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eVTOL Passenger Acceptance

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I. Abstract

With the expected introduction of electric vertical takeoff and landing (eVTOL) aircraft for urban air mobility (UAM) services, passenger acceptance has become an issue of interest to manufacturers and operators. This study took an initial look at what passengers expect from an eVTOL UAM flight experience – what aspects matter most, what might be acceptable, and where there are gaps in our understanding. The analysis included a literature search and interviews with experts from the aviation community to identify passenger concerns and potential mitigations. Passenger concerns were found to fall into six general categories: perceived safety, noise and vibration, availability and access, passenger well-being, concern for the environment, and vehicle motion. The study used a modified quality function deployment approach to correlate these passenger concerns with design and operational variables, highlighting how design and operational parameters can mitigate the passenger concerns. NASA research can address the passenger concerns by developing simulation capabilities and noise models, characterizing propulsion system performance, taking direct measurements during flight demonstrations, and conducting further studies of market demand and design methods.

II. Introduction

Urban Air Mobility (UAM) is broadly defined as a spectrum of new aviation capabilities serving densely populated areas with a variety of public and commercial services. Services include first responder and law enforcement functions, news reporting, infrastructure inspection, aerial photography, small package delivery, container positioning, air taxi, and many other value-added services. Although many of these services are enabled by all-electric and hybrid-electric vertical takeoff and landing (eVTOL) aircraft, UAM does not preclude conventional and other types of aerial vehicles that could also serve these markets. UAM is currently receiving considerable attention, with multiple studies envisioning vehicle and operational concepts with a market worth up to $500 billion by 2030 [1, 2, 3, 4].

An important segment of the UAM market involves passenger transport. Today's megacities face chronic traffic congestion, and public transportation is found by many to be slow, expensive, uncomfortable, and inconvenient. The slow and uncertain speed of travel through cities is becoming an impediment to business and leisure trips worldwide.

Helicopters have long been used to expedite transport in urban environments. With modest infrastructure requirements and flexible flight capabilities, helicopters are able to move people in and around cities with relative ease. However, cost and noise have severely constrained the ability of conventional helicopters to serve the UAM market. Helicopters are complex, high-maintenance machines that require skilled pilots. The operating cost of helicopters is so high that they have found economic success only in price-insensitive market niches such as emergency medical evacuation and high-value passenger transport. Community reaction to the noise generated by helicopters restricts their routes and the hours during which they are permitted to operate. Nevertheless, there is strong demand for passenger transport in and around urban environments that would support a vibrant market if these limitations could be overcome.

Recent advances in electric propulsion and battery energy density have ushered in a proliferation of eVTOL design concepts, such as the NASA X-57 Maxwell conceptual air vehicle shown in Figure 1.

Figure 1. Artist's Rendering of NASA X-57 Maxwell eVTOL Concept

These vehicles take many shapes, some with wings for more efficient flight in cruise, others that fly purely on the lift of multiple rotors. They all share several important features: vertical takeoff and landing for operational versatility, electric or hybrid propulsion for low cost and high reliability, and multiple rotors that are much smaller and quieter than conventional helicopter rotors. Piloting proficiency requirements can be alleviated through greater use of automation, ultimately leading to the possibility of full autonomy. As a result, there appears to be promise in the near future for a new generation of air vehicles that can perform passenger transport missions in and around cities, affordable enough for pervasive use by the general public.

With these projections about the affordability and versatility of eVTOL aircraft, the prospect of large-scale air service can be envisioned in the not-too-distant future. Two general operating models have been proposed: (1) scheduled services, and (2) on-demand ride hailing services. Scheduled service would operate between a fixed, relatively small number of high-volume vertiports transporting multiple passengers (6 or more) from city centers to popular destinations (such as outlying airports) – called Air Metro service – whereas on-demand Air Taxi service would require many more origin and destination vertiports and would carry fewer passengers (1 to 4) per trip.

In 2017, NASA commissioned a pair of studies focused on Urban Air Mobility markets [1, 2]. These studies investigated if and when UAM services could become economically viable businesses and what challenges were impeding their growth. Both studies found that for Air Metro and Air Taxi to become viable businesses, they must quickly achieve very large scale (many vehicles and operations in many locations) to affordably amortize the costs of producing an all-new vehicle and associated infrastructure. The Air Metro market is forecast to become viable somewhat sooner than Air Taxi, primarily because of the higher volume of passengers and lower infrastructure cost due to a need for fewer landing and takeoff locations than for a viable on-demand air taxi service. The viability of both markets is contingent on large demand combined with passengers' willingness to pay a premium over alternative transportation modes. The rationale for paying a price premium is associated with the advantages offered by air transportation over ground-based modes: time savings and reliability, as can be seen in the basic model of air transportation supply and demand in Figure 2, adapted from Tam and Hansman [5].

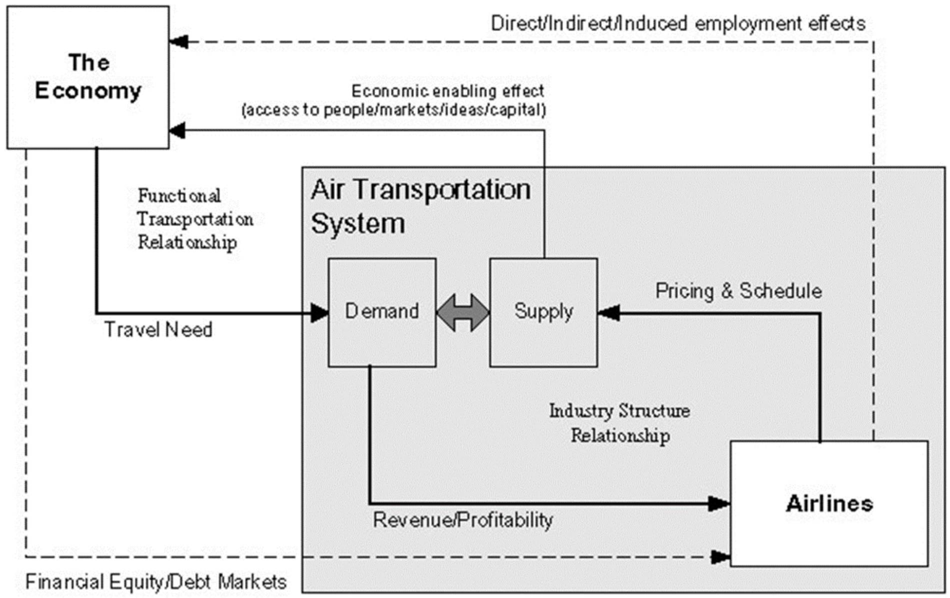


Figure 2. Macroscopic Model of Air Transportation Market Dynamics

Demand for air transportation is modulated by the costs and benefits associated with the service, while supply is modulated by access to capital and the expected return on investment. With cruise speeds of about 100 mph for intra-metro trips compared to the average automobile commute speed – often about 30 mph – eVTOL aircraft can reduce travel time by 50% or more, depending on the trip distance. The travel time by eVTOL will be less variable than with surface transportation, offering passengers time that would otherwise be buffered to accommodate the uncertainty in travel time. UAM transportation systems will be more resilient to disruptions and changing commuting patterns through flexibility of route structures not possible on the ground.

