Order of Presentation

Task Overview → Data Collection → Data Analysis → Recommendations → Summary
Task Overview
## Task Background and Scope

### Motivation
- The eVTOL industry is racing toward implementation of UAM
- The passenger experience will differ from current operations, but little has been done to address the differences
- Costly redesigns may be necessary to address passenger concerns, inhibiting industry growth
- Passenger needs should be accommodated early in development

### Objectives
- **Survey the existing body of knowledge** regarding aviation passenger experience
- **Understand current issues** pertaining to eVTOL passenger operations
- **Correlate passenger issues** to design and operational parameters
- **Identify mitigations** and gaps in understanding
- **Develop recommendations** for NASA research

### Approach
- Literature surveys
- SME interviews
- Data analysis
- Quality Function Deployment
- Design and operational mitigations
- Gap assessment
- Recommendations
Data Collection
Overview of Findings from Literature and SME Inputs

Overview

Data Collection

- Focused on turbulence in fixed-wing passenger aircraft
- Noise and vibration were primary stimuli
- Developed metrics for annoyance and motion sickness
- PRQA (Passenger Ride Quality Apparatus) built for human experiments

Large body of ride quality work done at LaRC in the 1980s

- Some studies focused on Hybrid Wing Body (focus on seating arrangement, egress, and visibility) and High Speed Civil Transport (focus on longitudinal flexibility)
- Exception: ride quality has been of continuing interest to helicopter community

Little passenger acceptance research performed for the next 20 years

- Motion sickness triggered in .25 - .50 Hz range, amplitude corresponding to 6 ft seas
- Changes of acceleration (“jerk”) are unsettling
- 12 Hz is worst frequency for visual acuity (degrades in range of 8-20 Hz)
- 40-50 Hz stimulates eyeball resonance

NASA research on human experience in launch conditions (acceleration, vibration), with focus on dexterity and cognitive performance

- Primary focus is to ensure safety
- Comfort is outside of its charter, unless mandated

FAA does not generally address passenger comfort

- Some studies of passenger comfort and cabin amenities, timing studies of ingress/egress for operational efficiency
- Accelerations and maneuvers are an acknowledged concern
- Demand modeling studies and surveys – willingness to pay, motivation to fly, alternatives

Little has been done to address passenger acceptance on new-generation V/STOL
The Role of Passenger Acceptance in an Air Transportation Supply / Demand Model

Overview

**Demand** is modulated by:
- Price
- Speed
- Convenience
- **Experience**
- Alternatives
- Expectations

**Supply** is modulated by:
- Price
- Profitability
- Risk/liability
- Barriers to entry
- Competition

Figure adapted from Tam and Hansman, AIAA 2002-5863
Legacy Model of Passenger Acceptance

Figure 1.- Passenger acceptance diagram.

Figure from Review of Ride Quality Technology Needs of Industry and User Groups, J. R. McKenzie and Stanley H. Brumaghim, in NASA TM X-3295 Ride Quality Symposium, 1975
NASA Langley Passenger Ride Quality Apparatus (c. 1976)

- Three degree-of-freedom simulator and noise generator
- Tourist-class commercial aircraft seating configuration interior
- Vibrational inputs varied from 1 to 30 Hz and .05 to .50 g.
- Surveys of discomfort, correlations of discomfort with vibration and noise
Early Assessments of Motion Sensitivity

Vibration amplitude \( >0.01g \) becomes objectionable to passengers

Figures from Ride Quality Overview, Ralph Stone, in 1972 Symposium on Vehicle Ride Quality, NASA TM X-2620, 1972
Passenger Response to Vibration

Vibrations <10 Hz are least acceptable to passengers

Figures from Development and Application of Ride Quality Criteria, David G. Stephens, NASA TM X-72008, 1974
Discomfort Depends on Both Noise and Vibration

- NASA Langley work in the 1970s developed a discomfort index based on noise and vibration.

- Helicopter discomfort level was evaluated through simulation of noise and vibration levels measured in flight tests.

Figure from Evaluation of Ride Quality Prediction Methods for Helicopter Interior Noise and Vibration Environments, Jack D. Leatherwood et al., NASA Technical Paper 2261, 1984
Theory of Passenger Comfort

Figure 3.- Components of a theory of comfort.

