On-Demand Mobility

Electric Propulsion Roadmap

Mark Moore, ODM Senior Advisor

NASA Langley Research Center

EAA AirVenture, Oshkosh July 22, 2015

NASA Distributed Electric Propulsion Research

Rapid, early experiments to understand this new technology

NASA Distributed Electric Propulsion Research

PHASE I

Requirements Definition,
Systems Analysis,
Wing System Design,
Design Reviews

Ground validation of DEP highlift system

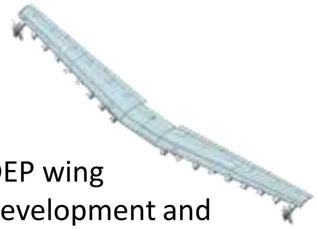
Flight testing of baseline Tecnam P2006T

Establishes Baseline Tecnam Performance

Establishes Test Pilot Familiarity

PHASE II

Concurrent Activities



DEP wing development and fabrication

Ground and flight test validation of electric motors, battery, and instrumentation.

Establishes Electric Power System Flight Safety

Establishes Electric Tecnam Retrofit Baseline

PHASE III

Flight test electric motors relocated to wing-tips, with DEP wing including nacelles (but no DEP motors, controllers, or folding props).

<u>Achieves Primary Objective</u> of High Speed Cruise Efficiency

PHASE IV

Flight test with integrated DEP motors and folding props.

<u>Achieves Secondary Objectives</u>
DEP Acoustics Testing
Low Speed Control Robustness
Certification Basis of DEP Technologies

What are the ODM Technical Challenges?

Current General Aviation (GA) Aircraft compared to Regional Airliners

- **Poor Aerodynamic and Propulsive Efficiencies**
  - Aerodynamic efficiency measured as Lift/Drag ratio is 9-11 compared to 17-20.
  - (Thermal) x (propulsive efficiency) of 20-24% compared to 36-40%.
- **Substantially Higher Operating Costs**
  - Compared to all other transportation options (car, airline, train).
- **Poor Emissions**
  - High Hydrocarbon, Green House Gas emissions, particulates and lead pollution, compared to JP fuel emissions.
- **Poor Community Noise**
  - Few improvements over the past 50 years, no significant change in certification requirements, compared to significant improvements.
- **Poor Ride Quality**
  - Low wing loading leads to bumpy ride along with gust sensitivity, compared to superior ride quality.

What are the ODM Technology Enablers?

Electric Propulsion Impact Across Technical Challenges

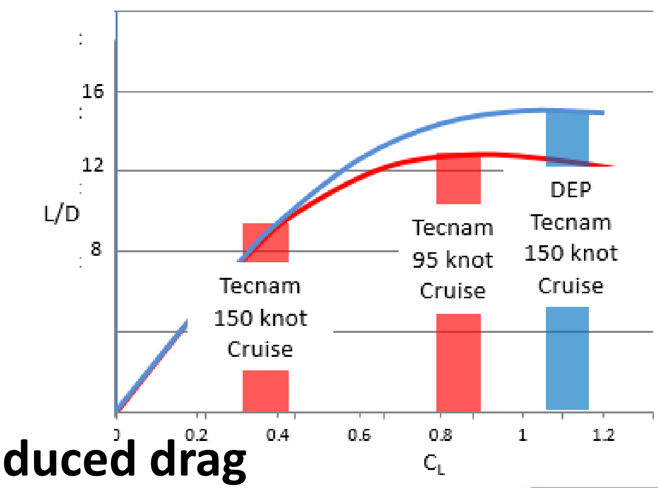
- **Aerodynamic Efficiency:** Lift/Drag ratio improved from 11 to 18.
- **Propulsive Efficiency:** Energy to thrust conversion efficiency improved from 22% to 84%.
- **Operating Costs:** Energy costs decrease from 45% of Total Operating Cost to 6%
- **Emissions:** Life cycle GHG decreased by 5x using U.S. average electricity.
- **Community Noise:** Certification noise level from 85 to <70 dB (with lower true annoyance).
- **Ride Quality:** Wing loading increased by 2-3x.

Aerodynamic and Propulsive Efficiency Goals

DEP integration into highlift system enables higher wing loading

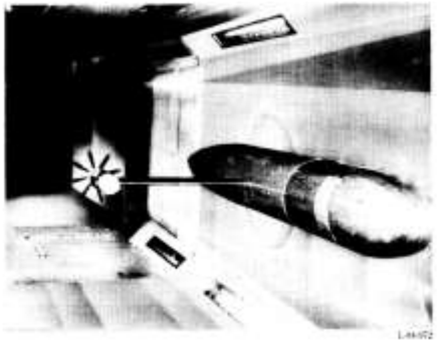
- CL_{max}: Increased from 2.0 to 5.5
- Wing area significantly decreased while maintaining stall speed and field length
- Smaller wing is able to cruise at peak aerodynamic efficiency (L/D_{max}) at high speed

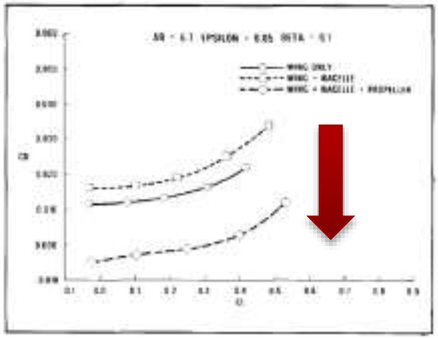
Lift/Drag Ratio vs Cruise C_L (General Aviation Aircraft)



