eVTOL Passenger Experience

Final Report | June 26, 2019

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FINDING SOLUTIONS

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Order of Presentation

Task Overview → Data Collection → Data Analysis → Recommen-dations → Summary

Task Overview

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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

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Overview of Findings from Literature and SME Inputs

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

- 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

Little passenger acceptance research performed for the next 20 years

- 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

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

- 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

FAA does not generally address passenger comfort

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

Little has been done to address passenger acceptance on new-generation V/STOL

- 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

The Role of Passenger Acceptance in an Air Transportation Supply / Demand Model

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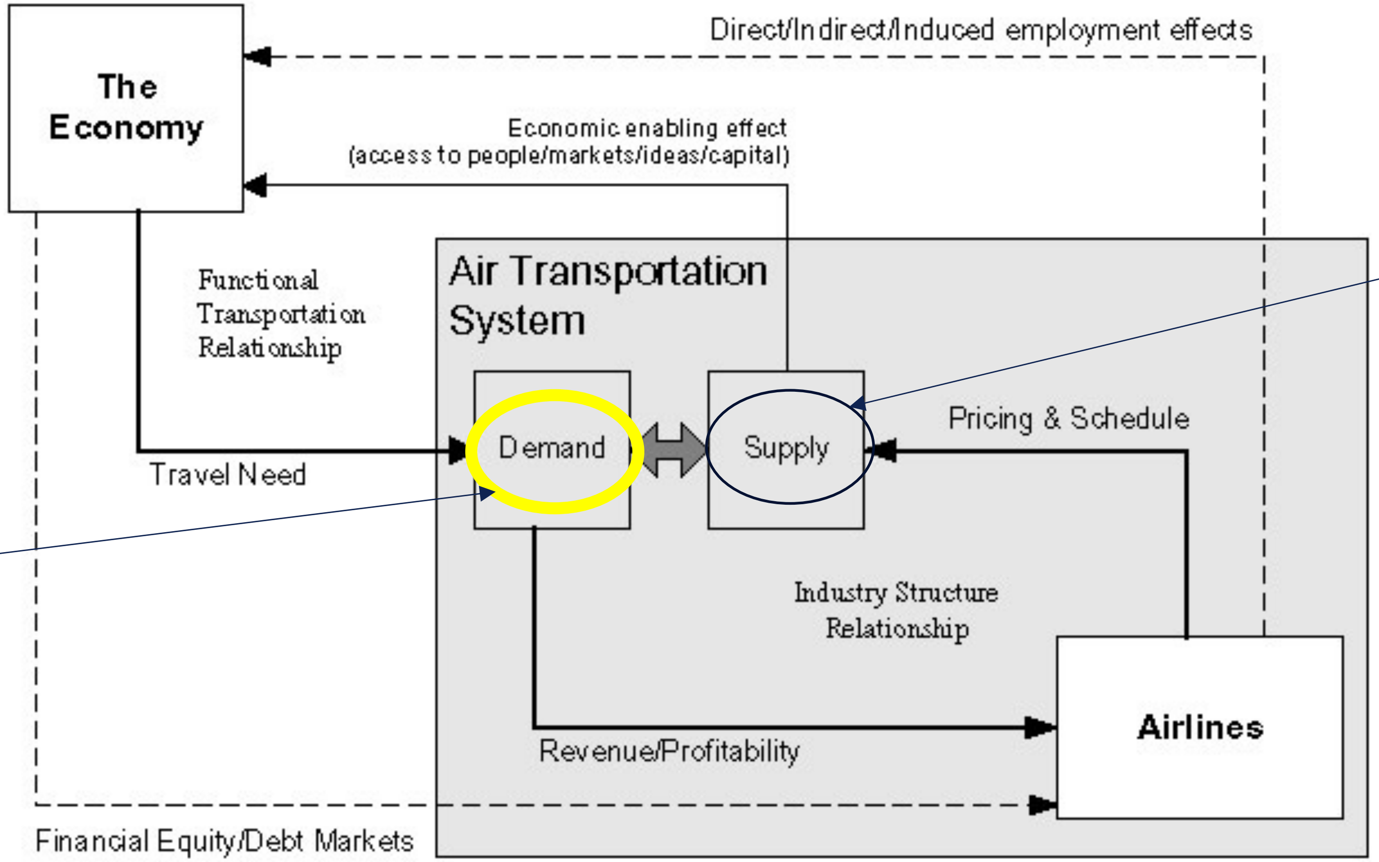


Demand is modulated by:
- Price
- Speed
- Convenience
- Experience
- Alternatives
- Expectations

