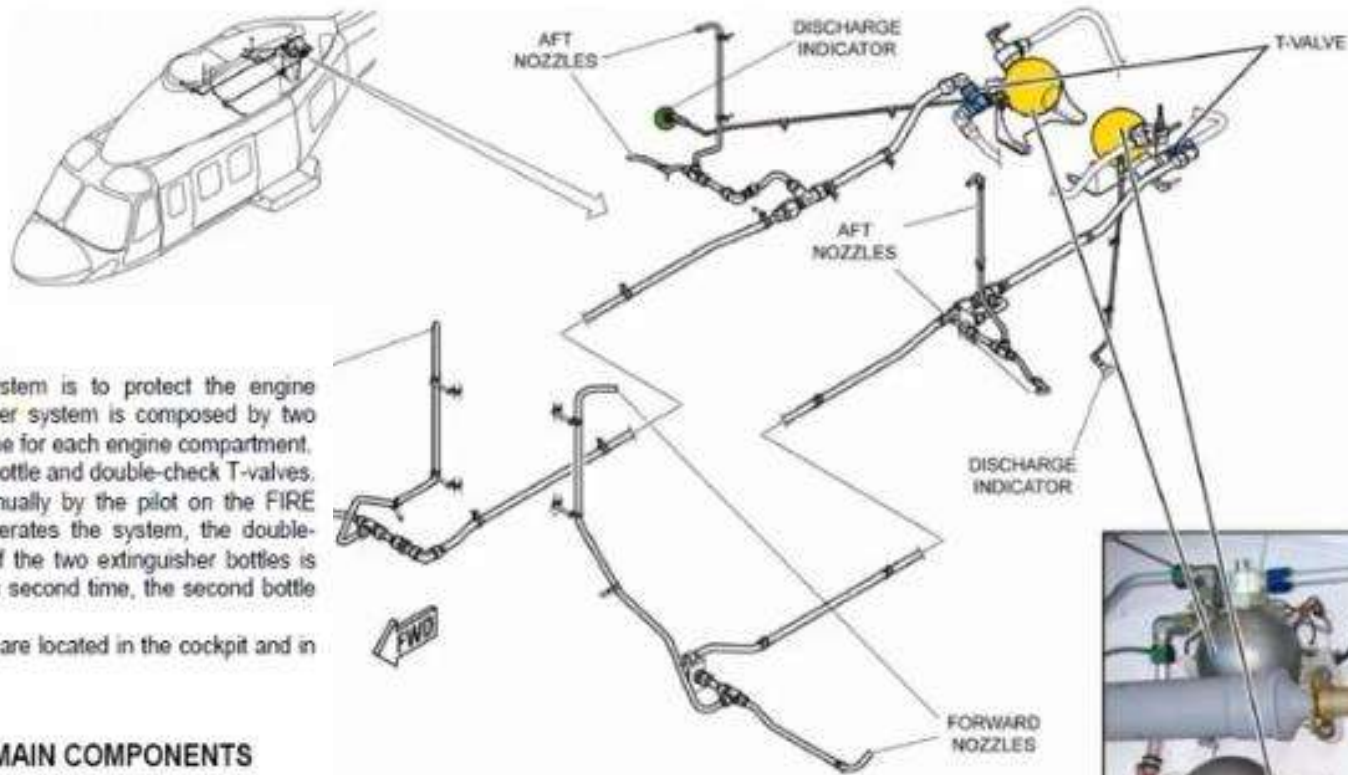


Volocopter's Automatic Battery Swapping



Detecting and Extinguishing Fire

Example: AW139 helicopter engine bay fire extinguishing system



FIRE EXTINGUISHING - GENERAL

The purpose of the fire extinguishing system is to protect the engine compartment from fire. The fire extinguisher system is composed by two identical and interconnected sub-systems one for each engine compartment. Each system comprises a fire extinguisher bottle and double-check T-valves. The extinguisher bottles are operated manually by the pilot on the FIRE EXTING control panel. When the pilot operates the system, the double-check T-valves make sure that only one of the two extinguisher bottles is operated. If the pilot operates the system a second time, the second bottle will be operated.

In addition two hand-held fire extinguishers are located in the cockpit and in the passenger cabin.

FIRE EXTINGUISHING SYSTEM - MAIN COMPONENTS

EXTINGUISHING BOTTLE

There are two 72 cubic inches extinguishing bottles filled with halon and pressurized with nitrogen gas. The bottles are installed on either side of the engine compartment and are cross-connected so that the content of any one of the two bottle can be discharged into any one engine bay and/or both bottles can be discharged into any one engine bay.

Each bottle is provided with a device which acts as a primary safety relief device. In case of overpressure, the halon agent is fully discharged outside the helicopter through the discharge indicator.

Upon discharge, the outer green disc is fired and a red circular band is displayed providing a visual indication during on ground inspection.