DEP integration into wingtip vortex decreases wing induced drag

- Open rotor at wingtip increases the effective wing span downwash flow field
- Function of rotor diameter / span ratio
- Function of reference velocity / rotor rpm
- Validated in wind tunnel tests in 1980's

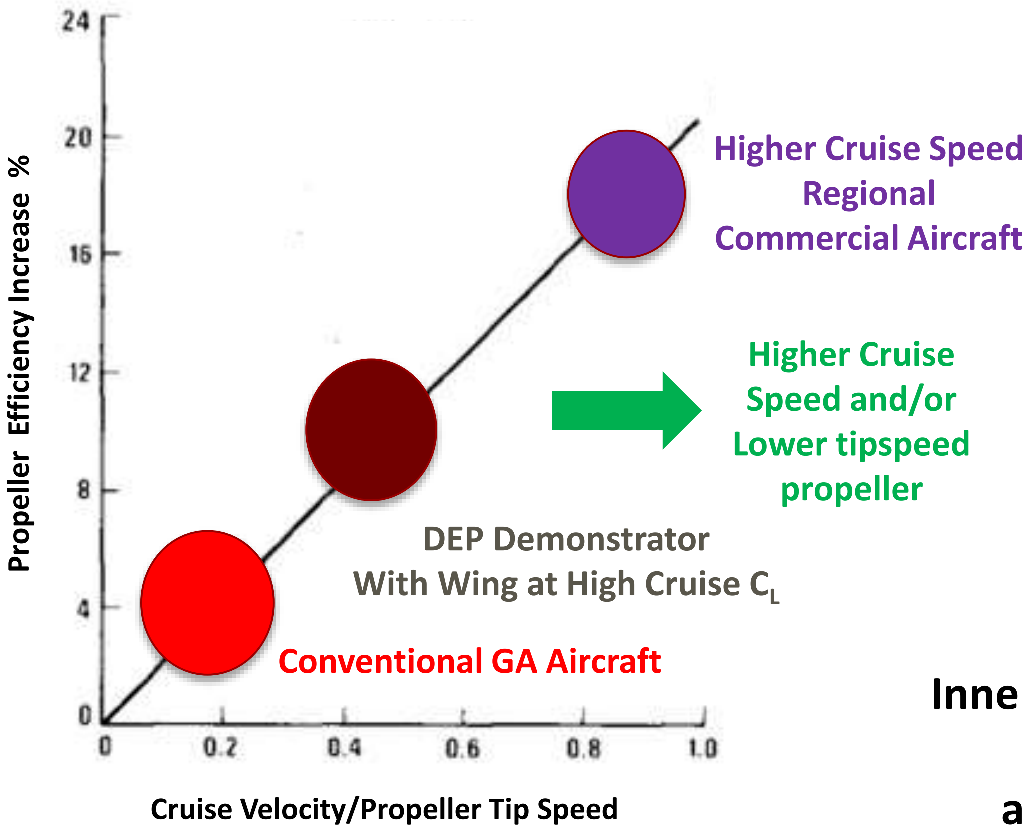




Electric motors (including controllers) are ~93%, compared to current aviation IC engines which are ~28% (IO-550) for a difference of 3.3x

Propulsive Efficiency Goal

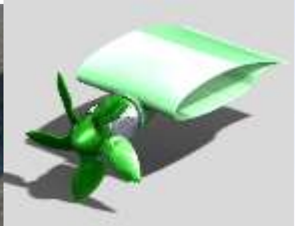
Wingtip Propulsors Increase Cruise Efficiency



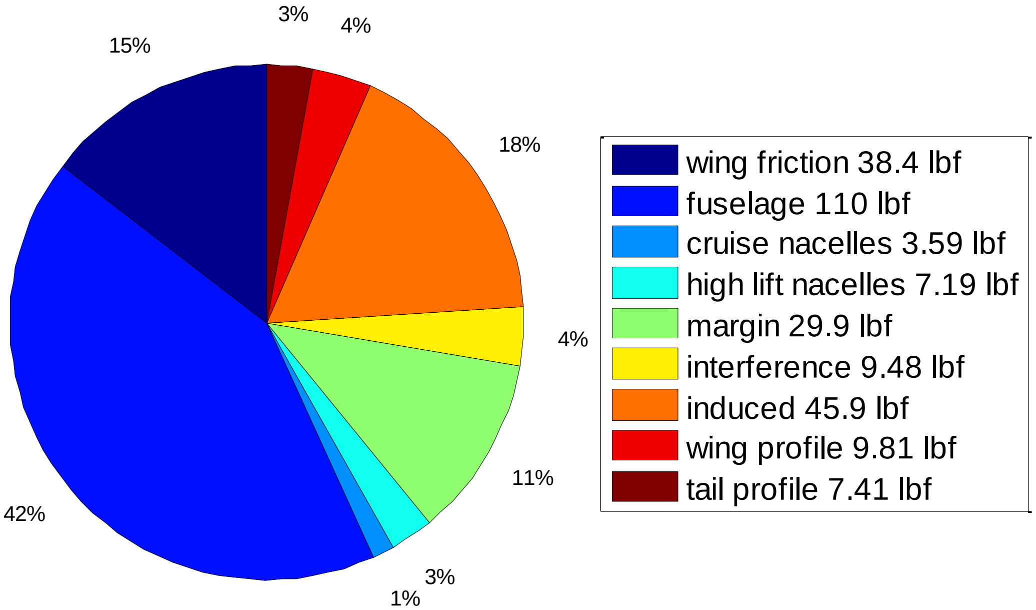
Cruise flight is performed with only the wingtip propellers.