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

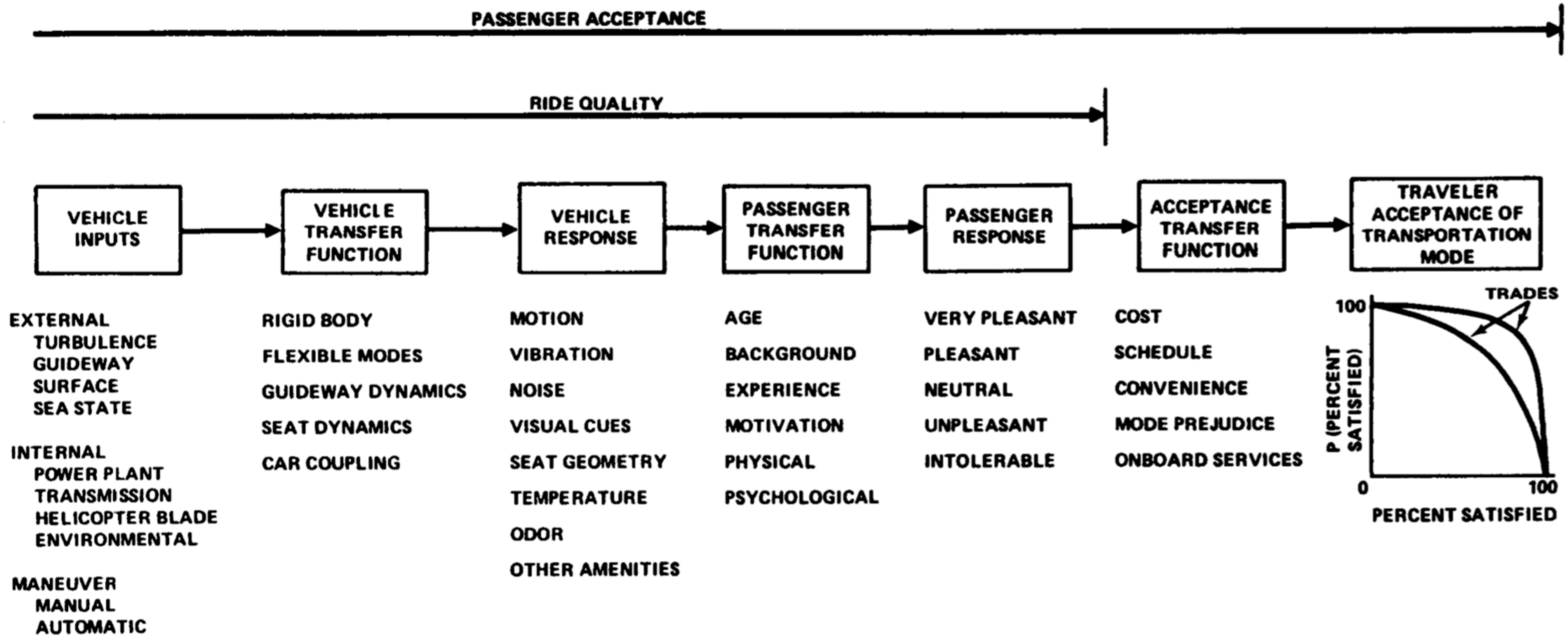
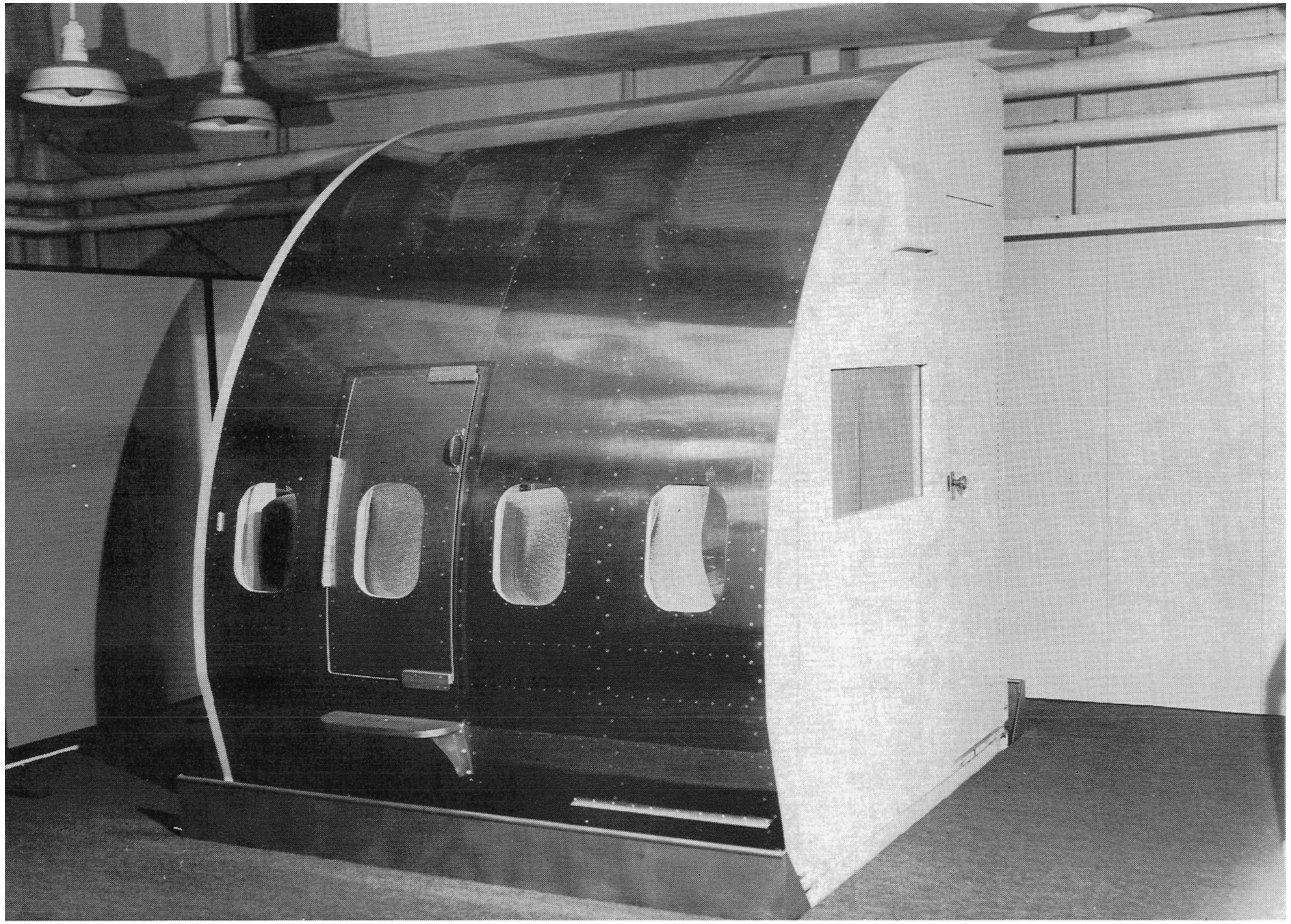


Figure 1.- Passenger acceptance diagram.

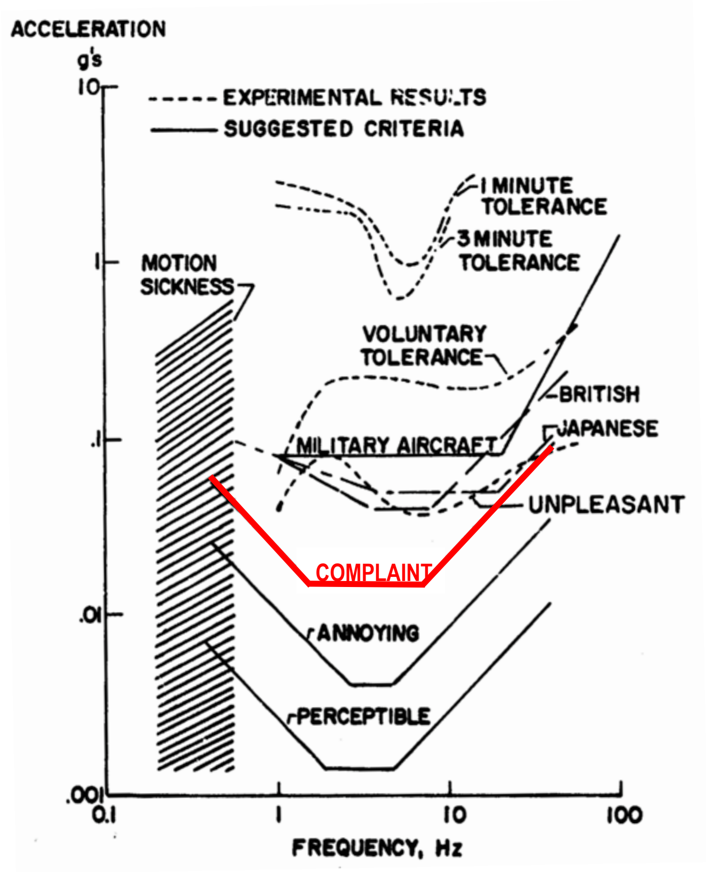
Figure from Review of Ride Quality Technology Needs of Industry and User Groups, J. R. McKenzie and Stanley H. Brumaghim , in NASA TM X-3295 Ride Quality Symposium, 1975