DOUBLE CHECK T-VALVE

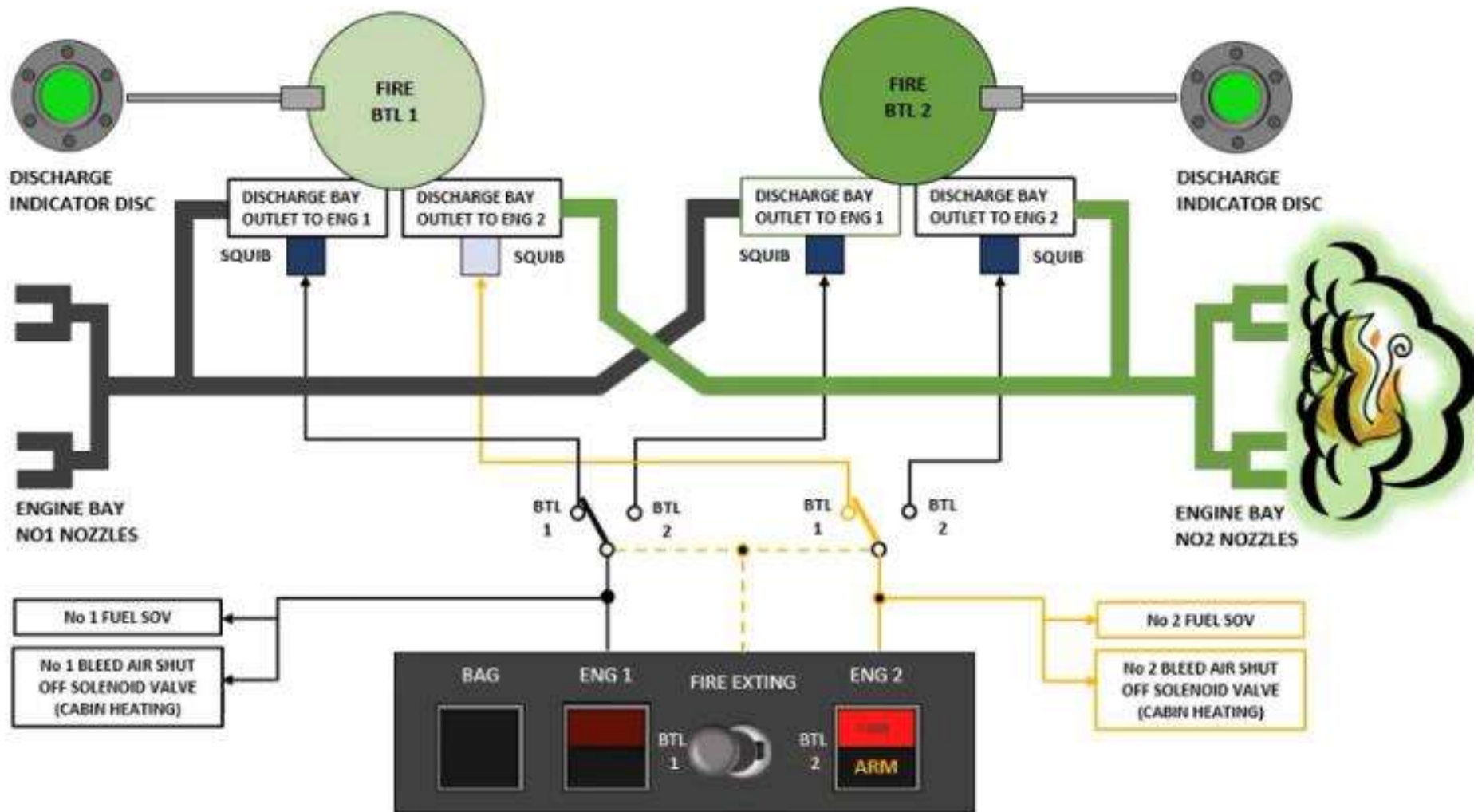
Double-check T-valves interconnect the two sub-systems allowing to discharge halon into any one of the two engine compartments.