Market studies, such as those cited above, model demand based on aggregate statistics, willingness to pay, benefits offered, availability of alternatives, and other macroscopic variables. These models are useful for evaluating the projected size of the market, potential industry earnings, volume of operations, and other features of the industry in question. However, these studies do not address subjective factors pertaining to whether a potential passenger is inhibited from making use of a new transportation mode such as an eVTOL air taxi. These vehicles will look and fly very differently than anything to which people are accustomed. Relatively few people have ever flown on a helicopter, which would bear the closest resemblance to the passenger experience in these new aircraft.

Even a helicopter trip will differ from the eVTOL flight experience. The eVTOL aircraft, with their comparatively light weight, multiple rotors, vertical takeoff, and transition to forward flight (whether on rotor-borne or wing-borne lift), will be unlike anything passengers have experienced. Because the aircraft will fly at low altitudes close to buildings, they are likely to frequently encounter turbulence. Light weight will lead to lower wing or disc loadings, and, hence, more significant gust responses than are experienced on commercial fixed-wing aircraft. Multiple small rotors will generate different noise footprints. Large windows will afford dramatic views, though possibly those views will intimidate less intrepid fliers. More pragmatically, passengers will want to work with electronic devices, communicate by phone, or enjoy a beverage during the flight. Will the ride be smooth and quiet enough to permit any of these activities? More fundamentally, will the flight be unsettling or trigger anxiety? Many factors such as these go into a passenger's evaluation of the value of a transportation mode, and they need to be understood and addressed effectively to ensure that the passenger's first ride is not also their last.

III. Approach

This initial, low-fidelity study was conducted to develop and refine the method, with three objectives:

1) To characterize the mapping of passenger acceptance concerns to design and operational considerations
2) To identify gaps in understanding that point to needs for additional research
3) To adapt the quality function deployment (QFD) methodology to this particular problem as a guide to future, more detailed studies that others may wish to undertake.

To characterize the significance and challenges presented by passenger experience issues, we undertook a broad assessment of past and current studies focused on passengers in aviation. Several market studies conducted in recent years to assess the viability of the eVTOL air taxi or air metro market have acknowledged the passenger acceptance issue. These studies provide additional context to decades of passenger experience research focused on commercial fixed-wing and rotary wing aircraft. Research on human performance in rocket launches also provides valuable insights into the impact of vibrations in the flight environment.

For a current perspective on the UAM passenger experience question, we conducted interviews with subject matter experts (SMEs) in the eVTOL and helicopter community, as well as academic experts and a NASA human factors researcher on astronaut performance. Considering the diversity of background represented by these experts, we found it most productive to engage them in open-ended conversations that focused on their work and issues of greatest interest to them. This proved to be a fruitful approach, yielding some unexpected and useful findings.

Leveraging the knowledge gained from the literature search and interviews, we constructed a mapping of passenger concerns to design parameters. We adapted the QFD method [6] to map passengers' concerns about eVTOL flight and the relationship of those concerns to system design issues.

Based on the information we collected and the results of the analysis, we identified knowledge gaps regarding passengers' acceptance of eVTOL service, and we formulated suggested research topics to address these gaps and to mitigate likely passenger concerns.

IV. Prior Work on Passenger Acceptance

Passenger experience has been a subject of interest since the beginning of the air transportation industry. In the 1970s, when jet aircraft first became the dominant mode of passenger air travel, numerous studies were conducted to characterize the passenger experience. Conventional aircraft and helicopters were studied for means to reduce vibration and noise levels that can cause discomfort and fatigue on longer flights. Although the studies focused principally on the human response to noise and vibration, several models were proposed that took into account other potential concerns. Kulthau and Johnson [7] proposed the model for passenger demand shown in Figure 3, which correlates the passenger's selection of transportation mode with a vehicle's disturbance response and the passenger's response to vehicle motion.

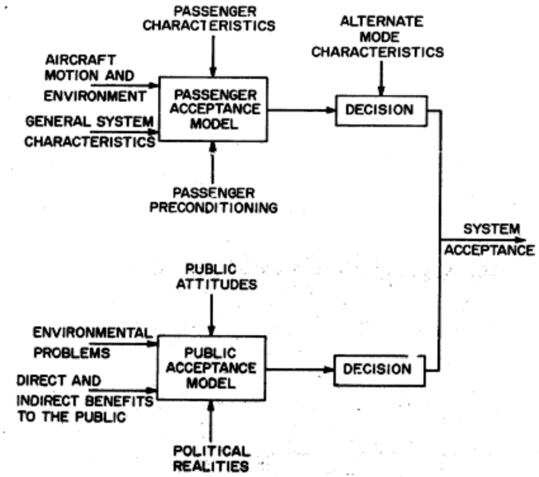


Figure 3. Kulthau and Johnson Model for Passenger Acceptance of New Transportation Options

Using this model, Kulthau and Johnson conducted surveys and developed a hierarchy of passenger concerns with respect to a new transportation option. Most important was safety, followed by reliability, time savings, convenience, and comfort. Figure 4 illustrates the relative importance of these and other factors. For their purposes, "comfort" included temperature, humidity, seat comfort, noise, vertical motion, lateral motion, smoke, pressure changes, work space, and facilities.