Figure from Passenger Ride Quality
Determined from Commercial Airline Flights,
L. G. Richards et al., in 1975 Ride Quality
Symposium, NASA TM X-3295, 1975
Helicopter Passenger Concerns

Frequently Asked Questions on helicopter operator websites reflect issues that operators see as passenger concerns

- **What should I wear?** Is the temperature on board really different?
- **Should I expect any flight turbulence?**
- **Can I hear** when the pilot is talking to me?
- **Space** – the cabin of a helicopter is a lot smaller than standard planes, so bear this in mind if feeling constricted contributes to your fear of flying.
- **Seating** – the front seat of the helicopter is the most ‘exposed’, as you have the widest field of vision. Consider sitting further back in the cockpit if it is your first flight and gradually build your confidence.
- **Noise** – a helicopter flight can get quite noisy with the air drag and the sound of the rotor blades. Wearing the headphones provided – or a pair of earplugs – may make you feel more comfortable.
- **View/visibility** – you will be able to see much more from a helicopter than you can from a plane.
- **Bumpy/swooping feeling** – helicopter flights are often not as smooth as those in an airplane, due to the smaller size of the aircraft.
- **Takeoff, landing, and quick altitude changes** when flying in a helicopter can bring on air sickness in many people...The noise from the propellers triggers air sickness in some people.
- **Fumes from helicopter fuel** can make you feel sick, especially on a hot day. Try to stay upwind of the helicopter so you don’t smell the fuel.
Helicopter Passenger Concerns
Rotorcraft operators interviews

Experts Interviewed
• CEO of scheduled helicopter service company
• Officers of two rotorcraft trade associations
• NASA manager and former military helicopter pilot
• Former chief helicopter R&D test pilots
• FAA rotorcraft expert

Leading Concerns
1. **Perceived safety**: critical attribute; may be affected by interaction with aircrew, environment similar to airliner, aircraft motion, crashworthiness features.
2. **Well-being**: vibration and internal noise, unexpected noises (e.g., jackscrews), cabin air quality (including fumes), jerkiness (e.g., takeoff flight profile), rotor wash at operating site, seating, cabin space, cabin climate, visual experience, “familiar surroundings.”
3. **Convenience**: connectivity to ground and internet, work space and amenities (for business travelers), minimum boarding and exit delay, baggage space and access, cost vs. comfort (varies according to market segment).
4. **Accessibility**: must be accessible and usable by passengers with physical limitations, which affects cabin entry and egress, seating, and interior design (ref. Americans with Disability Act).
eVTOL Passenger Concerns
Interviews of eVTOL leaders from industry, government, and academia

Experts Interviewed
- Four government officials with rotorcraft expertise
- Two academicians recognized as opinion leaders
- Three members of a leading air taxi operator
- Two leaders from eVTOL industry
- Two academicians engaged in UAM research
- FAA certification expert

Leading Concerns
1. **Passenger experience of paramount concern.** Strong interest in motion-based simulation, but too expensive to develop purpose-built simulator.
2. **Managing the transition to this new mode of transportation is critical** – strive for familiarity of surroundings and procedures; provide physical indicators of safety (e.g., hand holds, head rests, solid structure).
3. Perceived safety: **Establishing a safety case for power-out contingencies** will rely on redundancy and reliability.
4. **Presence of pilot or operator** is important for perceived safety.
5. **Noise and vibration characteristics** (ground footprint and inside cabin) of multirotors are not well understood.
Data Analysis
Establishing Design and Operational Constraints

Literature search identified five constraints for passenger acceptance

- Motion sickness
- Dexterity, discomfort
- Visual impairment
- Visual-vestibular disturbances
- Body organ resonance
- Body vibrations

Rate of Change in Pressure Altitude

- 850-1100 m/min
  - 50% report discomfort
- 250-350 m/min
  - Some report discomfort
- 0-150 m/min
  - No discomfort

Vibration, Hz


Longitudinal Acceleration

- 0.0-0.3g
  - No discomfort
- 0.4-0.6g
  - Some discomfort

Data from Ride Quality of Terminal-Area Flight Maneuvers, W. Elliott Schoonover, Jr., in 1975 Ride Quality Symposium, NASA TM X-3295, 1975
Design Factors for eVTOL Concepts

