

Accessibility Design and Operational Considerations in the Development of Urban Aerial Mobility Vehicles and Networks

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Urban aerial mobility vehicles and networks have recently gained considerable interest in the aviation community. These small, short-range vehicles with all-electric or hybrid-electric propulsion systems, tailored to metropolitan aerial transportation needs, promise to radically change passenger mobility and cargo distribution in cities. Accessibility issues have not been a major consideration in UAM vehicle and network discussions to date. This paper seeks to help change that.

Nomenclature

A	=	Frontal area of cabin, m ²
A_R	=	Area of rectangle circumscribing the cabin maximum cross-section, m ²
α	=	Vehicle angle of attack, Deg.
eVTOL	=	(all- or hybrid-) electric Vertical Takeoff and Landing vehicle
EMS	=	Emergency medical service
GW	=	Vehicle gross weight (total mass), kg
MEP	=	Mission equipment package, kg
UAM	=	Urban air mobility
UTM	=	Unmanned (air) traffic management
V	=	Vehicle cruise velocity, m/s

I. Introduction

URBAN aerial mobility (aka urban air mobility or eVTOL) has seen a substantial increase in interest within the aviation community over the past couple of years. Urban aerial mobility (UAM) is the proposed development of vertical takeoff and landing (VTOL) vehicles and vertiport-station networks to enable revolutionary transformation of metropolitan transportation. UAM vehicle design also seems to focus on multirotor configurations with all-electric or hybrid-electric propulsion. Interest in UAM in the past five years grew at an extraordinary pace, in part, due to the publication of Ref. 1. NASA Ames arguably, though, has been interested in UAM (at the time referred to as rotary-wing personal air vehicles) from a research perspective from nearly two decades ago, Ref. 2. Reference 3 has attempted to capture some of the ongoing progress on UAM.

Our society as a whole has taken great pride in the freedoms and opportunities that our automotive transportation network has afforded our country. And yet, there are many in the United States who because of disabilities and other factors cannot benefit equitably from those freedoms and opportunities. Progress is being made with respect to automobiles and public ground transportation systems – the potential of self-driving cars, for example, is a particularly promising recent development – but the rapidly emerging field of urban aerial mobility could, if precautions are not taken now, result in vehicles and infrastructure that are inadequately accessible. Ideally, UAM should be for everyone.

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Figure 1a-b is just one of a multitude of proposed and in-development notional UAM vehicle concepts. This particular vehicle concept will be a point of departure for subsequent discussion regarding UAM accessibility. Note that this concept was introduced in Ref. 4 and discussed in further detail in Ref. 5.

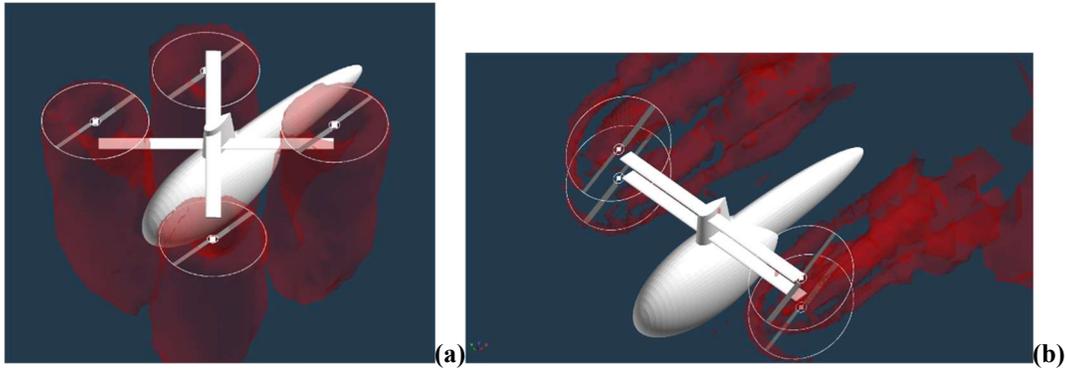


Figure 1. A notional urban aerial mobility vehicle platform (CFD predictions of rotor-wake velocity-magnitude isosurfaces being shown): (a) hover and (b) edgewise forward-flight cruise

The initial impression of this concept might be that it is just another quadrotor-type single- or small-passenger eVTOL such as one of the NASA Revolutionary Vertical Lift Technology (RVLT) project reference designs, e.g. refer to Ref. 6. The key differences lie in the use of scissor wings and partially tilting proprotor/propellers that are swept from a scissor angle of forty-degrees when hovering or in low-speed flight to zero degrees in high-speed cruise (forming a biplane-like wing configuration). This scissor-wing/rotor-nacelle tilt conversion schedule is shown in Fig. 2.

