ODM Technical Roadmap Report Out:

Electric Propulsion Roadmap

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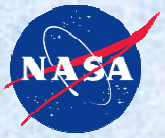
Electric Propulsion Scope

- Vision/Strategy
- ODM Goal Alignment
- Electric Propulsion Leveraging
- Electric Propulsion Technology Development Outcomes
- Electric Propulsion Study Outcomes
- Electric Propulsion Standards Development

Electric Propulsion Vision



Technologies with certification path for small commercial passenger aircraft, that achieve a compelling benefit value proposition

- Application to transformative, high-speed regional and urban transportation
- Pursue ODM goals through benefit strategies across
  - Operating cost and emission reduction through decreased energy/maintenance
  - Safety through propulsion system distribution/redundancy/reliability/robustness
  - Noise/Ride Quality through synergistic integration with aero/control/structures
- Focus on providing integrated flight demonstration opportunities across both CTOL and VTOL missions applications

Scale-up strategy has strong linkage to NASA's strong investment in commercial transport technologies

- Focus on pushing to higher power levels, more complex hybrid-electric bus

Scale-down strategy has strong linkage to UAV and professional hobbyist markets

- Leverage lower cost components produced to push towards COTS availability

ODM Roadmapping Process

Stakeholders
Industry, FAA
NASA

ODM Barriers,
Figures of Merit

Outcomes & Vision

Technology
Survey, Candidates

Research Themes

Roadmaps,
Technical Challenges

ARMD
Strategic
Thrusts

Specific project
challenges, Investments

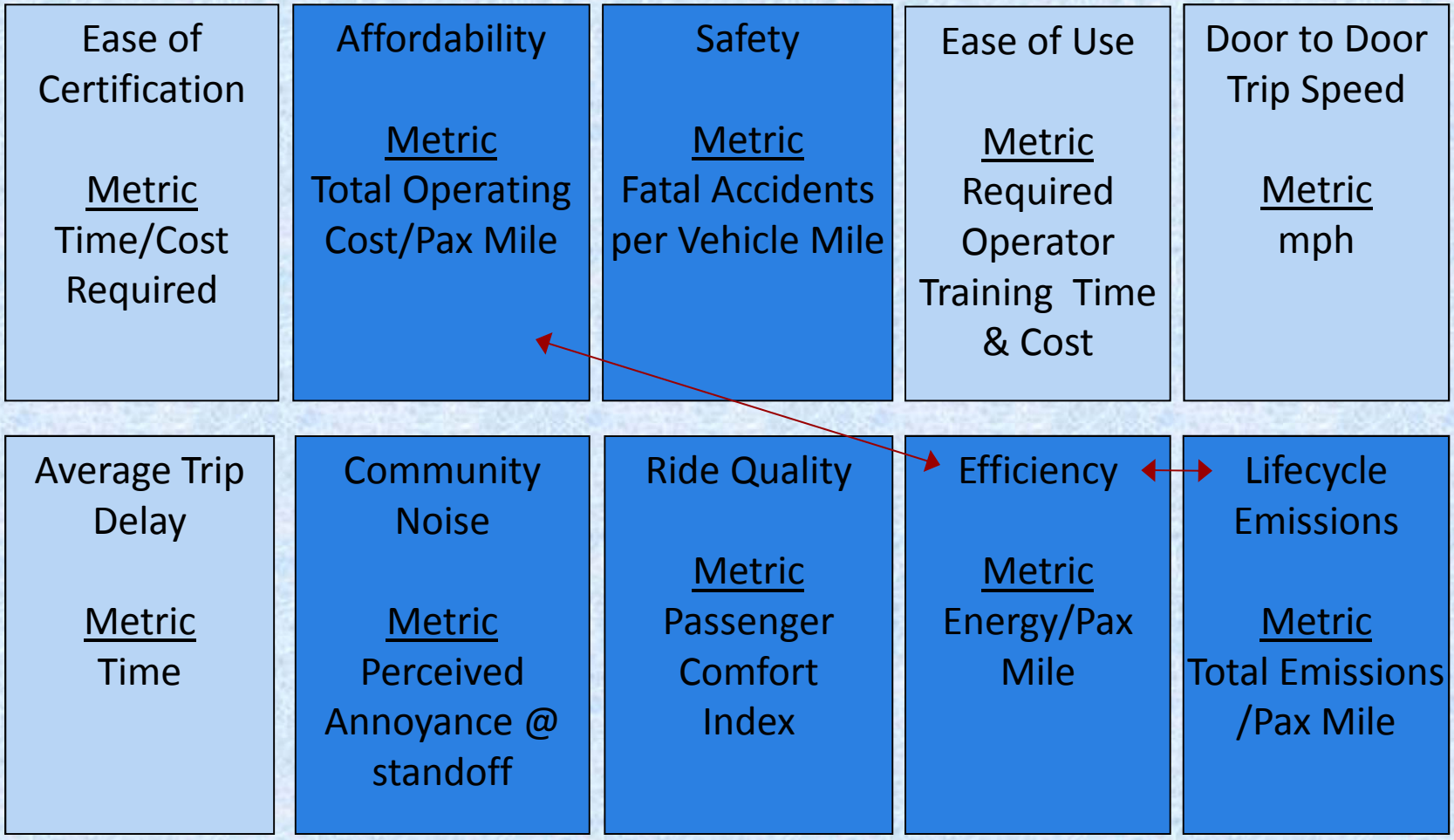
ODM Barriers & Figures of Merit

Ease of Certification Metric Time/Cost Required	Affordability Metric Total Operating Cost/Pax Mile	Safety Metric Fatal Accidents per Vehicle Mile	Ease of Use Metric Required Operator Training Time & Cost	Door to Door Trip Speed Metric mph
Average Trip Delay Metric Time	Community Noise Metric Perceived Annoyance @ standoff	Ride Quality Metric Passenger Comfort Index	Efficiency Metric Energy/Pax Mile	Lifecycle Emissions Metric Total Emissions /Pax Mile

