Updates to NASA Urban Air Mobility Reference Vehicles
Incorporating Recent Technology, Policy, and Economic Developments

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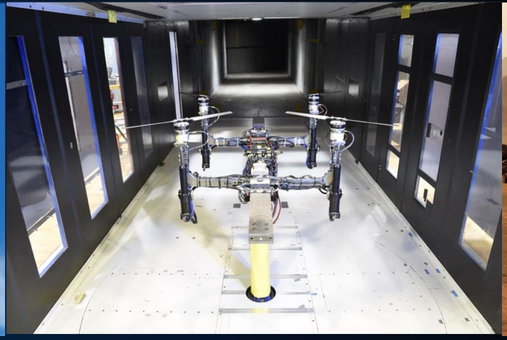
NASA Revolutionary Vertical Lift Technology Project

VFS Electric VTOL Symposium

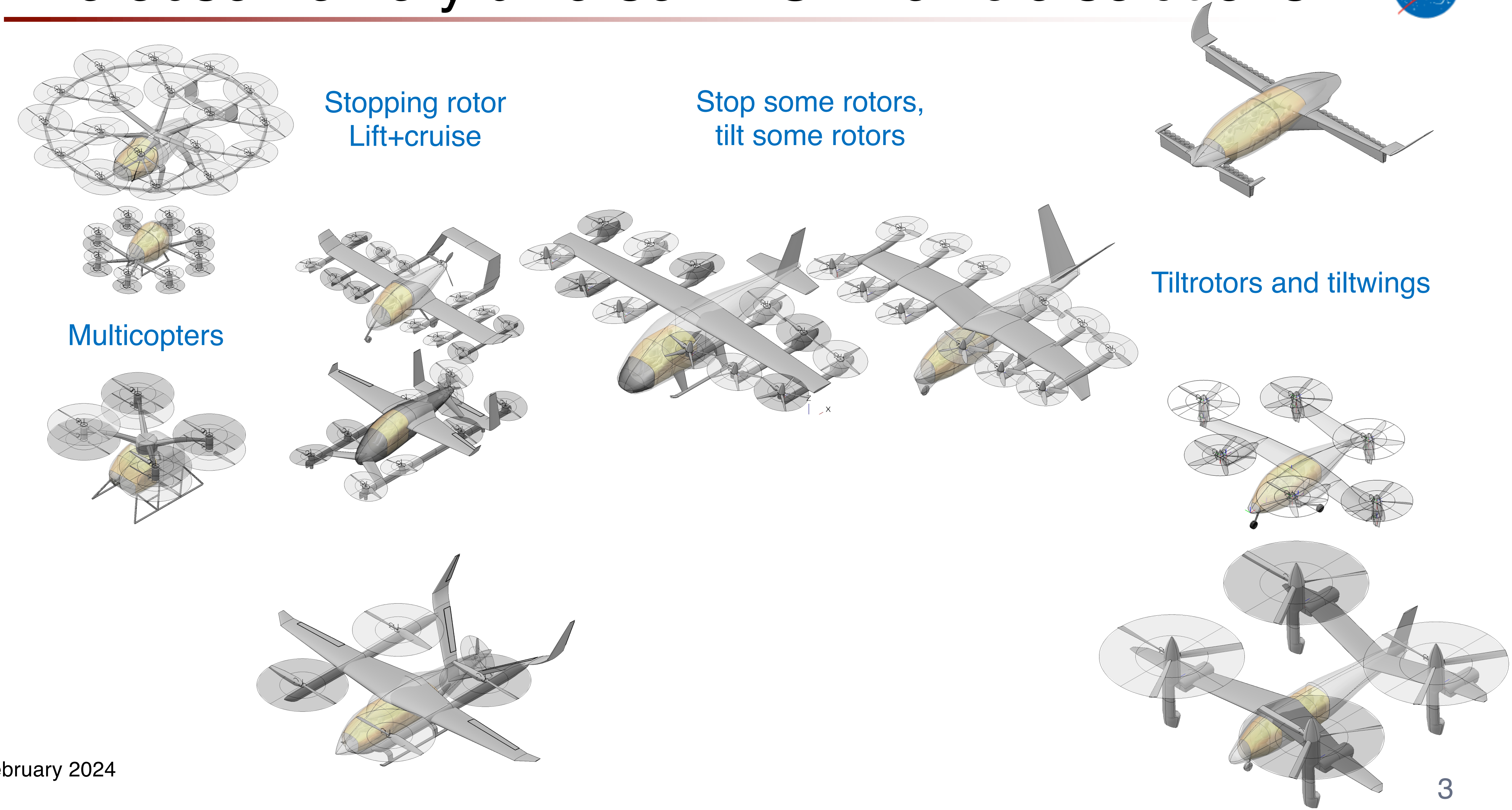
Santa Clara, California

6-8 February 2024



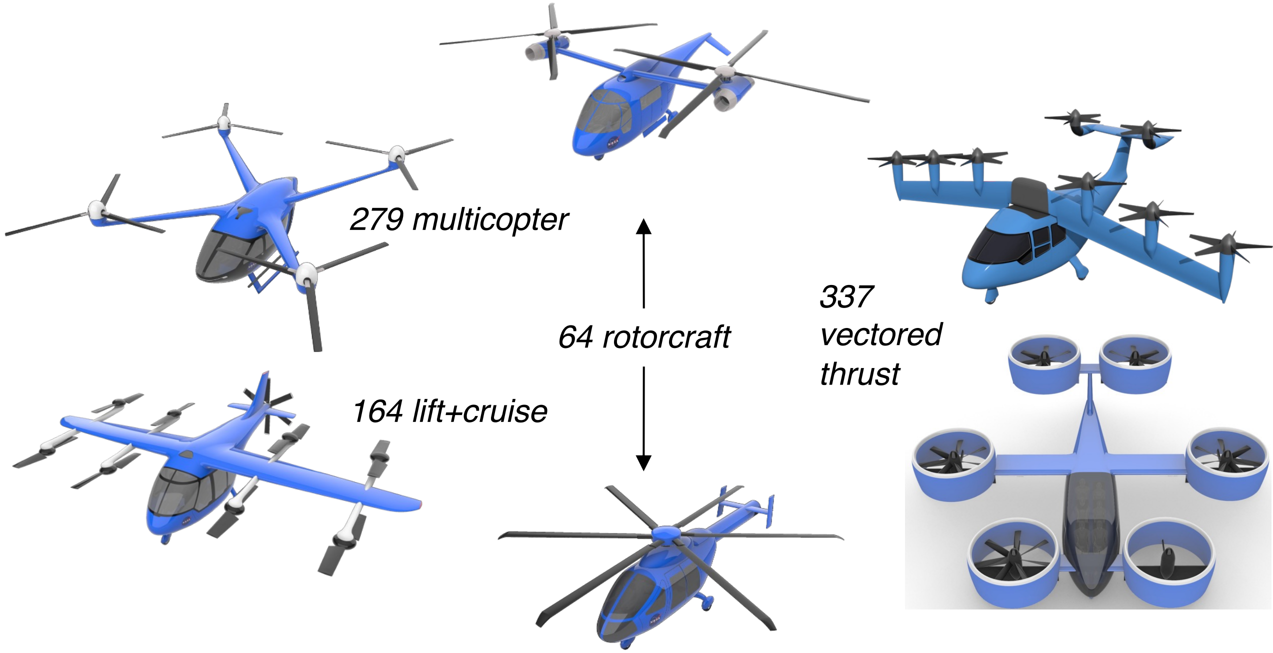

We observe very diverse VTOL vehicle solutions



February 2024

Why we designed the NASA reference vehicles

- **Vehicle model inputs and outputs publicly available**
  - Discussions can be quantitative
  - Demonstration cases for training
  - Features representative of vehicles
  - Missions and design conditions
  - Margins and reliability requirements
- **Focus and guide government research**
  - Enable contracted work to be published
  - Assess technology payoff
  - Guide tool development
  - Scope validation tests
- **No plan or desire to build the vehicles**
  - But these are not cartoons

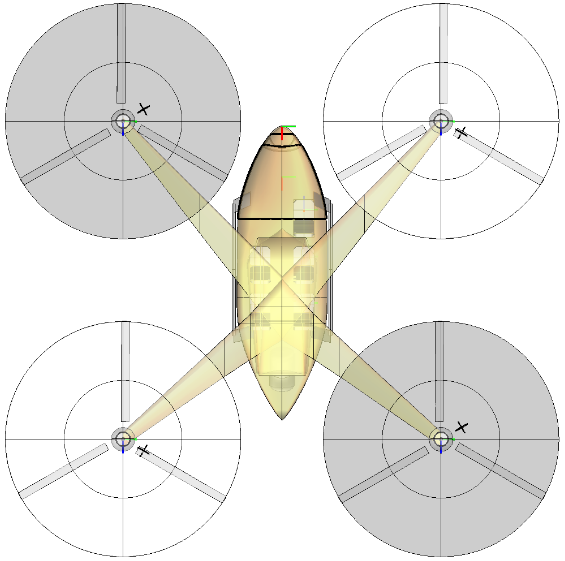


Count of vehicles in evtol.news listing as of 31 January 2024

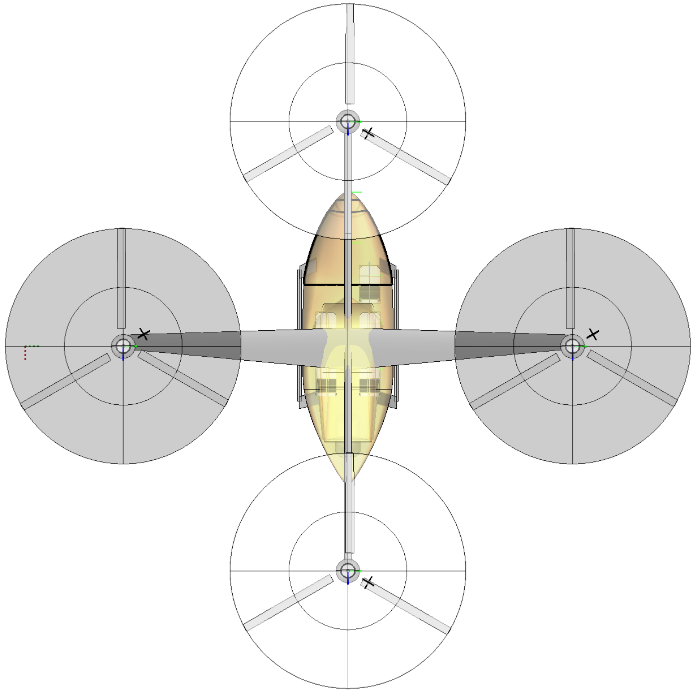
What is the composition of a reference vehicle model?

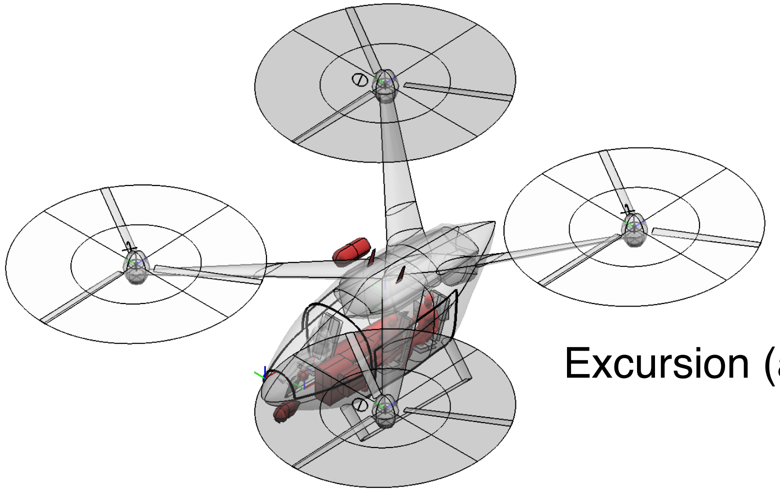
- **Baseline, excursions, and variants**
- **Reports**
- **NDARC design and off-design**
- **Geometry**
- **Comprehensive Analysis**
- **Structures**
- **Flight Dynamics**

Baseline aircraft



Variant (sub-type)





Excursion (alternate mission)

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Papers and journal articles

Concept Vehicles for VTOL Air Taxi Operations

Wayne Johnson — NASA Ames Research Center, Moffett Field, California, wayne.johnson@nasa.gov
Christopher Silva — christopher.silva@nasa.gov
Eduardo Solis — Science & Technology Corp., Moffett Field, California, eduardo.solis@nasa.gov

ABSTRACT

Concept vehicles are presented for air taxi operations, also known as urban air mobility or on-demand mobility applications. Considering the design-space dimensions of payload (passengers and pilot), range, aircraft type, and propulsion system, three aircraft are designed: a single-passenger (250-lb payload), 50-nm range quadrotor with electric propulsion; a six-passenger (1200-lb payload), 4x50 = 200-nm range side-by-side helicopter with hybrid propulsion; and a fifteen-passenger (3000-lb payload), 8x50 = 400-nm range tiltwing with turbo-electric propulsion. These concept vehicles are intended to focus and guide NASA research activities in support of aircraft development for emerging aviation markets, in particular VTOL air taxi operations. Research areas are discussed, illustrated by results from the design of the concept vehicles.