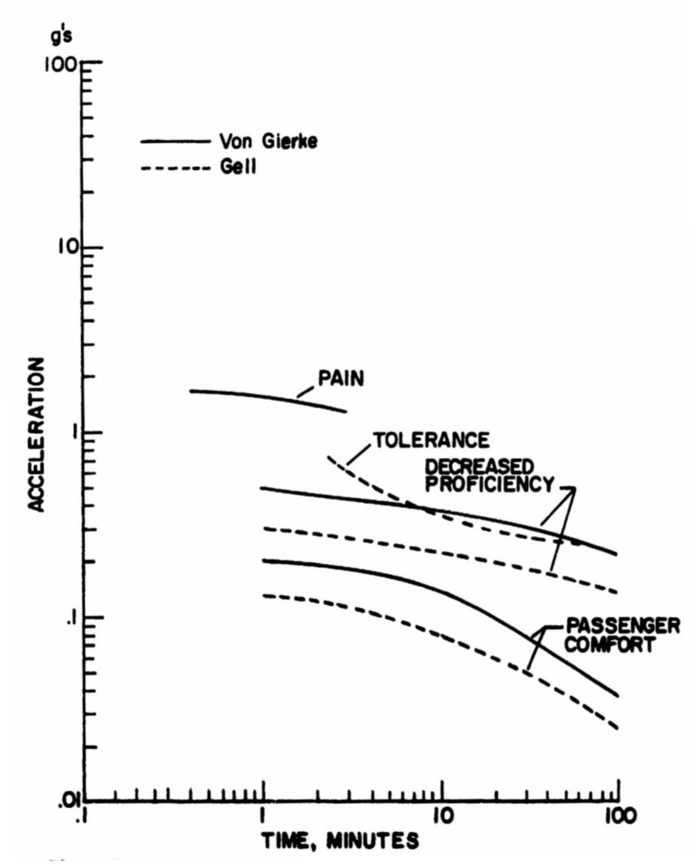
NASA Langley Passenger Ride Quality Apparatus (c. 1976)