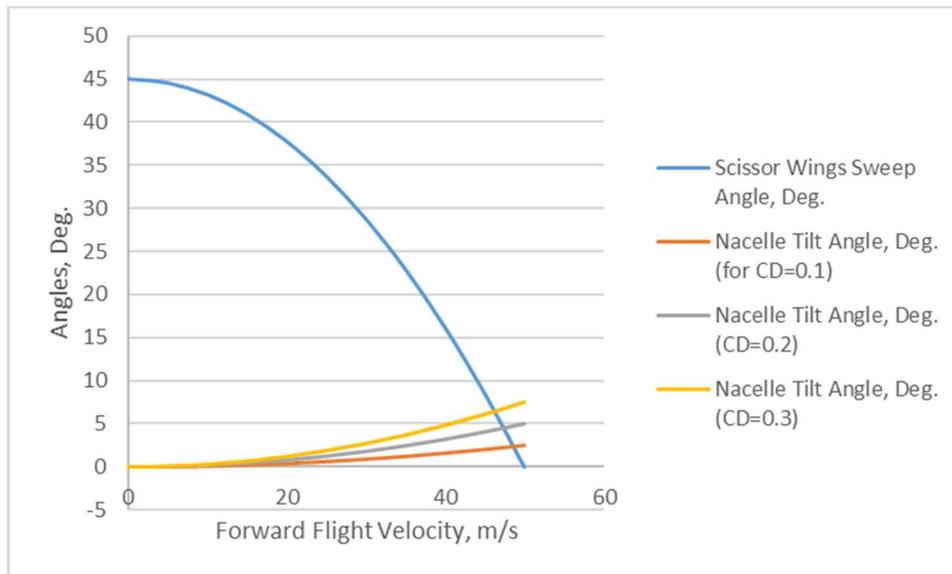
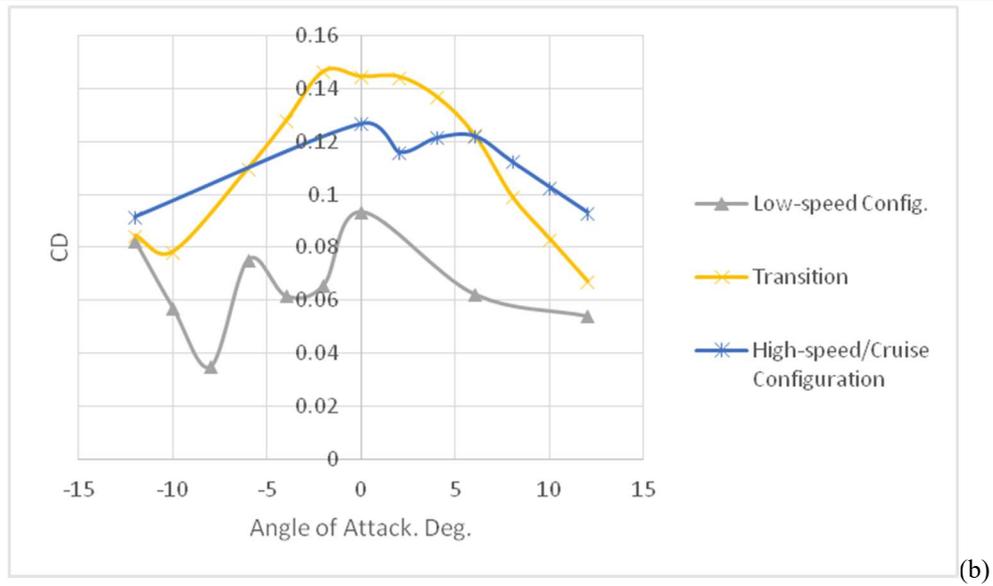
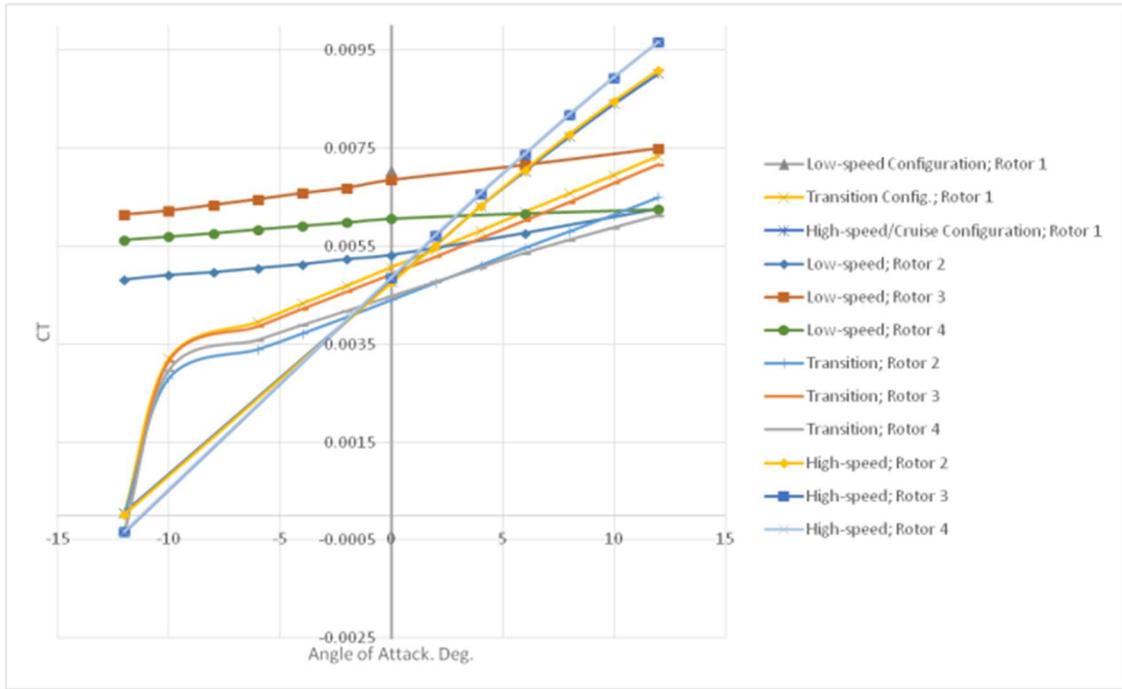