INTRODUCTION

Urban air taxi operations, also known as urban air mobility or on-demand mobility applications, are enabled by vertical take-off and landing (VTOL) capability, power and energy requirements are minimized by using low disk-loading rotors, and short range requirements permit consideration of non-traditional propulsion concepts. The community of innovation has recognized that technology advances in structures, automation and control, energy generation-storage-utilization, and tools for design and analysis, coupled with pressures of resource availability and population density, make this the right time to explore new ways to move people and goods (ref. 1). The objective of the present work is to identify concept vehicles that can be used to focus and guide NASA research activities in support of aircraft development for emerging aviation markets, in particular VTOL air taxi operations.

To meet this objective, the designs are carried far enough to identify crucial technologies and research requirements, to explore a range of aircraft types, propulsion system types, and size, and to examine sensitivities to trades of requirements. While identifying relevant issues and major technical deficiencies is important, resolving all questions is not necessary, and component weight estimates and performance models can be the subject of future work. With this approach, the specific design choices made are not important, as long as primary and relevant research requirements are covered. Indeed, to these ends it is best that NASA concept vehicles be different in appearance and design detail from prominent industry arrangements.

The air taxi design community is considering a wide range of aircraft attributes:

a) number of passengers (including pilot): 1, 2, 4, 6, 15, 30;
b) un-refueled range: 50, 100, 200, 400, 800 nm (here as multiples of 50 nm segments);
c) market: air taxis, commuter scheduled, mass transit, airline;
d) aircraft type: multicopter, side-by-side, tiltwing, tiltrotor, lift+cruise, vectored thrust, compound, helicopter;
e) propulsion system: turboshaft, turboelectric, electric, parallel hybrid, fuel cell, diesel.

Three concept vehicles are developed that span many elements of this design space:

Presented at the AHS Technical Conference on Aeromechanics Design for Transformative Vertical Flight, San Francisco, CA, January 16-19, 2018. This is a work of the U.S. Government and is not subject to copyright protection.

1

NASA publications

NASA/TM–20210017971

Design of a Tiltwing Concept Vehicle for Urban Air Mobility

Siena K. S. Whiteside, Beau P. Pollard, Kevin R. Antcliff, Nikolas S. Zawodny, and Xiaofan Fei
Langley Research Center, Hampton, Virginia

Christopher Silva
Ames Research Center, Moffett Field, California

Glenn L. Medina
Universities Space Research Association, Hampton, Virginia

June 2021

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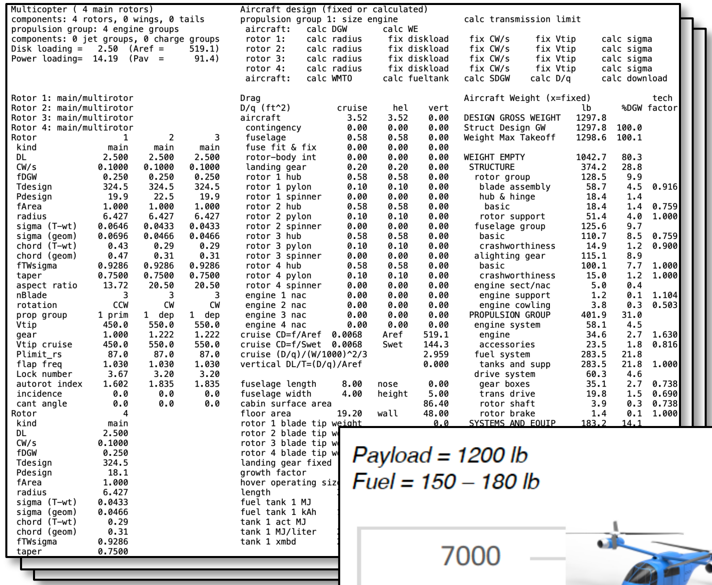
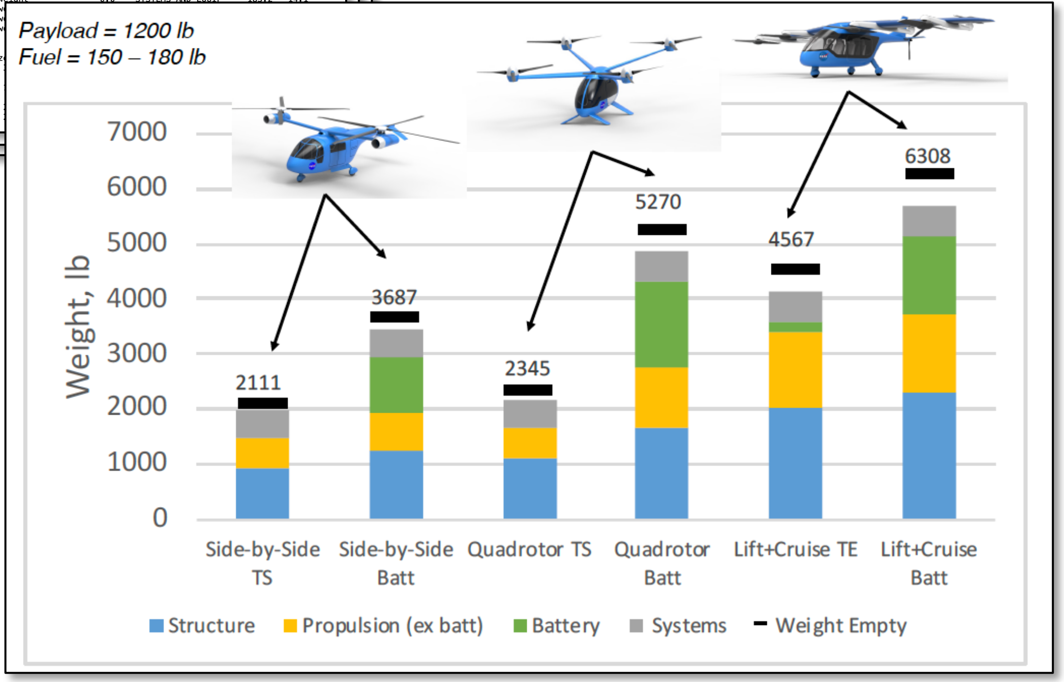
NDARC job outputs (text)



Charts of results



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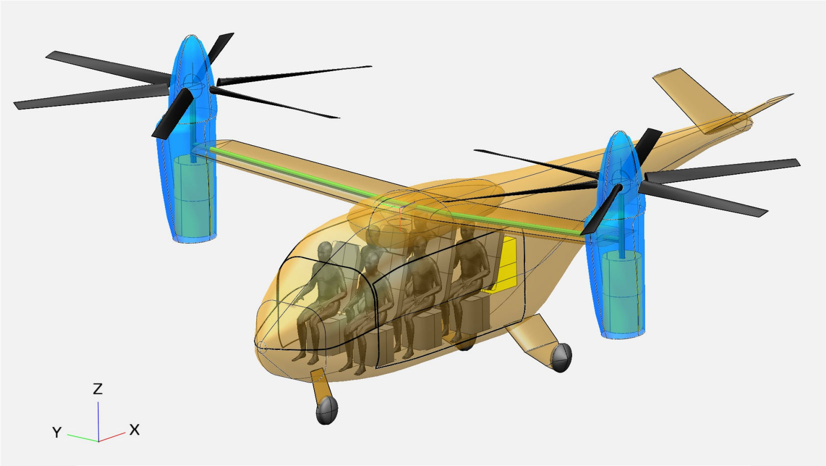
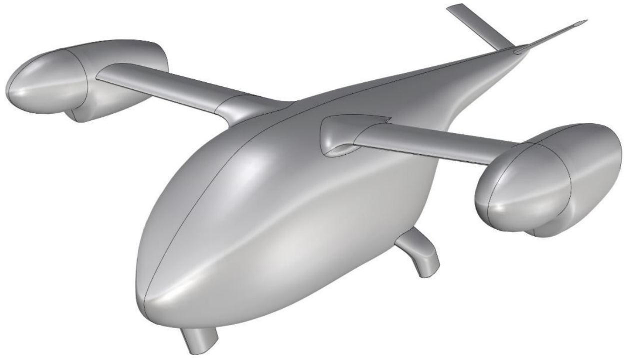


OpenVSP for initial design



Watertight, smoothed geometry for CFD

Rendered aircraft for communication and engagement

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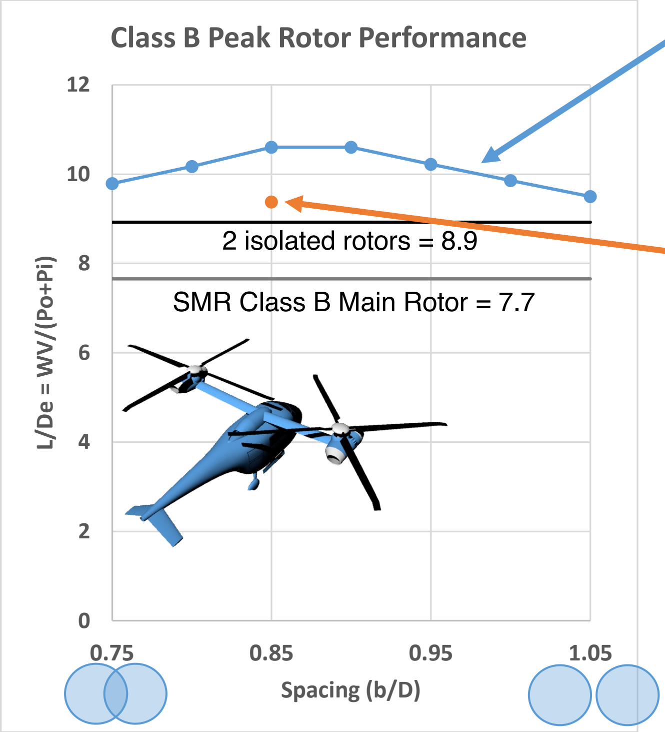
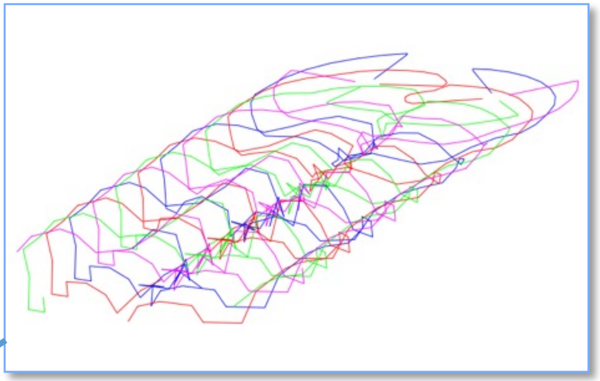
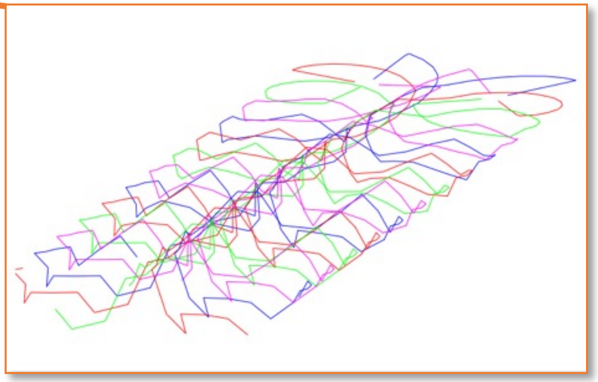
Effect captured in NDARC twin rotor interference parameters:

```
MODEL_twin='side-by-side’,
Kh_twin=.92,Kf_twin=1.0,
```