Source: www.youtube.com/watch?v=02awRrNXqMc

Radial Solution Systems produces good training videos on AW139 helicopter

Detecting and Extinguishing Fire

Example: AW139 helicopter engine bay fire extinguishing system

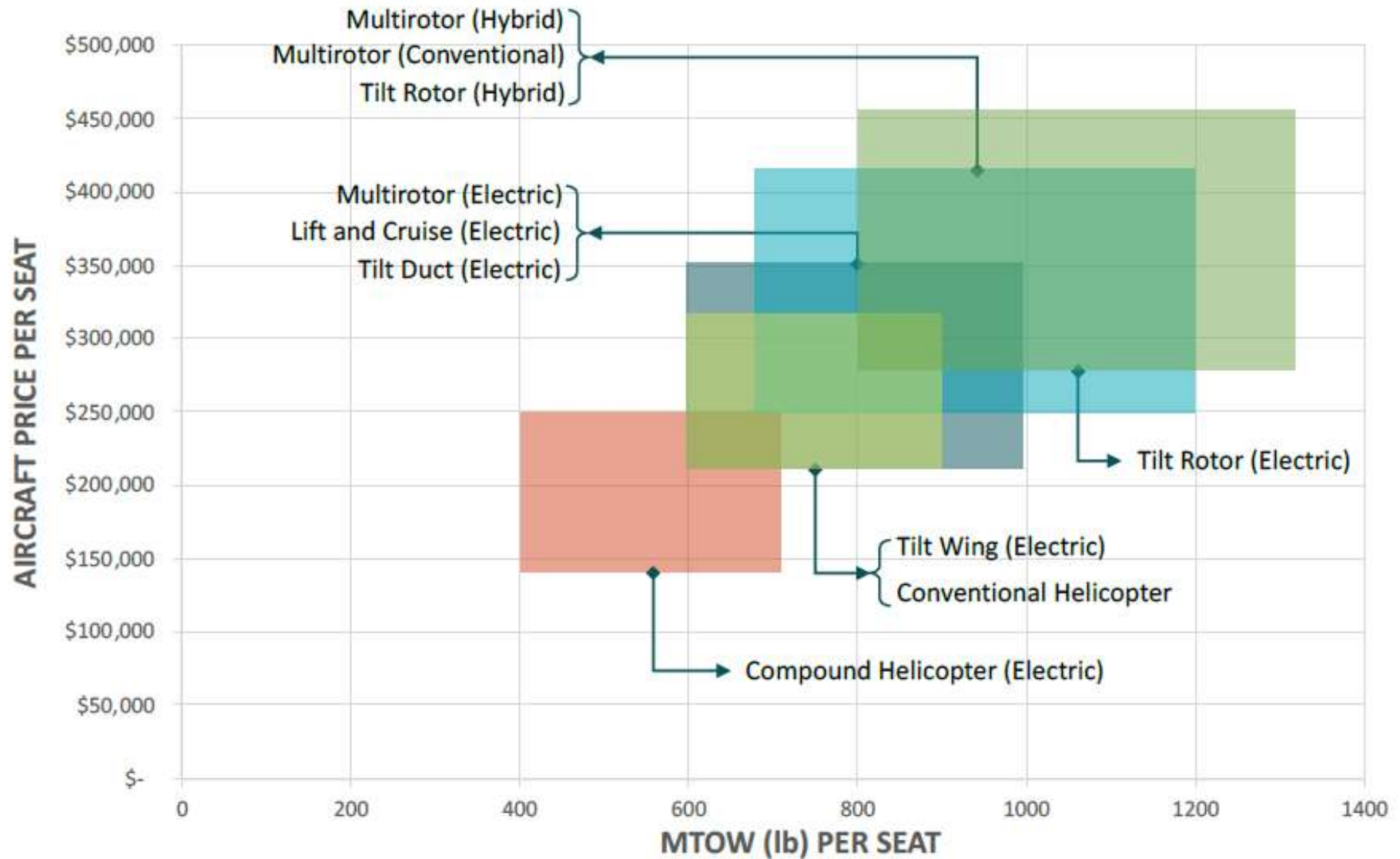


Source: www.youtube.com/watch?v=02awRrNXqMc

Radial Solution Systems produces good training videos on AW139 helicopter

Cost and Selling Price

Aircraft Price vs MTOW/Seat vs Configuration



Technical specifications of the vehicle types with uncertainty ranges; (top) Cruise Speed (mph) vs Range (miles), (bottom) Aircraft Price vs MTOW (lbs.)

One Way to Estimate Selling Price is by Using Price-per-Pound for Empty Weight

Vehicle	Vehicle type	Empty weight (lbf)	Price (\$US)	Price per unit empty weight
Cessna Citation Mustang	Very light jet	5,600	\$3,350,000	\$598.2
Robinson R44	Light helicopter	1,450	\$425,000	\$293.1
Cessna 172R	General-aviation aircraft	1,691	\$274,900	\$162.6
Ferrari 488	Sports car	3,362	\$272,700	\$81.1
Tesla Model S (75D)	Electric car	3,549	\$48,182	\$13.6
Honda Accord	Sedan	3,170	\$22,455	\$7.1

Source: https://convex.mit.edu/publications/arthur_ondemand.pdf

The **\$/lb** will for eVTOL aircraft will depend on the design's complexity, business model and volume. Example: for a MTGW=7000 lbs (empty weight = 5900 lbs) eVTOL aircraft, the selling price could be

250 \$/lb x 5900 lbs = US\$ 1.48 million

for wingless, multicopter type

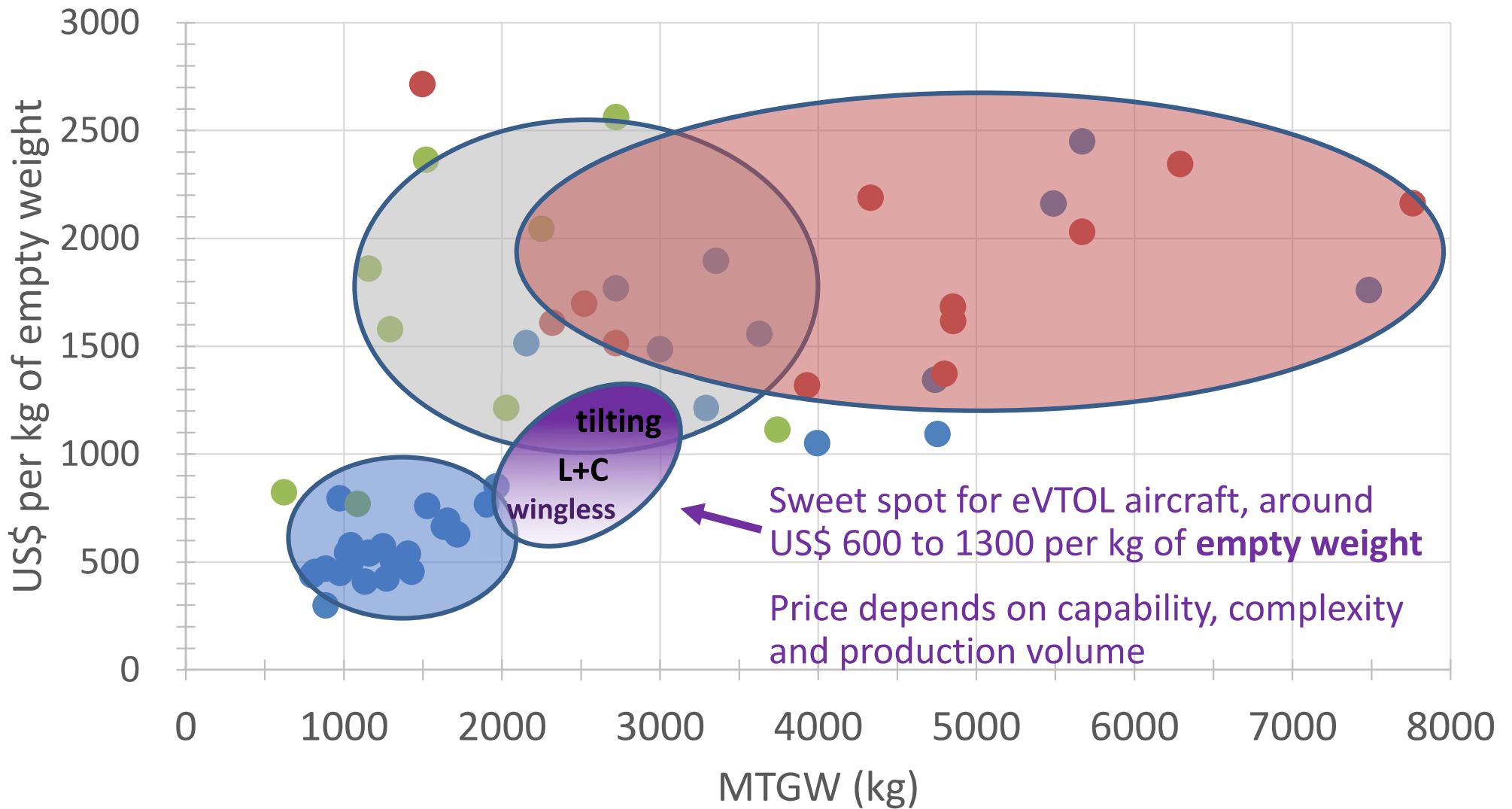
350 \$/lb x 5900 lbs = US\$ 2.07 million