Figure 2. “Conversion corridor” profile for notional vehicle (for different assumed vehicle drag coefficients, C_D)

Work to date on this concept has focused on its aeroperformance characteristics in various stages of its conversion from hover to cruise. Some example CFD results – using the software code RotCFD, e.g. Ref. 7 – are shown in Fig. 3a-d.



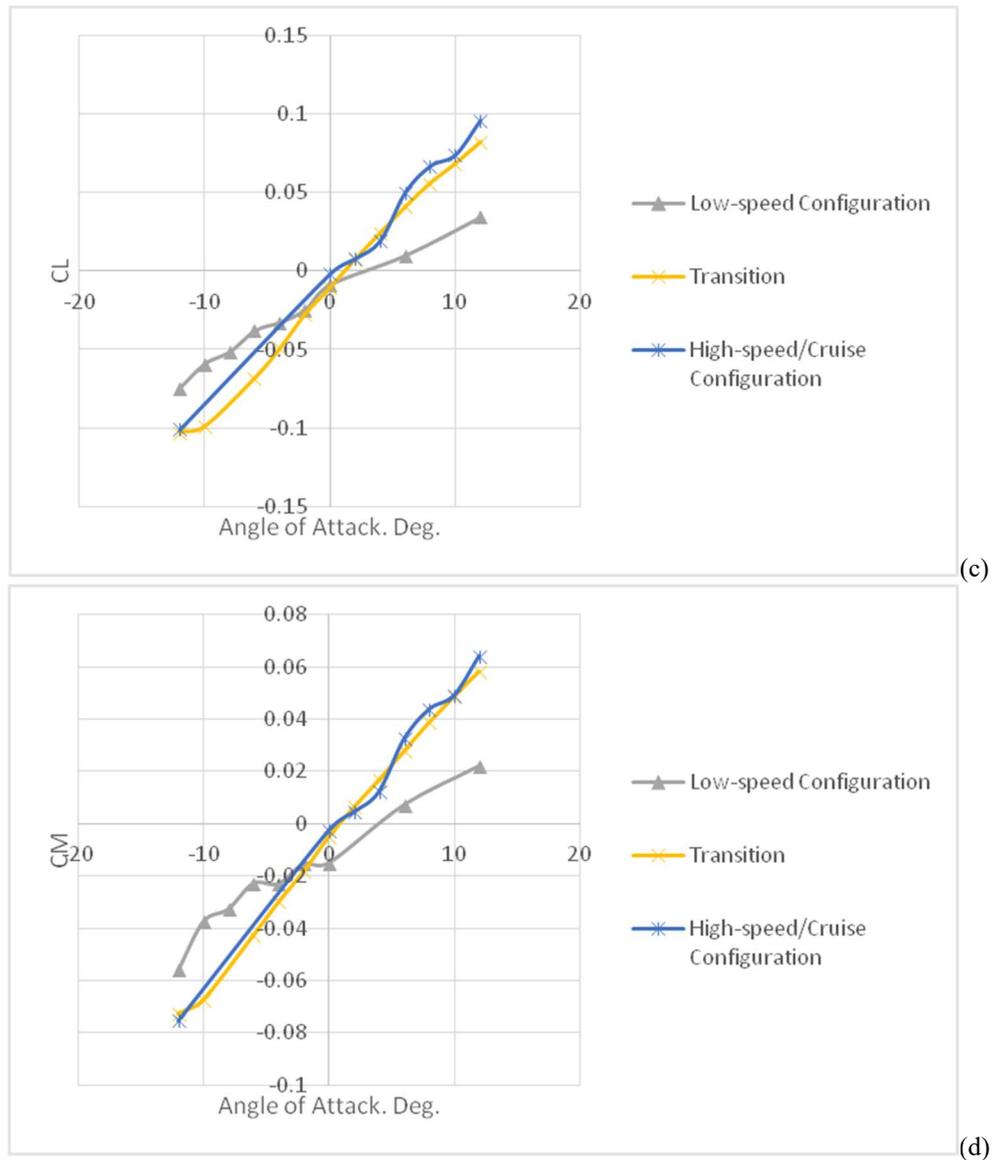


Figure 3. Relative forward-flight characteristics of a high-speed/cruise, versus transition, and low-speed notional vehicle with scissor-wings and partially-tilt-able rotors: (a) rotor CT for all four rotors vs. AOA; (b) vehicle CD vs. AOA; (c) CL vs. AOA; (d) CM vs. AOA

II. Some Fundamental Accessibility Considerations

Turning now from discussion of one possible UAM vehicle configuration, the remaining portion of the paper will focus on general design and operational attributes of such vehicles – and the networks that support them – that would ideally allow them to be of the greatest utility for providing accessibility. To aid in this discussion, a level-of-support metric for UAM vehicles is outlined immediately below. The proposed level-of-support metric ranges from no support to full EMS critical-care support. Not all UAM vehicles would necessarily have to be capable of providing all levels-of-support but, overall, there should be sufficient vehicles throughout the UAM fleet servicing a given metropolitan region that are capable of meeting the needs of the user community. (It is suggested, though,

that the automation and networking capability of many of the proposed UAM concepts currently being examined might be leveraged to provide more individual vehicle accessibility and medical-support capability than might be initially assumed.)

Levels of Support—

0. No support. Passenger is responsible for all aspects of getting/proceeding to aircraft, boarding, and abiding by all rules and instructions for inflight comport.
1. Minimal. Same general level of support provided by commercial airlines. I.E. assistance provided getting to and from aircraft cabin entry but passenger (and personal caretakers) responsible for making way to – and occupying – passenger seat(s).
2. Low. Assistance limited to the overall boarding and deplaning process.
3. Moderate. Assistance for not only boarding and deplaning but on-demand support during flight for passengers, caretakers, and service animals.
4. Moderate to high.
5. High-level of assistive support throughout the boarding and deplaning process and the flight itself; continuous remote monitoring via telecom and Datacom to ensure safety; automated processes and countermeasures to provide safety during emergencies.
6. Full critical-care support. Aircraft provides transport and medical care compatible with or beyond ambulances and EMS aircraft.