- 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

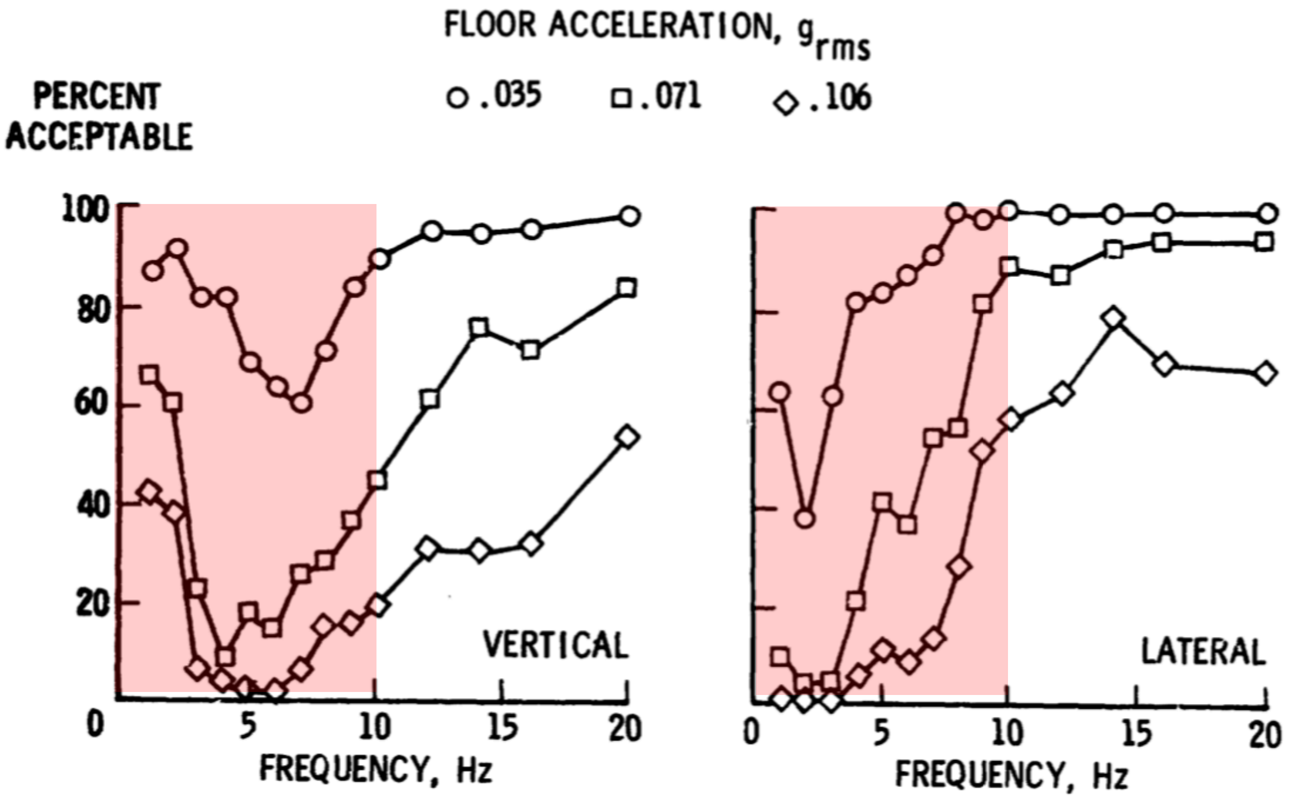




Vibration amplitude >.01g becomes objectionable to passengers

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

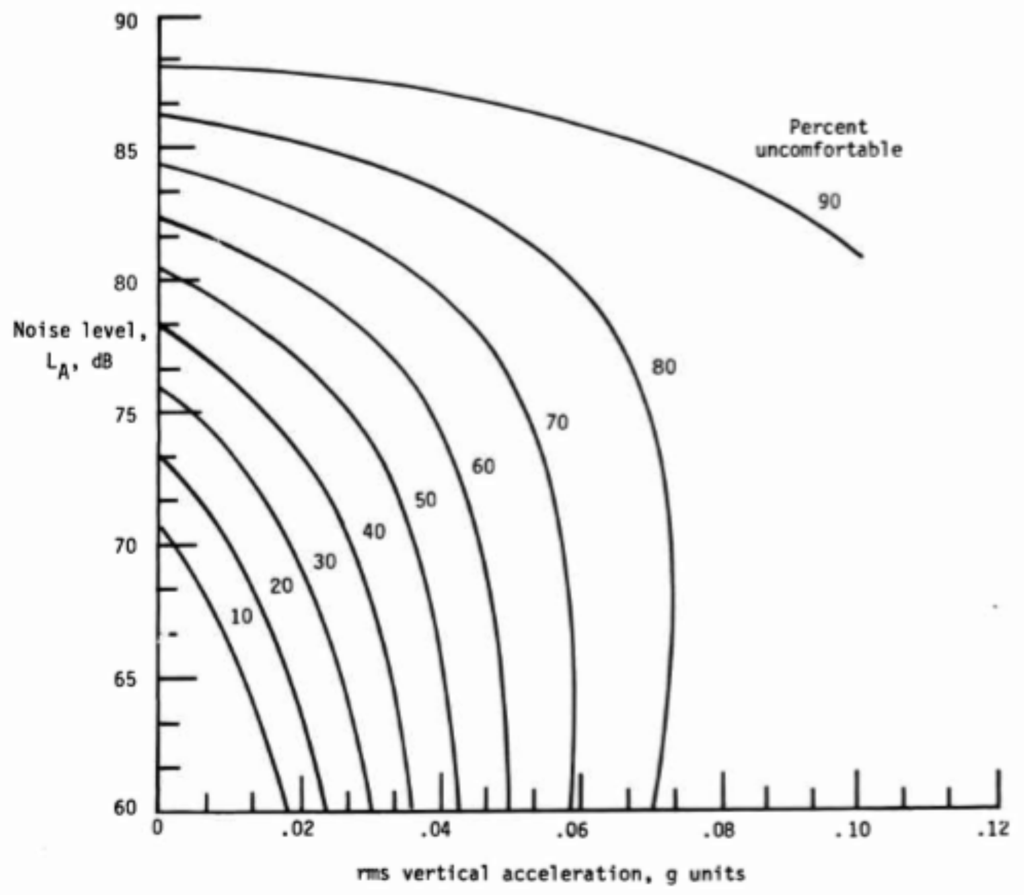


Figure 12.- Values of A-weighted noise level and rms vertical acceleration that produce constant values of discomfort.

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

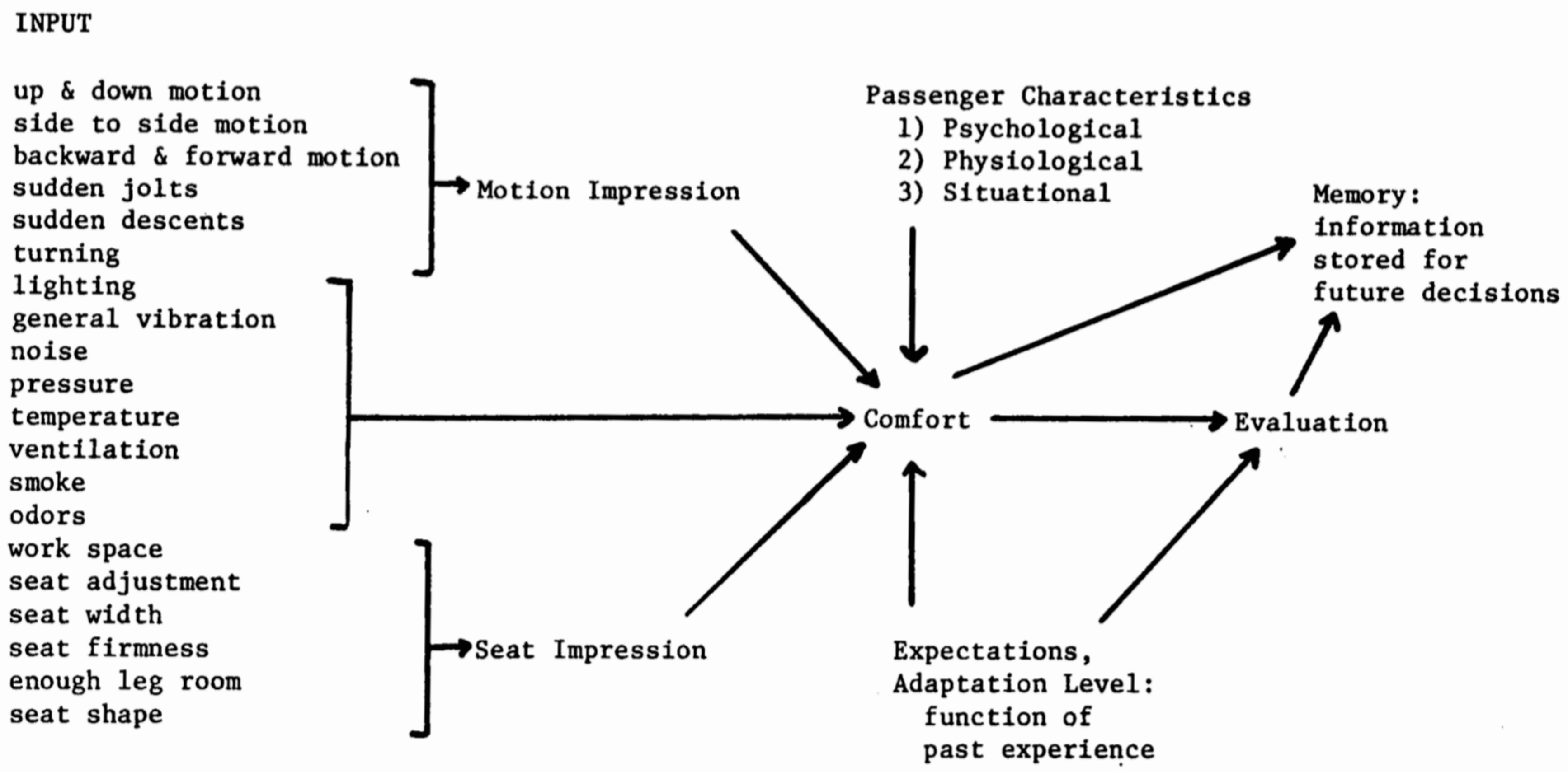


Figure 3.- Components of a theory of comfort.

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

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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

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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

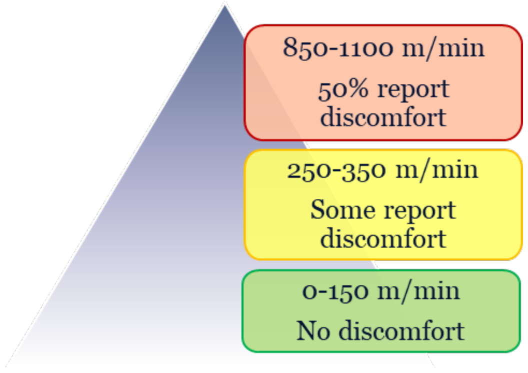
Leading Concerns

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.