for lift + cruise type

500 \$/lb x 5900 lbs = US\$ 2.95 million

for tiltrotor and tiltwing type

Price-per-kilo Selling Price **Data** for Many Aircraft



● Light Aircraft ● Very Light Jets ● Rotorcraft

The eVTOL \$/kg are author's estimate based on bottom-up calculations

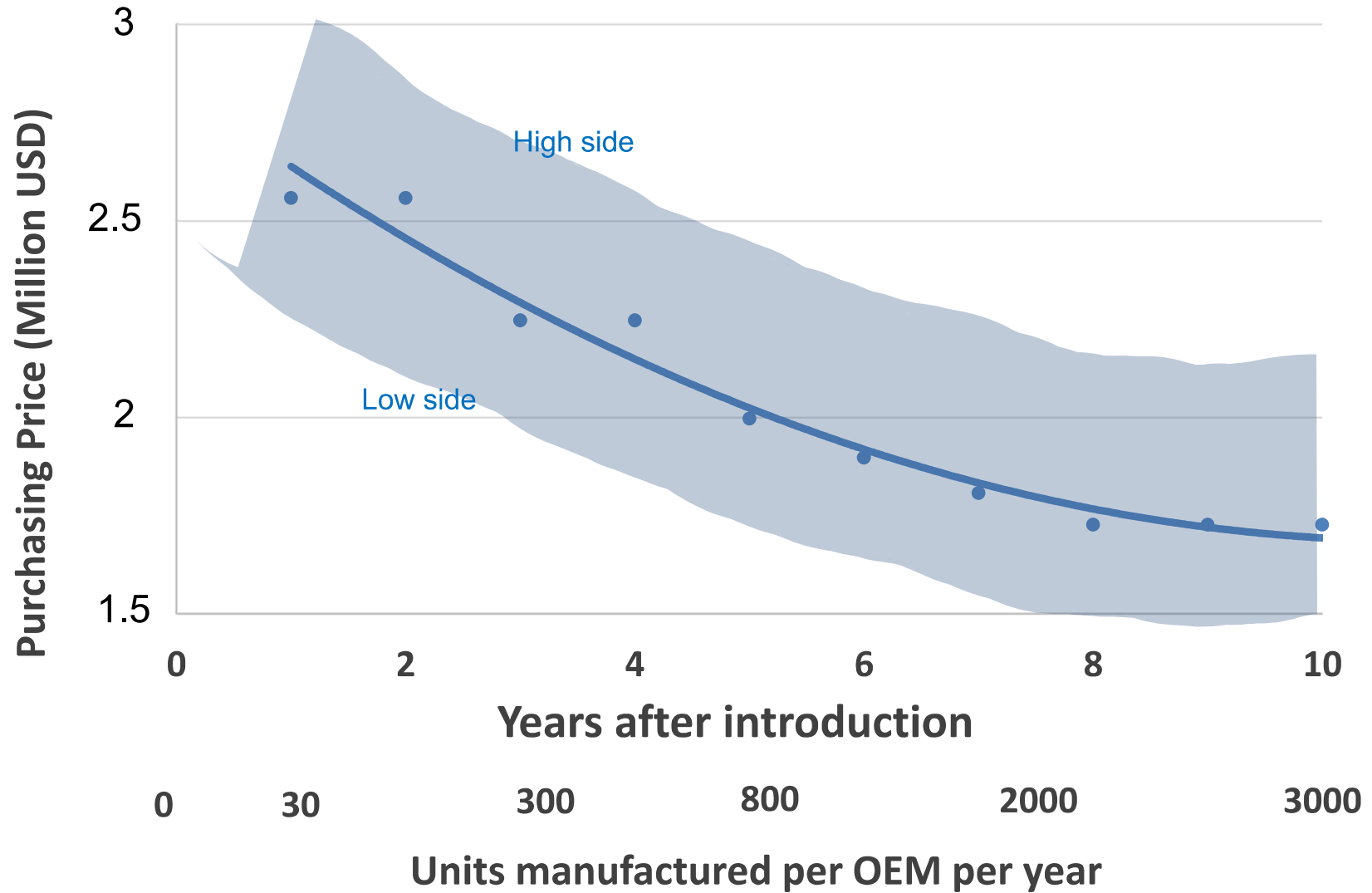
Should Also Conduct a Bottoms Up Estimate