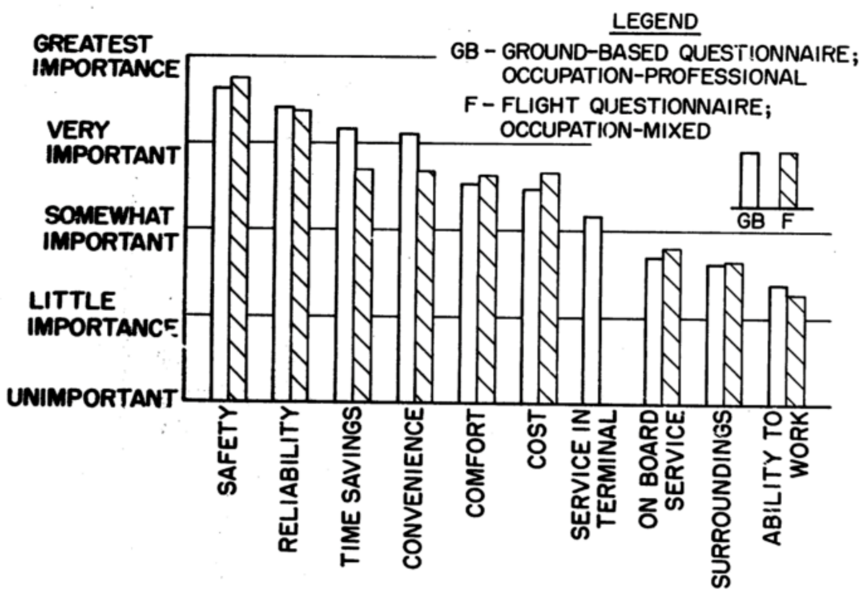


Figure 4. Comparative Importance of Various Passenger Experience Factors When Evaluating a New Transportation Option

McKenzie and Brumaghim, in a NASA-sponsored study [8], proposed the construct in Figure 5 relating passenger acceptance to vehicle attributes. They also attempted to quantify passenger acceptance criteria and identified metrics for acceptable ride quality.

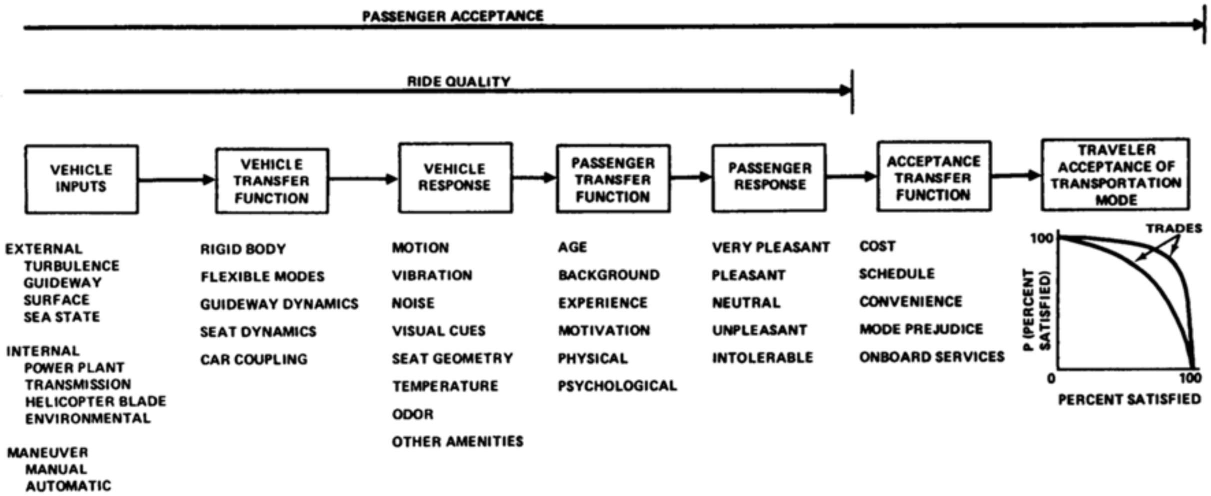
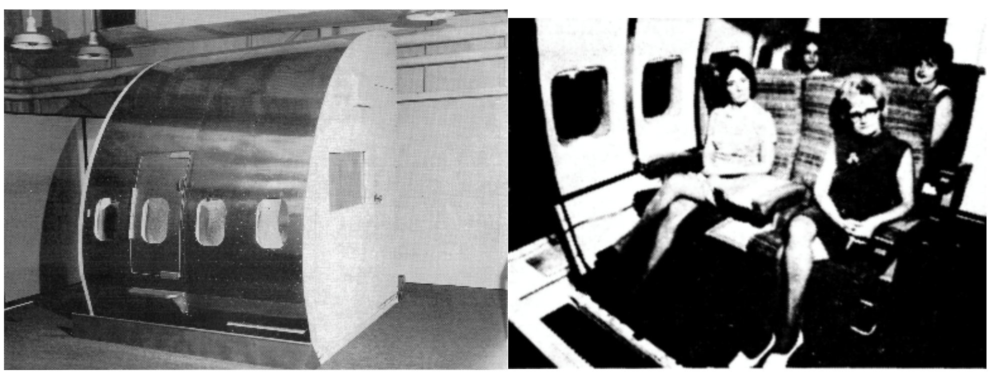


Figure 5. Factors Affecting Passenger Acceptance

NASA's work included a ride-quality program to develop vibration criteria applicable to air and ground transportation systems using the Passenger Ride Quality Apparatus, shown in Figure 6, at NASA's Langley Research Center [9].



Exterior View **Interior View**

Figure 6. NASA Langley Passenger Ride Quality Apparatus (c. 1976)

Studies based on simulation and field measurements developed criteria for acceptable levels of vibration, such as those shown in Figure 7 [10] and Figure 8 [11].