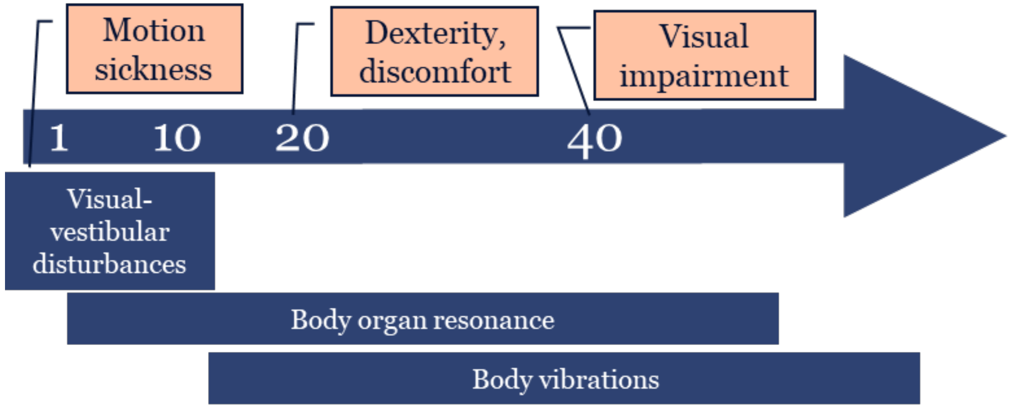
Data Analysis

Establishing Design and Operational Constraints

Literature search identified five constraints for passenger acceptance

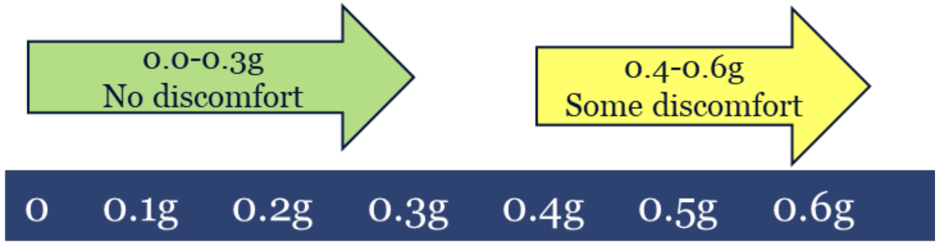


Rate of Change in Pressure Altitude

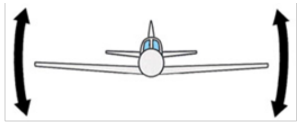


Vibration, Hz

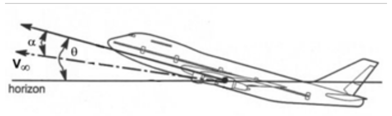
Data from Nonmotion Factors Which Can Affect Ride Quality, D. William Conner, in 1975 Ride Quality Symposium, NASA TM X-3295, 1975



Longitudinal Acceleration



Roll Angle <30 deg



Pitch Angle <10 deg

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

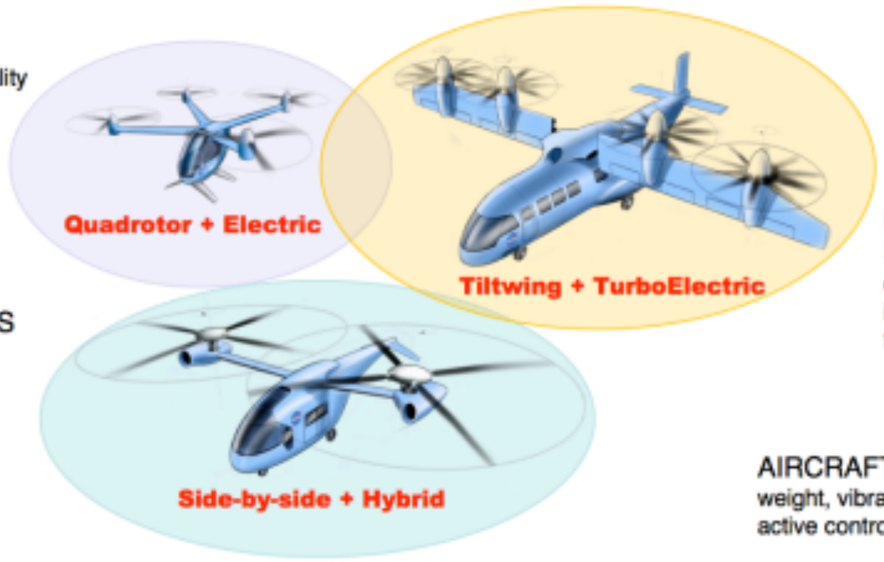
Design Factors for eVTOL Concepts

PROPULSION EFFICIENCY
high power, light battery
light, efficient, high speed electric motors
power electronics and thermal management
light, efficient diesel engine
light, efficient small turboshaft engine
efficient drives

PERFORMANCE
aircraft optimization
rotor shape optimization
hub and support drag minimization
airframe drag minimization

ROTOR-ROTOR INTERACTIONS
performance, vibration, handling qualities
aircraft arrangement
vibration and load alleviation

SAFETY and AIRWORTHINESS
FMECA (failure mode, effects, and criticality analysis)
component reliability
crashworthiness
propulsion system failures



ROTOR-WING INTERACTIONS
conversion/transition
interactional aerodynamics
flow control

OPERATIONAL EFFECTIVENESS
disturbance rejection (control bandwidth, control design)
all-weather capability
cost (purchase, maintenance, DOC)

AIRCRAFT DESIGN
weight, vibration, handling qualities
active control

NOISE AND ANNOYANCE
low tip speed
rotor shape optimization
aircraft arrangement
active noise control
metrics and requirements

STRUCTURE AND AEROELASTICITY
structurally efficient wing and rotor support
rotor/airframe stability
crashworthiness
durability and damage tolerance

Source: Research areas from Concept Vehicles for VTOL Air Taxi Operations, Wayne Johnson et al., 2018