Outboard advancing
Peak L/De ~ 10.5
Peak b/D ~ 0.85-0.9



Outboard retreating
Peak L/De ~ 9.4

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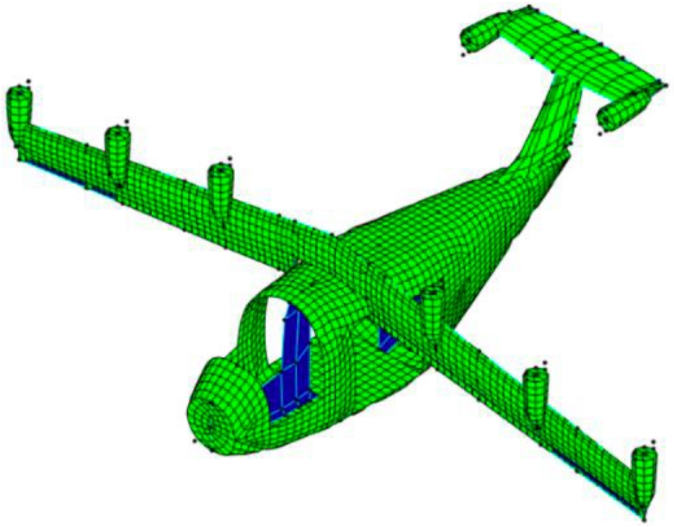
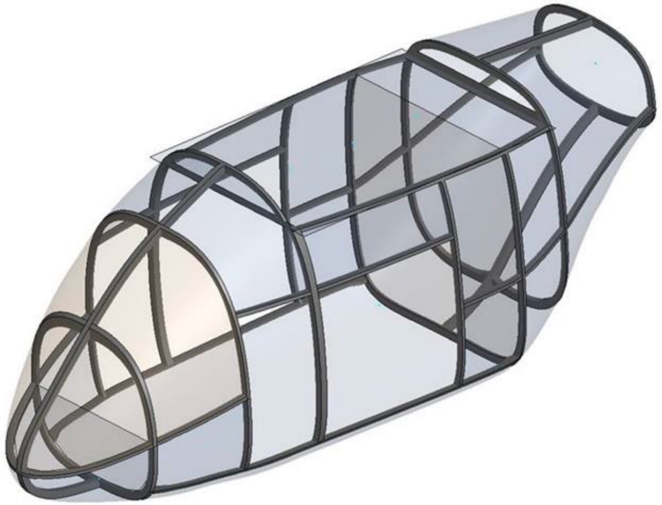


Tiltwing NASTRAN model



Lift+Cruise cabin crash test article structural components

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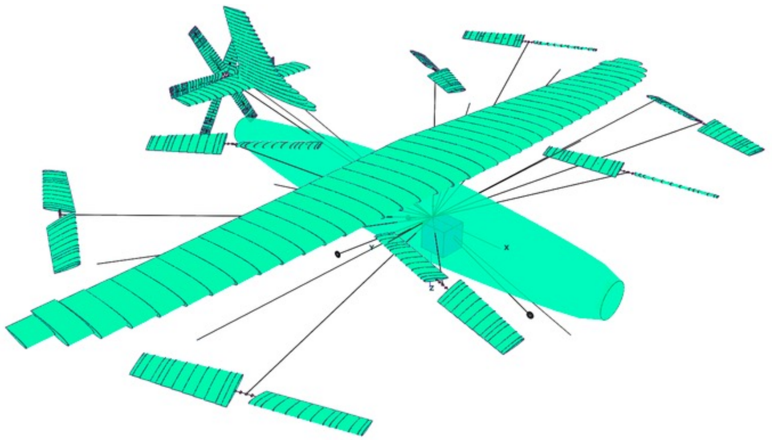
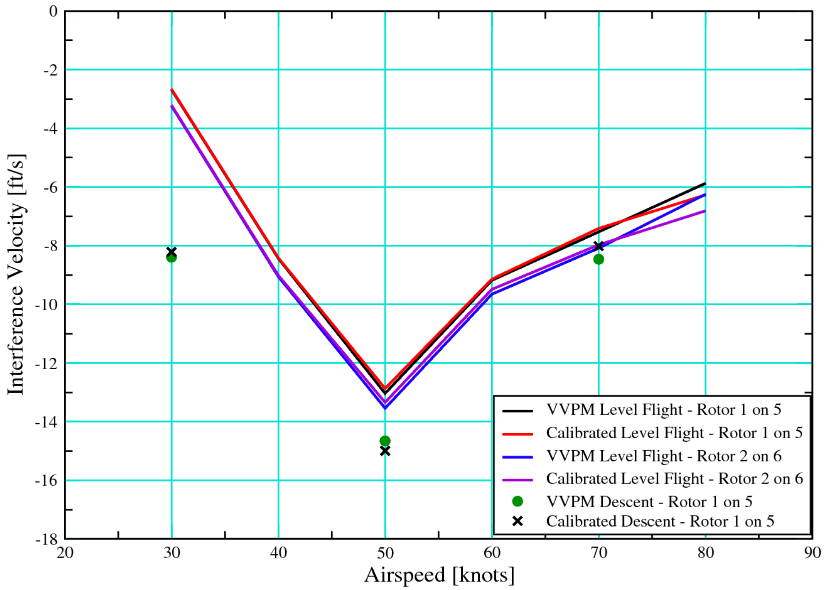


Lift+Cruise FlightLab geometry



Lift+Cruise FlightLab rotor-to-rotor interference

Reference vehicles for UAM: baselines & some trades we have performed

	Quadrotor	Side-by-side helicopter	Tiltwing
"Air taxi" *"UAM"*			
Occupants	**1**, 2, 4, **6**	**6**	**6**, **15**
Rotors	RPM, **collective** **Flapping,** stiff Nrotor= **4**, 6, 8 Rear rotor z/D	Rotor y/R Rotation	Collective+trim, **monocyclic**
Propulsion	Direct, gear, xshaft Turboshaft, diesel, **battery**	Turboshaft, **parallel hybrid**, battery	Direct, gear, **xshaft** Turboshaft, turboelectric, battery

Johnson, "Concept Vehicles for VTOL Air Taxi Operations," January 2018
- Vehicle type
- Mission range
- Propulsion type and topology
- Rotor control

Green = Initial exploratory baseline (2018 AHS SF) *Blue = 6 pax baseline (2018 AVIATION, 2020 VFS SF, 2020 AVIATION)*

Reference vehicles for UAM: baselines & some trades we have performed

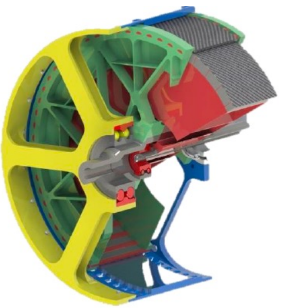
	Quadrotor	Side-by-side helicopter	Tiltwing	Lift+cruise compound	Quiet single main rotor helicopter	Tiltduct
“Air taxi” *“UAM”*						
Occupants	**1**, 2, 4, **6**	**6**	**6**, **15**	**6**	**6**	**6**
Rotors	RPM, **collective** **Flapping,** stiff Nrotor= **4**, 6, 8 Rear rotor z/D	Rotor y/R Rotation	Collective+trim, **monocyclic**, **coll+tiltrotor DEP**	**RPM**, collective Rotor z/D	NOTAR	Collective with TBD duct trades
Propulsion	Direct, **gear**, **xshaft** **Turboshaft**, diesel, **battery**	**Turboshaft**, **parallel hybrid**, battery	**Direct**, gear, **xshaft** Turboshaft, **turboelectric**, battery	**Turboelectric**, battery	**Turboshaft**, battery	**Turboelectric**, battery
Noise tech	Tip speed, tip shape, rear rotor z/D	Tip speed, tip shape, rotor y/R, rotation, IBC		Tip speed, rotor z/D, pitch trim	**NOTAR** **Droop** **Sweep** **IBC HHC**	

Green = Initial exploratory baseline (2018 AHS SF) *Blue = 6 pax baseline (2018 AVIATION, 2020 VFS SF, 2020 AVIATION)*

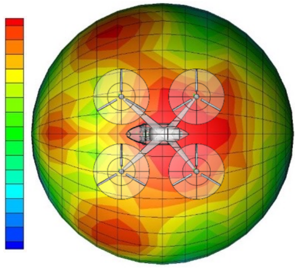
What have people been (publicly) doing with the models?

NASA

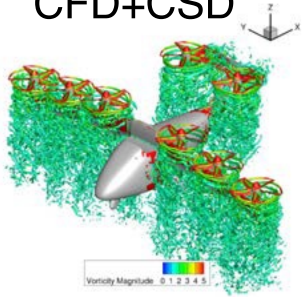
Electric propulsion



Noise

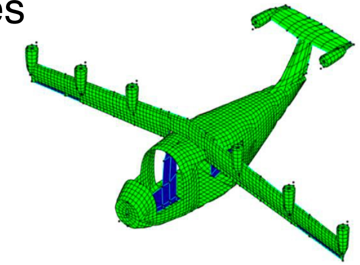


CFD+CSD

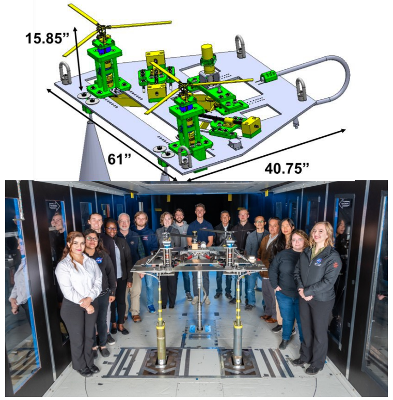


Flight dynamics, handling/ride qualities

Structures



Wind tunnel

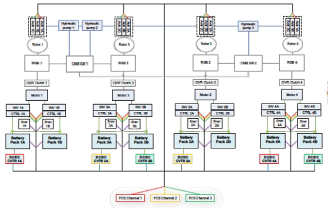


Crashworthiness

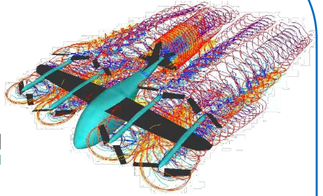
281 papers using the NASA UAM reference vehicles as of 1 January 2024