- **Avionics and flight control cost**
 - Flight computers, sensors, navigation instruments, communication equipment,.....
 - Control actuators
- **Battery cost**
 - Cells
 - Management system and cooling
 - Packaging
- **Structure cost**
 - Fuselage, wing, tail, windows, landing gear, motor pylon, tilting mechanism,
- **Propulsion cost**
 - Electric motor, inverter, electrical wiring, connectors, rotors, engine, generator,
- **Miscellaneous**
 - Furnishing: seats, cabin interior
 - Parachute?
 - Environmental control system?
 - Painting and final assembly
 - Contingency
- **Overhead, G&A, Marketing, Profit**

Optimistic Global eVTOL Market Forecast

2025	0 eVTOL	0 trip/year
2030	10,000 eVTOL	60 million trips/year
2040	200,000 eVTOL	1 billion trips/year
	8,000,000 eVTOL	45 billion trips/year

Aircraft Unit Price vs. Production Volume



Archer 2-Pax Maker



MANUFACTURING COST

\$1 200 000

Vertical VX-4A



MANUFACTURING COST

\$1 700 000

Joby S4

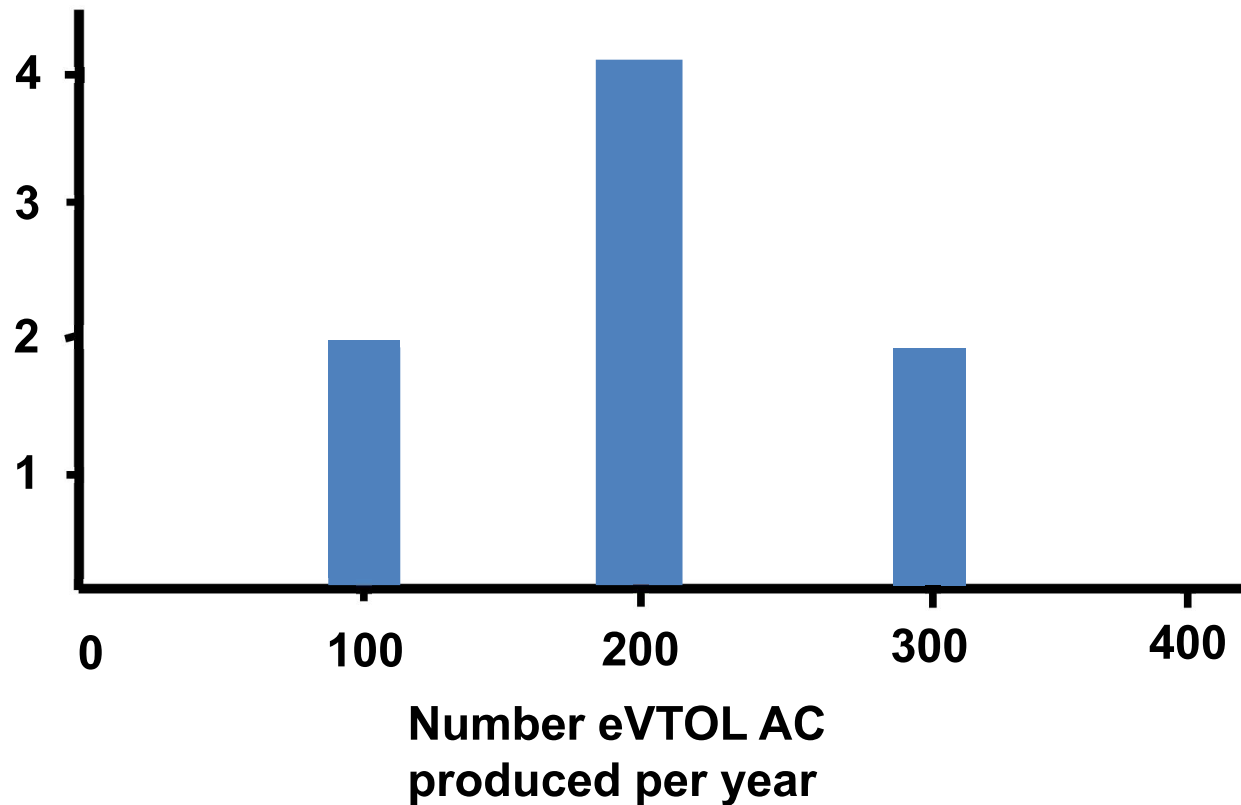


MANUFACTURING COST

\$1 300 000

Estimate eVTOL Aircraft Produced in 2030

Number of OEMs



Assume 8 OEMs received type certificates. 2 OEMs produce 100 eVTOLs / year, 4 OEMs produce 200 eVTOLs / year, and 2 OEMs produce 300 eVTOLs per year. Total = 1,600 eVTOL aircraft produced per year

Annual eVTOL Sales in 2030

Assumptions:

