

---

# Leading Edge

## Distributed Electric Propulsion Wing Concept for CTOL, STOL and VTOL Missions

Mark D. Moore, William Fredericks, Nicholas K. Borer, Daniel Palumbo,  
Steve Rizzi, Doug Nark, Casey Burley, Paul Rothhaar  
*NASA Langley Research Center, Hampton, Virginia*

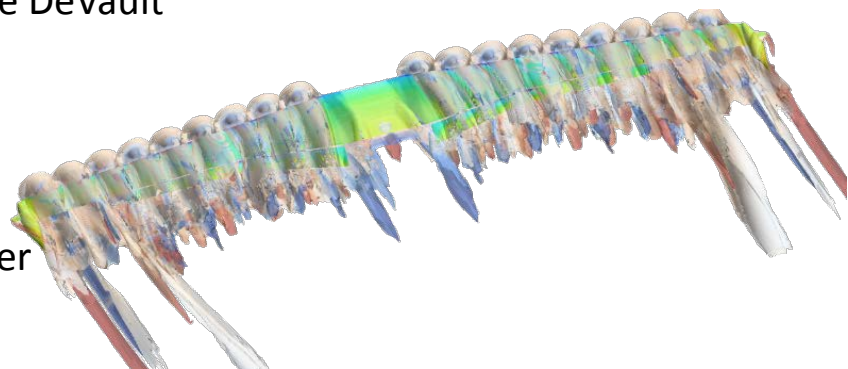
Sean Clarke, Starr Ginn, Yohan Lin  
*NASA Armstrong Research Center, California*

Alex Stol, JoeBen Bevirt, Alec Clark, Edward Stilson, Gabe DeVault  
*Joby Aviation, Santa Cruz, California*

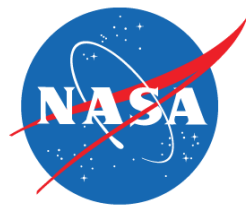
Dave Kinney, Kevin Reynolds  
*NASA Ames Research Center, California*

Andrew Gibson, Benjamin Schiltgen, Trevor Foster  
*ESAero, Pismo Beach, California*

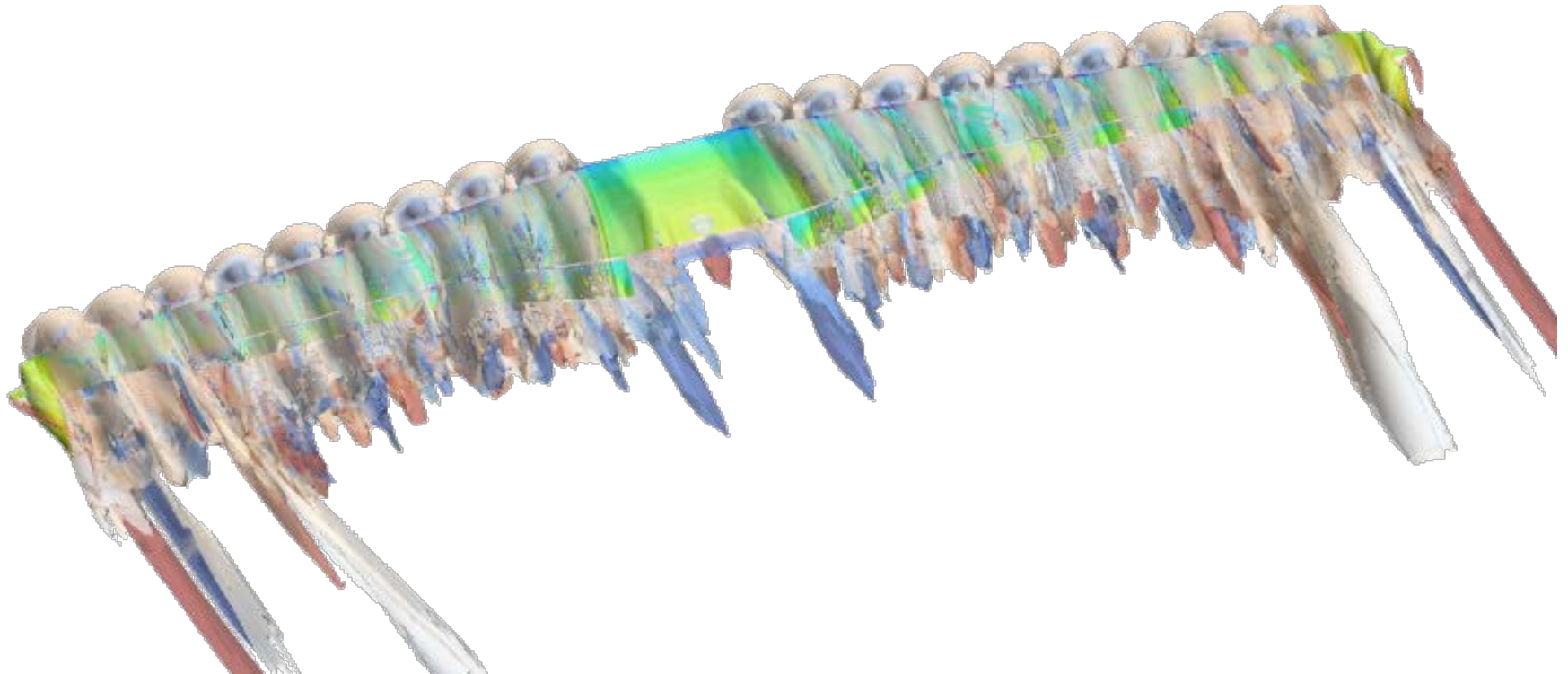
Michael Patterson, Brian German  
*Georgia Institute of Technology*



# The Big Picture: Associated Research

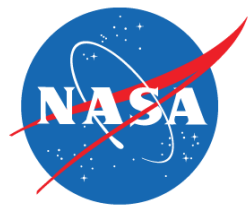


This research pulls together many discipline focused efforts into a single highly coupled, multi-disciplinary advanced concept called LEAPTech. Research efforts will be reported out across different AIAA Transformational Flight sessions during this Aviation 2014 conference.