Design Factors Relevant to Passenger Concerns

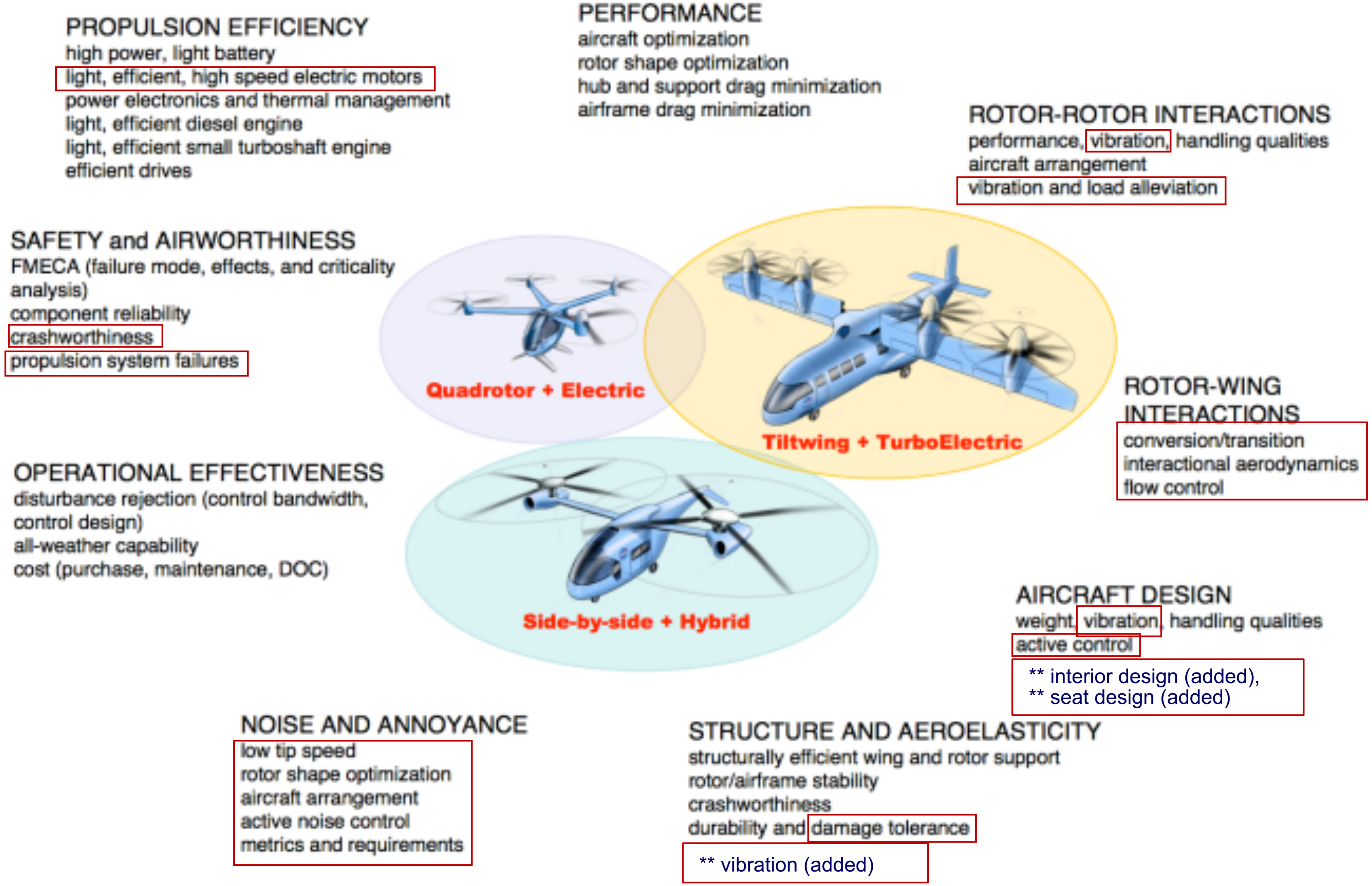


Figure Notes:
* Research areas from Concept Vehicles for VTOL Air Taxi Operations, Wayne Johnson et al., 2018
** Added research areas
Research areas applicable to passenger concerns

Operational Factors Relevant to Mitigating Passenger Concerns

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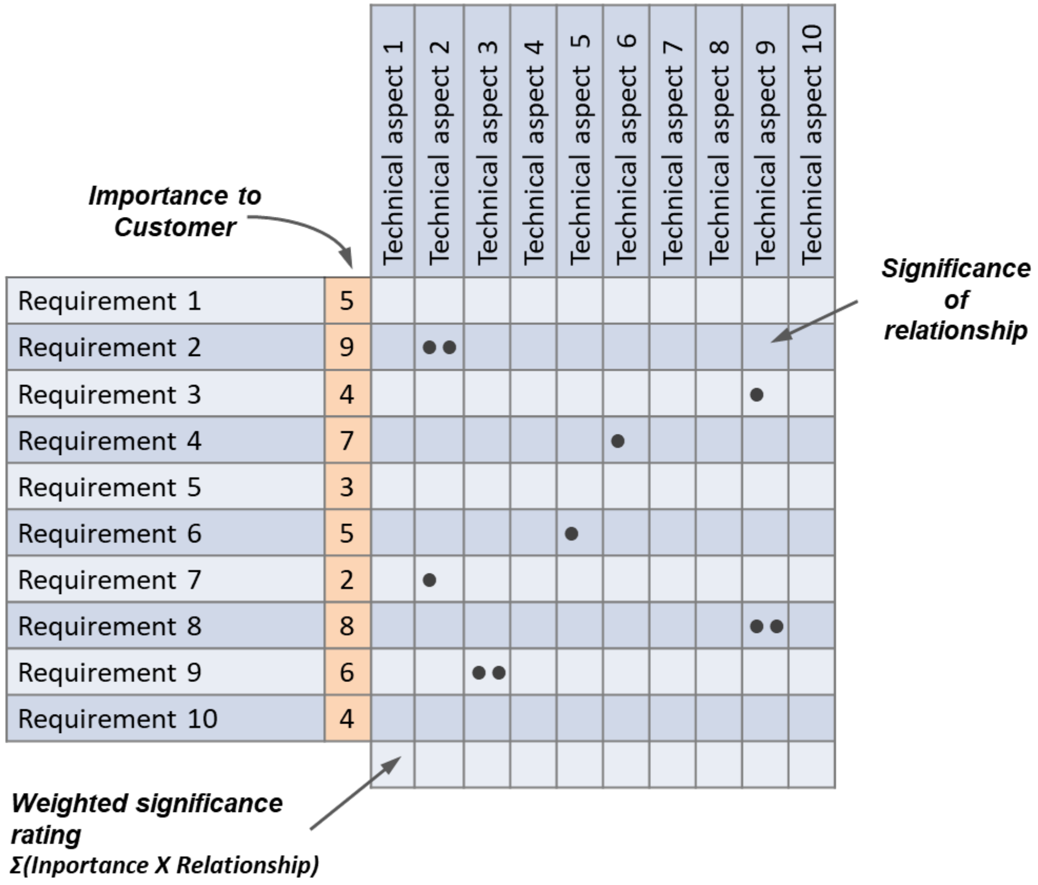
- Flight route tailoring
    - Minimize noise footprint
    - Reduce low-frequency accelerations
    - Reduce multi-axis rotations
    - Fly efficient routes
- Weather avoidance
    - Wind eddies around buildings
    - Turbulence
    - Weather minima
- Vertiport traffic management
    - Minimize disturbance 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



QFD Template

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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

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- 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