US Industry

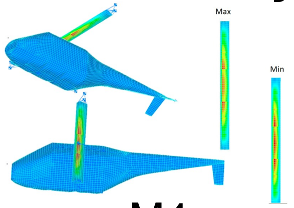
Boeing



CDI

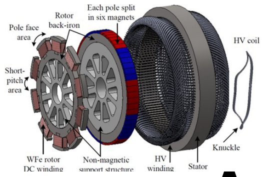


M4

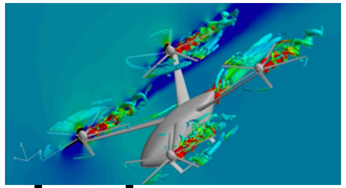


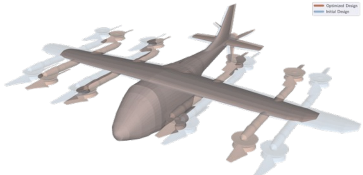
Academia

NDSU



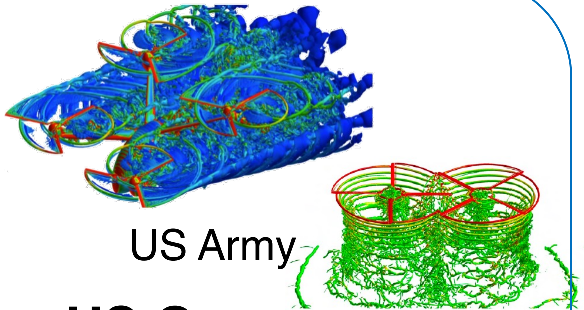
Georgia Tech



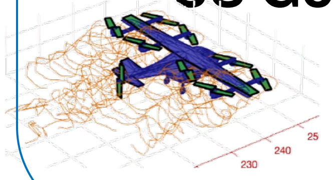


UCSD+SDSU+UCD+BYU+Aurora+M4

US Government

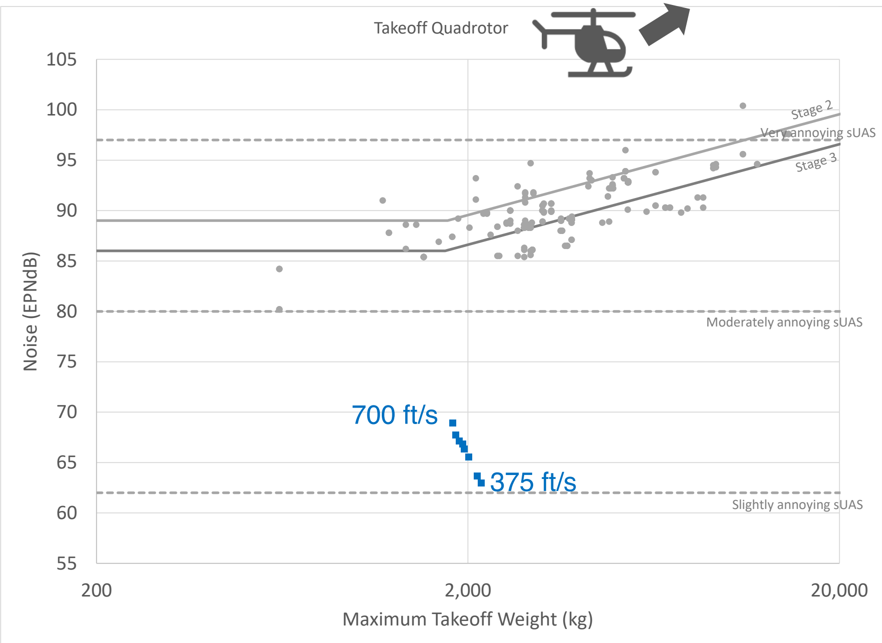


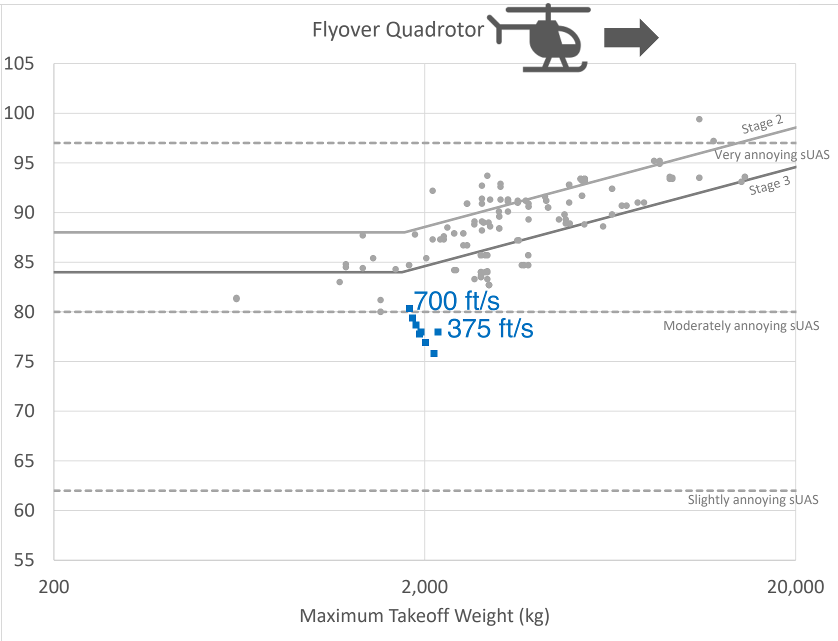
US Army

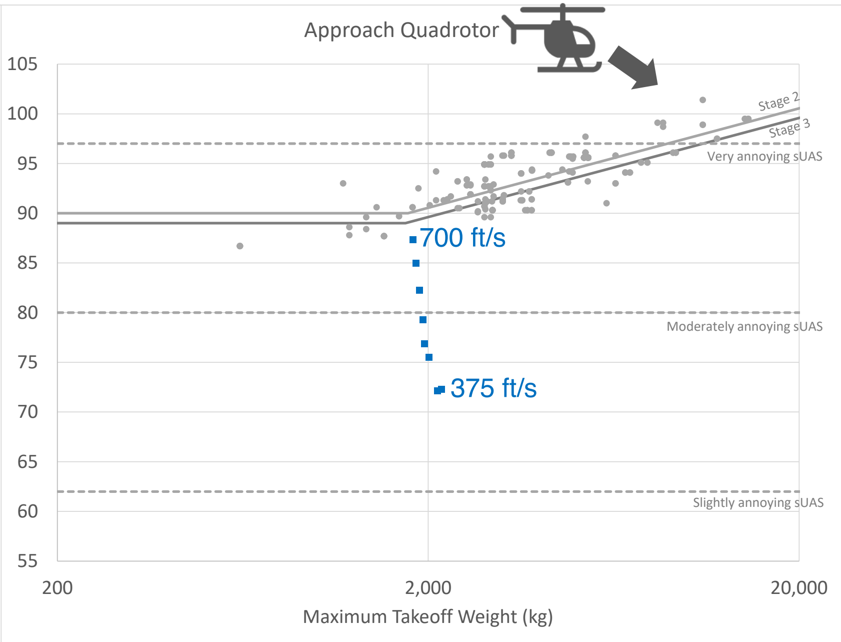


CDI+MIT+FAA

Tip speed: Quadrotor most (noise) improvement in approach

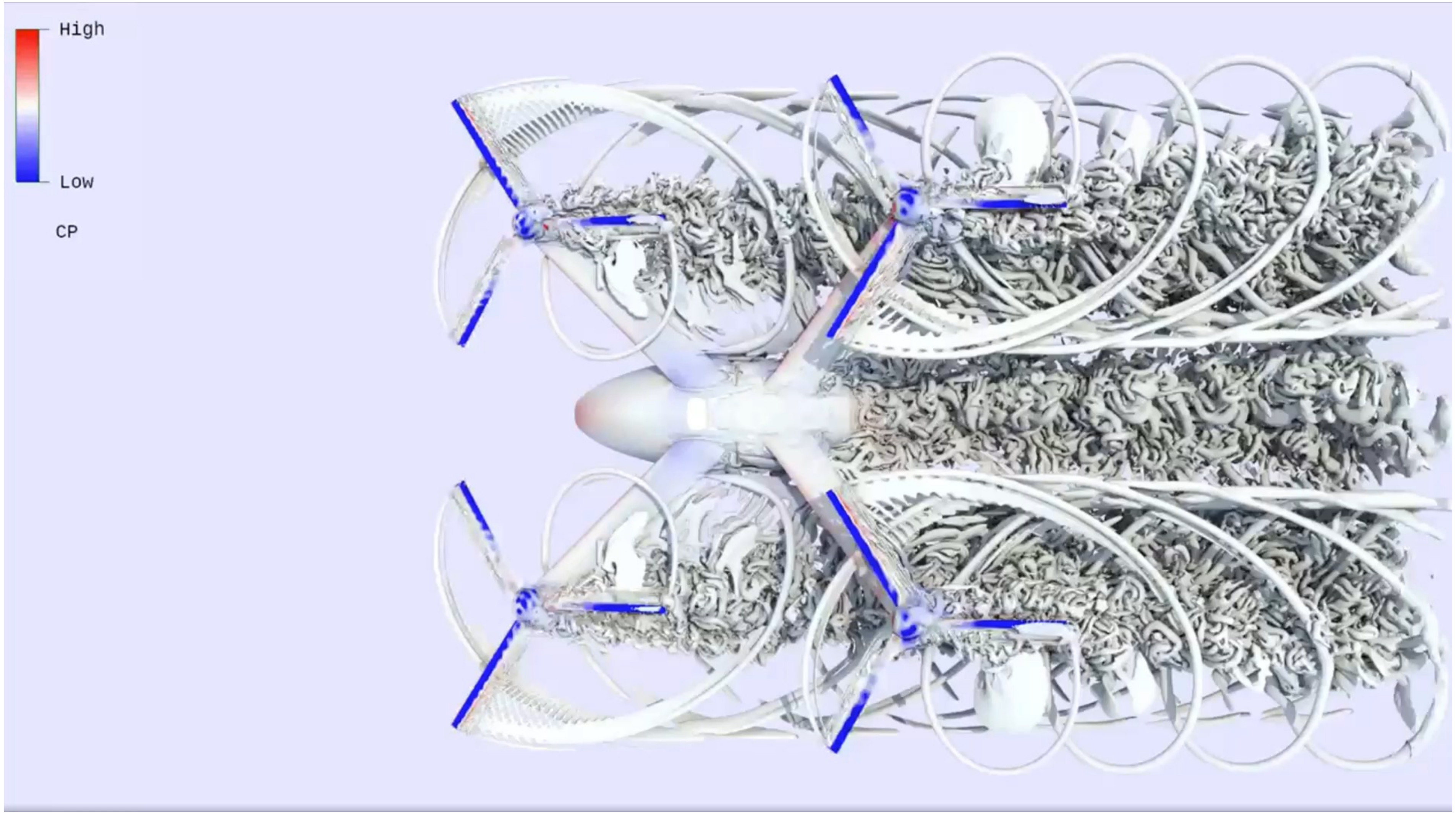






Tip speed (ft/s)	Δ Takeoff (EPNdB)	Δ Flyover (EPNdB)	Δ Approach (EPNdB)	Δ Empty Wt (%)	Δ Block time (%)	Δ Flyaway (%)
375	-3.9	0.2	-7.0	9%	18%	14%
400	-3.2	-2.0	-7.1	14%	10%	25%
450	-1.3	-0.9	-3.7	5%	7%	10%
500	-0.5	0.2	-2.4	1%	4%	4%
550				Baseline		
600	0.3	0.9	3.0	-3%	-2%	-3%
650	0.9	1.6	5.7	-7%	-3%	-6%
700	2.1	2.5	8.1	-9%	-1%	-9%

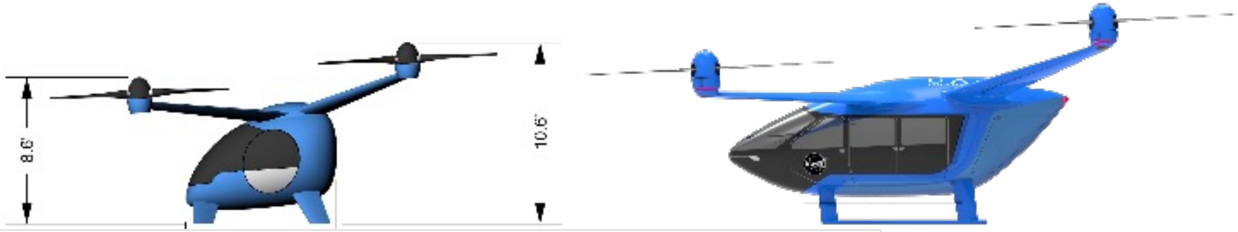
Loose-coupled CFD: Can we minimize bad interactions? (Ventura Diaz)

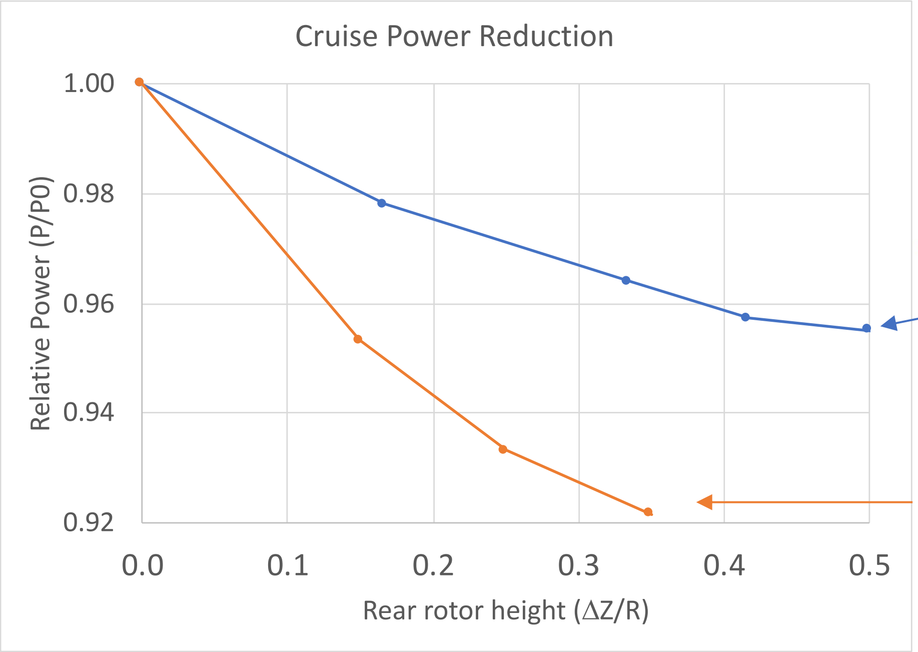


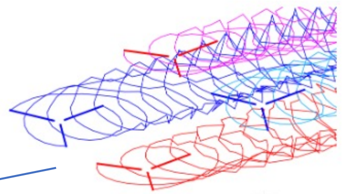
Perfomance trends similar to comprehensive analysis. Magnitudes vary.