**Leading Edge Asynchronous Propeller Technology  
(LEAPTech)**

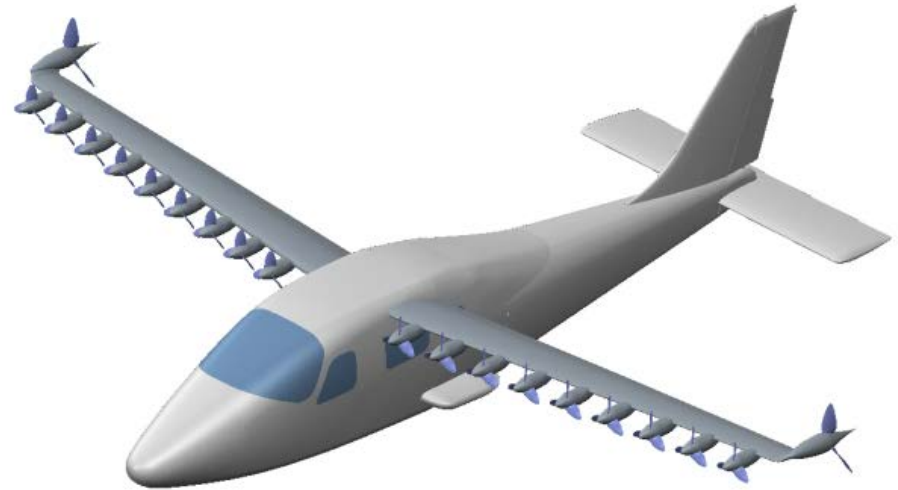
# The Big Picture Research Questions



Tecnam P2006T Light Twin



NASA LEAPTech Wing



**What happens if instead of having a standard twin engine configuration, electric propulsion enables highly distributed integration?**

What electric propulsion characteristics enable distribution?

What's the strategy for achieving highly coupled synergistic integration?

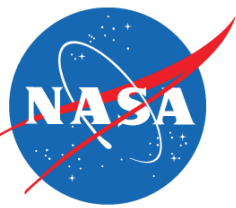
What problems does this new integration approach solve?

How does this integration approach extend across aviation markets?

What are some of the key relevant technologies?

What research path quickly develops understanding of this new technology?

# What Characteristics Enable Distribution?



## **Electric Propulsion Penalties**

*Energy Storage Weight (50x worse than aviation fuel)*  
*Energy Storage Cost (Tesla 65 kWhr battery is ~\$25,000)*  
*Certification?*

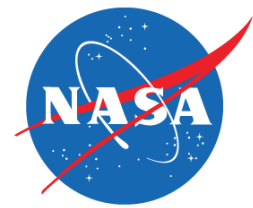
## **Electric Propulsion Benefits**

*~2x efficiency of turbine engines, 3-4x efficiency of piston engines*  
*High efficiency across >50% rpm range*  
*6x the motor power to weight of piston engines*  
*None air breathing - No power lapse with altitude or on hot days*  
*Extremely Quiet*  
*Zero vehicle emissions*  
*10x lower energy costs*

## **Electric Propulsion Integration Benefits**

*Scale independence*  
*Power to weight and efficiency don't degrade at smaller sizes*  
*Extremely compact*  
*High reliability – few moving parts*

# What's the Strategy for Achieving Highly Coupled Synergistic Integration?

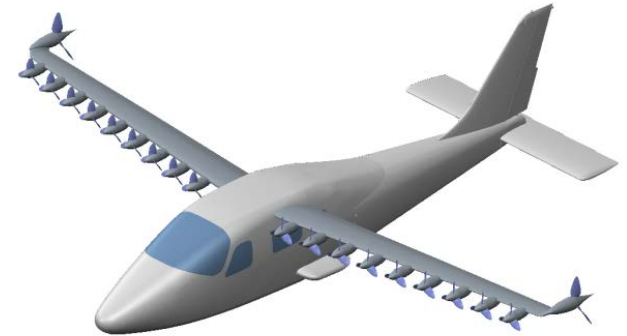


Existing Twin General Aviation Baseline



**Tecnam P2006T Light Twin**

Retrofit DEP GA Demonstrator



**NASA LEAPTech Wing**

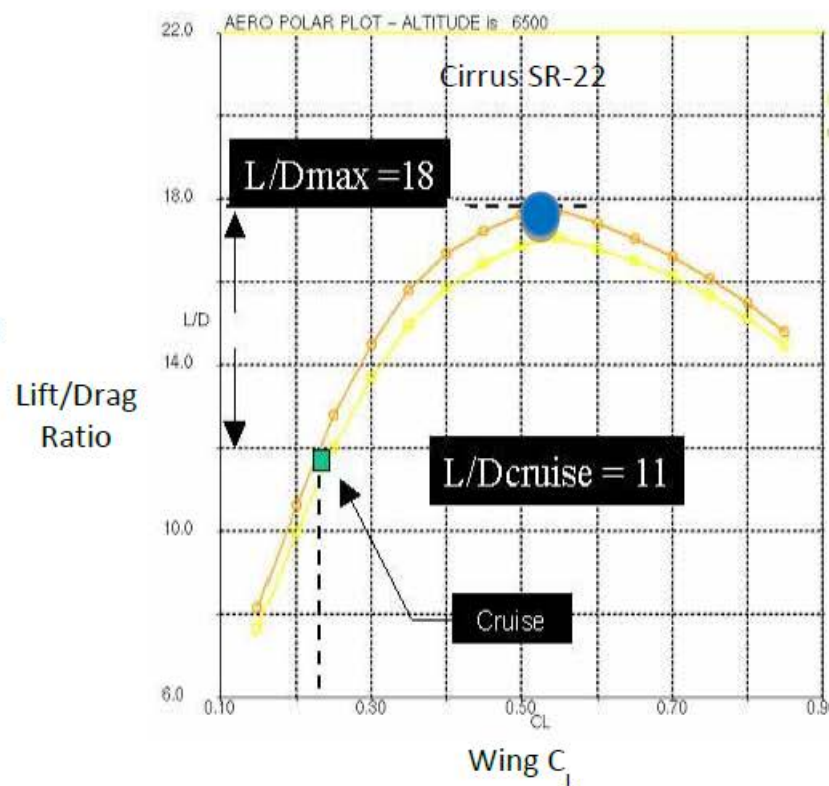
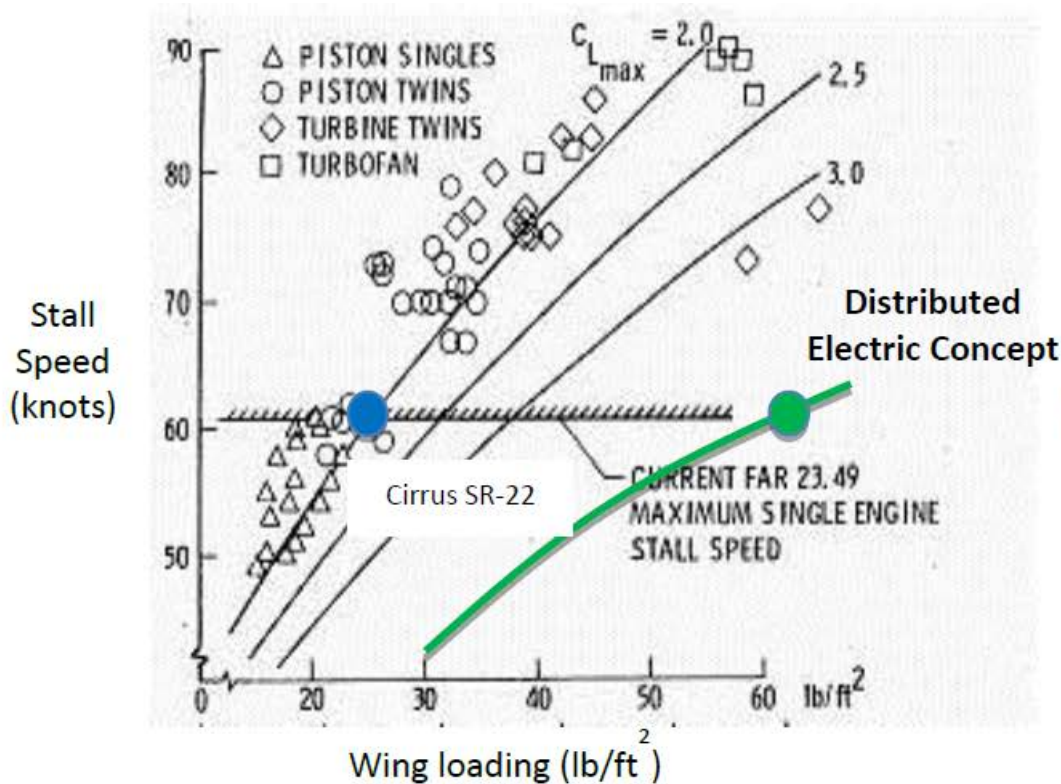
Distributed Electric Propulsion (DEP) Integration Approach