Passenger Concern Categories	Design and Operations Areas > Passenger Concerns	Vehicle Design							Controls		Operations			Cabin Accommodations					Vertiports		Energy
		Rotor/lift system design	Aircraft arrangement	Wing/disc Loading	Aerodynamic design	Structural design and damping	Design for redundancy and reliability	Crashworthiness	Flight controls	Piloting technique and automation	Weather limitations	Flight route selection and operational constraints	Operations in vertiport proximity	Sound-damping insulation	Noise-canceling headsets	Active noise and vibration control	Interior design – seats, windows, etc.	Cabin climate control	Vertiport design	Vertiport siting	Electric Power
Perceived Safety	Hard landing																				
	Evacuation																				
	In-flight medical emergency																				
	Security (rogue passenger)																				
	Security (interference with flight)																				
	Acceptance of automation - autonomy vs. pilot on board																				
Vehicle Motion	Vehicle acceleration - frequency, amplitude duration, axes																				
	Maneuvers (steep descents, jerk, turbulence/gust response)																				
	Visibility and visual cues (vertigo)																				
Noise & Vibration	Noise and vibration - frequency, amplitude duration																				
	Noise and vibration long-term exposure effects																				
	Sudden unexpected transient noise																				
Availability & Access	Vertiport location and accessibility																				
	Schedule integrity																				
	Access to aircraft at vertiport																				
	Access for people with disabilities																				
	Downwash at vertiport																				
Envir. Con-cern	Community noise concerns																				
	Energy use concerns																				
Passenger Well-being	Aircraft ingress/egress																				
	Ingress/egress/seating for people with disabilities																				
	Personal space - leg room, seat width, cabin height, etc.																				
	Stowage space and accessibility																				
	Lighting, décor, amenities																				
	In-flight connectivity and productivity - phone call, reading, etc.																				

QFD "Test Run"

Assessment of relationships between technology and passenger concerns

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- 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

Passenger concerns

Importance ratings

Average of importance ratings

Design and Operations Areas

Relationship ratings

Average of importance-weighted relationship ratings

Passenger Concerns (Scorers>)	TD	TE	SH	GP	Avg	Dev
Perceived Safety (Hard landing; Evacuation; In-flight medical emergency; Security - rogue passenger; Security - interference with flight; Acceptance of automation - autonomy vs. pilot on board)	1.0	1.0	1.0	1.0	1.00	0.00
Vehicle Motion (Vehicle acceleration - frequency, amplitude duration, axis/axes; Maneuvers - steep descents, jerk, turbulence/gust response; Visibility and visual cues - vertigo)	1.0	1.0	1.0	0.5	0.44	0.44
Noise & Vibration (Noise and vibration - frequency, amplitude, duration; Noise and vibration long-term exposure effects; Sudden unexpected transient noise)	1.0	0.5	1.0	0.5	0.38	0.38
Availability and Access (Vertiport location and accessibility; Schedule integrity; Access to aircraft at vertiport; Access for people with disabilities; Downwash at vertiport)	0.5	0.5	0.5	1.0	0.31	0.31
Concern for the Environment (Community noise concerns; Energy use concerns)	0.5	0.5	0.5	0.5	0.25	0.25
Passenger Well-being (Aircraft ingress/egress; Ingress/egress/seating for people with disabilities; Personal space - leg room, seat width, cabin height, etc.; Stowage space and accessibility; Lighting, décor, amenities; In-flight connectivity and productivity - phone call, reading, etc.)	0.5	0.5	0.5	0.0	0.19	0.28
Relative Importance x Significance for Design and Operations Area						

Design and Operations Areas >	Vehicle Design (Rotor/lift system design; Aircraft arrangement; Wing/disc loading; Aerodynamic design; Structural design and damping; Design for redundancy and reliability; Crashworthiness)							Controls (Flight controls; Piloting technique and automation)						
Passenger Concerns	TD	TE	SH	GP	Avg.	Dev.	Inf x Imp	TD	TE	SH	GP	Avg.	Dev.	Inf x Imp
Perceived Safety	1.0	1.0	1.0	1.0	1.00	0.00	1.00	1.0	1.0	1.0	0.5	0.88	0.19	0.88
Vehicle Motion	1.0	1.0	1.0	1.0	1.00	0.00	0.44	1.0	1.0	1.0	1.0	1.00	0.00	0.44
Noise & Vibration	1.0	1.0	1.0	1.0	1.00	0.00	0.38	0.5	0.0	0.5	0.5	0.38	0.19	0.14
Availability and Access	0.5	0.0	0.5	0.5	0.38	0.19	0.12	0.0	0.0	0.0	0.0	0.00	0.00	0.00
Concern for the Environment	0.5	0.5	0.5	1.0	0.63	0.19	0.16	0.0	0.0	0.0	0.0	0.00	0.00	0.00
Passenger Well-being	1.0	0.0	1.0	0.5	0.63	0.38	0.12	0.0	0.0	0.0	0.0	0.00	0.00	0.00
Relative Importance x Significance for Design and Operations Area							0.37							0.24

Design and Operations Areas >	Operations (Weather limitations; Flight route selection and operational constraints; Operations in vertiport proximity)							Cabin Accommodations (Sound-damping insulation; Noise-canceling headsets; Active noise and vibration control; Interior design: seats, windows, etc.; Cabin climate control)						
Passenger Concerns	TD	TE	SH	GP	Avg.	Dev.	Inf x Imp	TD	TE	SH	GP	Avg.	Dev.	Inf x Imp
Perceived Safety	0.5	0.5	0.5	1.0	0.63	0.19	0.63	0.0	1.0	0.5	0.5	0.50	0.25	0.50
Vehicle Motion	1.0	1.0	0.5	1.0	0.88	0.19	0.38	0.0	0.5	0.5	0.0	0.25	0.25	0.11
Noise & Vibration	0.5	0.0	0.0	0.0	0.13	0.19	0.05	1.0	0.5	1.0	1.0	0.88	0.19	0.33
Availability and Access	0.5	0.5	0.5	0.0	0.38	0.19	0.12	0.0	0.0	0.0	0.0	0.00	0.00	0.00
Concern for the Environment	1.0	0.5	0.5	1.0	0.75	0.25	0.19	0.0	0.0	0.0	0.0	0.00	0.00	0.00
Passenger Well-being	0.0	0.0	0.0	0.0	0.00	0.00	0.00	1.0	1.0	1.0	1.0	1.00	0.00	0.19
Relative Importance x Significance for Design and Operations Area							0.23							0.19