More detailed look into rotor-rotor interactions (Ventura Diaz)

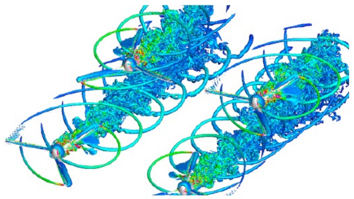
- **Wakes impact downstream rotors**
- **Mid-fidelity tools predict the cost / benefit**
- **High-fidelity to confirm effects (or not!)**



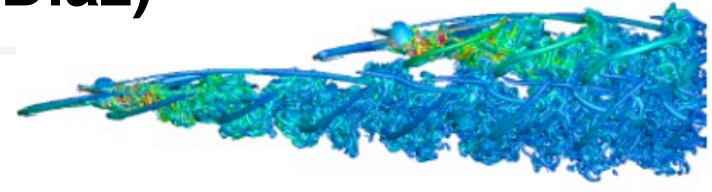




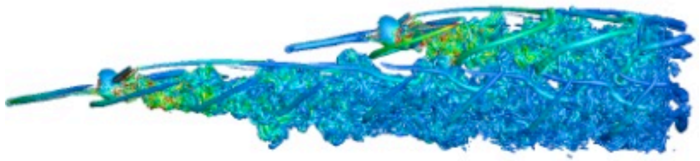
Comprehensive Analysis
1 pax



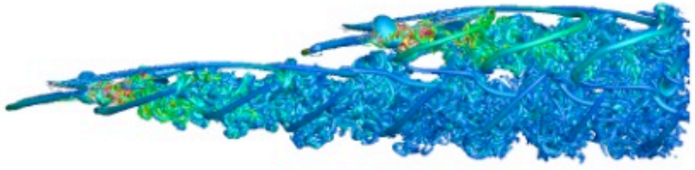
CFD+CA
6 pax



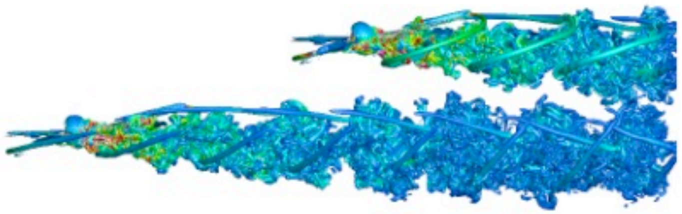
(a) Q-criterion iso-surfaces, $z_{rear} = 0.25R$