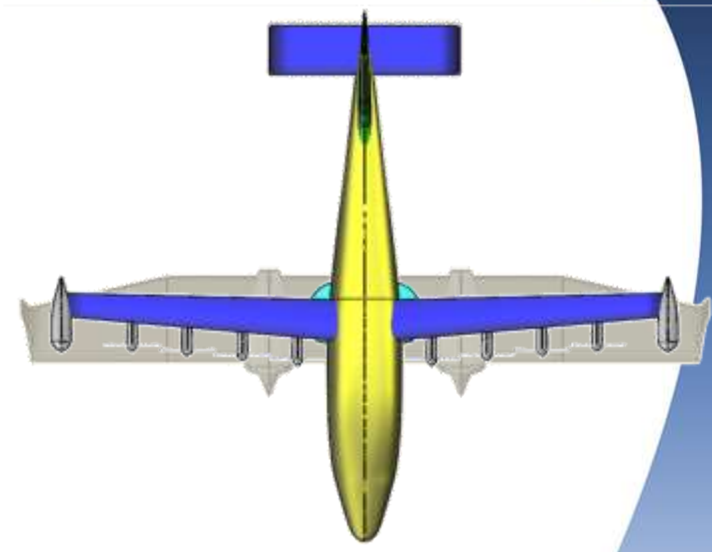
Inner span propellers are fixed pitch and fold conformal against the nacelle, and are only active at low/slow flight.

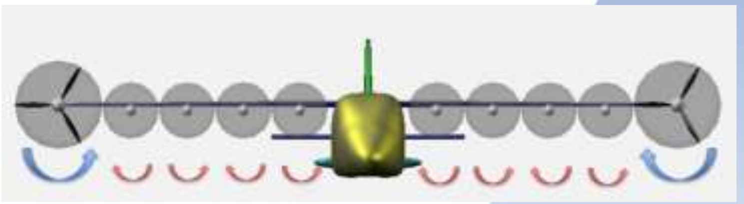
Aerodynamic Effects of Wingtip Mounted Propellers and Turbines,
Luis Miranda AIAA Paper 86-1802



Aerodynamic Efficiency Goal

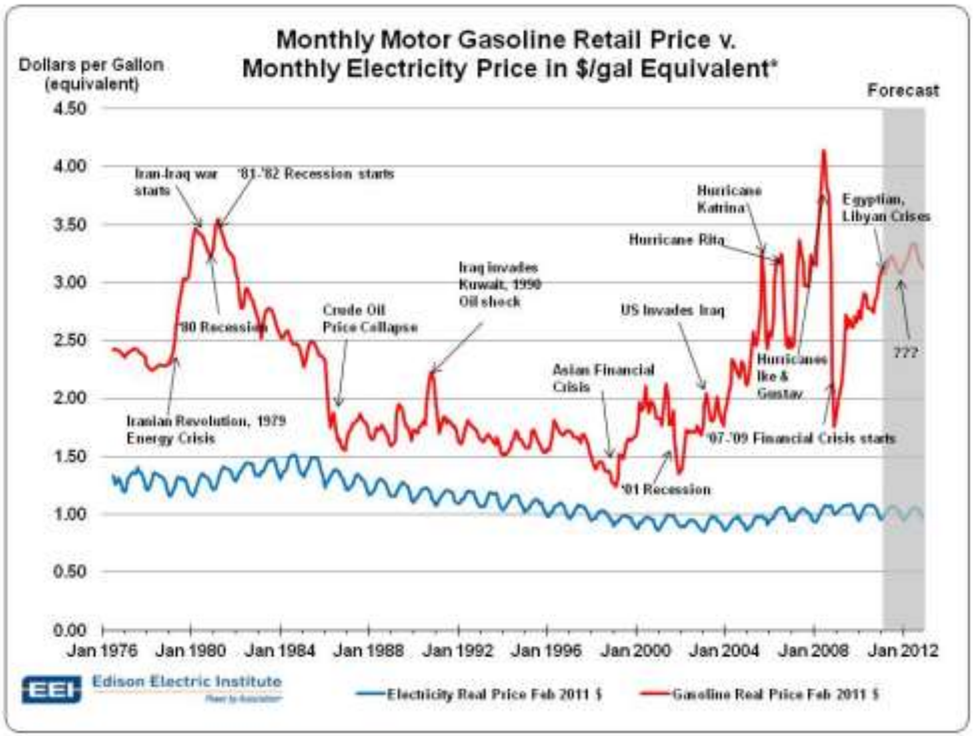


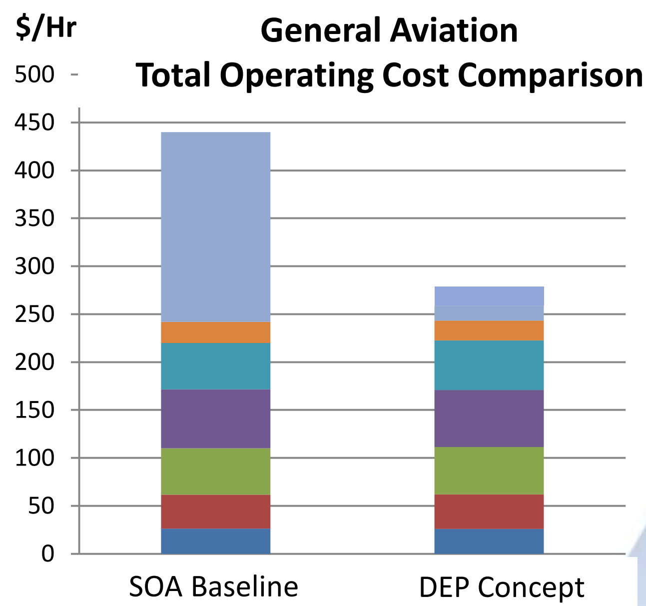




Current design shows that the fuselage drag now dominates, suggesting technologies such as fuselage Boundary Layer Ingestion could provide a significant synergistic benefit.