Defining the level-of-support metrics is only a first step. It is then necessary to consider what might be the vehicle design implications of providing such varying levels of support. Table 3 illustrates a mapping the above defined levels-of-support to a first-order set of notional design/mission requirements.

Table 3. Vehicle Design Requirements as a function of Level of Support

Level of Support	Min. # of Passengers	Passenger Effects (kg)	Personal Assistive Equipment (kg)	Range (km)	Energy Margin (min.)	MEP for Accessibility (kg)
0	1	25	0	100	15	0
1	2	50	25	100	15	0
2	2	50	200	100	15	50
3	2	60	200	125	15	50
4	3	75	200	125	30	100
5	3	75	250	125	30	200
6	4	100	250	150	30	200

The exact numeric values in Table 3 are debatable. However, the key point to be made here is that UAM mission and design requirements should not be defined only in terms of some subset of the general population but, instead, should be as inclusive as possible. The numeric values in the above table also intentionally highlight that some of the challenges of UAM development – in terms of autonomy and electric propulsion to single out two sets of critical technologies – may be even more daunting than vehicle developers are currently contemplating.

If there is justification and infrastructure in place to enable “flying air taxis” that can fly anywhere at any time then it also behooves developers and municipalities to consider “flying ambulance” UAM derivatives.

Accordingly, vehicle sizing exercises should also consider this possibility – i.e. provide room/access for stretchers/gurneys, medical equipment, and EMT’s in UAM “flying taxi” variants. A single passenger “flying motorcycle” concept similar to those that has been promoted by some UAM developers would be a very poor vehicle configuration to attempt to provide for this medical emergency utility. Now, again, it is not a reasonable expectation that there will be a one-size-fits-all philosophy as to vehicle development. On the other hand, some level of standardization that provides a minimal accepted set of onboard emergency supplies should be reasonably expected. It would be assumed, for an example, that a first-aid kit should be onboard any UAM vehicle. Also, it can be reasonably anticipated that automated rerouting because of an inflight medical emergency will need to be supported; having this capability would be valuable irrespective if the passengers had preexisting disabilities or not. Just as commercial aircraft have oxygen tanks and defibrillators available because of medical emergencies, it would make sense that such capabilities find their way into UAM vehicles. The challenge in having such emergency resources onboard, though, is that there may not be any flight crew to support these potentially autonomous aircraft. Finally, many metropolitan authorities may dictate UAM fleets to serve upon need in emergency response and disaster relief actions.