(c) Q-criterion iso-surfaces, $z_{rear} = 0.4R$

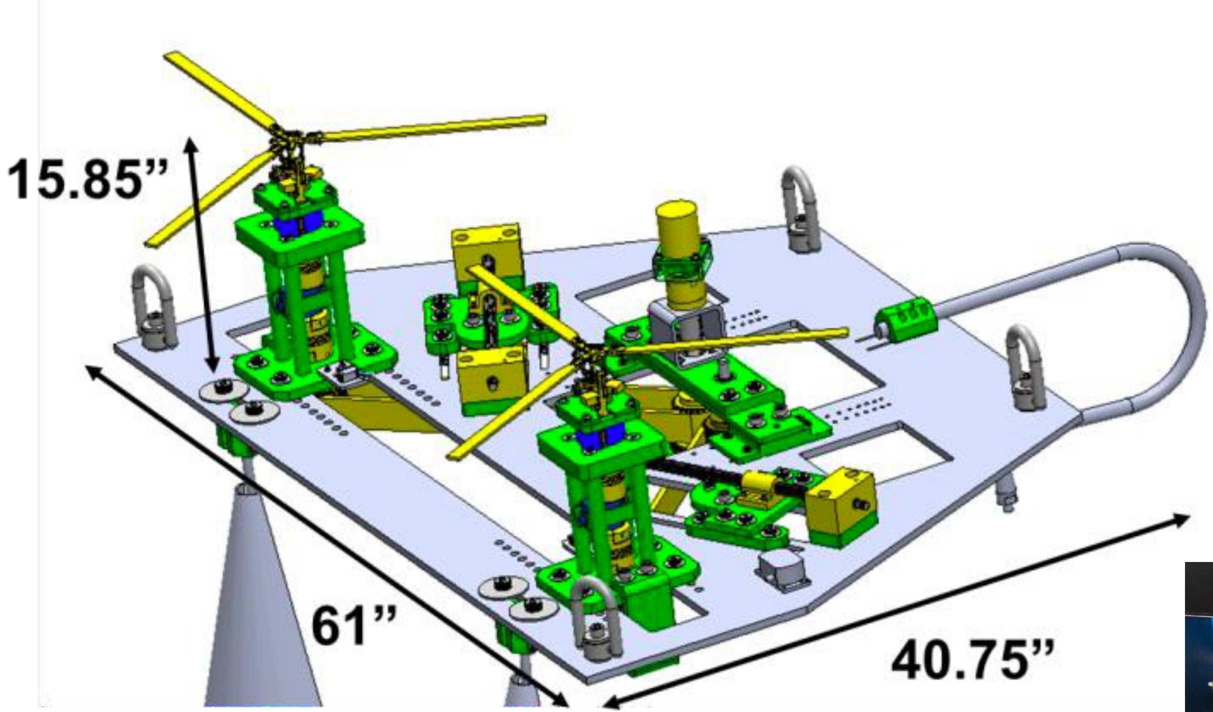


(e) Q-criterion iso-surfaces, $z_{rear} = 0.5R$

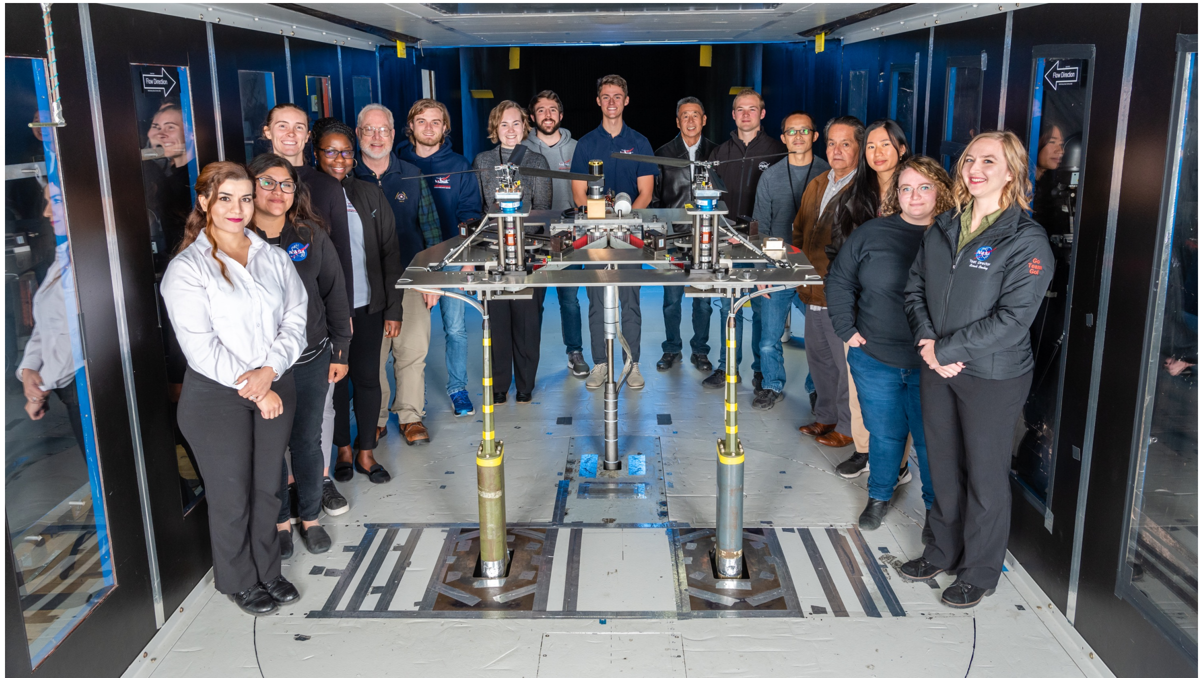


(g) Q-criterion iso-surfaces, $z_{rear} = 0.6R$

If you can predict productive interference, might as well measure it

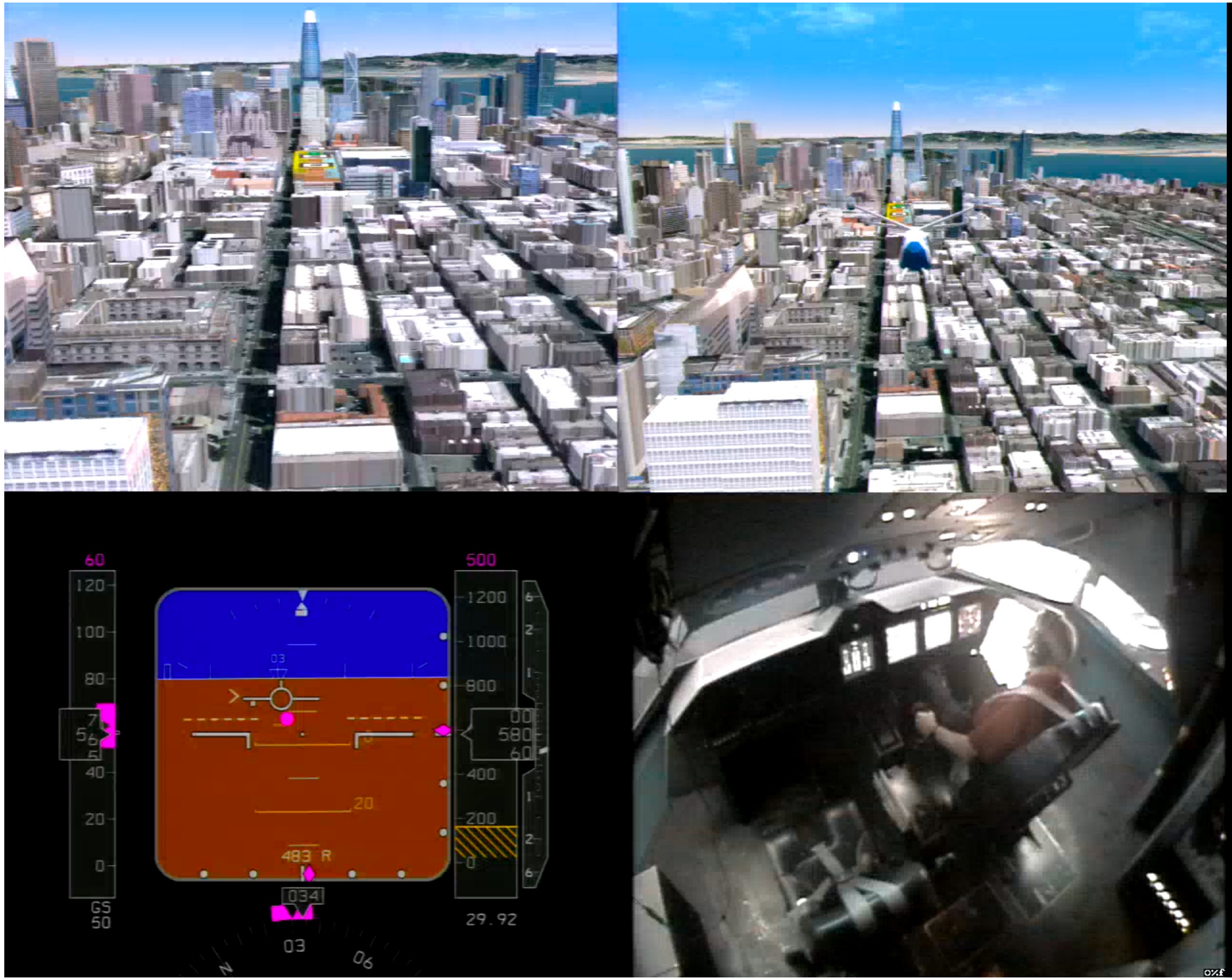


Side-by-Side Test Rig for rotor performance in Army 7x10



VMS testing and handling qualities analysis

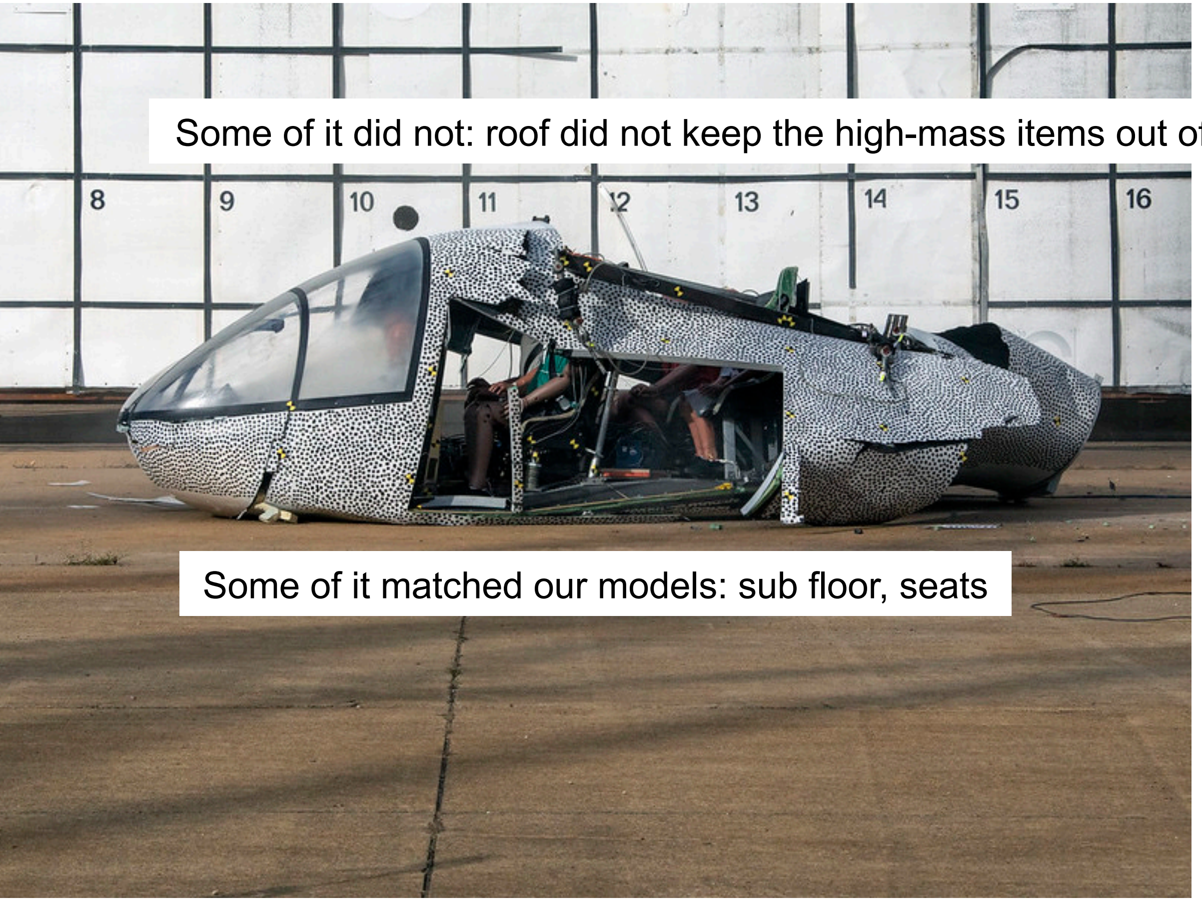
- **RPM sluggish and sloppy if motors not capable of at least 2x the torque required for steady operation**
  - Pilots really dislike sluggish RPM
  - Passengers dislike sloppy RPM
  - Motor sizing needs to be updated
- **Small rotors for reasonable RPM control**
  - This is one argument for Distributed Electric Propulsion (DEP)
  - Somewhere around 5 ft radius probably the cutoff, but not sure yet




ARCH

Fantastic news! We get to do more engineering!

Some of it did not: roof did not keep the high-mass items out of the passenger volume



Some of it matched our models: sub floor, seats

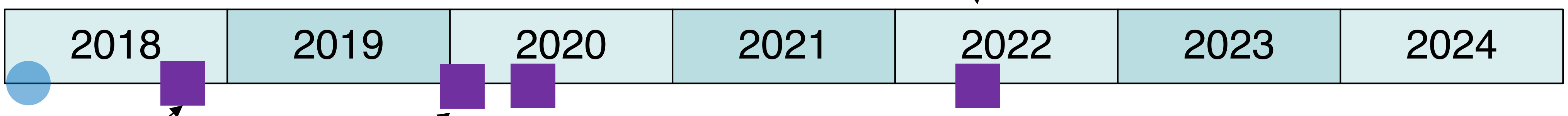
The UAM landscape was a bit different in early 2018

2018	2019	2020	2021	2022	2023	2024

Some major policy developments in Europe and USA

FAR Part 23 vs Part 21.17(b) powered lift (May 2022)

- May be similar to tiltrotor requirements
- 2-control trainer aircraft



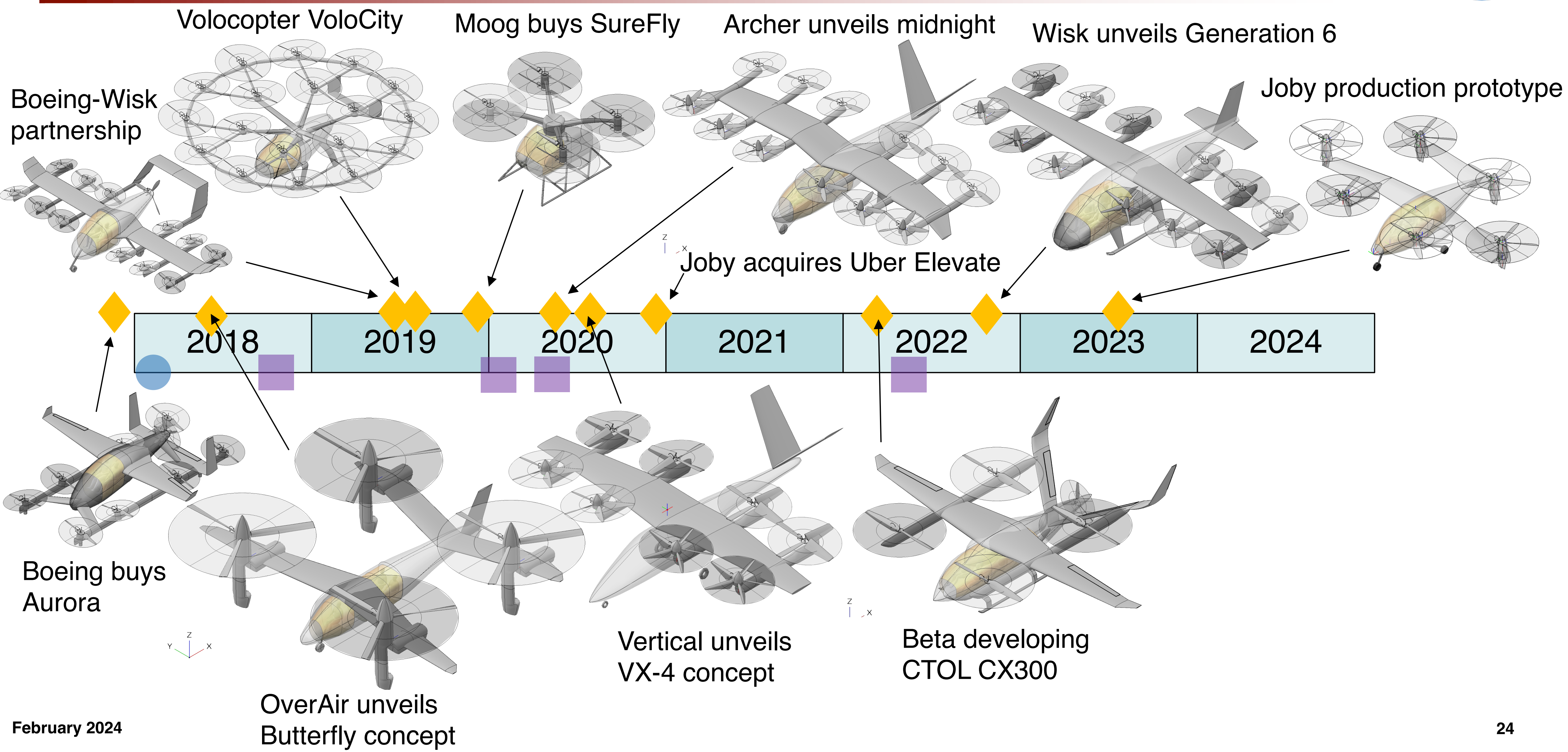
EASA Means of Compliance published (May 2020; MOC-4 SC-VTOL, December 2023)

Proposed Special Condition: Electric/Hybrid Propulsion System (SC-E-19, January 2020)

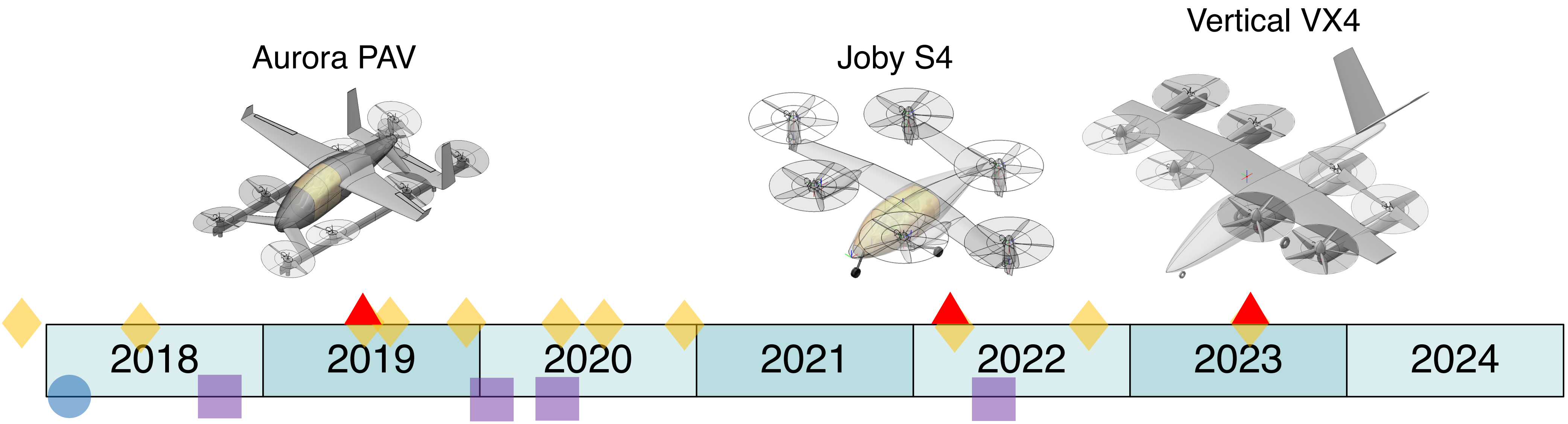
EASA Special Condition for VTOL (SC-VTOL-01, October 2018)

- Allowing operation into and at low altitudes above European urban areas
- No single point of failure in rotating parts
- 10^{-9} catastrophic failures per flight hour over populated areas

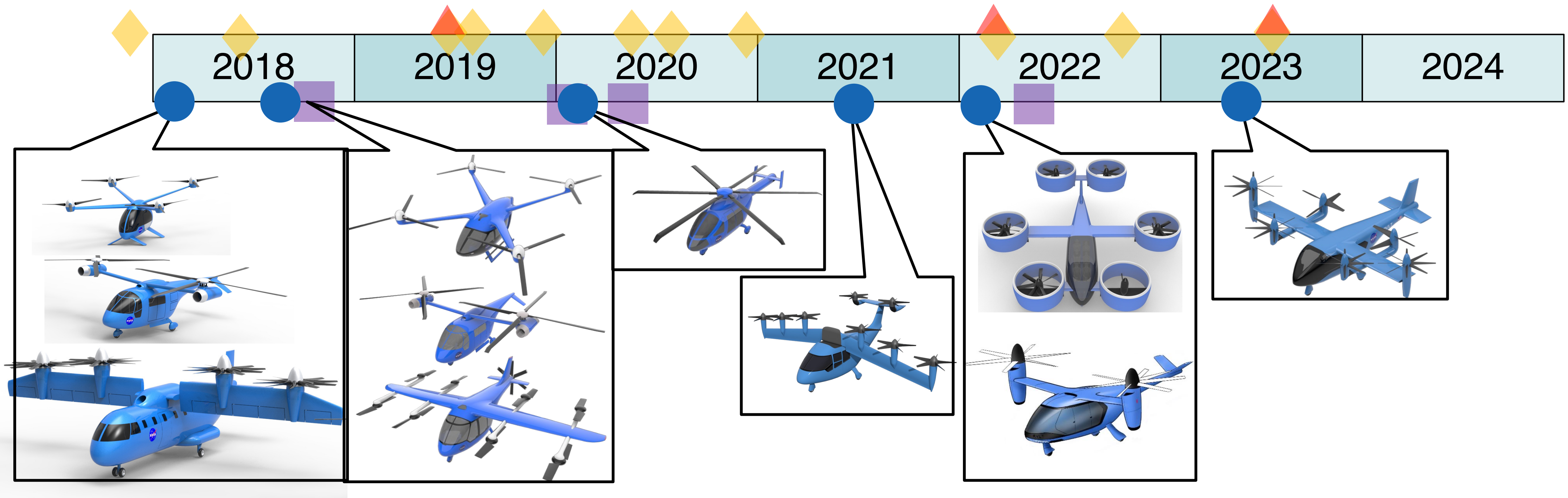
(Just a few of the many) New companies and changed vehicles