Source: Research areas from Concept Vehicles for VTOL Air Taxi Operations, Wayne Johnson et al., 2018
Design Factors Relevant to Passenger Concerns

Figure Notes:
* Research areas from Concept Vehicles for VTOL Air Taxi Operations, Wayne Johnson et al., 2018
** Added research areas applicable to passenger concerns
Operational Factors Relevant to Mitigating Passenger Concerns

• Flight route tailoring
  • Minimize noise footprint
  • Reduce low-frequency accelerations
  • Reduce multi-axis rotations
  • Fly efficient routes

• Weather avoidance
  • Wind eddies around buildings
  • Turbulence
  • Weather minima

• Vertiport traffic management
  • Minimize disturbance to passengers embarking/disembarking from noise and downwash
  • Reduce congestion and delays
  • Vertiport siting and design
Quality Function Deployment (QFD) - Background

- Method for deriving quantitative design requirements and priorities from qualitative customer preferences
  - QFD has been proposed as a method to address eVTOL passenger concerns
    - Many concerns can be mitigated through vehicle design
    - Some concerns are better addressed through operational factors
  - We used an adaptation of QFD to evaluate its utility in guiding NASA research on eVTOL passenger experience
A Compact Set of Passenger Acceptance Concerns

- Safety
  - Hard landing
  - Evacuation
  - In-flight medical emergency
  - Familiarity
  - Track record

- Vehicle acceleration
  - Frequency
  - Amplitude
  - Duration
  - Axis/axes of rotation

- Noise and vibration (frequency, amplitude, duration)
- Maneuvers (steep descents, jerk, turbulence/gust response)
- Pilot on board
- Cabin temperature, humidity, odors
- In-flight productivity (conversation, phone call, reading, writing, keyboarding)
- Rate of change of cabin pressure
- Visual cues
- Ventilation
- Security
  - Interference with flight
  - Unruly passenger
- Ingress/egress
- Vertiport experience – wait time, downwash
- Personal space (leg room, seat width, cabin volume)
- Seating arrangement (theater, campfire)
- Lighting and décor
- Long-term exposure effects
- Environmental impact

- Perceived Safety
- Vehicle Motion
- Noise & Vibration
- Availability and Access
- Passenger Well-Being
- Concern for the Environment
A Compact Set of Design and Operational Factors Relevant to Mitigating Passenger Concerns

- Flight controls
- Aerodynamic design (wing/disc loading)
- Sound-damping insulation
- Interior layout – seats, windows
- Cabin climate control
- Structural design and damping
- Rotor design
- Vertiport design
- Piloting technique
- Noise-canceling headsets
- Flight route selection
- Weather limits
- Vertiport proximity operations
- Crashworthiness
- Flight routes
- Vertiport traffic management
- Weather avoidance

Vehicle Design
Controls
Operations
Energy
Vertiport
Cabin Accommodations
### Template for Correlating Passenger Concerns to Design Parameters

<table>
<thead>
<tr>
<th>Passenger Concern Categories</th>
<th>Design and Operations Areas</th>
<th>Vehicle Design</th>
<th>Controls</th>
<th>Operations</th>
<th>Cabin Accommodations</th>
<th>Vertiports</th>
<th>Energy</th>
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<tbody>
<tr>
<td>Perceived Safety</td>
<td>Hard landing</td>
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<td>Security (rogue passenger)</td>
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<td>Security (interference with flight)</td>
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<td>Acceptance of automation - autonomy vs. pilot on board</td>
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<tr>
<td>Vehicle Motion</td>
<td>Vehicle acceleration - frequency, amplitude duration, axes</td>
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<td>Maneuvers (steep descents, jerk, turbulence/gust response)</td>
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<td>Visibility and visual cues (vertigo)</td>
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<td>Noise &amp; Vibration</td>
<td>Noise and vibration - frequency, amplitude duration</td>
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<td>Noise and vibration long-term exposure effects</td>
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<td>Sudden unexpected transient noise</td>
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<td>Availability &amp; Access</td>
<td>Vertiport location and accessibility</td>
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<td>Access to aircraft at vertiport</td>
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<td>Access for people with disabilities</td>
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<td>Downwash at vertiport</td>
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<td>Exit Concern</td>
<td>Community noise concerns</td>
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<td>Passenger Visibility</td>
<td>Aircraft ingress/egress</td>
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<td>Ingress/egress/seating for people with disabilities</td>
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<td>Personal space - leg room, seat width, cabin height, etc.</td>
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<td>Lighting, décor, amenities</td>
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<td>In-flight connectivity and productivity - phone call, reading, etc.</td>
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**Design and Operations Areas:**
- Rotorcraft & system design
- Aircraft arrangement
- Wing/disc loading
- Aerodynamic design
- Structural design and damping
- Design for redundancy and reliability
- Crashworthiness
- Flight controls
- Flying technique and automation
- Weather limitations
- Flight route selection and operational constraints
- Operations in vertiport proximity
- Sound-damping insulation
- Noise-canceling headphones
- Active noise and vibration control
- Interior design – seats, windows, etc.
- Cabin climate control
- Vertiport design
- Vertiport siting
- Cabin climate control
QFD “Test Run”
Assessment of relationships between technology and passenger concerns