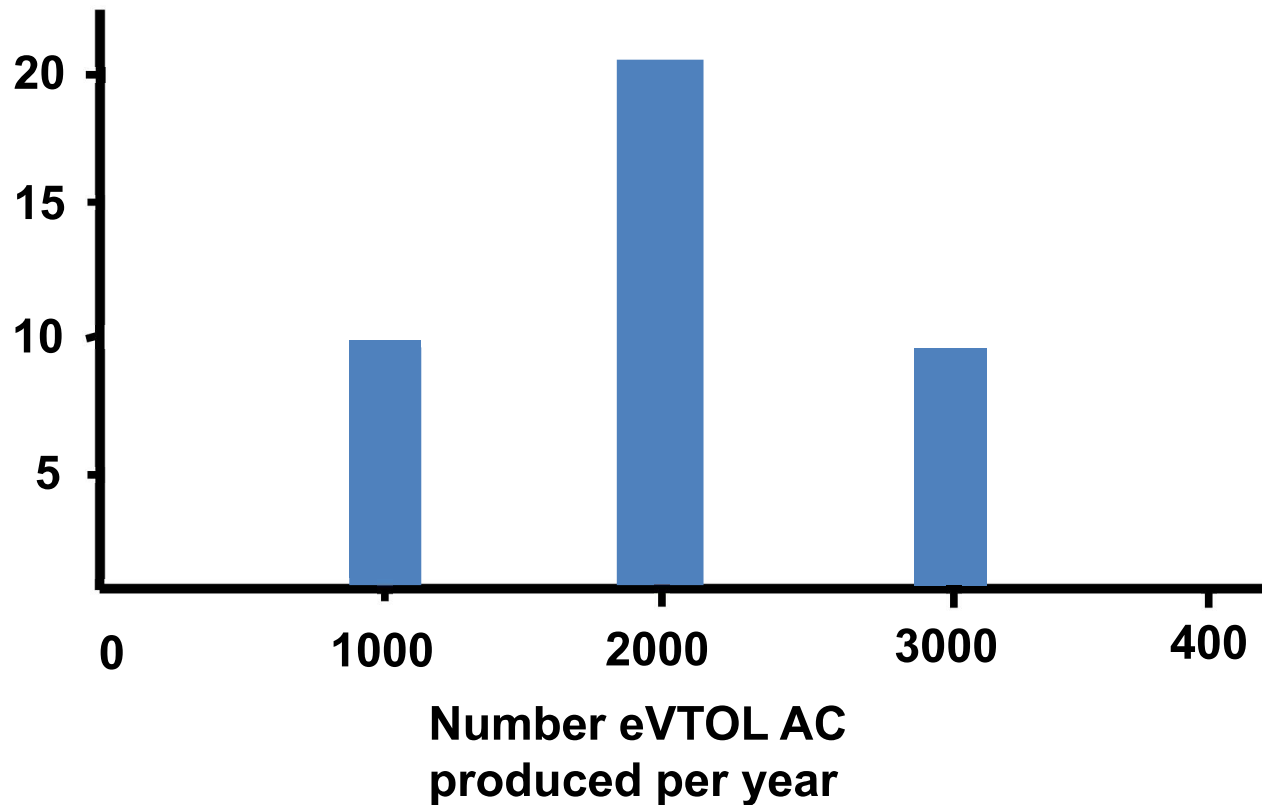
- 1600 eVTOL Aircraft produced per year
- US \$2.2 million per aircraft (today's dollar)

Annual aircraft sales = $1600 \times \$2.2\text{M} = \3.52 billion

Compare this to the forecasted global new civil helicopter sale for 2030 which could be around US\$6-\$8 billions annually (not including spares, support and training).

Estimate eVTOL Aircraft Produced in 2040

Number of OEMs



Assume 40 OEMs received type certificates. 10 OEMs produce 1000 eVTOLs / year, 20 OEMs produce 2000 eVTOLs / year, and 10 OEMs produce 3000 eVTOLs per year. Total = 80,000 eVTOL aircraft produced per year

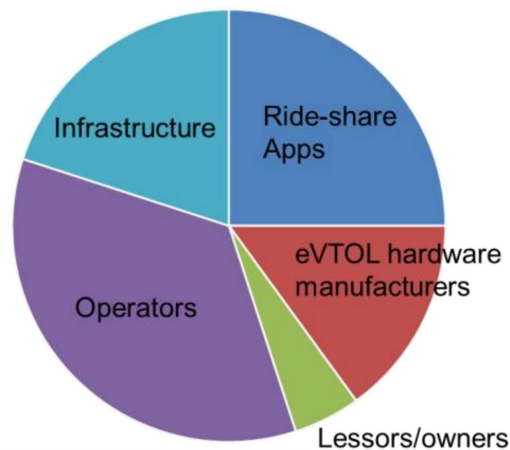
Annual Market Size in 2040

Assumptions:

- 80,000 eVTOL Aircraft produced per year
- US \$1.6 million per aircraft (today's dollar)

Annual aircraft sales = $80,000 \times \$1.6M = \128 billions
Adding spares and support could total \$200 billions