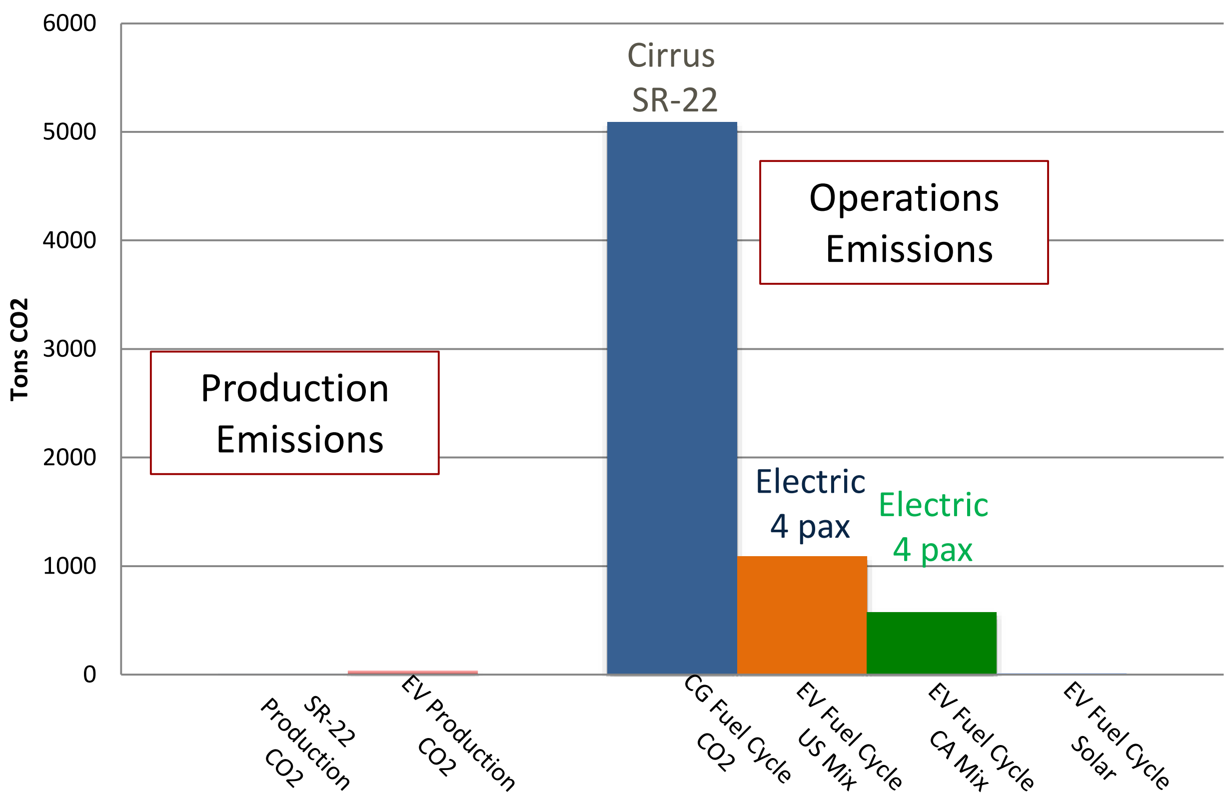
Operating Cost Goal





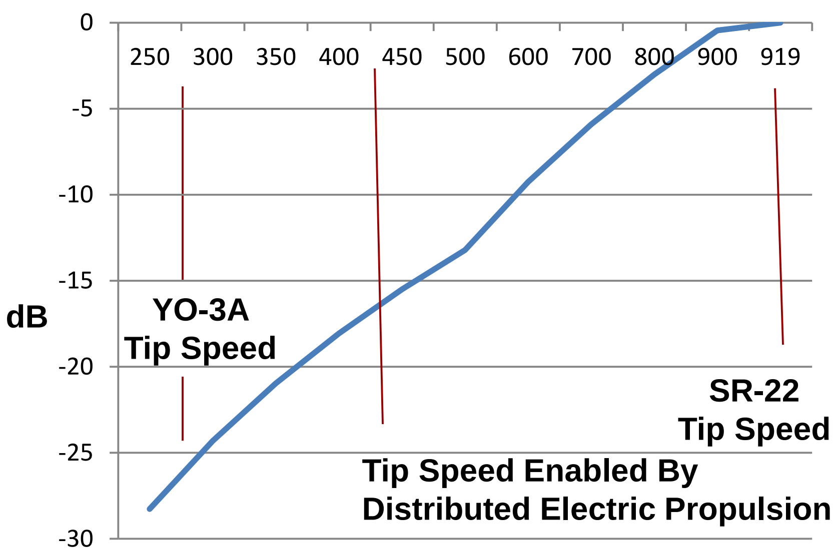
Electricity based aircraft energy provide a decrease in price variability and cost risk as well as a true renewable energy path (100LL fuel is ~2x higher cost than auto gas)