Product of Kansas City Workshop, Oct. 2015

ODM Barriers & Figures of Merit

Electric Propulsion Contributions



Primary **Secondary**

Electric Propulsion Leveraging

Flight Demonstrators: ODM-scale integrated test beds (FDC investments)

- Current RFI for VTOL and CTOL hybrid-electric approaches

STTR/SBIR: Distributed Electric Propulsion STTR, and Electric VTOL SBIR

Energy Storage: ODM-scale increase energy density (CAS investments)

- Solid Oxide Fuel Cell (SOFC) FUELEAP ~100 kW complete flight system

Scale-up: Regional commercial transports (Leverage AATT and TTT investments)

- High voltage power systems, hybrid-electric power bus architectures
- High aspect ratio wing structures and DEP aeroelastic behavior
- DEP and low tip speed acoustics

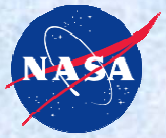
Scale-down: UAVs (Leverage CAS and SBIR investments)

- Series hybrid range extenders: 1.5 kW Launchpoint, 28 kW GSE reciprocating, 40 kW Metis micro-turbine

External Leveraging:

- Batteries: High specific energy batteries capable of 3C discharge/high cycles
- Chargers: Higher voltage/power, pulse chargers capable of rapid charging

Electric Propulsion Technologies



ODM Electric and Hybrid-Electric Power System Development

- Turbine-alternator-recuperator series hybrid system (likely desired size of ~300 kW to meet both Urban VTOL and Thin-Haul CTOL needs, also relevant to commercial APU scale-up)
- Advanced electric motor/controller, methods to limit need for gearboxes and liquid cooling complexity, achieve integrated thermal management, tighter motor-controller integration, with ODM-scale hardware demonstrations (at ground and flight TRLs)

ODM Electric Aircraft Optimized Energy Storage

- Battery cell to pack mass fraction improvement while achieving cell spacing and cell failure propagation containment, lightweight battery management/monitoring systems, as well as crash containment able to meet FAA certification requirements
- Advanced battery cell chemistry and packaging optimization to meet aviation mission loads, discharge profiles, recharging turn-around needs, and reserve requirement/high cycle life