- Tight aero-propulsion coupling increases effective  $C_{L_{max}}$  from 1.8 to 5.0
- Wing loading is increased from 17 lb/ft<sup>2</sup> to 48 lb/ft<sup>2</sup>, with same stall speed and field performance capability.
- Because electric motors don't experience power lapse with altitude (i.e. they're non air breathing), the inner span propellers can be stopped and folded back at cruise. This permits the inner propellers to be optimized for ultra low noise at takeoff/landing, without cruise penalty.

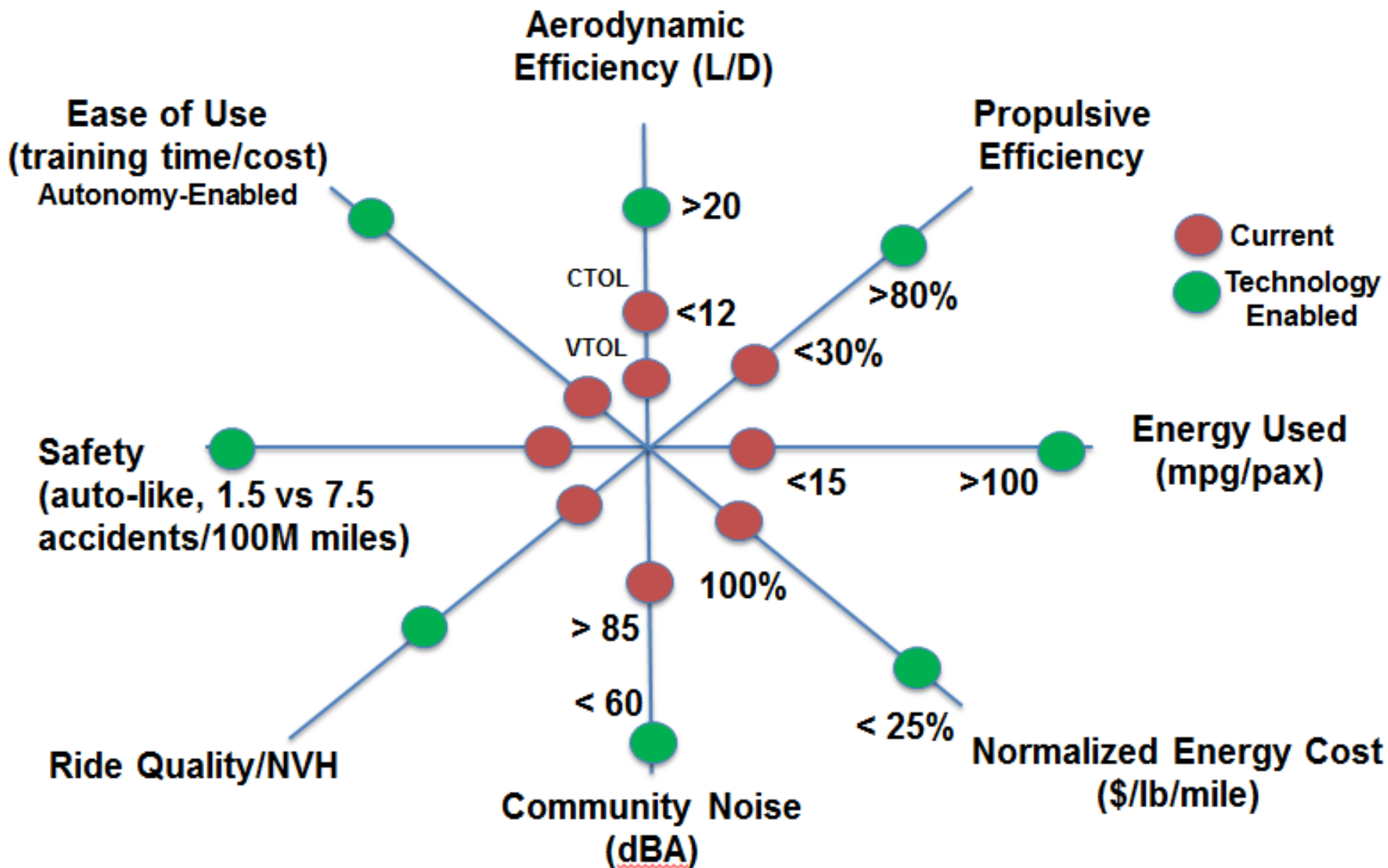


# Integration Strategy Wing Sizing Impact

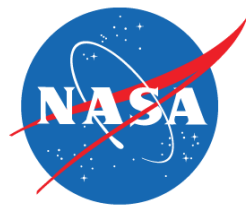
Increasing wing loading is critical for achieving higher aerodynamic efficiency



# What Problems Does this New Integration Strategy Solve?



# How does this Integration Approach Extend Across Aviation Markets?



**General Aviation SOA provides large benefit advantages for early market success to provide more rapid tech acceleration.**