Emissions Goal



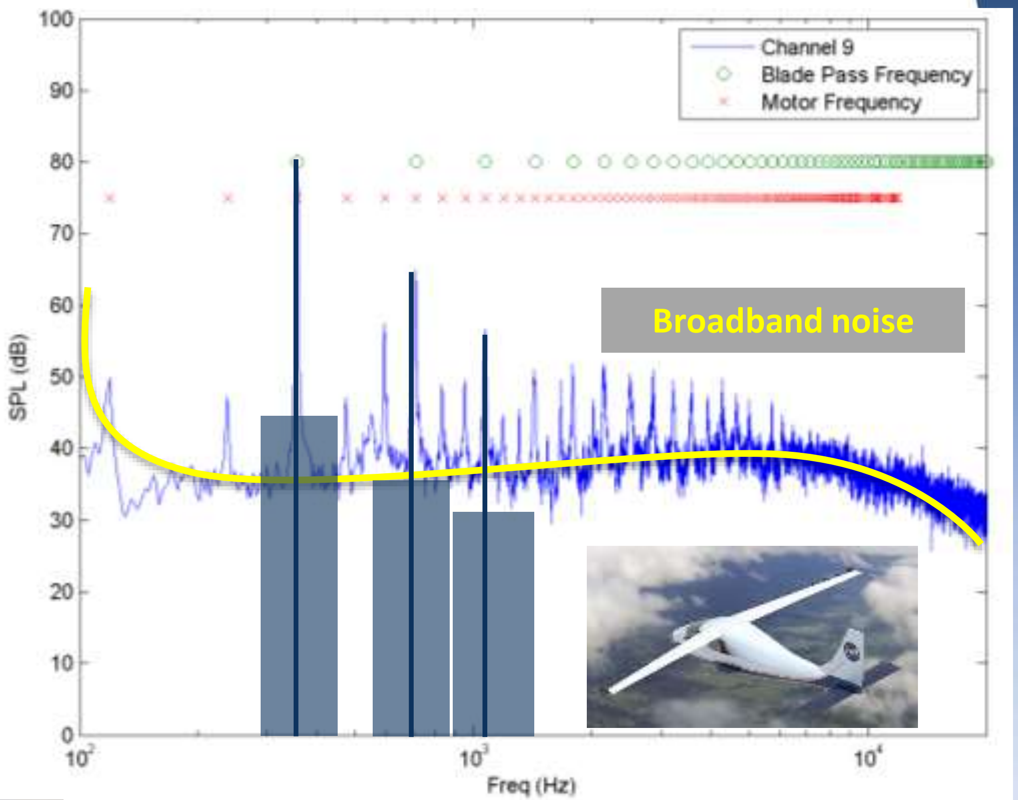
Community Noise Goal

Tip Speed (ft/sec)



Effect of Propeller Tip Speed on Noise Level
(a 5th order function)

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 instead of 1 that blends into the broadband as 'white noise'

YO-3A

Cirrus SR-22

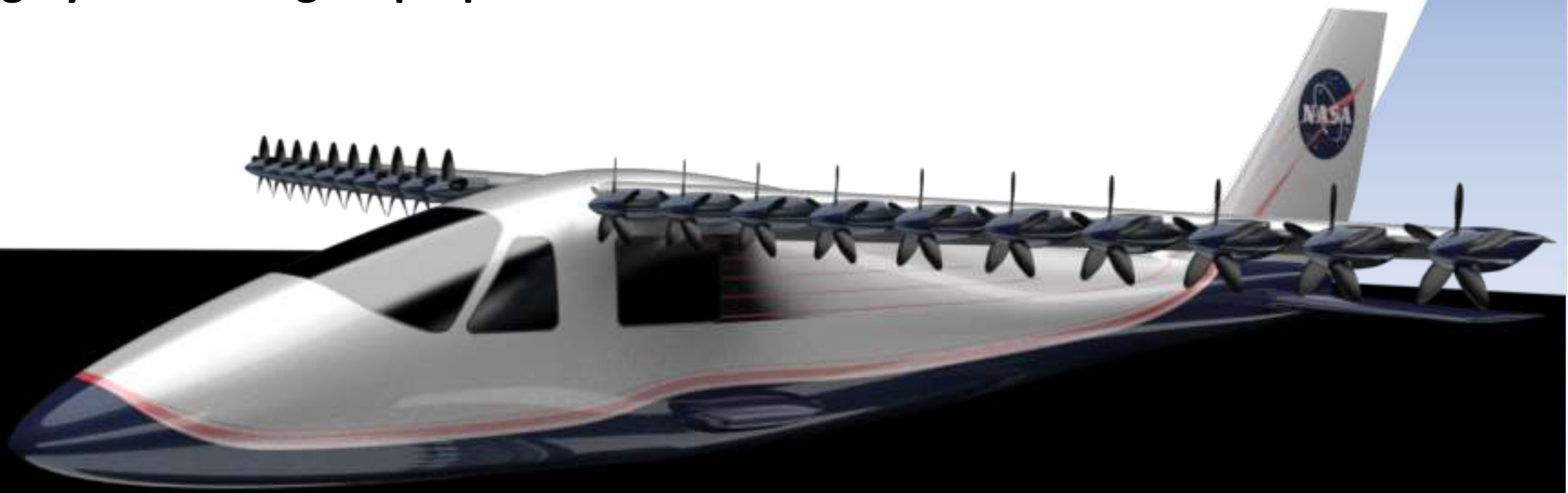
Robust Control Goal

Robust control is targeted by maximizing control authority at the low and slow operating conditions where accidents typically occur and is a combination of…

Lateral thrust based control augmentation through aero-prop coupling which increases effectiveness as lower speeds (prop induced velocity effects)