If eVTOL hardware = 15% of total manned air mobility ecosystem



Steady state revenue
2035 and beyond

Then the total annual market value is $\$200b / .15 =$ **US \$1.3 trillion**

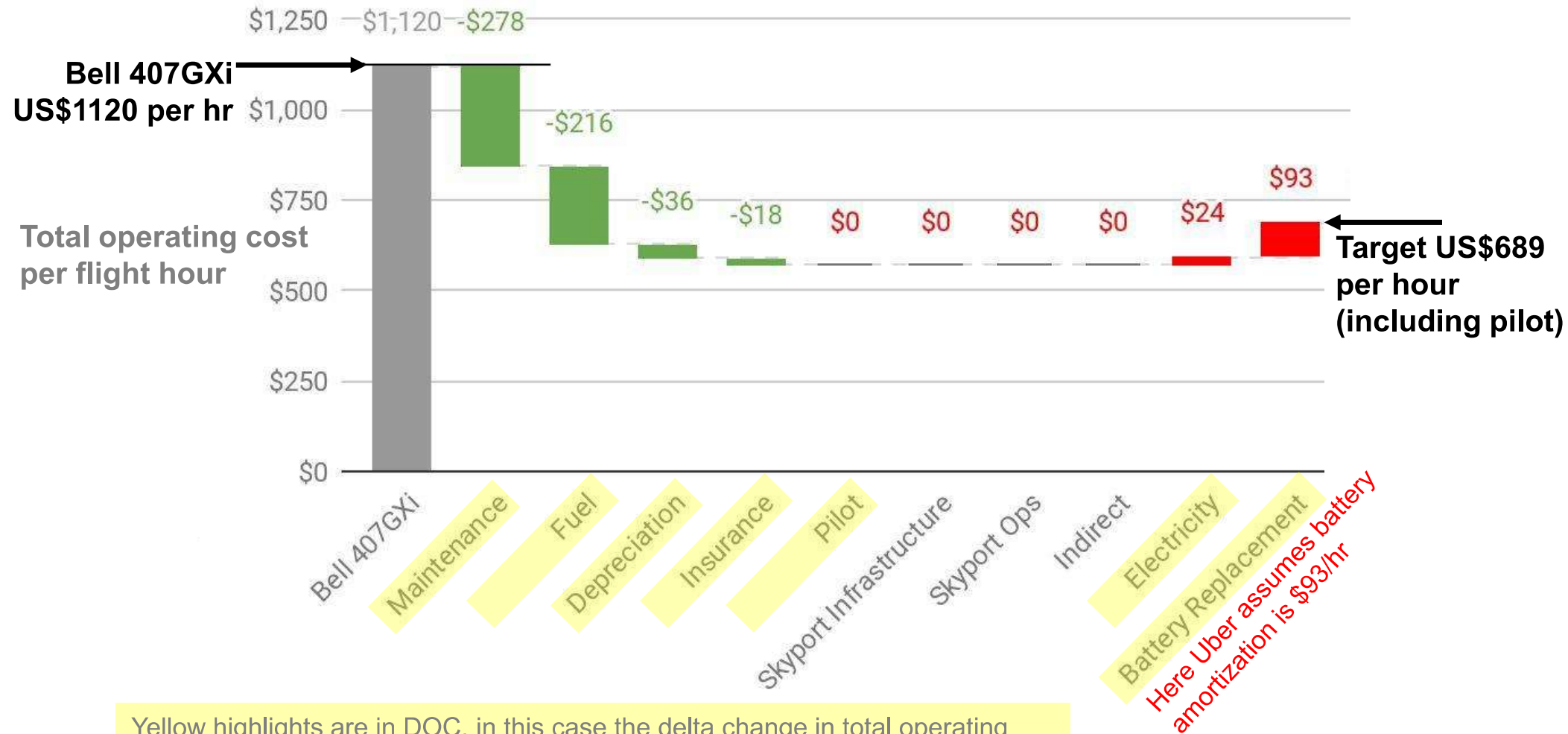
Battery Amortization is the Key Component in Direct Operating Cost (DOC) for eVTOL

- Assume the battery can last 400 charge cycles. Assume each cycle delivers half hour flight time or 100 km range with reserve. That means a total of 200 hours of usage. Then, the total kilometers travelled = 40,000 km
- Assume for a 3175 kg eVTOL aircraft, the battery we use is 1,000 kg and 250 wh/kg at pack level, then that gives 250 kwh capacity.
- If the battery *pack* cost is US \$100 per kwh, then $\$100/\text{kwh} \times 250 \text{ kwh} = \$25,000$ ← *Note, aviation may pay 2x or 3x more than auto battery !*
- $\$25,000 / 40,000 \text{ km} = \$0.625 \text{ per flight kilometre} = \text{US\$1 per mile}$
- $\$25,000 / 200 \text{ h} = \125 per hour is battery amortization cost, also need to add electricity charging cost ($\$0.12/\text{kwh}$ in US, $\$0.21 \text{ per kwh}$ in Europe)

The operating cost of eVTOL aircraft is higher than electric cars because aircraft consumes more kWh of energy per hour of operation.

UberAir Targets a Total Operating Cost for eVTOL to be 35% lower than operating helicopters