Single Aisle: Boeing 737  
Gross Weight ~150,000 lb  
L/D<sub>cruise</sub> ~ 18  
Wing loading 111 lb/ft<sup>2</sup>



Turbo-props: Bombardier Q300  
Gross Weight ~ 43,000 lb  
L/D<sub>cruise</sub> ~ 16  
Wing loading 71 lb/ft<sup>2</sup>

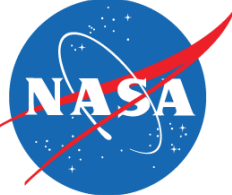


Commuters: Cessna Grand Caravan  
Gross Weight ~ 6200 lb  
L/D<sub>cruise</sub> ~ 10  
Wing loading 22 lb/ft<sup>2</sup>

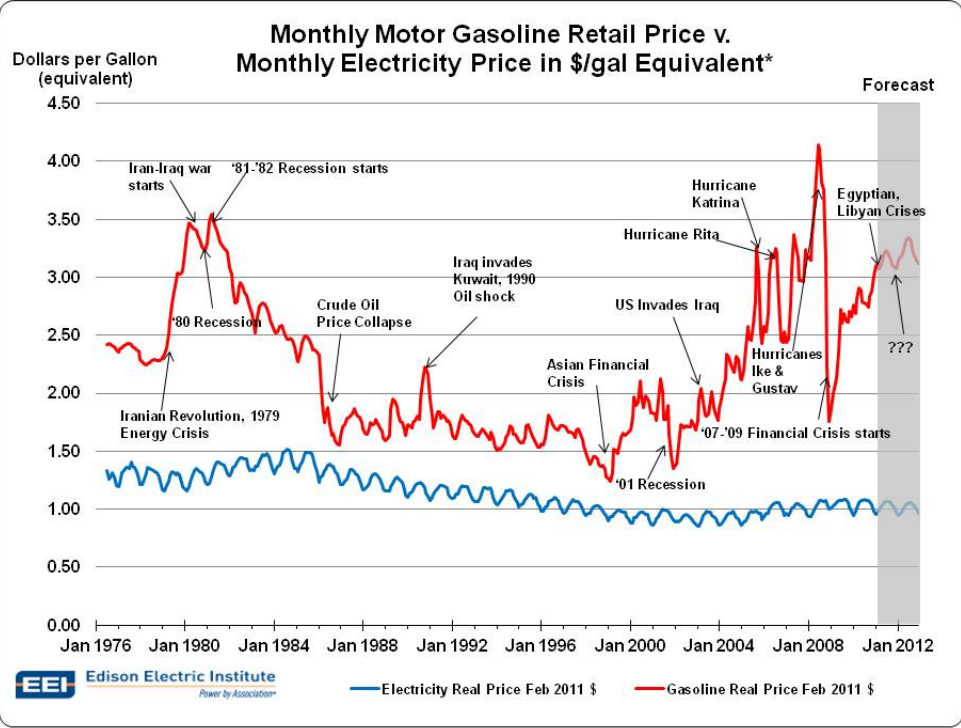


General Aviation: Cirrus SR-22  
Gross Weight ~ 3400 lb  
L/D<sub>cruise</sub> ~ 11  
Wing loading = 25 lb/ft<sup>2</sup>

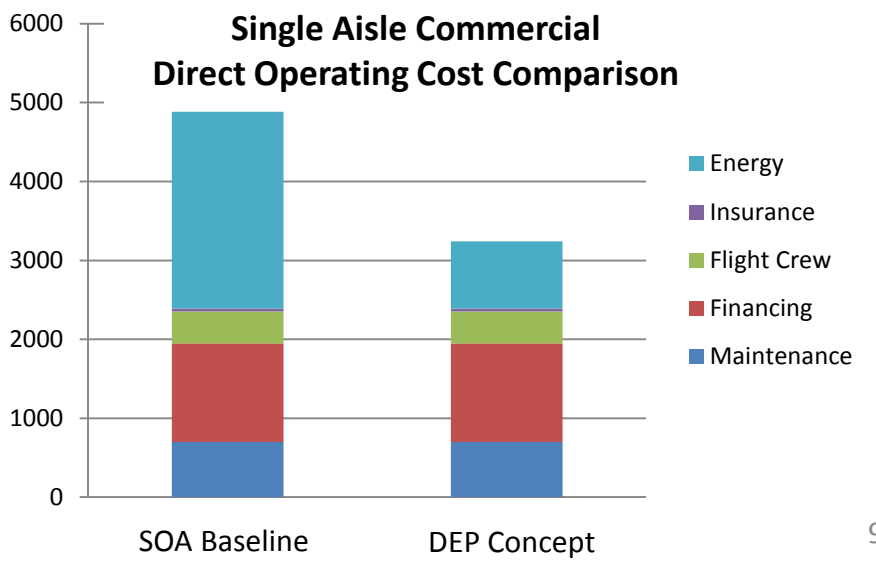
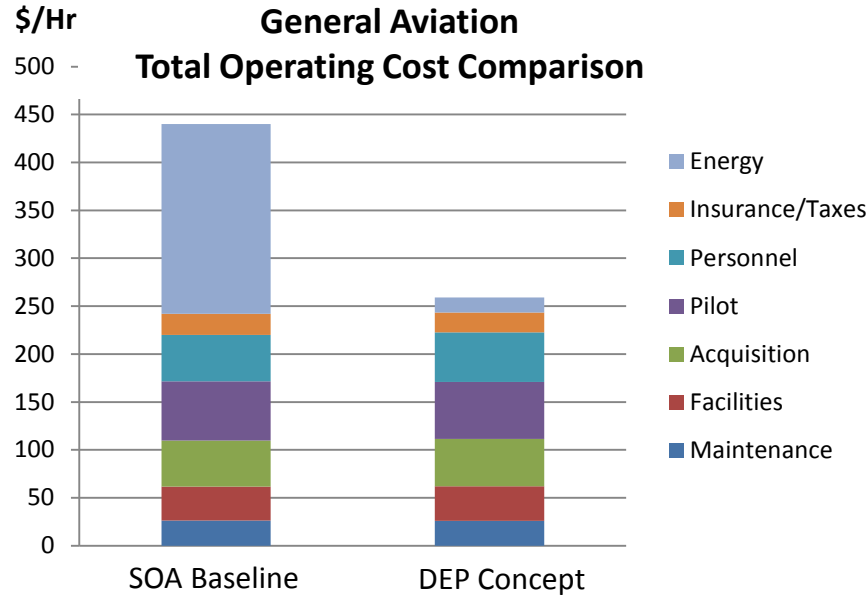
**Electric propulsion integration benefits decrease with larger aircraft due to the superior baseline metrics, but still offer compelling benefits across efficiency, emissions, noise, and operating costs.**