Judicious consideration of the cabin environmental conditions will be necessary. For example, should cabin windows be provided? Another example would be whether or not flight status monitors are provided that show planned and actual flight paths and perhaps other aircraft in the immediate vicinity. Passenger sensitivity to cabin noise and vibration may be an even more crucial design consideration in making UAM vehicles generally accessible.

III. Challenges to providing accessibility to Urban Aerial Mobility Vehicles and Networks

Ultimately, UAM is all about time. Time saved by avoiding grid-lock due to congestion of urban public and private ground transportation systems. It is not, though, simply a matter of the time in in-flight transit but, instead, the total time from point A to point B, or “door to door.” Inevitably the total point-to-point travel time has to also consider the time for the not-in-flight phases of travel. Accordingly, it is important to consider not only accessibility from the perspective of just the vehicle but the overall system-of-systems network inherent in the UAM concept. Some initial consideration of these system-of-systems issues was discussed earlier in Refs. 8-9.

Passengers with disabilities could greatly benefit from enhanced mobility potentially afforded by UAM vehicles and networks. Their support needs must not be relegated to a secondary design or operational afterthought. The ideal UAM “door to door” transportation of people could significantly reduce the amount of transit time and effort required for all passengers.

Table 1 highlights some of the anticipated design and operational challenges of providing adequate UAM accessibility. This is not a comprehensive list and, instead, should be considered as an aid to enable the overall UAM research and development community to begin to consider these potential accessibility issues early in this emerging field of study and aviation sector.

Table 1. Potential Challenges to UAM Accessibility

Challenge	Network (N) or Vehicle (V)	Anticipated Severity and Frequency	Description of Potential Problem
Ease of standard boarding and deplaning vehicle; includes consideration of personal belonging and/or baggage	N and V	Moderate & Frequent	The ability to safely load and unload passengers with accessibility equipment and care support is critical (this is a major focus of this paper). However, also need to provide positive assurance to passengers that they are safely secured in the cabin for any eventually and, yet, can also safely egress in case of an emergency (this is especially true if major aspects of the boarding/deplaning is automated).