Redundant propulsion that is single fault tolerant

Highly reliable digital propulsion



Ride Quality Goal

Baseline Tecnam P2006T
17 lb/ft2 Wing Loading

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

NASA DEP Tecnam P2006T
~50 lb/ft2 Wing Loading

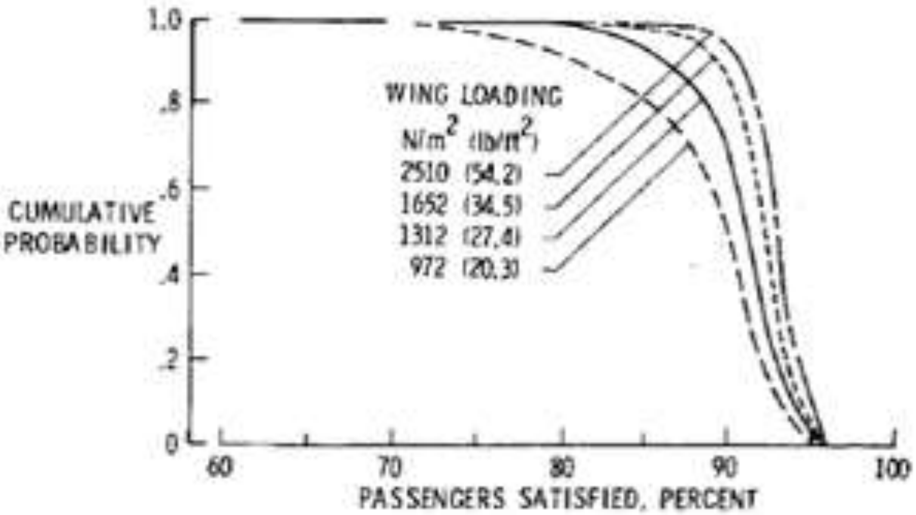


Fig. 9 Effect of variation of wing loading on ride satisfaction of commuter-type transport aircraft.

NASA Aeronautics Strategic Thrusts

Safe, Efficient Growth in Global Operations

- Enable full NextGen and develop technologies to substantially reduce aircraft safety risks

Innovation in Commercial Supersonic Aircraft

- Achieve a low-boom standard

Ultra-Efficient Commercial Vehicles

- Pioneer technologies for big leaps in efficiency and environmental performance

Transition to Low-Carbon Propulsion

- Characterize drop-in alternative fuels and pioneer low-carbon propulsion technology

Real-Time System-Wide Safety Assurance

- Develop an integrated prototype of a real-time safety monitoring and assurance system

Assured Autonomy for Aviation Transformation

- Develop high impact aviation autonomy applications

NASA Aeronautics Strategic Thrusts

Safe, Efficient Growth in Global Operations

- **Enable full NextGen and develop technologies to substantially reduce aircraft safety risks**

Innovation in Commercial Supersonic Aircraft

- Achieve a low-boom standard

Ultra-Efficient Commercial Vehicles

- Pioneer technologies for big leaps in efficiency and environmental performance

Transition to Low-Carbon Propulsion

- Characterize drop-in alternative fuels and pioneer low-carbon propulsion technology

Real-Time System-Wide Safety Assurance

- Develop an integrated prototype of a real-time safety monitoring and assurance system

Assured Autonomy for Aviation Transformation

- **Develop high impact aviation autonomy applications**

NASA Aeronautics Strategic Thrusts

Outcome: Pioneer low-carbon propulsion technology

ODM Contributions: Enable practical, wide-scale operational use of electric and hybrid-electric population in manned aircraft with a strategy of incentivizing low carbon solutions through dramatic reductions in direct operating costs at shorter ranges.

Outcome: Pioneer technologies for big leaps in efficiency and environmental performance.