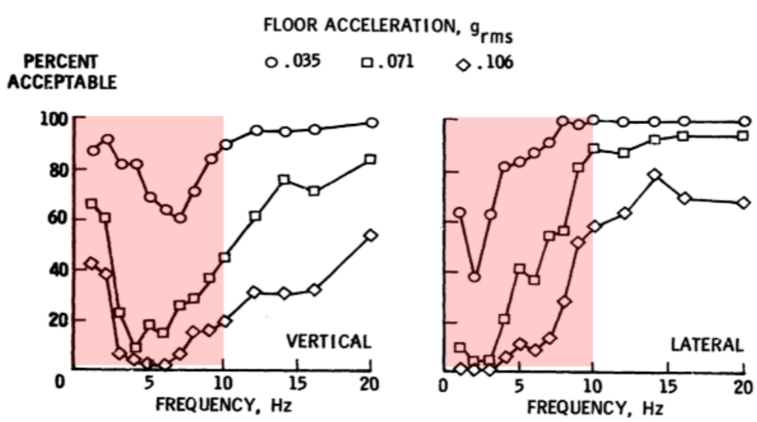


Figure 7. Vibrations <10 Hz are Least Acceptable to Passengers

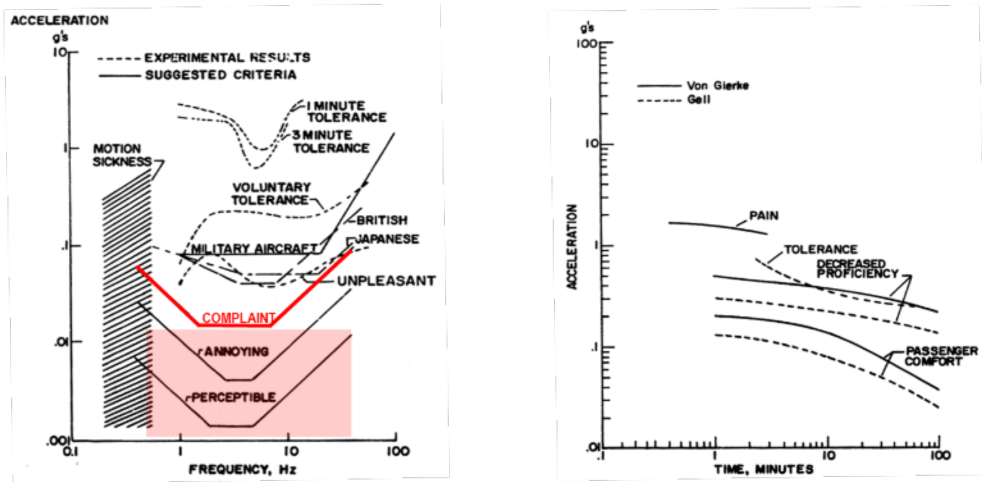


Figure 8. Vibration Amplitude >.01g Becomes Objectionable to Passengers

Table 1, below, presents suggested criteria for acceptable passenger ride quality from two studies based largely on the NASA-sponsored research conducted during the 1970s.

Table 1. Candidate Criteria for Acceptable Passenger Ride Quality

Factor	Criterion for 50%-Acceptable Response
Cabin noise	< 80 dBA [12]
Vibration	< .04g amplitude [12]
Rate of change in pressure altitude	< 850 to 1,100 m/min [12]
Pitch angle	< 10 deg. [13]
Roll angle	< 30 deg. [13]
Longitudinal acceleration	< 0.4 to 0.6g[13]

Work during that period included developing methods to assess comfort level based on a wide variety of factors, as illustrated in Figure 9 [14]

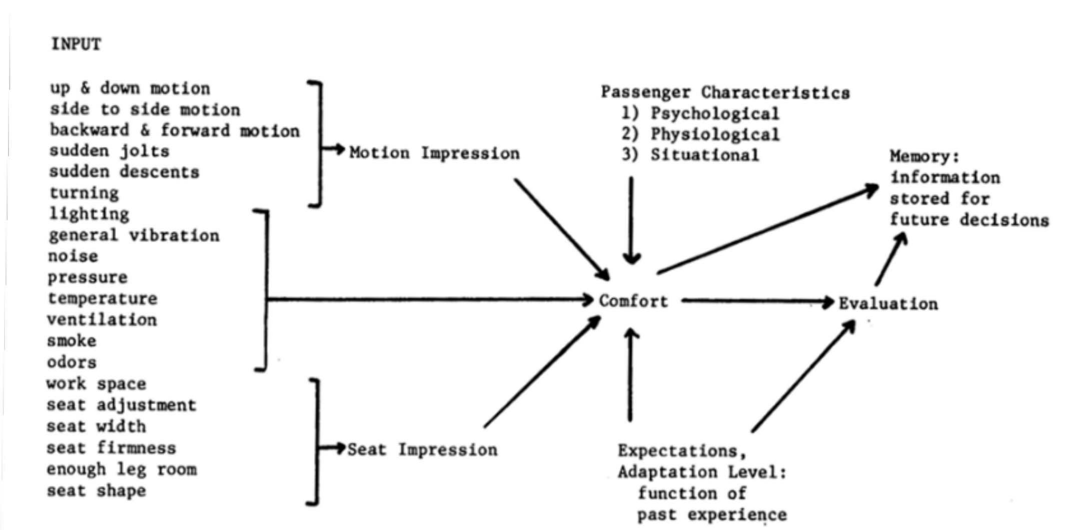


Figure 9. Components of a Theory of Comfort

Passenger comfort ratings were found to be independent of demographics (age, gender, weight) and previous flying experience. Vibrations below 1 Hz were not evaluated due to highly variable and individualized responses, though it is generally understood that vibrations in the .2 to .5 Hz range are principally responsible for motion sickness [15]. The duration of exposure is an important factor in passengers' overall evaluation of their experience [16]. This work led to ISO Standard 2631 for Vibration Dose Value and Motion Sickness Dose Value, which correlates passenger ratings to the cumulative exposure to vibration environments [17]. Research has also demonstrated that seat materials and designs can have a significant effect on the sensations transmitted to the passenger. Low frequency vibrations tend to be amplified, whereas high frequencies are often attenuated [18, 19].

NASA Langley work in the 1970s developed a discomfort index based on noise and vibration. This index was validated by simulations subjecting humans to noise and vibration levels measured in flight tests of then-current military helicopters [20]. Figure 10 shows the relationship between the index (percent uncomfortable) and combinations of noise and vibration.

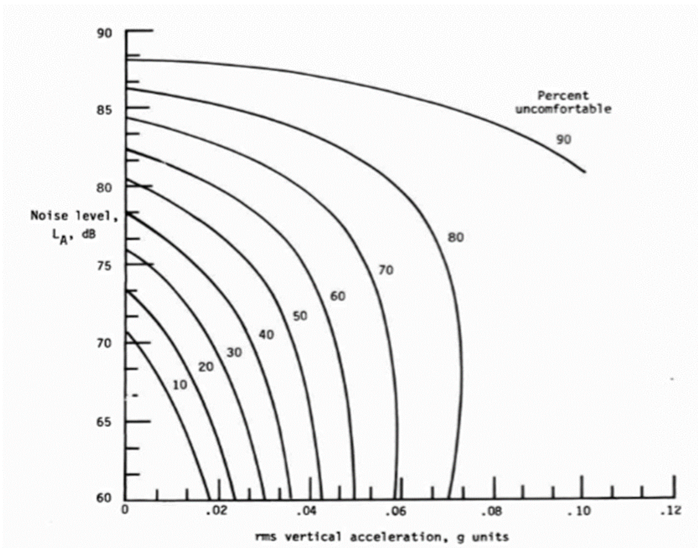


Figure 10. Values of A-weighted Noise Level and rms Vertical Acceleration that Produce Constant Values of Discomfort

Comfort ratings have been shown to accurately predict the percentage of passengers willing to fly again [21], validating the utility of measuring passenger experience for use in demand forecasting. More generally, passengers are not receptive to accepting a new transportation mode until their perception of safety satisfies a high standard. Convenience is the next most important criterion, with comfort being least important [22]. This finding correlates with Maslow's hierarchy of needs that motivate human behavior, which asserts that physiological and safety needs must first be satisfied before humans will pursue higher-level needs [23].