Reducing takeoff and landing and maneuvering acceleration and deceleration levels to safe and comfortable levels	V	Low-to-Moderate & Frequent	It is currently unclear as to what are acceptable acceleration and deceleration profiles for potential UAM passengers in general. It is even less clear as to what the maximum non-emergency profiles should be for passengers with accessibility issues.
Minimizing cabin noise and vibration levels to acceptable levels	V	Low-to-Moderate & Frequent	Noise and vibration levels should be examined not only from a general passenger perspective but also from one in which the passengers might be extra sensitive to noise and vibration.
Providing for safe emergency deplaning	N/V	Moderate-to-High & Infrequent	Emergency deplaning procedures and equipment must be adequately provided so as to insure <u>all</u> passengers can safely deplane from a UAM vehicle in an emergency.
Countermeasures for turbulence and severe weather conditions	N/V	Low-to-Moderate & Frequent	In general a number of countermeasures could be considered to deal with these extreme turbulence and weather conditions: (a) automated network increased vehicle spacing during severe weather conditions; (b) special bad-weather dynamic flight paths; (c) embedding high levels of onboard sense and avoid sensors and sensor fusion (avoiding over-reliance on network guidance/control) to deal with extreme weather conditions, particularly lack of reliable automated visual navigation systems; (d) special cabin active vibration control actuator systems to increase passenger comfort and safety during extreme turbulence; (e) cabin layout design to minimize passenger hazards during extreme turbulence. Caution must be taken to insure that turbulence or otherwise extreme weather condition countermeasures are not unsafe with respect to all passengers, including those with disabilities.
Providing for safe countermeasures for emergency maneuvers and landing	V	High & Very Infrequent	In general a number of countermeasures could be considered to deal with emergency maneuvers: (a) overriding flight computer max, min, and rate limitations on control inputs and rotor rpm; (b) deployment of parachutes and/or internal/external airbags; (c) deployment of contingency anti-torque devices such as single-use cold/hot-gas thrusters on tailboom, wings, or cross-arms; (d) special "crash landing" flight computer algorithms. Caution must be taken to insure that turbulence or otherwise extreme weather condition countermeasures are not unsafe with respect to all passengers, including those with disabilities.
Providing for effective communication (including emergency and medical telecom and datacom) between passenger(s) and remote operators and operation centers	N/V	Moderate-to-High & Infrequent	Ultimately, UAM vehicles will be fully automated and will not have onboard pilots. Further, it is not likely that there will be onboard flight attendants or other UAM service provider representatives. Consequently, it is critical to consider telecom/datacom systems/services onboard the vehicles to insure the safety/security of all passengers, especially those with medical considerations or who additional support.
Cabin interior safety monitoring (especially important for multiple, and potentially unruly, passengers) and "panic button"	N/V	Low-to-Moderate & Infrequent	See the immediately-above comment.
Mid-flight course correction(s) for emergency for cabin and external emergencies (including rerouting to ER's and urgent care facilities)	N	Moderate-to-High & Infrequent	It is reasonable to assume and provide for mid-flight deviation of the vehicle from the originally planned network flight profile/schedule to redirect the vehicle to emergency care centers if an immediate inflight medical emergency occurs that insures the fastest medical response.
Enhanced or unique crashworthiness requirements and/or mitigation provisions	V	High & Very Infrequent	Some of the notional crashworthiness safety features that could be built into UAM vehicles include: external and cabin airbags, crushable flooring and or seating/wheelchair-attachment-hardware, and ballistic parachute systems for the whole vehicle. But, accordingly, these systems could be designed to be universally applicable /usable for all passengers without major configuring of the vehicles or specialized/tailored vehicles being provided.
Providing for adequate cabin space and care provisions for service animals	V	Moderate & Frequent	Ideally, all UAM vehicles should have the capacity to carry and provide for service animals accompanying passengers who need the animals support. In a worst case scenario, UAM service providers might significantly restrict the transport of service animals.
Appropriate balance between situational awareness versus "insulation" of passengers from the exterior environment	V	Large & Frequent	Should the cabin have small or large windows (or windows at all) or displays showing external views of passengers? Would the combination of a lack of an onboard pilot and flying at low-altitude and maneuvering in "urban canyons" be too disturbing (anxiety provoking)? Or would lack of windows and other situational awareness tools provoke some level of claustrophobia?
Adequate vertiport loading and	N	Moderate	Some ground-transportation public transit systems provide for

unloading extreme weather shelters, ramps, jetways, and other manual or automated boarding/deplaning equipment		severity & Moderate frequency	accessible shelters for extreme weather conditions. But, generally, such accessible shelters are comparatively few in number. UAM vertiports and overall networks should provide substantial support by way of providing all-weather shelters for boarding and deplaning.
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The table 1 accessibility challenges will now be discussed in more detail in the next few sections.

Accessibility for UAM Networks

Some of the on-demand, anywhere at any time, UAM network concepts will by necessity have to rely on partial- or non-full-featured vertiports and/or informal landing areas. Other UAM networks would require more regularly scheduled and formal prescribed routes that rely on full-featured vertiports and transit stations. Ground-infrastructure architectural guidelines for providing accessibility for full-featured UAM vertiport stations will likely be based off of, in large part, standards developed for airports, railway/subway stations, and public buildings. Providing for accessibility for partial-featured vertiports or informal landing zones will perhaps require innovation in new vehicle designs and onboard equipage.

Informal landing areas:

This scenario perhaps presents the greatest challenge with regards to safety and accessibility. It is essential that a minimum set of guidelines and requirements be defined such that the on-demand, door-to-door, anywhere at any time operational model (business model) can be safely effected while at the same time providing for full accessibility.

Even if the proposed UAM network CONOPs (concept of operations) relies on a station-to-station model, providing for emergency landings must allow for the safe use of informal landing areas.

To provide for the reliable ability to land at informal landing areas (either for regular service or emergencies) will require developing design guidelines for vehicle cabin layouts and onboard equipage to ensure safe and efficient access/egress of all passengers. The addition of large cabin doors, emergency-removable hatches/panels, lifts, ramps, reduced-profile or adjustable-height landing gear, and passenger support-equipment may all well be required.

Partial- or non-full-featured vertiports:

Rooftop “helipads” and other partial- or non-full-featured vertiports co-located as secondary facilities of commercial and public buildings may be an acceptable compromise (versus full-featured stations) as being part of a UAM vertiport network. Existing commercial and public space provisions for accessibility could perhaps be augmented (rather than developed wholly new) to support accessibility. An example of such augmentation may be that current building rooftops might currently only be reached by staircase; such buildings would have to be retrofitted to accommodate elevator or lift access to a rooftop-based partial-featured vertiport.