Crashes in full-scale flight test

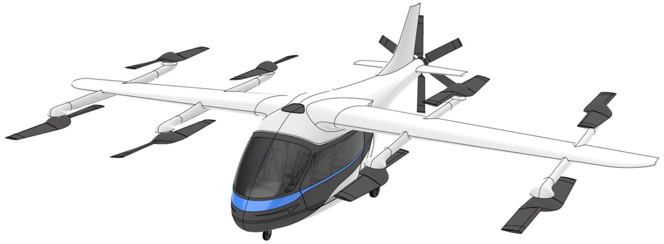


Incremental updates and additions to NASA UAM Reference Vehicles

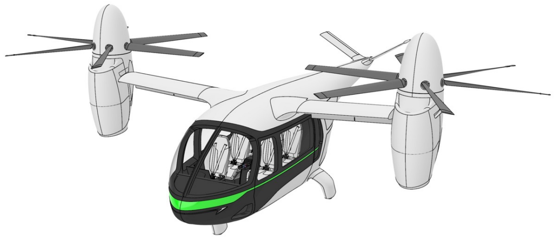
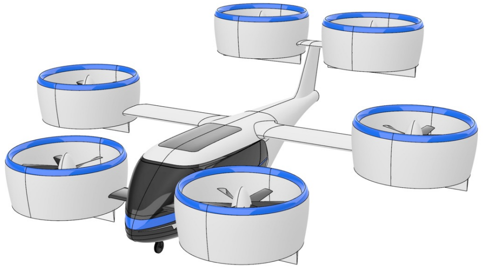
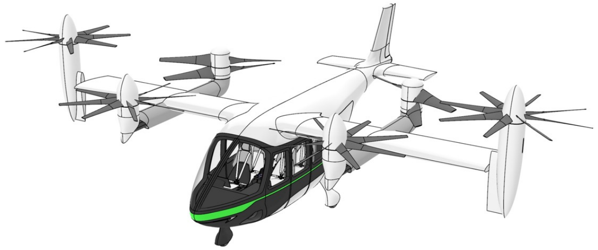


Updated NASA UAM Reference vehicles



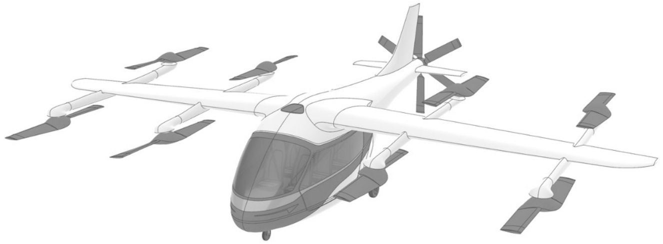
Rotors	**1+1**	**2**	**4**	**8 + 1**
Tilting				
RPM?			Variant	Yes: 8
Stopping?				Yes: 8

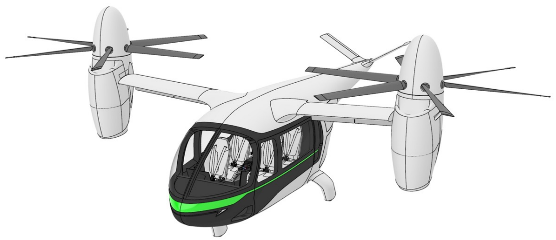
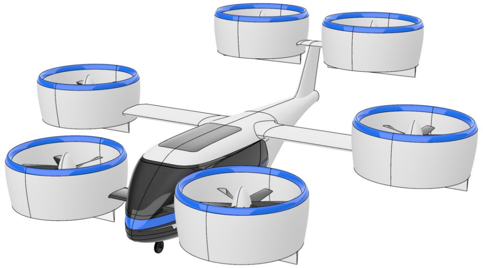
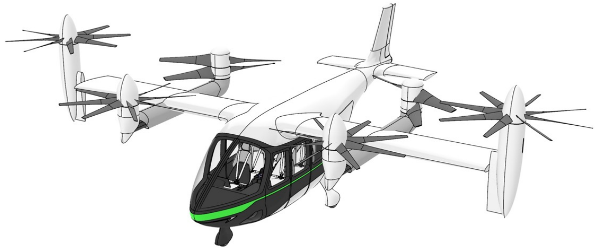

Rotors	**2**	**6**	**6**	**8**
Tilting	Yes	Yes	Yes: 4	Yes
RPM?			Variant: 2	
Stopping?			Yes: 2	

Updated NASA UAM Reference vehicles



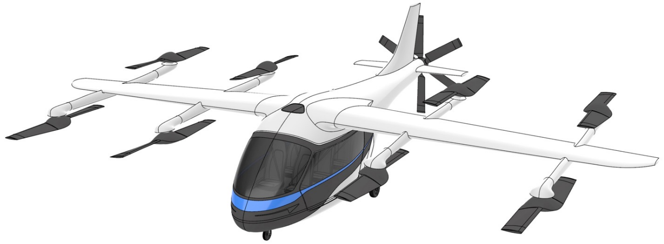
Rotors	1+1	2	4	8 + 1
Tilting				
RPM?			Variant	Yes: 8
Stopping?				Yes: 8

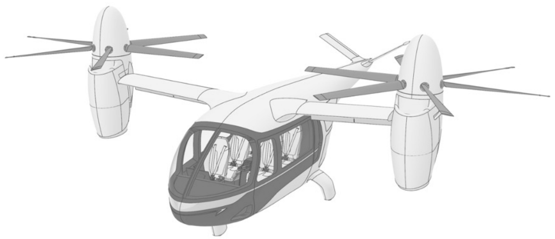
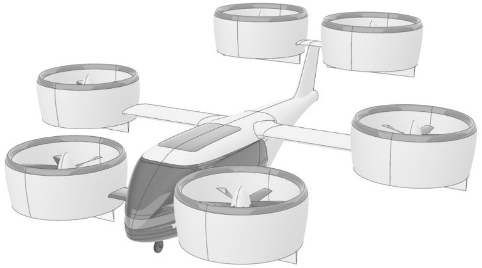
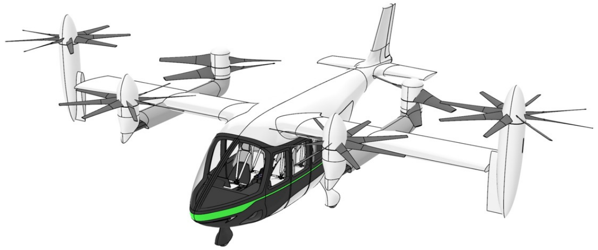
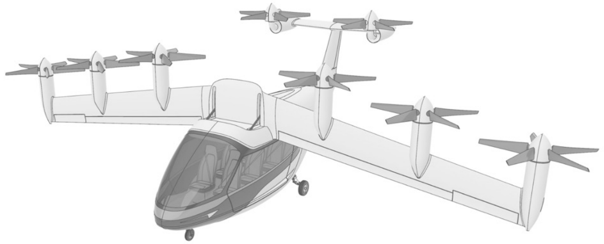

Rotors	2	6	6	8
Tilting	**Yes**	**Yes**	**Yes: 4**	**Yes**
RPM?			Variant: 2	
Stopping?			Yes: 2	

Updated NASA UAM Reference vehicles



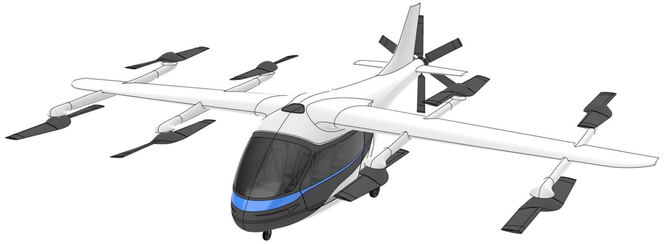
Rotors	1+1	2	4	8 + 1
Tilting				
RPM?			**Variant**	**Yes: 8**
Stopping?				Yes: 8

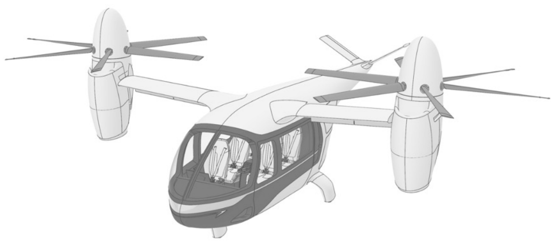
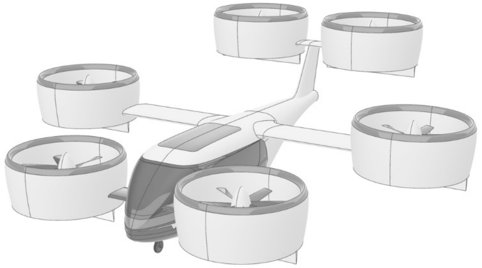
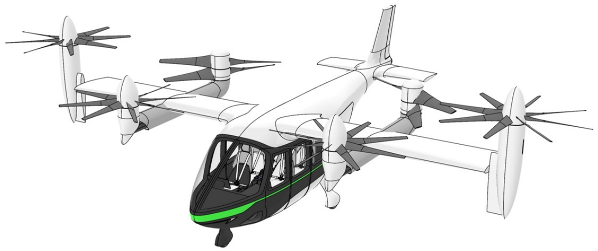
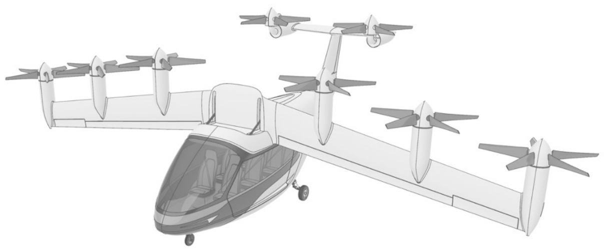
Rotors	2	6	6	8
Tilting	Yes	Yes	Yes: 4	Yes
RPM?			**Variant: 2**	
Stopping?			Yes: 2	

Updated NASA UAM Reference vehicles



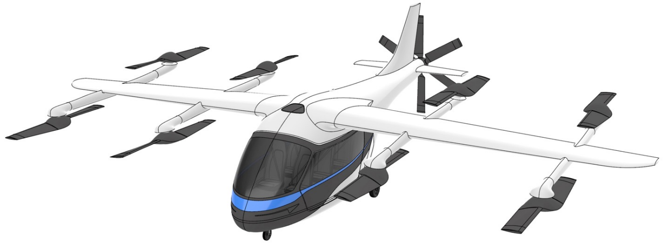
Rotors	1+1	2	4	8 + 1
Tilting				
RPM?			Variant	Yes: 8
Stopping?				**Yes: 8**

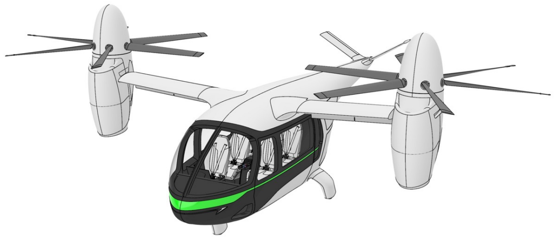
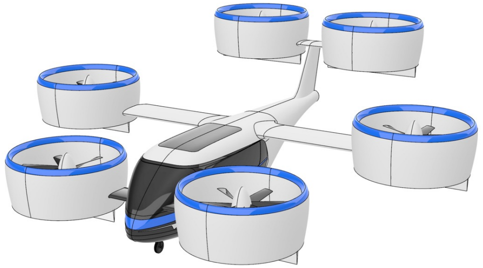
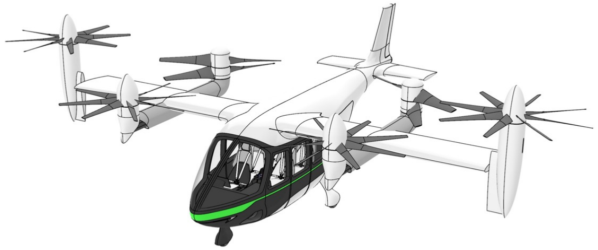
Rotors	2	6	6	8
Tilting	Yes	Yes	Yes: 4	Yes
RPM?			Variant: 2	
Stopping?			**Yes: 2**	