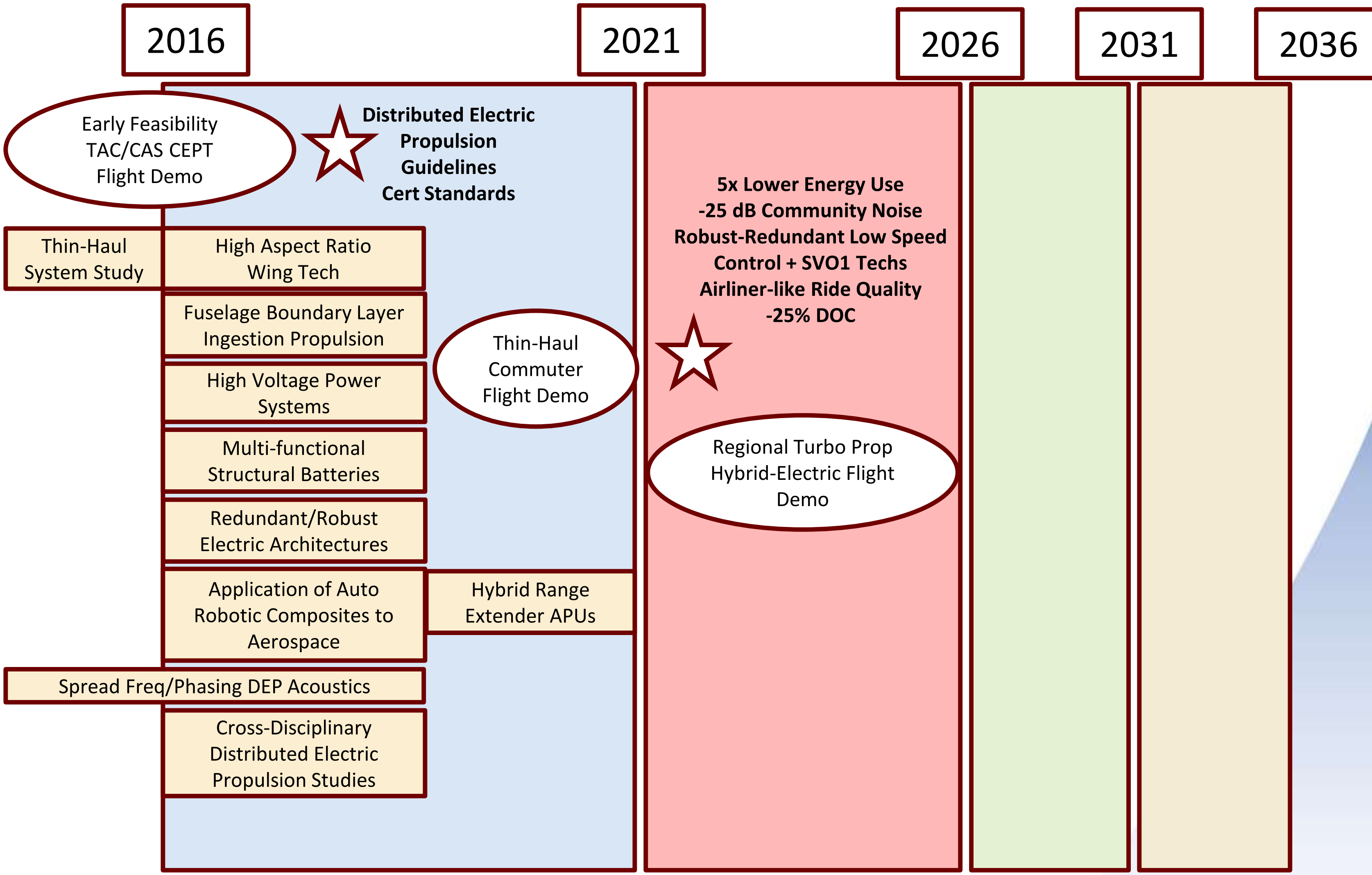
ODM Contributions: Lower cost sub-scale demonstrations of multi-use technologies (i.e. high aspect ratio wing aeroelastic tailoring, fuselage boundary layer ingestion, distributed electric propulsion integration across disciplines, hybrid-electric power architectures, robust low speed control, spread frequency and phased acoustics, cruise efficient STOL, low cost robotic composite manufacturing, etc).

ODM provides a path for introduction, validation, early adoption and certification of advanced technologies with lower cost/consequence.

ODM Outcomes to Roadmaps: Pioneer Electric Propulsion as Low Carbon Solution

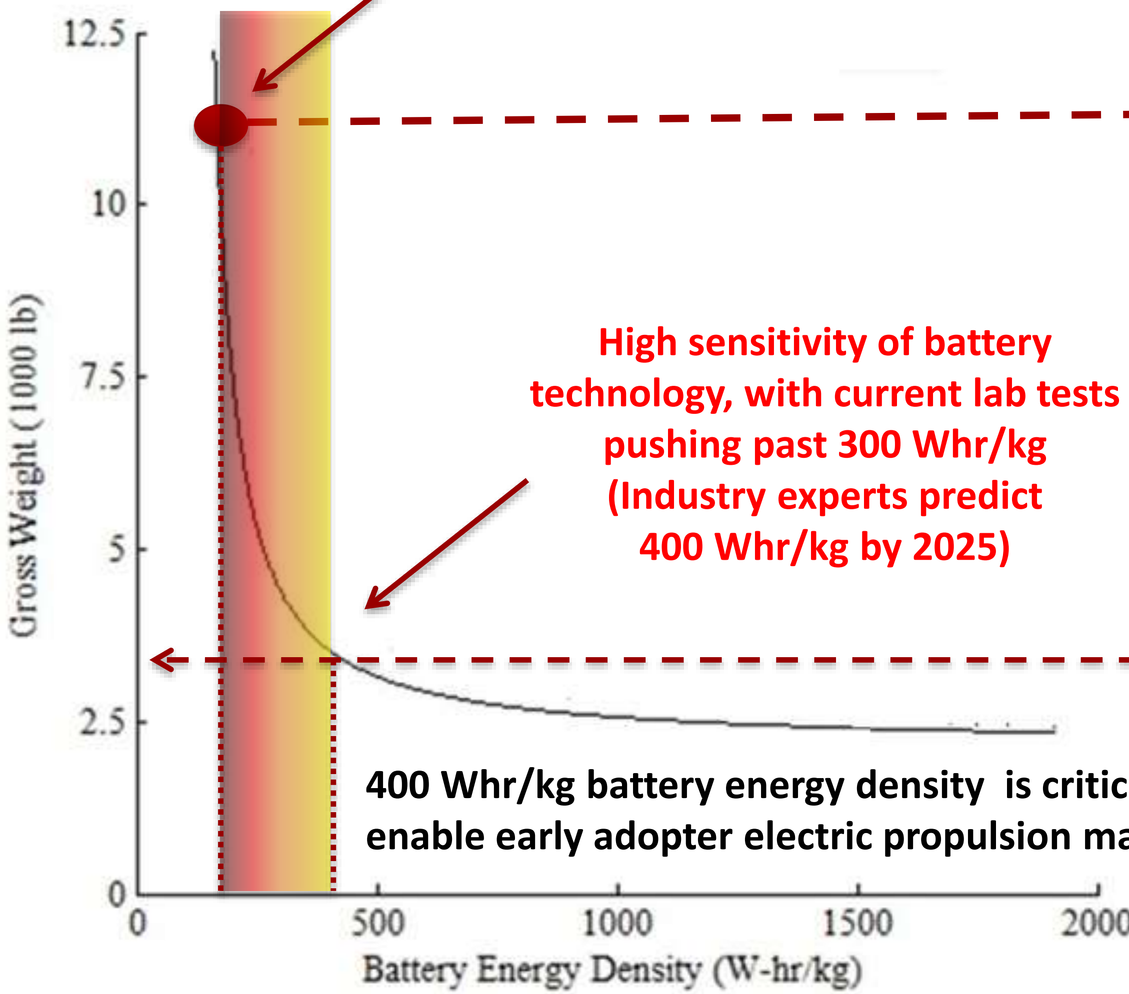
- **Electric propulsion provides a method of addressing multiple barriers with a single technology that integrates across many disciplines.**
  - Propulsive and aerodynamic efficiency, emissions, noise, control, ride quality, and structural characteristics can be significantly improved through tight coupling of distributed electric propulsion.
- **New integration strategies that maximize synergistic cross-disciplinary coupling benefits to achieve optimal vehicle system solutions**
- **Advanced electric motors and controllers**
- **Redundant and robust high voltage (>400 volts) architectures**
- **Advanced batteries and integration solutions**
  - Feasibility for ODM markets is at the 400 to 500 Whr/kg battery pack level
  - Multi-functional structural batteries to reduce battery installation weight while meeting aerospace safety standards.
- **Hybrid-electric range extenders**
  - Practical ranges of 300 to 600 nm in the near-term require hybrid-electric systems with small power systems to augment energy storage.