Full-featured vertiports and transit stations:

As noted earlier, this metropolitan aerial transportation scenario would likely build off of regulations, requirements, and guidelines established and implemented for other analogous public ground transportation systems, including those for public transit stations. Some of the ground-infrastructure issues attendant with full-featured vertiport stations is detailed in Ref. 8. Full-featured stations could be integrated into a complete multimodal transportation network, thereby minimizing door-to-door transit time and maximizing the ease of urban travel. Full-featured vertiport stations could also be magnets for urban economic development.

Novel Vertiport Station Concepts (floating islands and/or amphibious vehicles):

Reference 8 briefly introduced and Ref. 10 details the concept of the vertiports located on littoral waterway shores and or “floating island” vertiport stations that could be used to support amphibious UAM vehicles. Many of the metropolitan regions in the United States are near bays/sounds or other ocean or freshwater waterways. With real estate cost and overall availability being a key consideration in the development of vertiport stations. And, further, with community noise being a key concern with respect to the overall UAM concept, flying over water for a significant fraction of a UAM flight has to be of substantial benefit. Accordingly, development of amphibious UAM vehicle would seem to be an essential element of such novel UAM network stations. Concurrent, with the vehicle development are possible unique accessibility issues for loading/unloading from such amphibious vehicles as well as mitigation provisions necessary to be developed for emergency landing on open-water. Finally, difficulty of navigation and flight-control over waterways might be compounded by increased likelihood of morning/evening fogs and gusts/shear-winds at low-altitude near water.

Novel Vertiport “Stations” in the context of vehicle as habitat:

For more speculative UAM transportation system related concepts, Ref. 11 introduces the concept of a vehicle that serves as both a multimodal transportation-system element and a transportable (personal living-/working-space) habitat. The simplest version of this concept is a “fifth-wheeler” type camper on wheels that can be transported by conventional automobiles, automated/self-driving ground-mobile “tugs,” railways (by loading onto freight-car-type conveyances), and even UAM vehicles and other aircraft (as slung loads, internal payloads, or external hard-mounted payloads) that are transported to residences, dedicated residential areas/parks, and dedicated office complexes/parks. More exotic variants of the overall concept are also discussed in Ref. 11. The consequence of this new transportation/habitation system concept is that where people live, work, and congregate becomes entirely flexible and can vary from day-to-day and even hour-to-hour. (Reference 12 previously proposed a relatively more modest concept by proposing a UAM flight vehicle that, upon demand, integrates with and transports ground-transportation modules; the integration of habitat-themed elements into the overall system-of-systems is not proposed in this earlier work.)

Potential Accessibility (and other) Implications of Private, Corporate, or Public Ownership of vehicles and networks:

Whether a proposed UAM network is considered to primarily be either a public, private, corporate, or mixed-use transportation system will inevitably have significant implications on the development and operation of that network. Though standards can and will be developed for UAM vehicles and infrastructure that will generally be applicable for all of these types of operations, there will still be challenges with respect to harmonization of mixed-use transportation system networks. One debatable point, for example, will be whether or not the highest levels of support for accessibility for private UAM vehicles will need to be met generally, or if the required level of support be addressed on case by case basis. Another example, how standardized will internal and external assistance equipage need to be between private, corporate, or public vehicle fleets and networks.

UAM takeoff and landing trajectories and implications for ride quality for passengers:

UAM accessibility considerations should include the relative severity of the acceleration and deceleration profiles of UAM vehicle takeoff and landing trajectories and their implications as to safe ride quality for passengers. Inherent in this question is both the physical robustness of passengers but also the unique G-loads that might have be endured by accessibility support equipment and, perhaps, service animals. What might be acceptable G-levels for one set of passengers might be wholly unacceptable for another set of passengers.