# Rapid Technology Adoption is Incentivized through Operating Cost Robustness and Reductions



**Electricity based aircraft energy provide a decrease in price variability and cost risk as well as a true renewable energy path (100LL fuel is ~2x higher cost than auto gas)**

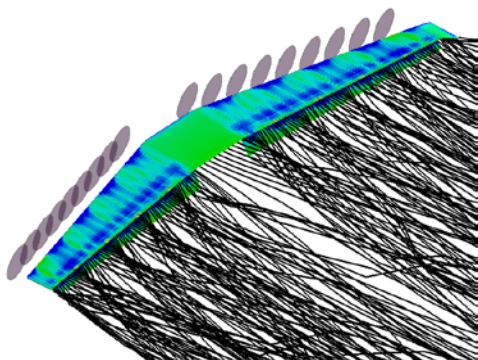




# Key Relevant Discipline Technologies

## Distributed Aero-Propulsion Tools

(Patterson-German/Georgia Tech)



## Aero-Propulsive Highlift System

(Stoll/Joby Aviation)

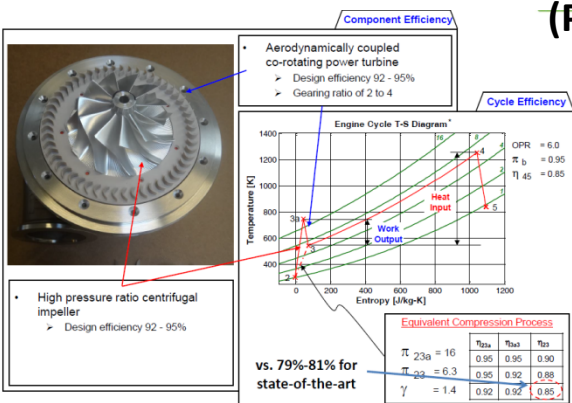
## Low Tip Speed Propellers

(Borer/NASA Langley presentation)



## Asynchronous Motor/Propeller Frequency Spreading

(Palumbo-Allen/NASA Langley presentation)



## Range Extender APUs

(Keogh/Metis presentation)

## Advanced Electric Motors

(Ricci/Launchpoint presentation)



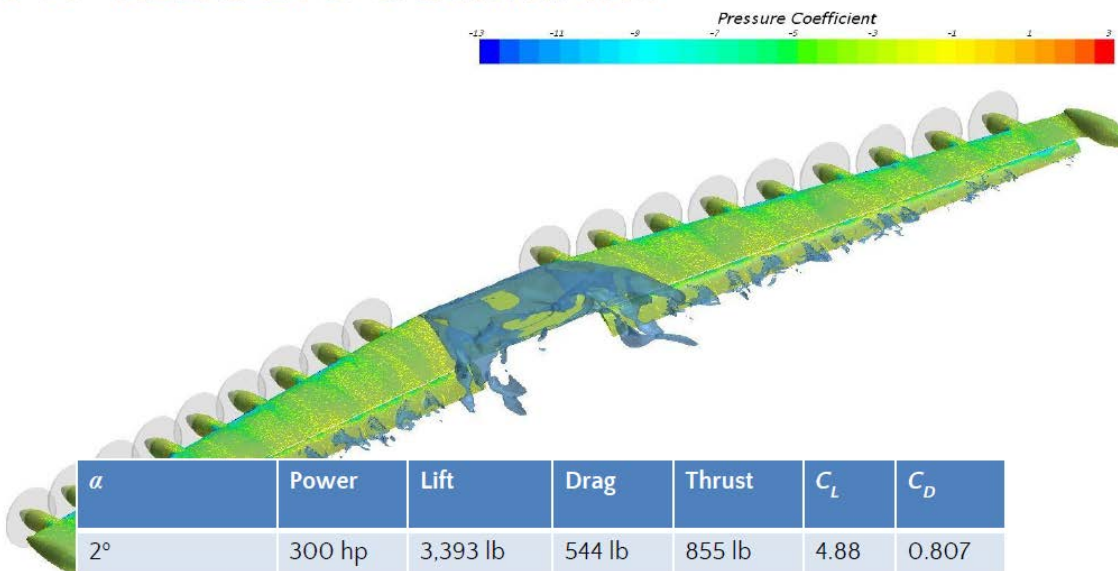
## Robust/Redundant Aero-Propulsive Digital Control

(Rothhaar/NASA Langley presentation)

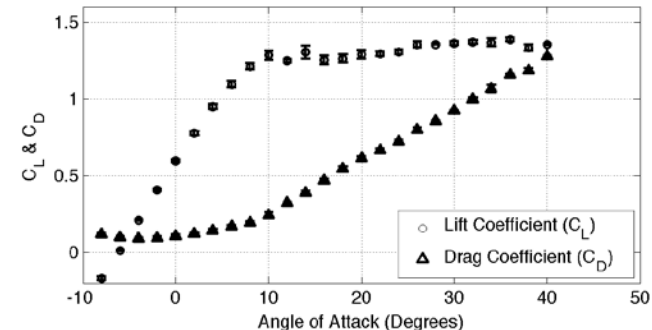
# Aero-Propulsive Highlift Integration Effects



## CFD RESULTS SUMMARY



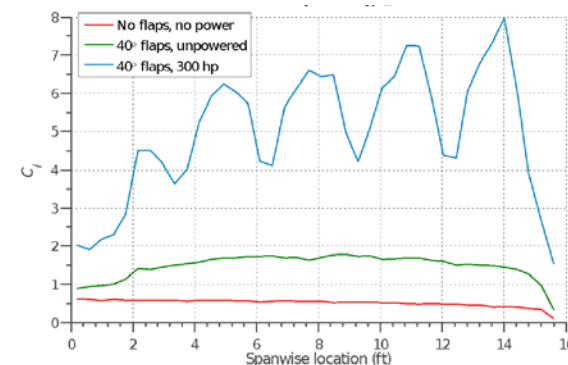
$\alpha$	Power	Lift	Drag	Thrust	$C_L$	$C_D$
2°	300 hp	3,393 lb	544 lb	855 lb	4.88	0.807
6°	300 hp	3,498 lb	622 lb	855 lb	5.03	0.923
8°	300 hp	3,376 lb	715 lb	855 lb	4.86	1.061
10° (shown)	300 hp	3,368 lb	756 lb	855 lb	4.85	1.123