• Modified QFD formulation
  • Based on matrix of passenger concerns vs. design & operations areas
  • 25 passenger concerns x 20 design & operations areas (500 cells) consolidated to 6 passenger concern categories x 6 groups of design & operations areas (36 cells)
  • Assessments included (1) importance of each passenger concern category and (2) relative influence of each design & operations area on each passenger concern category
  • Numerical ratings were defined as high (1.00), significant (0.50), and insignificant (0)
  • Evaluators were four senior SMEs with experience in air transportation analysis, research, and technologies

• Results of assessment “test run”
  • Perceived safety, vehicle motion, and noise & vibration ranked as top passenger concerns
  • Vehicle design ranked as the top technology and operations area

• Observations
  • More meaningful results would require:
    • Assessments by a larger, more diverse group of evaluators
    • Definitions for each of the topics
    • Definition of target mission parameters and market segments
### QFD Assessment of Correlation Between Passenger Concerns and Design & Operations Parameters

<table>
<thead>
<tr>
<th>Design and Operations Areas</th>
<th>Vehicle Design</th>
<th>Controls</th>
<th>Operations</th>
<th>Cabins/ Accommodations</th>
<th>Data Collection</th>
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<tbody>
<tr>
<td>Passenger concerns</td>
<td>Vehicle Design</td>
<td>Controls</td>
<td>Operations</td>
<td>Cabins/ Accommodations</td>
<td>Data Collection</td>
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</table>

#### Design and Operations Areas

- **Passenger Concerns**
  - Safety
  - Comfort and accessibility
  - Service
  - Environmental impact
- **Vehicle Design**
  - Aerodynamics
  - Structural design and damping
- **Controls**
  - Flight controls
  - Pilot technique and automation
- **Operations**
  - Weather/interchange
  - Flight route selection
  - Operational constraints
  - Operations (in-vertiport proximity)
- **Cabins/Accommodations**
  - Interior design: seats, windows, etc.
  - Cabin climate control
- **Data Collection**
  - Noise and vibration
  - Sudden movements
  - Community noise concerns
  - Energy use concerns

#### Importance and Relationship Ratings

- **Importance Ratings**
  - Passenger safety
  - Comfort and accessibility
  - Service
  - Environmental impact
- **Relationship Ratings**
  - Aerodynamics
  - Structural design and damping
  - Flight controls
  - Pilot technique and automation
  - Weather/interchange
  - Flight route selection
  - Operational constraints
  - Operations (in-vertiport proximity)
  - Interior design: seats, windows, etc.
  - Cabin climate control

#### Average of Importance-Weighted Relationship Ratings

- **Passenger Concerns**
  - Safety
  - Comfort and accessibility
  - Service
  - Environmental impact
- **Vehicle Design**
  - Aerodynamics
  - Structural design and damping
- **Controls**
  - Flight controls
  - Pilot technique and automation
- **Operations**
  - Weather/interchange
  - Flight route selection
  - Operational constraints
  - Operations (in-vertiport proximity)
- **Cabins/Accommodations**
  - Interior design: seats, windows, etc.
  - Cabin climate control
- **Data Collection**
  - Noise and vibration
  - Sudden movements
  - Community noise concerns
  - Energy use concerns