Design and Operations Areas >	Vertiport (Vertiport design; Vertiport siting)							Energy (Electric power)						
Passenger Concerns	TD	TE	SH	GP	Avg.	Dev.	Inf x Imp	TD	TE	SH	GP	Avg.	Dev.	Inf x Imp
Perceived Safety	0.5	0.5	0.5	0.5	0.50	0.00	0.50	0.5	0	0	0.5	0.25	0.25	0.25
Vehicle Motion	0.5	0.0	0.0	0.0	0.13	0.19	0.05	0.5	0	0.5	0	0.25	0.25	0.11
Noise & Vibration	0.5	0.0	0.0	0.0	0.13	0.19	0.05	1	1	0.5	1	0.88	0.19	0.33
Availability and Access	1.0	1.0	1.0	1.0	1.00	0.00	0.31	0	0	0	0	0.00	0.00	0.00
Concern for the Environment	0.5	0.5	0.5	0.5	0.50	0.00	0.13	0.5	1	1	1	0.88	0.19	0.22
Passenger Well-being	0.5	0.0	0.0	0.5	0.25	0.25	0.05	0	0	0	0	0.00	0.00	0.00
Relative Importance x Significance for Design and Operations Area							0.18							0.15

Sum of weighted relationship ratings

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QFD "Test Run" Highlights Potential Knowledge Gaps

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

Perceived safety vs. Vehicle design

Noise & vibration vs. Vehicle design

Noise & vibration vs. Cabin accommodations

Availability & Access vs. Vertiport

Design and Operations Areas >							Vehicle Design (Rotor/lift system design; Aircraft arrangement; Wing/disc loading; Aerodynamic design; Structural design and damping; Design for redundancy and reliability; Crashworthiness)						
Passenger Concerns — Scorers>	TD	TE	SH	GP	Avg	Dev	TD	TE	SH	GP	Avg.	Dev.	Inf x Imp
Perceived Safety (Hard landing; Evacuation; In-flight medical emergency; Security - rogue passenger; Security - interference with flight; Acceptance of automation - autonomy vs. pilot on board)	1.0	1.0	1.0	1.0	1.00	0.00	1.0	1.0	1.0	1.0	1.00	0.00	1.00
Vehicle Motion (Vehicle acceleration - frequency, amplitude duration, axis/axes; Maneuvers - steep descents, jerk, turbulence/gust response; Visibility and visual cues - vertigo)	1.0	1.0	1.0	0.5	0.44	0.44	1.0	1.0	1.0	1.0	1.00	0.00	0.44
Noise & Vibration (Noise and vibration - frequency, amplitude, duration; Noise and vibration long-term exposure effects; Sudden unexpected transient noise)	1.0	0.5	1.0	0.5	0.38	0.38	1.0	1.0	1.0	1.0	1.00	0.00	0.38
Availability and Access (Vertiport location and accessibility; Schedule integrity; Access to aircraft at vertiport; Access for people with disabilities; Downwash at vertiport)	0.5	0.5	0.5	1.0	0.31	0.31	0.5	0.0	0.5	0.5	0.38	0.19	0.12
Concern for the Environment (Community noise concerns; Energy use concerns)	0.5	0.5	0.5	0.5	0.25	0.25	0.5	0.5	0.5	1.0	0.63	0.19	0.16
Passenger Well-being (Aircraft ingress/egress; Ingress/egress/seating for people with disabilities; Personal space - leg room, seat width, cabin height, etc.; Stowage space and accessibility; Lighting, décor, amenities; In-flight connectivity and productivity - phone call, reading, etc.)	0.5	0.5	0.5	0.0	0.19	0.28	1.0	0.0	1.0	0.5	0.63	0.38	0.12
Relative Importance x Significance for Design and Operations Area													0.37

	Controls (Flight controls; Piloting technique and automation)							Operations (Weather limitations; Flight route selection and operational constraints; Operations in vertiport proximity)						
Passenger Concerns	TD	TE	SH	GP	Avg.	Dev.	Inf x Imp	TD	TE	SH	GP	Avg.	Dev.	Inf x Imp
Perceived Safety	1.0	1.0	1.0	0.5	0.88	0.19	0.88	0.5	0.5	0.5	1.0	0.63	0.19	0.63
Vehicle Motion	1.0	1.0	1.0	1.0	1.00	0.00	0.44	1.0	1.0	0.5	1.0	0.88	0.19	0.38
Noise & Vibration	0.5	0.0	0.5	0.5	0.38	0.19	0.14	0.5	0.0	0.0	0.0	0.13	0.19	0.05
Availability and Access	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.5	0.5	0.5	0.0	0.38	0.19	0.12
Concern for the Environment	0.0	0.0	0.0	0.0	0.00	0.00	0.00	1.0	0.5	0.5	1.0	0.75	0.25	0.19
Passenger Well-being	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.00	0.00	0.00
Relative Importance x Significance for Design and Operations Area							0.24							0.23

	Cabin Accommodations (Sound-damping insulation; Noise-canceling headsets; Active noise and vibration control; Interior design: seats, windows, etc.; Cabin climate control)							Vertiport (Vertiport design; Vertiport siting)							Energy (Electric power)						
Passenger Concerns	TD	TE	SH	GP	Avg.	Dev.	Inf x Imp	TD	TE	SH	GP	Avg.	Dev.	Inf x Imp	TD	TE	SH	GP	Avg.	Dev.	Inf x Imp
Perceived Safety	0.0	1.0	0.5	0.5	0.50	0.25	0.50	0.5	0.5	0.5	0.5	0.50	0.00	0.50	0.5	0	0	0.5	0.25	0.25	0.25
Vehicle Motion	0.0	0.5	0.5	0.0	0.25	0.25	0.11	0.5	0.0	0.0	0.0	0.13	0.19	0.05	0.5	0	0.5	0	0.25	0.25	0.11
Noise & Vibration	1.0	0.5	1.0	1.0	0.88	0.19	0.33	0.5	0.0	0.0	0.0	0.13	0.19	0.05	1	1	0.5	1	0.88	0.19	0.33
Availability and Access	0.0	0.0	0.0	0.0	0.00	0.00	0.00	1.0	1.0	1.0	1.0	1.00	0.00	0.31	0	0	0	0	0.00	0.00	0.00
Concern for the Environment	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.5	0.5	0.5	0.5	0.50	0.00	0.13	0.5	1	1	1	0.88	0.19	0.22
Passenger Well-being	1.0	1.0	1.0	1.0	1.00	0.00	0.19	0.5	0.0	0.0	0.5	0.25	0.25	0.05	0	0	0	0	0.00	0.00	0.00
Relative Importance x Significance for Design and Operations Area							0.19							0.18							0.15

SME selections of top issues

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

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

CCI

- 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

CCI

- 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

	Perceived Safety	Vehicle Motion	Noise and Vibration	Availability and Access	Concern for Environment	Passenger Well-Being
Simulation capability	X	X	X	X		X
multirotor noise			X		X	X
Propulsion system reliability	X			X	X	
Grand Challenge measurements		X	X		X	
Analysis of passenger concerns	X	X	X	X	X	X

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?

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Thank You

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