Wind Tunnel Test Unpowered CL's



Simulated Humpback Whale Tubercles

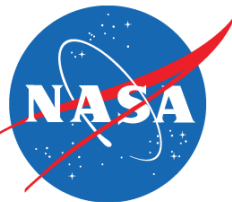


Lift Distribution at CLmax

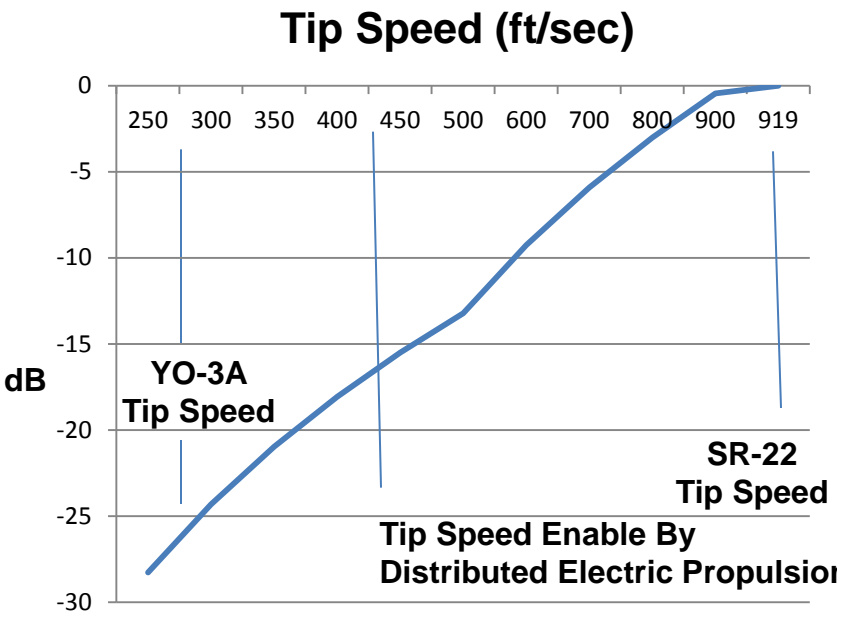


Aero-propulsive CFD results at 40 deg flap condition  
(Courtesy Alex Stoll/Joby Aviation)

See: Theoretical and Experimental Investigation of the Leading Edge Tubercles on the Wing Performance, AIAA Paper 2013-4300

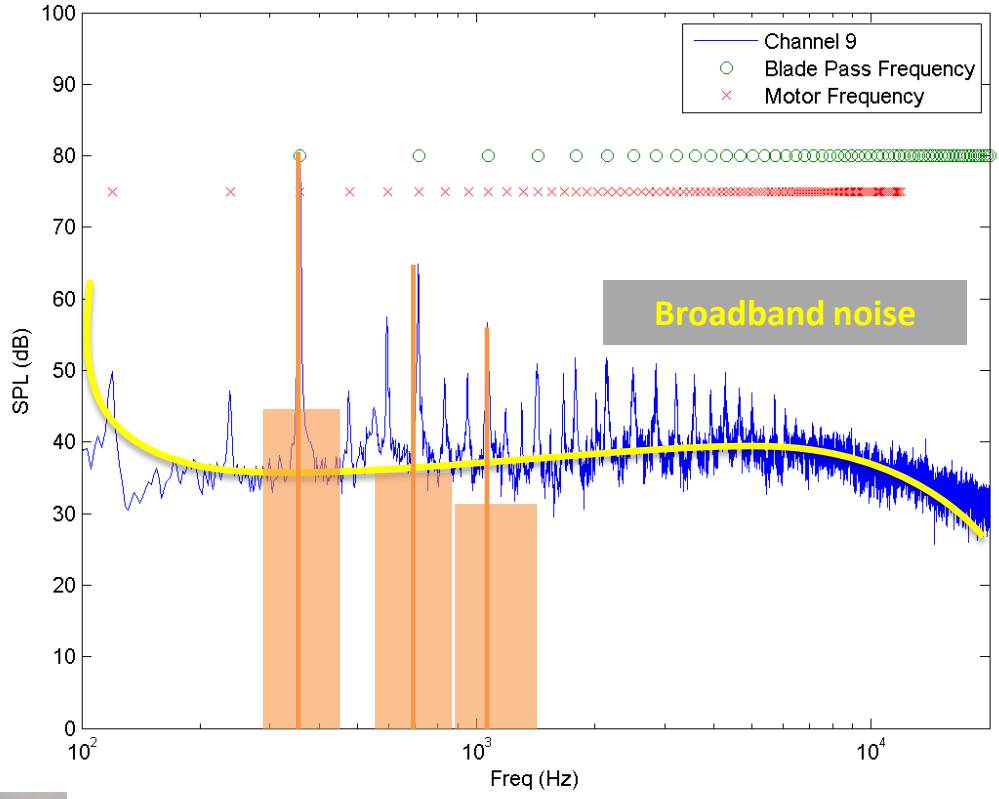


# Low Tip Speed/Asynchronous Propeller Acoustics



Effect of Propeller Tip Speed on Noise Level

## Conceptual Effects of Frequency Spreading

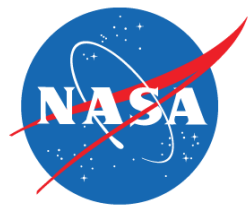


## Conventional Single 3-Bladed Propeller Harmonics

(18) Asynchronous 5-Bladed Propellers that Spread a single Blade Passage Harmonic across 30 Harmonics that Blend into the Broadband as 'White Noise'

# Research Path for Quickly Understanding this New Technology

---



**Rapid conceptual design study**

**Wind tunnel testing**

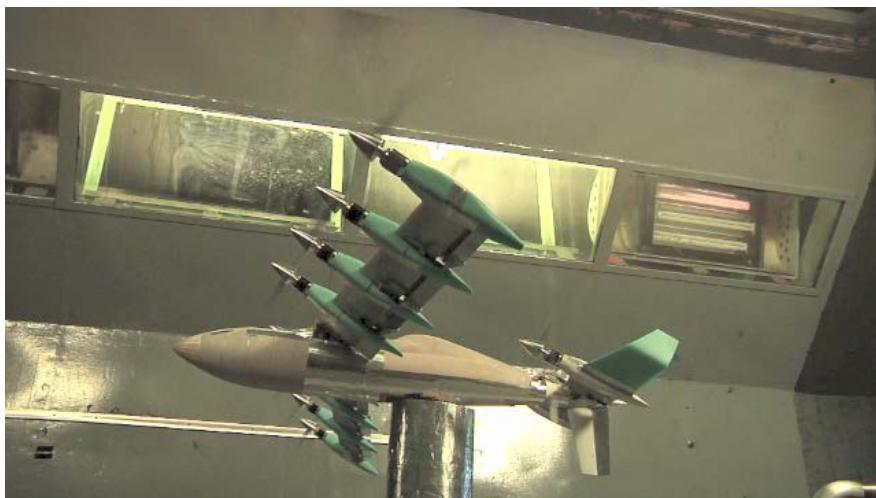
**Sub-scale UAV flight testing**

**General Aviation scale mobile ground rig testing**

**General Aviation X-Plane demonstrator**

**(With design iteration between each spiral development phase)**

# Rapid Sub-Scale Testing to Achieve Hardware Experience



12' LaRC wind tunnel testing for establishing the control aerodynamic database



Compare to XC-142 and CL-84 Tiltwings which experienced transition buffet control issues