ODM Optimal Electric Power Architectures

- High voltage (400-800 volt) power architectures that investigate combinations of battery types, superconductors, fuel cell, hybrid-engines, etc. to achieve high stability/robustness, including the ability to achieve low EMI interference with instrumentation/control communications

Electric Propulsion Studies

Investigation of Distributed Electric Propulsion Integration Strategies

- Aerodynamic Investigations: Highlift system, Wingtip vortex, Fuselage boundary layer coupling, Split-wing embedded integration, …
- Control Investigations: Enhanced control through digital-fly-by-wire integration of propulsion into inner-loop control augmentation.
- Structural Investigations: Multi-functional and distributed energy storage application to configurations.
- Acoustic Investigations: Integration approaches that utilize variable propeller speed, airframe shielding, blade harmonic frequency tuning, etc.

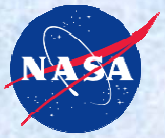
Energy and Maintenance Cost Reduction Quantification

- Energy: Urban VTOL/Thin-Haul CTOL working group focused fleet studies
- Maintenance: Electronic power system component reliability studies…

Life Cycle Emissions Reduction Quantification

- Wings to well analysis studies that can provide common emissions basis across ODM missions and electric/hybrid-electric architecture approaches

Electric Propulsion Standards



- **Modified Electric Energy Reserves:** Activities already initiated in GAMA/EPIC potentially needing supporting simulation/mission studies that can provide analytical basis for reduced reserves specifically for shorter range trips with high density of alternate emergency landing locations.
- **Multi-Engine Control for Electric Aircraft:** Provide basis for control of multi-electric motor propulsion solution through integrated motor controller and the associated required pilot training. (i.e. address E-fan certification dilemma and initiate DEP master controller implementation pathways)
- **Electric Energy Storage State of Charge Management:** Establish standard for determination of distance/time/power level available across operating conditions (temperature, battery life, etc). Including human interface issues that assist with decision making across electric and hybrid-electric power systems.
- **Electric Motor/Controller Testing:** Part 33 equivalence while accounting for flight criticality integration determination of redundant propulsion and energy storage
  - Is a small series hybrid engine a flight critical component if a battery provides sufficient energy to meet reserves.
  - Are partial failure modes addressed, i.e. dual windings on a single motor with multiple controllers.

Electric Propulsion Roadmap Timeline

2016	2021	2026
Proof of Feasibility, Concept Exploration, Certification Requirements, Basis	Design, Development, Certification, Validation of Operational Prototypes	Early Operations, Maturation, Redesign, Extension, and Technology Scaling


X-57

Thin-Haul X-Plane


VTOL X-Plane

Scale-Down Tech Integration


Initial Operational Vehicles


Scale-Up Tech Integration

Leveraging

- Thin-Haul Hybrid System Flight Demonstrator
- VTOL Hybrid System Flight Demonstrator
- SBIR/STTRs
- High Aspect Ratio DEP Aeroelastic Wing
- High Voltage Systems
- SOFC System
- Integrated Motor-Controller
- DOE 500 Batteries Chargers
- DEP and Low Tipspeed Acoustics
- Beyond Lithium Batteries
- Small Scale Range Extenders

Studies

- Distributed Electric Propulsion Integration for ODM Missions
- Boundary Layer Ingestion Propulsion Validation
- Energy and Maintenance Cost Quantification
- Life Cycle Emissions Quantification

Technologies

- ~300 kW Recuperated Turbine-Alternator
- Optimized Batteries for Aviation Discharge/Recharge Profiles
- Highly Stable Hybrid Power Architecture with EMI/Comms
- Aircraft Optimized Energy Storage
- Integrated Thermal Management Surface Cooling
- Advanced Electric Motors-Controllers Avoiding Gearbox, Liquid Cooling

Standards

- *Modified Electric Energy Reserves (Initiated by GAMA)*
- *Multi-Engine Control for Electric Aircraft*
- *Electric Motor-Controller Testing*
- *Electric Energy Storage Management*