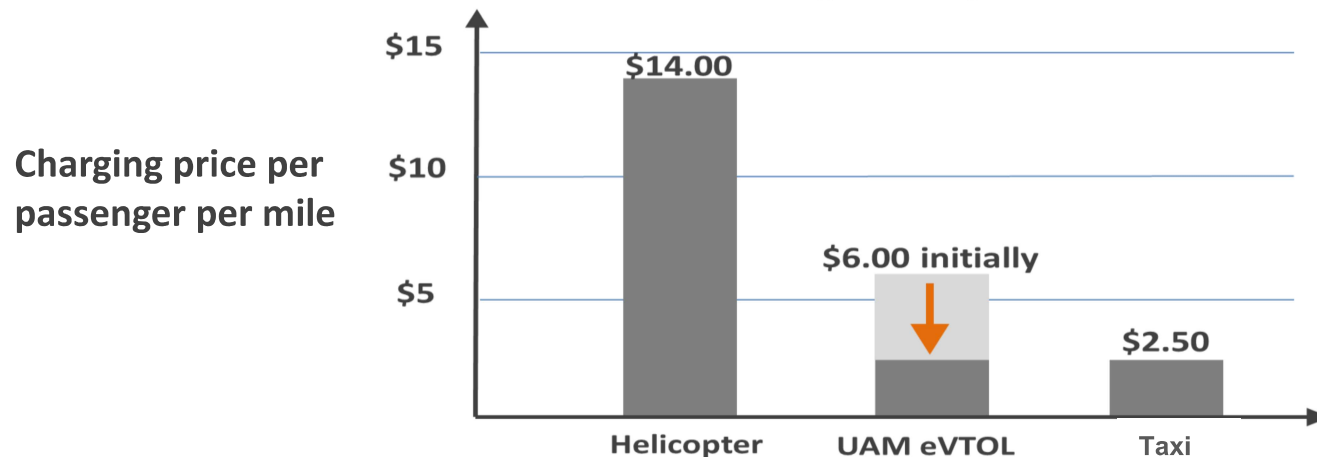
407GXi to Uber Air Ideal Comparison



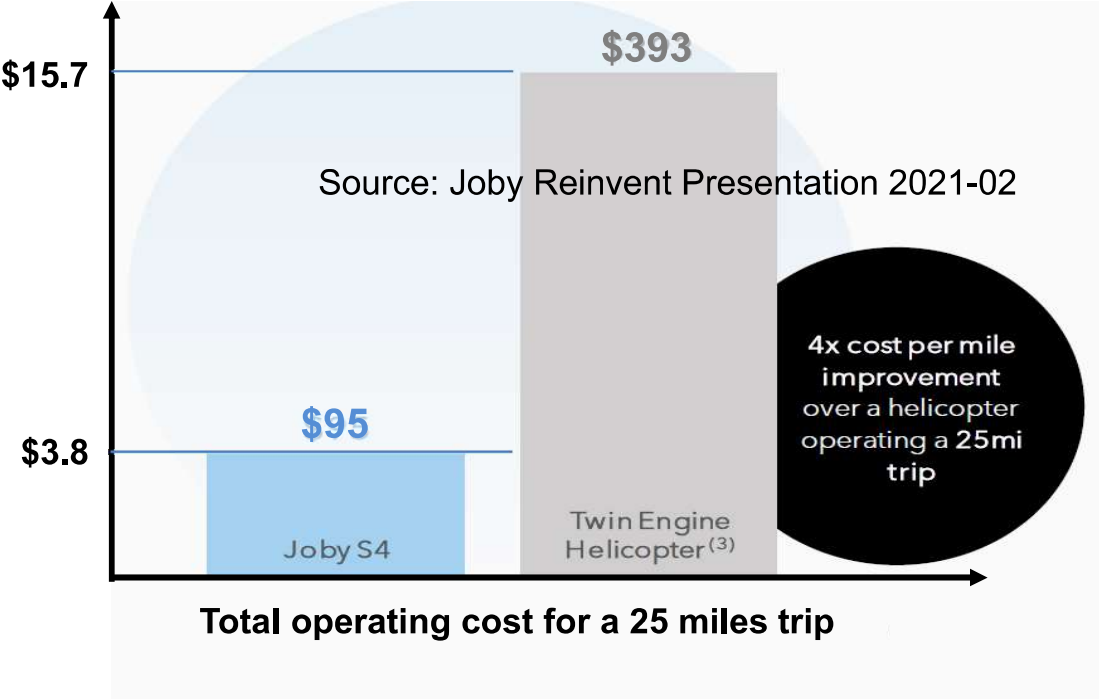
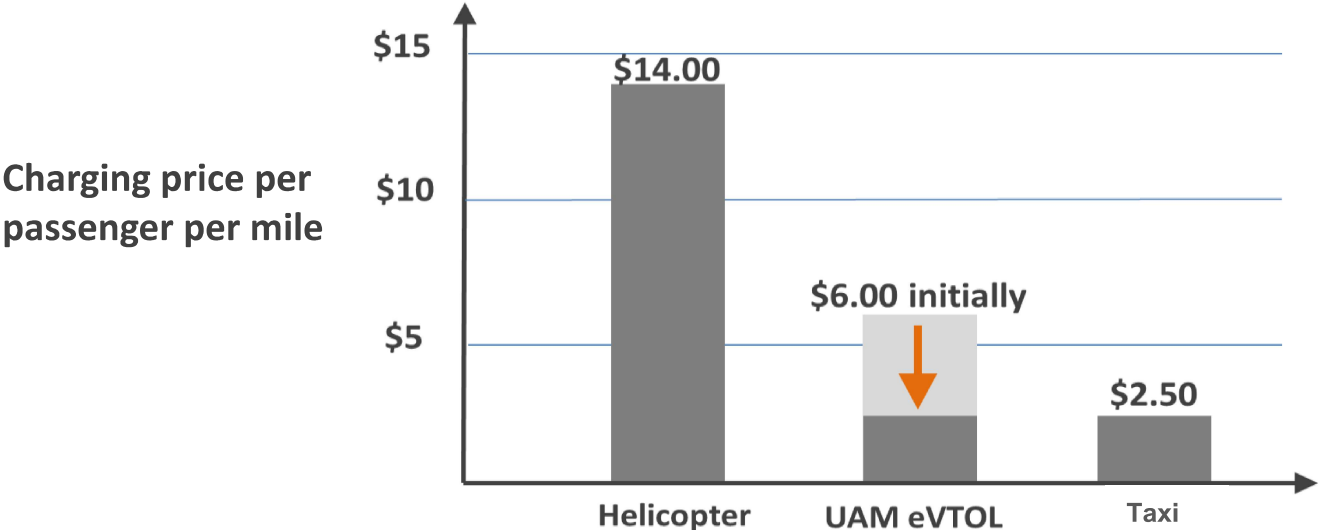
Yellow highlights are in DOC, in this case the delta change in total operating cost or DOC = $-\$278 - \$216 - \$36 - \$18 + \$24 + 93 = -\431

The “Cost” to the Operator per Pax per Mile

- Let’s say the eVTOL total operating cost = US\$ 700 /hr includes pilot, depreciation, insurance, vertiport charge...
- Average passenger load factor = 67%, then $0.67 \times 4 \text{ pax} = 2.68 \text{ pax per flight}$
- Average mission = roughly 20 minutes (include ground run up)
- Average mission distance = 25 mile
- The “Cost” to the operator per pax per mile = $\$700 / 2.68 / 3 / 25 \text{ mile} = \3.48
- The operator can initially charge US\$5 to \$6 per pax per mile for UAM. This sums up to what was presented at the beginning of the Short Course.



Compare Our Calculation to What Joby Has Presented



7. Benchmarking and Cost Estimation

by Dr. James Wang

SNUevtolclass@gmail.com

For students to use in the 2022 eVTOL Design Short Course at SNU,
please do not reproduce or distribute