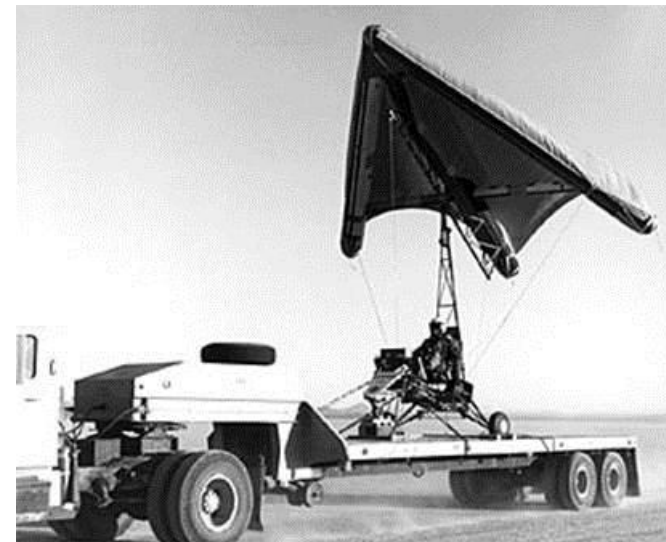
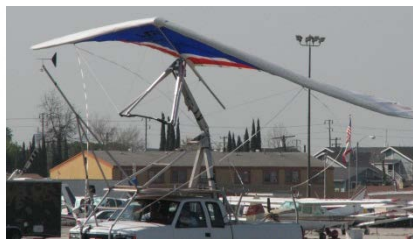
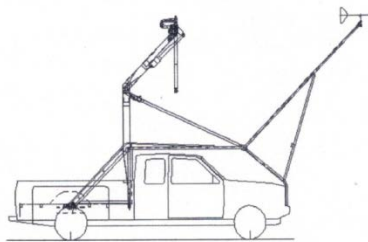


NASA GL-10 sub-scale flight demonstrator (10' span, 62 lbm)



# Larger Scale Affordable Flight Testing

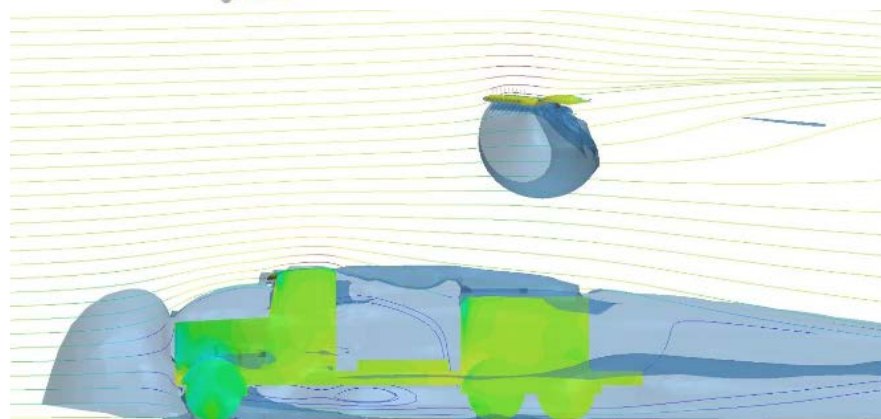
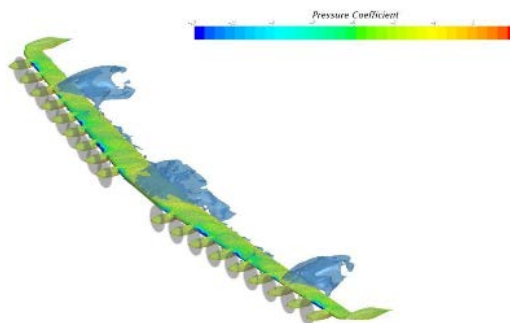
Many prior attempts (successes and failures) formed the basis to determining how affordable mobile ground testing could be utilized.



# Current Year Testing

Phase I FY14 ARMD Team Seedling Research (LaRC/AFRC/Ames/GRC Collaboration)