The level of effort devoted to this topic declined significantly following the period of active research on passenger ride quality in the 1970s and early 1980s. Some effort was directed to understanding the differences in passenger experience with new configurations and flight conditions versus the baseline of data for conventional fixed-wing transport aircraft. NASA's research into ultra-efficient subsonic aircraft configurations included a hybrid wing-body design, illustrated in Figure 11, that presented a new arrangement of seats and a reduction in window area. Industry studies indicated that these issues could be mitigated through acclimatization and electronic displays providing a synthetic out-the-window view.

Figure 11. Artist's Rendering of NASA Hybrid Wing Body Concept

At about the same time, preliminary design studies of proposed supersonic transport aircraft revealed the potential for motions due to coupling between structural flexibility and the control system. Termed dynamic aeroservoelasticity, this phenomenon was shown to generate motion in the cockpit that rendered the aircraft uncontrollable by the pilot due to the severity of motion. This condition was mitigated with adjustments to the structure and control system [24]. NASA also conducted passenger experience surveys as part of its flight research program to assess the fuel-saving benefits of wake surfing (flying in trail to extract energy from the wake of a preceding aircraft). Wake surfing results in continuous low-level turbulence that was found to present no discomfort to passengers and was described as being comparable to flight in calm air. Flying in turbulence, on the other hand, was found to be significantly less comfortable, largely due to the low-frequency content of that motion [25].

Work on space launch vehicles also provides insights into the extremes of ride quality. Although the environment is not entirely analogous to aircraft because of the additional g-load of vertical acceleration, NASA studies of human performance in simulated launch scenarios have provided valuable knowledge. Vibrations in the range of 8 to 20 Hz have the greatest impact on visual acuity, with a peak impact at 12 Hz. Vibrations at 40 to 50 Hz excite eyeball resonance, which can further degrade visual acuity [26]. Researchers also noted a higher than random occurrence of Benign Paroxysmal Positional Vertigo (BPPV), which produces transient episodes of dizziness, in subjects exposed to high-g, high-vibration environments [27]. Motion sickness has been associated with vibrations at .25 to .50 Hz, as well as with jerk (changes in linear acceleration) and multi-axis rotation. It is, therefore, important to understand the motions, g-forces, and vibrations expected in UAM flights that may create discomfort in passengers. For example, helicopters with three- or four-bladed rotors typically generate vibrations of 3 to 8 Hz, often with higher harmonics. This happens to be the frequency range that induces whole-body resonance in humans, which can lead to discomfort, particularly for people with back pain. In fact, the highest incidence of back pain and back disorders in aerospace operations is reported for helicopter pilots [28]. Studies of human performance in flight environments over many years has enabled NASA to establish requirements and limits to the flight environment for humans in space. These requirements are expressed in terms of rate of pressure change, temperature and humidity limits, exposure to acceleration, noise, and vibration [29].

V. Passenger Concerns

To identify potential passenger concerns with prospective eVTOL operations, we performed a literature search and conducted discussions with experts familiar with current helicopter operations, UAM, and eVTOL concepts and technologies. Our discussions with the eVTOL community engaged four academicians, four NASA researchers, and two industry representatives from leading eVTOL organizations. For views on passenger experience with current helicopter operations, we reviewed operator websites and interviewed seven members of the rotorcraft community, including the CEO of an operator providing scheduled helicopter service, the chief officers of two rotorcraft trade associations, two former chief helicopter R&D test pilots, a NASA manager and former military helicopter pilot, and an FAA rotorcraft expert.

The prospect of autonomous vehicle operations raises a variety of concerns. Several potential eVTOL operators have declared their intention to fly autonomously, either at the outset or after transitioning from piloted operations, but there is a strong consensus in the aviation community that the technology is far from ready to operate autonomous passenger-carrying vehicles. Whereas inner-loop control is comparatively straightforward to automate – flight management systems have steadily increased their use of automation for decades – processes that require diagnosis, addressing ambiguity, and anticipation are much less mature. The methods and capabilities to verify, validate, and certify autonomous systems lag the technology significantly. Moreover, passengers have expressed reluctance to fly on a vehicle that has no pilot on board.

The NASA-sponsored UAM market studies did not address passenger concerns in detail, although they recognized that such concerns could impact demand, and thereby affect the business analysis. They found that passengers generally trust human pilots over automation and are more comfortable associating with large, known brands. Personal security and privacy were highlighted as priorities for UAM passengers.

One of the studies found that 25% of more than 2,500 consumers surveyed report that they are comfortable with unmanned aerial technology, whereas approximately 25% report they will not use UAS or eVTOLs when services become widely available, citing concerns about safety, privacy, job security, environmental threats, noise, and visual disruption. Although the study concluded that "nearly half of all consumers surveyed are potentially comfortable with [package] delivery and UAM use cases," [30]. it is equally true that 75% of potential passengers are likely to have some concerns about the new technologies, beyond the customary attributes of safety, monetary cost, and value of time.

Whether piloted or not, eVTOL aircraft will need to employ novel techniques to establish the required levels of safety in power-out scenarios. In general, these vehicles are capable of neither a controlled power-out landing, as with conventional fixed-wing aircraft, nor autorotation, as with conventional helicopters. New approaches that include the use of redundant, highly reliable systems (rotors, motors, batteries, etc.), along with (potentially) parachutes, air bags, and energy-absorbing structures, will need to demonstrate that they do not pose an undue risk to passengers and people and structures on the ground. Certification of power-out contingencies presents a significant challenge to operators, and there are few applicable precedents to guide the process.

Surveys of consumer demand reveal that prospective air taxi passengers care not only about their own experience using this transportation mode, but also about the impact these operations have on the general population. The number and placement of vertiports, the noise footprint generated by air taxi operations, and the environmental impact of this new transportation mode all figure into passengers' willingness to accept eVTOL aircraft [31].

The issue of multirotor noise, both inside and outside the vehicle, was raised by nearly everyone consulted in this study. While some configuration-specific noise measurements have been made, a general, validated model to predict multirotor noise does not exist. Air taxi manufacturers are keenly focused on noise and vibration as potential passenger issues, and they are integrating these concerns early in the vehicle design process with the stated goal of an automobile-like environment. Other concerns being addressed by airframers include adequate ventilation to compensate for heat flux through large windows, ducted fans to contain noise and provide an additional measure of safety, and ample hand holds, head restraints, and foot braces to promote passengers' sense of safety. Another concern associated with multirotor configurations without cyclic pitch control is greater pitch and roll motion while executing flight maneuvers, which could exacerbate motion discomfort. It is not yet known if this issue is significant enough to require mitigations.