Updated NASA UAM Reference vehicles



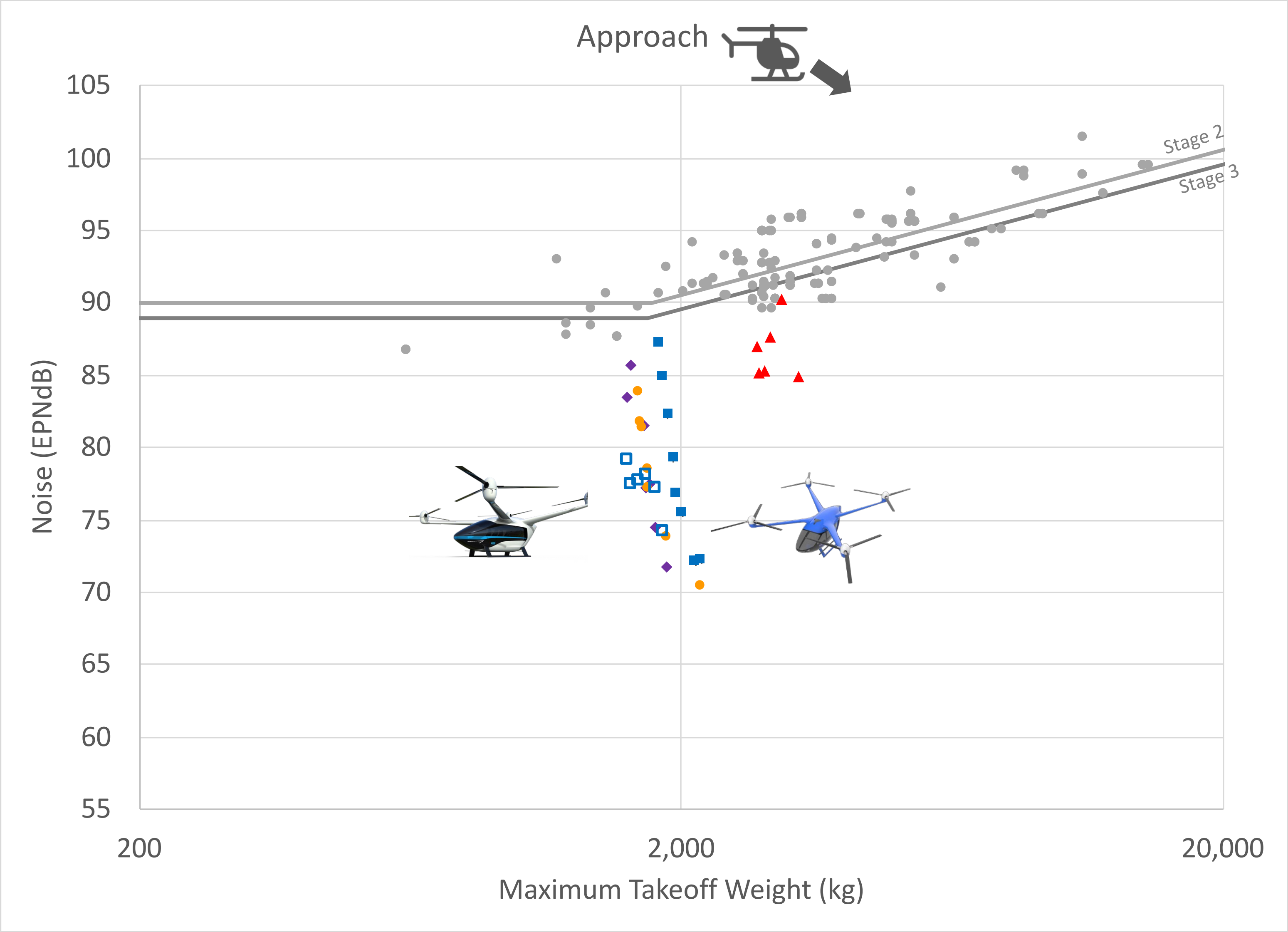



Rotors	1+1	2	4	8 + 1
Tilting				
RPM?			Variant	Yes: 8
Stopping?				Yes: 8


Rotors	2	6	6	8
Tilting	Yes	Yes	Yes: 4	Yes
RPM?			Variant: 2	
Stopping?			Yes: 2	

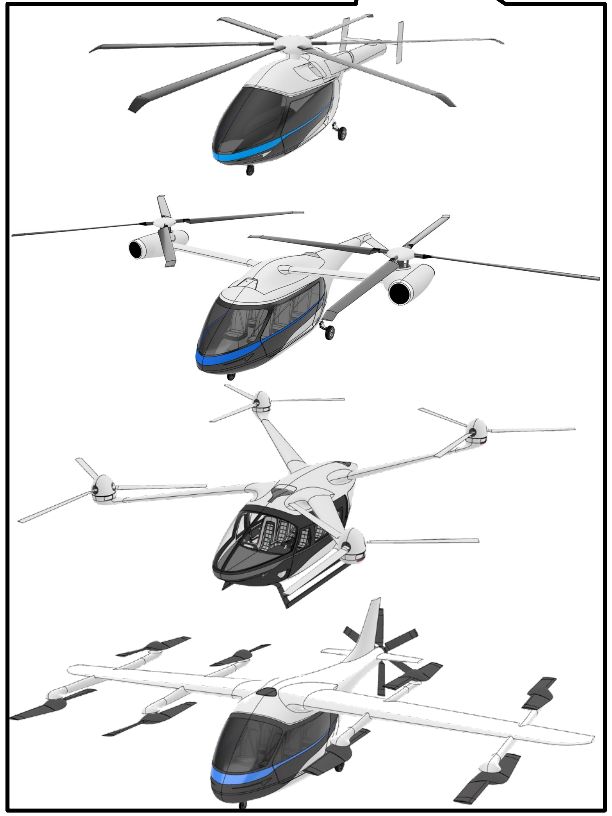
Part 36H Certification Approach Noise Prediction

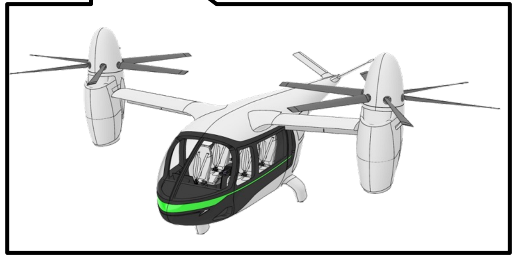


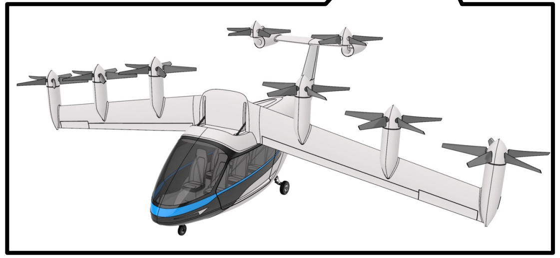

AIR RESCUE

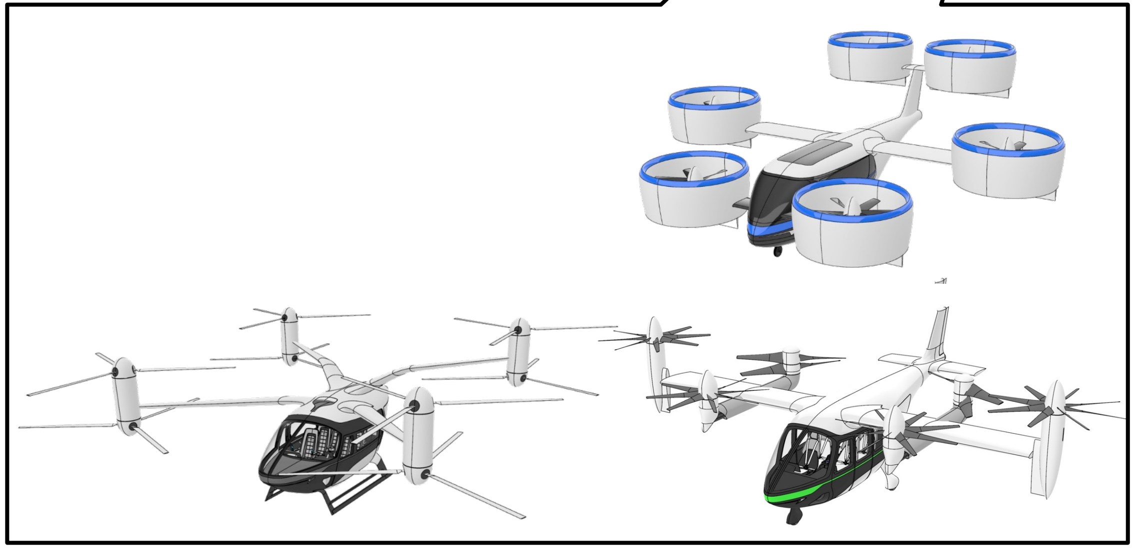
When will updated UAM Reference Vehicle models be available?

2024				2025				TBD Future
Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec	



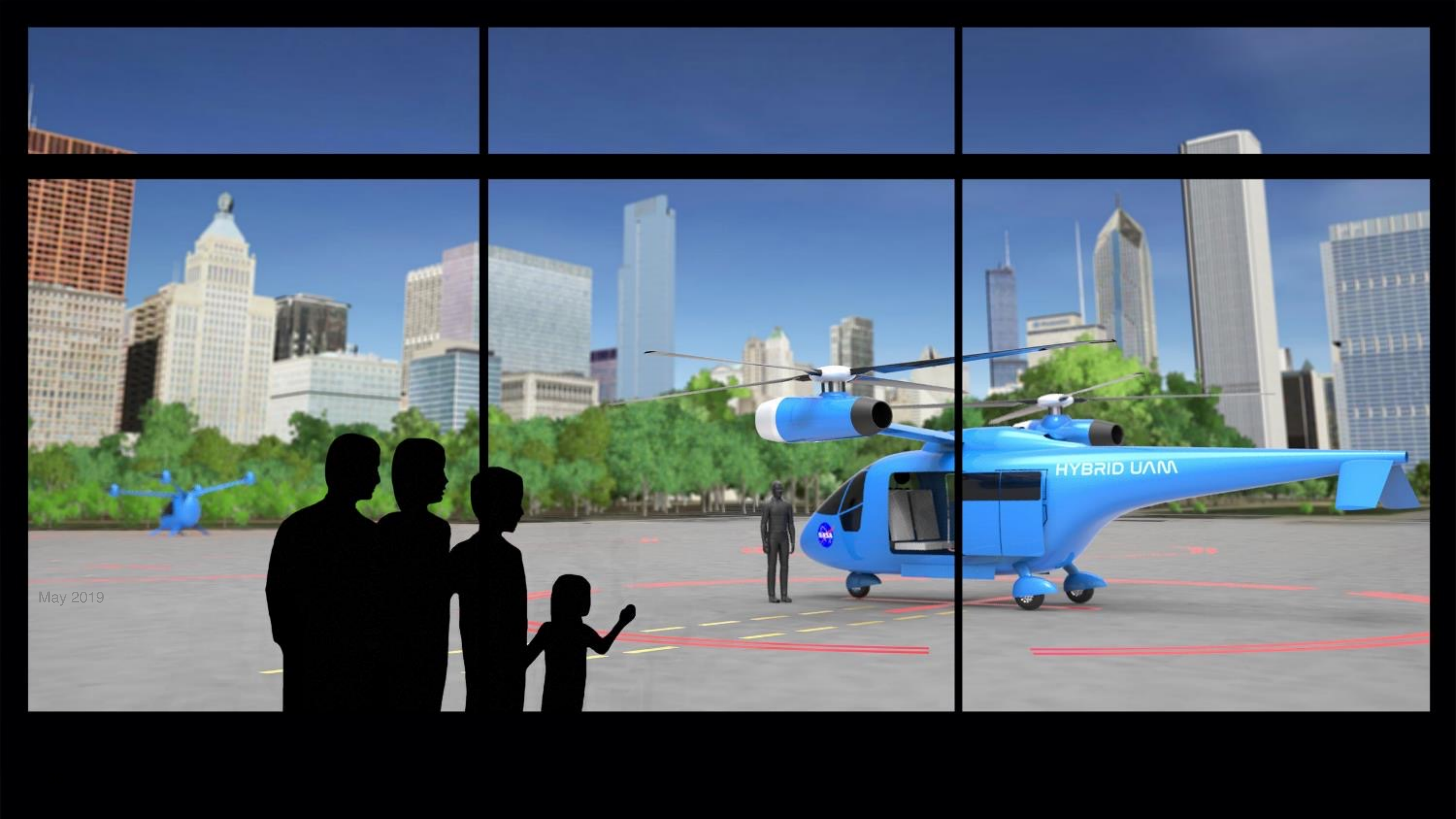






How can you get the models?

- **NDARC website – NDARC Users**
  - https://rotorcraft.arc.nasa.gov/ndarc/
    - Request NDARC: https://software.nasa.gov/software/ARC-16265-1
- **Langley Research Center - Systems Analysis and Concepts Directorate- Aeronautics Systems Analysis Branch (LaRC SACD ASAB) – Publicly available**
  - https://sacd.larc.nasa.gov/uam-refs/
- **NASA Technical Reports Server – Publicly available (reports only)**
  - https://ntrs.nasa.gov



May 2019