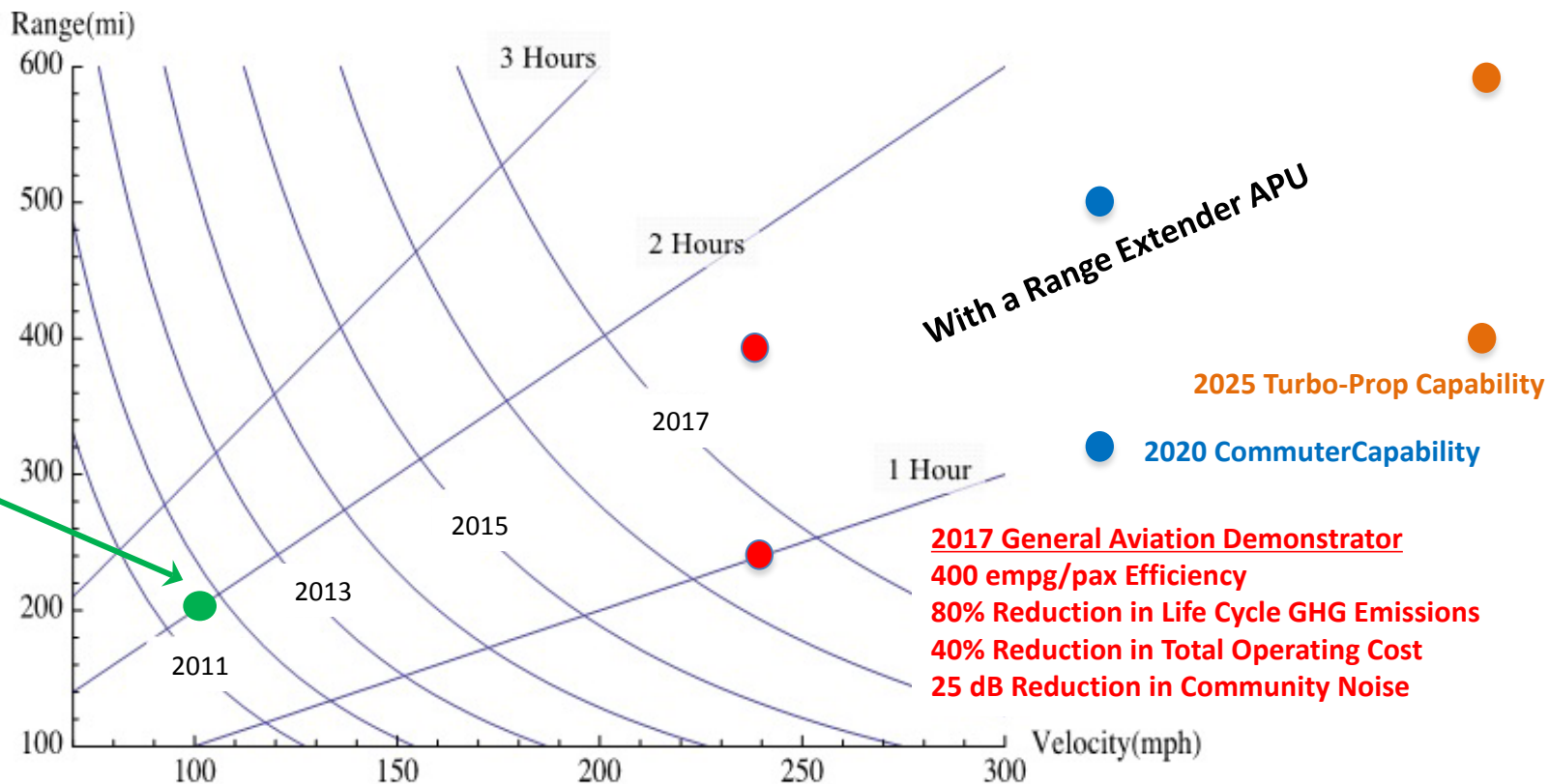
- Provides full-scale 31 ft span test validation of the critical highlift system CFD metric at the actual 61 knot stall speed conditions (TRL advanced from 3 to 5)
- Provides validation of a low cost mobile tractor-trailer ground rig 'flight' testing capability, with <math><5\%</math> error and particular relevance to the challenges existing in wind tunnel testing of aero-propulsive concepts with high induced mass flows.





# LEAPTech Development Timeline

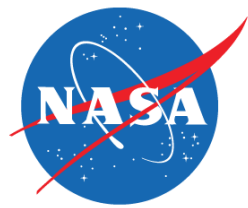
2011  
Green  
Flight  
Challenge  
403  
empg/pax



Compelling efficiency, emissions, acoustic and cost benefits could dramatically accelerate the development of DEP, initially for General Aviation, then Turbo-props, and perhaps even 737 class airliners.

# Potential Penalties Introduced by this Integration Approach

---



**Limited Range**

**High Battery Mass**

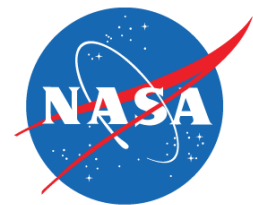
**Power Management Complexity**

**EMI Issues of High Power Cabling**

**Wing Structural Mass of Aspect Ratio 17 Wing**

**Aeroelastic Behavior with Distributed Wing Masses**

**Complexity (True vs Perceived)**



# Conclusion

NASA Langley, along with cost sharing industry partners, is developing an advanced concept through spiral development that will result in low cost flight validation that likely exhibits transformational capabilities, as a pathway to ultra-low emission commercial aviation.

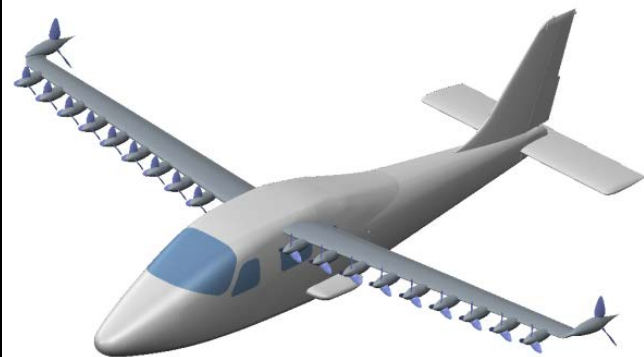
## Research Goals:

5 to 9x Lower Energy Use/Cost and Emissions  
~25 dB Lower Community Noise / Lower True Annoyance  
Robust/Redundant Aero-Propulsion Control  
Dramatically Improved Ride Quality

Retrofitting only the wing provides a low cost flight demonstration path with clear evidence of the key differences DEP integration provides, and direct comparison to reference baseline flight data.



Tecnam P2006T Light Twin



NASA LEAPTech Concept



# The Big Question

## Is Electric Propulsion Integration an Emerging Disruptive Technology?

EADS has recently funded 4 electric propulsion integration flight demonstrations

- To quickly become familiar with this new technology areas
- That have the potential to completely change the way aircraft are designed
- Offering new aviation capabilities critical to societies evolving needs

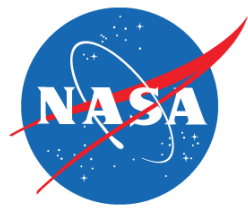
This type of spiral development provides the opportunity to

- Achieve experimentation and TRL advancement relevance across vehicle sizes due to the scale-free nature of electric technologies
- Greater control of discrete spiral element costs and risks
- Approach agility with rapidly accelerating technologies
- Experiment at low cost and consequence
- Establish early certification basis
- ‘Fail early, Often’



# Electric Propulsion Technology Integration

## Is Well Matched to Sub-Scale Concept Spiral Development



### Scale-free Nature of Electric Technologies

- Maintain most characteristics across a broad scaling range (i.e. efficiency, reliability, power to weight)
- Internal combustion and turbine propulsion technologies do not scale well (Reynolds #, surface/volume ratio, manufacturing tolerances, etc.)

### Rapidly Accelerating Technologies

- Battery energy storage is improving at a long-term rate of ~8% per year, with a 3x improvement in specific energy over the past 15 years
- Motor and controller power to weight are increasing at an ~20% per year
- Aerospace tech acceleration rates are substantially slower

### Early Certification Basis

- Composites and flat panel displays were first introduced into GA aircraft that provided lower certification hurdles, and early market entry opportunities
- Electric propulsion certification basis is currently being developed in the new ASTM F44 GA consensus standards, as the first certification basis for electric flight
- Aviation lithium batteries would have benefited from this same tech adoption pathway, as this would have provided a benefit to U.S. aerospace to establish statistical evidence and improved standards prior to large aircraft/fleet introduction (i.e. 787)