#### Sum of Weighted Relationship Ratings

- **Passenger Concerns**
  - Safety
  - Comfort and accessibility
  - Service
  - Environmental impact
- **Vehicle Design**
  - Aerodynamics
  - Structural design and damping
- **Controls**
  - Flight controls
  - Pilot technique and automation
- **Operations**
  - Weather/interchange
  - Flight route selection
  - Operational constraints
  - Operations (in-vertiport proximity)
- **Cabins/Accommodations**
  - Interior design: seats, windows, etc.
  - Cabin climate control
- **Data Collection**
  - Noise and vibration
  - Sudden movements
  - Community noise concerns
  - Energy use concerns

#### Overview

- **Analysis**
  - Passenger concerns
  - Importance ratings
  - Average of importance ratings
  - Design and Operations Areas
  - Relationship ratings
  - Average of importance-weighted relationship ratings

- **Data Collection**
  - Noise and vibration
  - Sudden movements
  - Community noise concerns
  - Energy use concerns
QFD “Test Run” Highlights Potential Knowledge Gaps

Ratings by CCI SMEs identify candidate top issues for further analysis and research

### Design and Operations Areas

|------------------|-------------------|-------------------------------------------|-----------------------------------|

### Vehicle Design

**Motor/air system design; Aircraft arrangement:** Wing/loft/landing; Aerodynamic design; Structural design and damping; Design for safety and reliability; Vehicle design

**Vehicle motion:** Vertical motion; Vibration; Vertigo

**Control:** Flight controls; Piloting technique and automation

**Operations:** Weather/trafﬁc; Flight route selection and operational constraints; Operations in limited space

**Aviation:** In-ﬂight distress; Interference with ﬂight; Acceptance of automation - autonomy vs. pilot on board

**Acceptance:** Entry/egress; Ingress/egress/seating for people with disabilities; Security/rogue passenger; Security/airports

**Accessibility:** In-vehicle width, cabin height, etc.; Stowage space and accessibility; Lighting,餐饮, amenities; In-flight connectivity and productivity - phone call, reading, etc.

**Convenience:** Comfort, seating, etc.; Comfort, seating, etc.; Comfort, seating, etc.

### Noise & Vibration

**Perceived safety:** Hard landing; Evacuation; In-ﬂight medical emergency; Security - rogue passenger; Security - interference with ﬂight; Acceptance of automation - autonomy vs. pilot on board

**Noise & vibration:** Vehicle acceleration - frequency, amplitude duration, anticipated; Aircraft acceleration - frequency, amplitude duration, turbulence/ gust response; Visibility and visual cues - vertigo

**Vehicle motion:** Noise and vibration vs. vehicle design

**Vibration:** Vehicle vibration - frequency, amplitude duration, anticipated; Aircraft vibration - frequency, amplitude duration, turbulence/gust response; Visibility and visual cues - vertigo

**Controls:** Flight controls; Piloting technique and automation

**Operations:** Weather/interference; Flight route selection and operational constraints; Operations in limited space

**Aviation:** In-flight distress; Interference with ﬂight; Acceptance of automation - autonomy vs. pilot on board

## SME selections of top issues

### Differences among ratings for Passenger well-being vs. Cabin accommodations

### QFD “Test Run” Highlights Potential Knowledge Gaps

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Observations from QFD Test Run

• **Factor descriptions must be clear** and mean the same thing to all respondents to produce tractable results

• **Considerable effort is necessary to produce a matrix that is sufficiently granular** to obtain meaningful results while not overwhelming respondents with the number of responses required

• **The relative priority of passenger concerns exhibited the largest variance** in our results

• **Responses will likely vary** with different markets, e.g. trip length

• **The importance of perceived safety is much greater than other factors**, suggesting that a finer-grained scale for this concern would be helpful

• **Perceived safety concerns** are strongly mitigated by all factors except Energy

• **Passenger well-being concerns** are mitigated principally by cabin accommodations
RECOMMENDATIONS
for NASA R&D
**Method Used to Develop Recommendations**

- Evaluate priority passenger concerns identified by SMEs or highlighted in QFD test run

- Identify important design and operational factors, filter for elements that are appropriate NASA roles and where capability exists or could be developed

- Recommend NASA investments that would mitigate concerns or address knowledge gaps
Recommendations – Preview