We found that, consistent with prior research, noise and vibration are leading concerns and are probably significant for eVTOL vehicles, but little has been done to understand their magnitude and how to mitigate them. The discussions with technical experts produced a large list of potential issues related to passenger concerns, presented below without prioritization, but grouped into thematically similar sets:

Potential Passenger Concerns Identified by Technology Experts

Passenger perceptions of safety

- Expectations about safety of nominal operations
- Pilot proficiency requirements
- Failure modes (motor, rotor, structural, control system, etc.)
- Crash mitigation (restraint systems, crumple zones, autorotation)
- Conflict detection and resolution, collision avoidance
- Robustness to weather
- Abort procedures, including ability to execute emergency landing
- Accommodation for incapacitated pilot
- Handling passenger medical emergencies
- How to protect from a rogue passenger in a ride share
- How to protect from a hacked autonomous flight or incapacitated pilot

Vehicle motion

- Acceleration and jerk
- Susceptibility to motion sickness
- Emergency evacuation procedures

Noise and vibration

- Cabin motion, noise, and vibration in all phases of flight
- Acceptable continuous vibration amplitude and frequency (e.g., structural vibrations, normal atmospheric turbulence at altitude)
- Acceptable transient vibration amplitude and frequency levels (e.g., vibrations from gusts or maneuvers)

Availability and access

- Schedule integrity
- Vertiport accessibility
- Accommodation for passengers with disabilities

Passenger well-being

- Ability to embark and disembark independently
- Ease of seating and movement in the cabin
- Ability to sit in groups, if desired
- Accommodations for hand luggage and larger cargo
- Cabin visibility – out-the-window field of view, control of light through the window, proximity to rotors and motors
- Cabin temperature control and power requirement
- Ability to converse, connect to the internet, read, write, and use a keyboard
- Ability to drink, eat, and sleep
- Privacy

We sought to gain further insights into passenger concerns by considering helicopter operations as an analogue to UAM. The "frequently asked questions" posted on helicopter operators' websites provided a convenient method to capture some of these concerns. The examples listed below represent issues that operators considered to be of interest to prospective passengers.

Examples of “Frequently Asked Question” on Helicopter Operators’ Websites

- Safety – Should you do a private helicopter tour if you’re afraid of flying?
- Turbulence – Should I expect any flight turbulence?
- Motion – Takeoff, landing, and quick altitude changes when flying in a helicopter can bring on air sickness in many people.
- Bumpy/swooping feeling – Helicopter flights are often not as smooth as those in an airplane, due to the smaller size of the aircraft.
- 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.
- Noise – Can I hear when the pilot is talking to me?
- Noise – The noise from the propellers triggers air sickness in some people.
- Cabin 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.
- Cabin temperature – What should I wear? Is the temperature on board really different?
- View/visibility – You will be able to see much more from a helicopter than you can from a plane.
- Fumes – 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.

Our interviews with operationally knowledgeable individuals were structured to elicit judgments about critical passenger concerns based on experience with current helicopter passenger-carrying service. The responses identified 25 concerns, listed below.

Passenger Concerns Identified by Seven Interviewees with Operational Knowledge

Cited by six interviewees

- Safety

Five interviewees

- Takeoff profiles
- Vehicle motion

Four interviewees

- Reaction to turbulence
- Internal noise
- Seating
- Familiarity with the cabin environment

Three interviewees:

- Vibration
- Cabin air quality

Remaining concerns

- Acceptance of new technology
- Interaction with the flight crew
- Ease of access (boarding and seating)
- Rotor wash at the vertiport
- Access for people with disabilities
- Availability of vertiports
- All-weather performance
- Noise footprint on the ground
- Visibility from the cabin

- Cabin interior design
- Cabin space
- Seating arrangement
- Carry-on baggage space
- Ease of maintaining cleanliness
- Passenger control of lighting
- Comfort
- Static electricity
- Fumes from fuel and hydraulics
- Connectivity with the ground
- Productive use of time

VI. Relationship of Passenger Concerns to eVTOL Design and Operation

To develop an initial understanding of how eVTOL vehicles can be designed and operated to mitigate passenger concerns, we developed and applied a method to correlate passenger acceptance needs with design considerations. We consolidated the issues uncovered in the literature search, the surveys of knowledgeable individuals, and information from the websites of current helicopter operators into 25 discrete passenger concerns grouped into six categories. Similarly, we identified 20 design and operations topics, also organized into six areas.

Figure 12 presents the matrix linking the passenger concerns with design and operations topics. Each intersection of a row and a column indicates a possible contribution of a design or operations topic to mitigation of a passenger concern.

Passenger Concern Categories	Design & 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 routes 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																				
Environm. Concern	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 & productivity - phone call, reading, etc.																				

Figure 12. Passenger Concerns Correlated to Design and Operations Topics

QFD is one method that can be used to correlate stakeholder concerns with product characteristics. To help in understanding the effects of eVTOL on passengers' experience, we adapted this method to indicate (1) the relative contributions of system design and operations topics to passenger concerns and (2) the issues involved in using this method to identify and shed light on relevant knowledge gaps.

A complete QFD evaluation would involve assessment of each of the 500 elements in the matrix in Figure 12. For this exploration, we chose to reduce the level of detail by performing the assessment for the six categories of passenger concerns and the six design and operations areas, thereby reducing the number of elements to 36.

We asked each of four in-house senior SMEs with extensive aeronautics backgrounds to independently judge (1) the relative importance of each passenger concern category and (2) the potential influence of each design and operations area on each passenger concern category. In light of the purpose of this initial trial, we used a simplified scale for each judgment: High, Significant, and Insignificant or Zero. To analyze and aggregate the results, we converted the SMEs' judgments into numerical scores of 1, 0.5, and 0, respectively. For each passenger concern category, as well as each element of the matrix, we calculated the mean value of the scores and the average deviation from the mean among the four scores assigned by the SMEs. We also calculated the importance of the passenger concern multiplied by the value of the potential influence score as an indicator of significance for each of the 36 elements of the matrix, as well as the sum of the significance values for each design and operations area, normalized to scale with a maximum achievable value of 1.

The initial assessments were then discussed with the SMEs as a group to identify reasons for differences in scores and to make any revisions based on the discussion. This step resulted in eight changes to the scores. The purpose of discussing differences was primarily to understand how the SMEs arrived at different scores, not necessarily to reconcile the scores. The discussion uncovered shortcomings in the process that could contribute to inconsistent results, helping to refine the model for future use.

Figure 13 presents the results of the SME assessment, with the passenger concern categories arranged in descending vertical order of importance and the design and operations areas arranged in left-to-right descending order of total significance. The dark shaded cells represent the top 25% of elements, based on calculated significance.