Electric Propulsion Technologies Roadmap



Electric Aircraft Penalty: Range

200 Whr/kg batteries



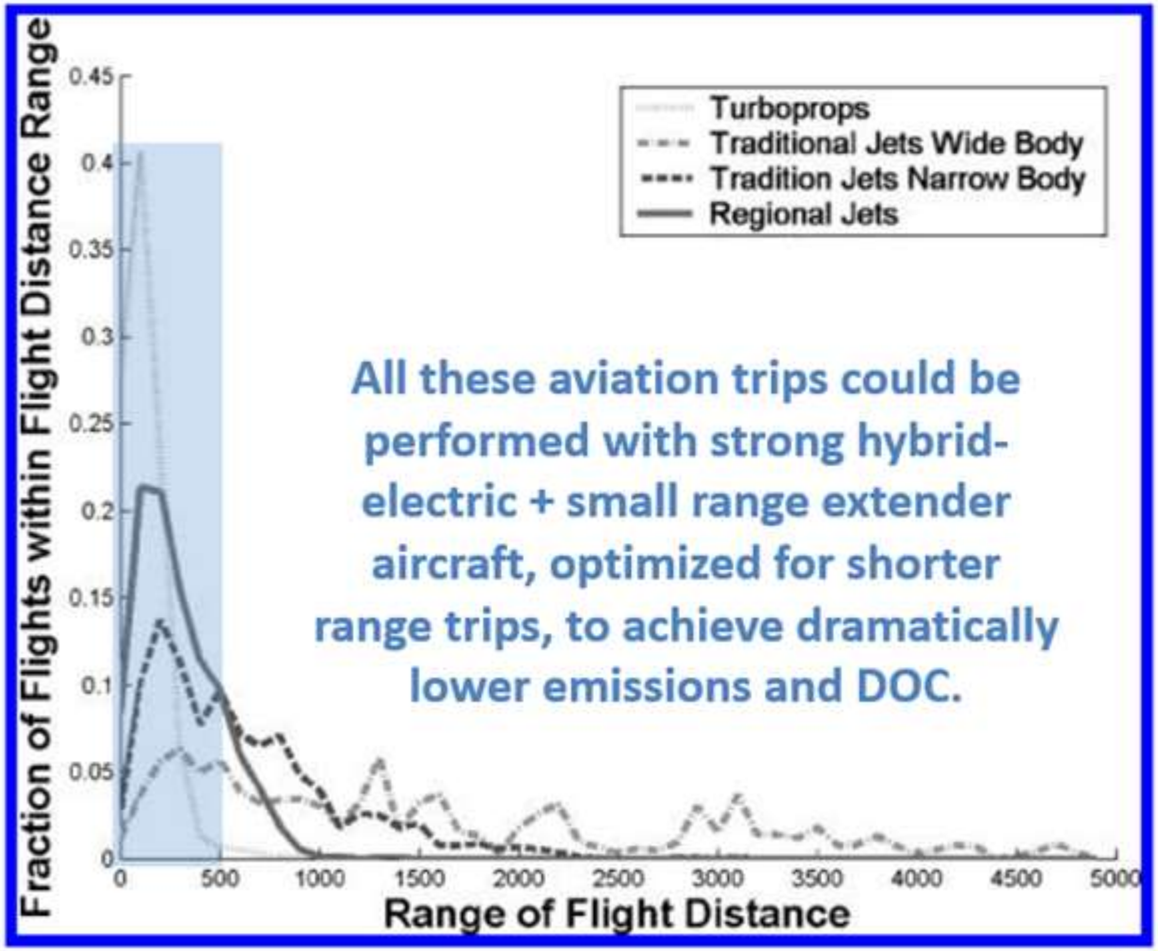
High sensitivity of battery technology, with current lab tests pushing past 300 Whr/kg (Industry experts predict 400 Whr/kg by 2025)

400 Whr/kg battery energy density is critical to enable early adopter electric propulsion markets

Cirrus SR-22
with Retrofit Electric Propulsion
200 nm range + reserves
11,300 lb

Cirrus SR-22
General Aviation Aircraft
500 nm range + reserves
3400 lb

Electric Aircraft Penalty: Range



Aviation Trip Range Distribution
Across all commercial aviation sectors
(Number of trips vs distance nm)