1. Develop an eVTOL multi-fidelity (fast time, real-time, and full-mission) simulation capability

2. Characterize and model noise from multirotors

3. Assess reliability and failure modes of hybrid and all-electric propulsion systems

4. Instrument the flights conducted during the UAM Grand Challenge to obtain relevant passenger experience data

5. Conduct refined analyses of passenger demand and concerns
Develop an eVTOL Multi-fidelity Simulation Capability

• Rationale
  • Many aspects of the eVTOL flight experience are new to aviation, and there is a great need to expand the database of flight experience for many purposes
    • Handling qualities
    • Pilot proficiency
    • Flight route development
    • Ride quality
    • Passenger experience
    • Safety case and certification
  • Flight simulation is an established, cost-effective tool to inform designs early in the process through certification and operations
  • NASA has played a valuable role in the course of many aircraft development cycles by providing flight simulation capabilities for its own research as well as in partnership with industry to inform designs

• Recommendation: Develop an eVTOL multi-fidelity flight simulation capability
  • Fast-time: library of trajectories and flight statistics for use in motion-based simulators
    • Leverage existing agent-based architecture
  • Real-time: handling qualities, pilot proficiency, flight route design, contingency planning, passenger experience, certification data
    • Large motion platform capable of replicating sustained g-forces experienced in takeoff, transition, and landing operations
  • Full-mission: scheduling and congestion management, conflict detection and resolution
    • Live, virtual, and constructive environment
Characterize and Model Noise from Multirotors

• Rationale
  • Noise is one of the most important concerns articulated by passengers, operators, and the community
    • Community noise is a prominent concern for every form of aviation
    • Cabin noise in helicopters requires use of headsets to hear and be heard – this requirement would be detrimental to the eVTOL market
  • Multirotor noise is not sufficiently well understood to address it in design and operations
    • Compared to helicopters, eVTOLs have significantly different noise characteristics – existing models are insufficient
    • Predicting noise propagation into the cabin will new structural transmission models

• Recommendation: Develop reconfigurable multirotor test capability to build a database for calibration and validation of internal and external noise models
Assess Reliability and Failure Modes of Hybrid and All-electric Propulsion Systems

• Rationale
  • Perceived safety will depend heavily on an excellent safety record
  • eVTOL aircraft will be less capable of controlled descent and landing than conventional fixed-wing aircraft and helicopters
  • The power-out safety case will be built on reliability and redundancy of the propulsion system
  • Compared to turbine engines, hybrid and electric systems have very little performance data on which to build reliability arguments
  • Incremental envelope expansion, of which Extended Operations (ETOPS – formerly Extended Range Operation with Two-Engine Airplanes) is an example, offers an efficient approach to building a safety record for new concepts

• Recommendation: Develop a capability to characterize the reliability, failure modes, mean time between failures, and other performance statistics of integrated hybrid-electric and all-electric propulsion systems
Instrument the Flights Conducted During the UAM Grand Challenge to Obtain Relevant Passenger Experience Data

• Rationale
  • Flight data is valuable and hard to get
  • The UAM Grand Challenge represents an excellent opportunity to gather data pertinent to passenger experience
  • For realism, simulations need to be grounded in actual measured parameters

• Recommendation: Measure linear and angular accelerations inside the cabin during UAM GC flights, as well as noise footprints on the ground
Conduct Refined Analyses of Passenger Demand and Concerns

• Rationale
  • Passenger acceptance is critical to the success of the UAM industry
  • The relationship of the importance of passenger concerns to other factors influencing demand is not adequately understood
  • The capability to mitigate passenger concerns through design and operational measures is not well defined

• Recommendation: Conduct additional UAM demand modeling surveys with emphasis on passenger acceptance criteria and implement a finer-grained QFD analysis to inform design and operational trade studies
## Passenger Concern Coverage by Recommendations

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<tr>
<th></th>
<th>Perceived Safety</th>
<th>Vehicle Motion</th>
<th>Noise and Vibration</th>
<th>Availability and Access</th>
<th>Concern for Environment</th>
<th>Passenger Well-Being</th>
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Summary

• Conducted a literature review of passenger concerns for current aircraft

• Interviewed SMEs from the eVTOL and helicopter industry, government, and academia

• Organized the concerns into a compact set

• Developed a QFD framework to understand how design and operations can mitigate passenger concerns

• Developed recommendations for NASA R&D to address passenger concerns
Questions?
Thank You