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)			**Operations** (Weather limitations; Flight route selection and operational constraints; Operations in vertiport proximity)			**Controls** (Flight controls; Piloting technique and automation)			**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	Importance	*Average Deviation*	Influence	*Average Deviation*	**Influence x Importance**	Influence	*Average Deviation*	**Influence x Importance**	**Influence**	*Average Deviation*	Influence x Importance	Influence	*Average Deviation*	**Influence x Importance**	Influence	*Average Deviation*	**Influence x Importance**	Influence	*Average Deviation*	**Influence x Importance**
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**	*0.0*	1.0	*0.0*	**1.0**	0.6	*0.2*	**0.6**	0.9	*0.2*	**0.9**	0.5	*0.3*	**0.5**	0.5	*0.0*	**0.5**	0.3	*0.3*	**0.3**
Vehicle Motion *(Vehicle acceleration - frequency, amplitude duration, axis/axes; Maneuvers - steep descents, jerk, turbulence/gust response; Visibility and visual cues - vertigo)*	**0.4**	*0.4*	1.0	*0.0*	**0.4**	0.9	*0.2*	**0.4**	1.0	*0.0*	**0.4**	0.3	*0.3*	**0.1**	0.1	*0.2*	**0.1**	0.3	*0.3*	**0.1**
Noise & Vibration *(Noise and vibration - frequency, amplitude, duration; Noise and vibration long-term exposure effects; Sudden unexpected transient noise)*	**0.4**	*0.4*	1.0	*0.0*	**0.4**	0.1	*0.2*	**0.0**	0.4	*0.2*	**0.1**	0.9	*0.2*	**0.3**	0.1	*0.2*	**0.0**	0.9	*0.2*	**0.3**
Availability and Access *(Vertiport location and accessibility; Schedule integrity: Access to aircraft at vertiport; Access for people with disabilities; Downwash at vertiport)*	**0.3**	*0.3*	0.4	*0.2*	**0.1**	0.4	*0.2*	**0.1**	0.0	*0.0*	**0.0**	0.0	*0.0*	**0.0**	1.0	*0.0*	**0.3**	0.0	*0.0*	**0.0**
Concern for the Environment *(Community noise concerns; Energy use concerns)*	**0.3**	*0.3*	0.6	*0.2*	**0.2**	0.8	*0.3*	**0.2**	0.0	*0.0*	**0.0**	0.0	*0.0*	**0.0**	0.5	*0.0*	**0.1**	0.9	*0.2*	**0.2**
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.)*	**0.2**	0.3	0.6	*0.4*	**0.1**	0.0	*0.0*	**0.0**	0.0	*0.0*	**0.0**	1.0	*0.0*	**0.2**	0.3	*0.3*	**0.0**	0.0	*0.0*	**0.0**
Relative Influence x Importance for Design and Operations Area					**0.4**			**0.2**			**0.2**			**0.2**			**0.2**			**0.2**
Average Deviation		***0.3***		***0.1***			***0.2***			***0.1***			***0.1***			***0.1***			***0.1***	

Figure 13. SME Assessment of Passenger Concerns vs. Design and Operations Areas (All scores on a scale of 0 to 1, rounded to one decimal point)

Since this "test run" served two purposes – first, to formulate an approach for considering issues associated with passenger concerns, and second, to develop indications about possible mitigations of those concerns – the results of the QFD analysis can be presented in terms of process and results, corresponding to those two purposes.

1. Process

The QFD approach shows promise for both characterizing passenger concern issues and drawing conclusions about possible mitigations. The overall average deviation among the four sets of scores for all cells was 0.14 on a scale from 0 to 1, indicating a large degree of agreement among the SMEs at the level of granularity used in this study. The discussions indicated that the major causes of variances were differing interpretations of the terms used to describe design and operations areas and different assumptions about specific missions and markets. The major issue was a need for clear narratives defining the elements being scored and criteria for the assigning particular scoring values. It was also pointed out that the assigned scores could vary significantly depending on the details of the particular mission and market characteristics. For example, passenger comfort preferences could vary significantly depending on the purpose and duration of a trip, and the preferences of early adopters could vary significantly from those of the average traveler. Thus, clearer definitions of terms, missions, and markets would likely enhance the validity of results.

The four SMEs represented a variety of areas of expertise, including VTOL vehicle research, design, and analysis; analysis of air transportation systems and markets; and air traffic management research, analysis, and operations. A more diverse set of evaluators, including transportation system operators, market analysts, and members of other stakeholder groups, might well show greater variance in their initial judgments, but multiple iterations with successive refinement could lead to convergence on more robust results, with the remaining variance among the refined judgments serving as a possible indicator of uncertainty. The Delphi method [32], which refines the opinions of experts through a series of questionnaires interspersed with information and opinion feedback, is one technique for doing that in a formal structured manner.

The QFD approach enables the inclusion of both analytical information and SME judgments within a single consistent framework. Because the number of elements to be judged increases exponentially with increasing levels of detail, this approach may become unwieldy for assessing either passenger concerns or design and operations areas in more detail. However, its hierarchical structure enables combining more detailed or higher fidelity analyses in some areas with qualitative or less granular assessments in other areas where these may suffice or knowledge is limited. Thus, the level of detail may be selectively expanded to address, for example, the most important elements of the matrix.

2. Results

Several tentative conclusions may be inferred from the results. In light of the scope of the work, these should be considered indicative rather than conclusive, but they provide a useful guide for further work.

The largest average deviation in our results was for the importance of each of the six passenger concern categories, indicating that more work may be warranted to understand the relative importance of each passenger concern and how it may be mitigated. These factors will likely vary for different markets; for example, the importance of issues related to comfort could be much greater for longer-duration trips than for trips of less than 15 minutes.

Perceived safety seems so much more important than other concerns that it should be addressed at a finer scale with research to determine how various issues affect the perception of safety and how to achieve the level of perceived safety needed to enable passenger acceptance. The influence scores indicate that perceived safety can be influenced in a meaningful way by every mitigation factor except energy, if "meaningful" is defined as an average score of 0.5 (on a scale from 0 to 1) or more. Passenger well-being is meaningfully addressed only through cabin accommodations – all other mitigations play a minor role.[1]

VII. Recommendations

Our analysis has identified five areas where R&D efforts initiated today could mitigate passenger acceptance risk and produce more successful outcomes for eVTOL vehicles and air metro or air taxi operations in the future.

1. Develop a Multi-fidelity Simulation Capability for eVTOL missions

Flight simulation is a well-established tool to perform rapid design iterations in a safe and cost-effective manner. Since the most important passenger concerns we identified relate to vehicle operations, an eVTOL simulator could be a powerful tool to evaluate and refine mitigations. A fast-time simulation capability would be useful for constructing a library of trajectories representing nominal and off-nominal operations, which could be used to replicate motions and gather trajectory statistics to characterize them. Fixed-base, part-task simulators would be useful for developing piloting techniques, assessing pilot proficiency, and evaluating the viability of different flight paths.

Full-motion flight simulation will be necessary to address the most important passenger and piloting concerns. The air vehicles are likely to experience sustained g-forces of up to a few seconds while performing climb-outs, accelerations, and approach maneuvers. Creating an immersive experience in a high-fidelity flight simulator would enable research addressing several of the most important passenger concerns, including vehicle motion, vibration, noise, and out-the-window visibility. Although NASA's prior work related passenger comfort to the combination of noise and vibration and, separately, to the duration as well as amplitude of vibration, no metric has been developed relating passenger acceptance to magnitude and duration of the combination of noise, vibration, and vehicle motion. Additionally, since pilot-in-the-loop simulations and evaluations of passenger responses will be necessary to develop requirements and procedures for operations close to urban structures and in the presence of micro-weather, this environment would also be valuable for understanding piloting capabilities and limitations.

Full mission simulation, including interaction with the air traffic system, will enable further exploration of issues related to passenger concerns, such as too much maneuvering to avoid conflicts and transitions between flight phases, such as initiating steep descents. Approaches to landing areas and operations in urban canyons may involve frequent tight maneuvers and encounters with micro-weather phenomena, which may affect pilot performance as well as passenger comfort and perceptions of safety, and which may require mitigation through flight path management and air traffic control procedures.

2. Characterize and Model Noise from Multirotors

Our assessment indicated that aircraft noise affects not only public acceptance, but also acceptance by passengers concerned with the environmental impact of their choice of transportation modes.

Although there exist a robust database and validated models for noise generation and propagation by conventional rotorcraft, little data exists to predict and mitigate noise generated by the multiple rotors in use on many eVTOL concepts. There is a wide variety of configurations, all of which will possess different characteristics that need to be understood. A test rig could be equipped with rotors in candidate configurations and run to generate noise profiles. Measurements of noise and propagation properties would

[1] There was a significant average score (0.63) for vehicle design vs. passenger well-being, but discussion with the raters found that this was due largely to different interpretations of which attributes are included in vehicle design vs. cabin accommodations.

produce a valuable database to develop and validate eVTOL noise models useful to vehicle and airspace designers and for community outreach.

To help develop a standard to which an aircraft developer can design, NASA has gathered extensive data on the human response to noise generated by supersonic aircraft. [33] Studies have included individual response experiments, community response studies, and assessments of structural transmission. The data gathered provided not only the confidence for regulators to propose a standard, but also the understanding for designers to refine techniques to meet the standard. A similar process to address eVTOL noise requirements would help give the industry the confidence to move forward with products.

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

Passengers' perception of safety is the most important concern we identified. Because eVTOL configurations generally have limited capability to execute a safe landing in the event of loss of power, accurately characterizing the performance of eVTOL propulsion and power systems will be essential to gaining public confidence and FAA certification for new operations. Whereas there exists an immense performance database for turbofan engines, industry's collective experience with distributed electric propulsion is in its infancy. Failure modes, mean time between failure, and operability after a failure are all factors that must be well understood when defining safety cases and contingency plans.

Test stands to operate and measure the performance of characteristic systems could facilitate progress in characterizing hybrid and all-electric propulsion. The NASA Electric Aircraft Testbed [34] is a good candidate for this purpose. Safety cases for hybrid and electric-powered aircraft will rely on redundancy and reliability of these systems; requiring data and analysis to formulate a logical argument for a safety case built on redundancy and reliability. Incremental envelope expansion, of which Extended Operations (ETOPS – formerly Extended Range Operation with Two-Engine Airplanes [35]) is an example, offers an efficient approach to building a safety record for new vehicle and operational concepts.

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

NASA's UAM Grand Challenge will involve some of the first flights of a variety of eVTOL design concepts. This undertaking presents an ideal opportunity to gather data that will refine models and parameters relevant to the passenger experience. Measuring the noise levels and vibration characteristics inside the cabin during flight will help define the likely range of these parameters to expect on operational vehicles. High-fidelity measurements of the four-dimensional trajectory for these vehicles while flying reference missions will provide validation data for the flight dynamics models in simulators, as well as providing the capability to play back scripted trajectories in the simulator, both of which will inform assessments of passengers' response to accelerations and motions encountered in flight. Ground-based microphone arrays can acquire noise footprints useful to validate noise propagation models and to inform community noise predictions.

5. *Conduct refined analyses of passenger demand and concerns*

Passenger demand studies have heretofore focused on demographic and economic dimensions of the market for eVTOL transportation. Our study indicates that passenger concerns are an equally important aspect to forecasting ridership, and thus industry viability. Future demand studies should characterize attitudes about the types of passenger concerns identified in this study to ensure that the sensitivity of demand to these issues is given proper weight.

Our low-fidelity implementation of QFD analysis demonstrated its utility to guide the approach and provide preliminary indications of the most important parameters. However, refined analyses would be necessary to capture the nuances of passenger concerns related to specific market segments and mission profiles. We propose a selective approach to such an analysis by identifying and focusing on the most critical elements affecting demand.

VIII. Summary and Conclusions

This report has taken an initial look at the design considerations for eVTOL aircraft from the passenger's perspective. The success of any new vehicle platform is critically dependent on acceptance by the customer, and eVTOL aircraft present a different set of issues than have been dealt with in more conventional aircraft. Factors including the design of the vehicle, the way it flies, what passengers can see and do in flight, and the vertiport experience will all play into the passenger's evaluation of eVTOL as a transportation option. Considering the size of the investment required not only for vehicle development but also for establishing the necessary infrastructure, it is essential to define a commercially viable product from the outset. Discovering issues after the vehicles go into operation will necessitate costly retrofits and will impact business prospects. Thus, it is of great importance to understand as much as possible about design and operational approaches that can address passenger concerns so as to incorporate them into the design at the outset, when it is relatively inexpensive.

Based on prior research as well as input from current helicopter operators, we have highlighted several issues that should be addressed early in the design and development cycle, including perception of safety, vehicle motion, noise and vibration, availability and access, environmental impacts, and passenger well-being. The eVTOL flight experience will be unlike any that have come before: electric propulsion, multiple rotors, high levels of automation, and low-altitude flight in urban environments are among the differences that will be immediately apparent to passengers. Research in specific areas will be needed to address these unique concerns. We have offered several recommendations for research that would produce valuable information to guide and foster the emergent eVTOL ecosystem.

Acronyms and Abbreviations

BPPV	benign paroxysmal positional vertigo
dBA	A-weighted decibel(s)
deg	degree(s)
ETOPS	Extended Operations
eVTOL	electric vertical takeoff and landing (aircraft)
Hz	Hertz
m	meter(s)
min	minute(s)
mph	miles per hour
QFD	quality function deployment
R&D	research and development
rms	root mean square
SME	subject matter expert
UAM	urban air mobility

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