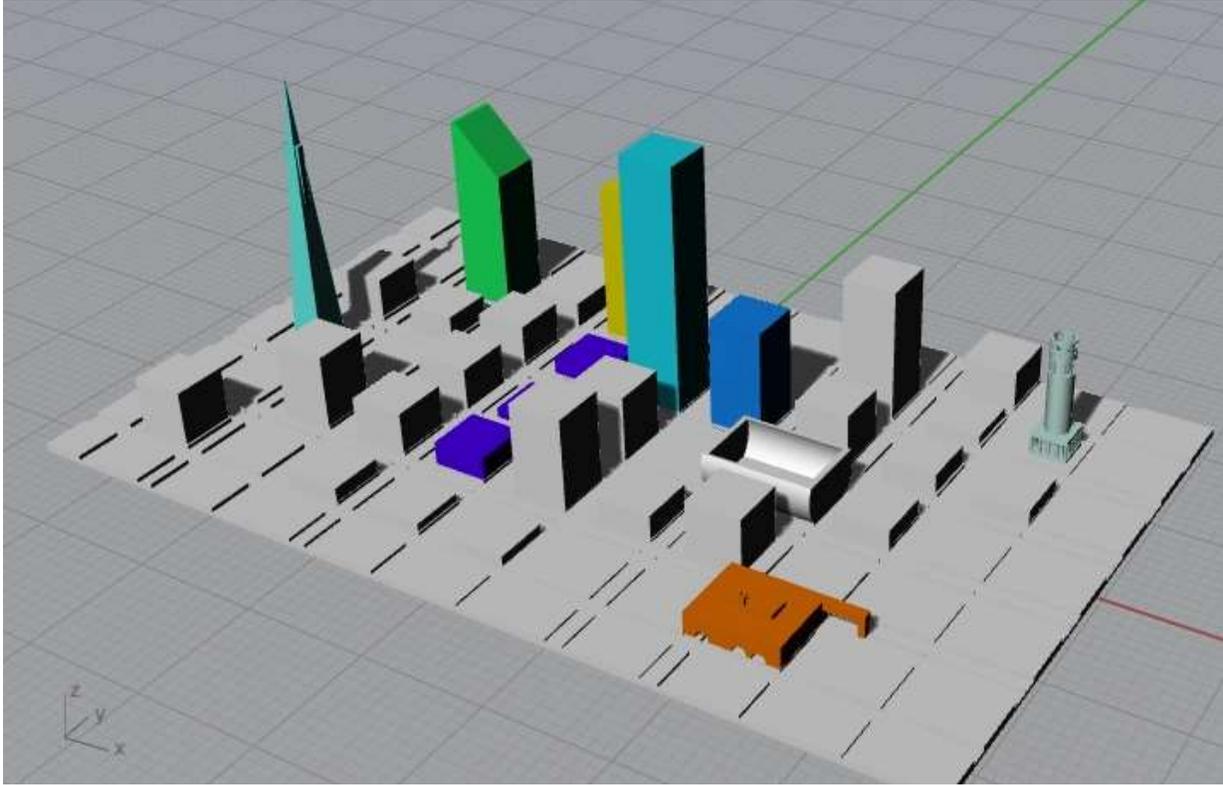


Figure 4. Successfully navigating in an “urban canyon” environment with a UAM Vehicle

It is anticipated that UAM trajectories, because of the urban environment in which they will operate in, coupled with a variety of landing site/vertiport-stations they might land at, might be quite varied in nature. Accordingly, there will be challenges defining acceptable trajectory profiles for passengers of varying sensitivity levels to a spectrum of potential attitude, velocity, and acceleration/deceleration profiles.

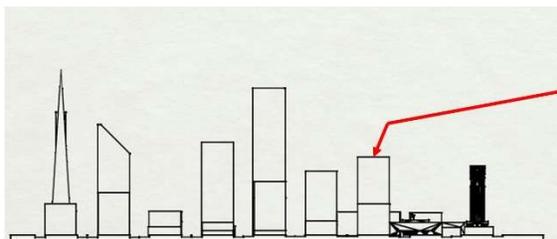
There has been extensive work performed by the rail and bus public transit communities looking into acceptable acceleration and deceleration G-levels for passengers (both standing and sitting). Only a limited amount of work has been focused on the implications of acceleration and deceleration profiles on the discomfort and safety of passengers in wheelchairs. The general conclusions from this past work seems to be (Refs. 13-24) that if the wheelchairs are secured by straps and other retention mechanisms – and if some sort of shoulder seat belts are also provided – the passengers in wheelchairs can safely undergo the same G-levels as other seated passengers. The recommended maximum acceleration and deceleration profile magnitudes in the literature (Refs. 13-24) are approximately 0.12G longitudinal, 0.07 lateral, and 0.1G vertical. (Note, though, that Ref. 15 cites higher G-levels for “severe maneuvers” for fixed-route buses (0.2G acceleration, 0.4G braking, and 0.1G lane changes) and van-based shuttles/transit (0.33G acceleration, 0.77G braking, and 0.8G lane changes).) Though this seems to be the current thinking with regards to rail and bus mass transit, it is conjectured that UAM acceleration and deceleration profiles might be at or below these G-levels for metropolitan aerial transportation systems for those passengers with disabilities. The above “comfort” G-level limits are primarily derived from rail-type transportation, where walking and standing in a vehicle occurs more often than in an automotive situation where the passengers (except for buses) are mostly sitting in seats. Accordingly, it will be a major design decision for UAM vehicle designers and operators to decide whether or not to allow passengers to leave their seats while in flight.

It can be anticipated that, as vehicle altitude decreases, the less straight line will be the cruise leg segments; instead, as the vehicle flies lower and lower, the more the flight path will have to conform to the cityscape layout (i.e. shorter leg segments, more turns/banks, and steeper ascent/descent angles). At its most extreme, at very low

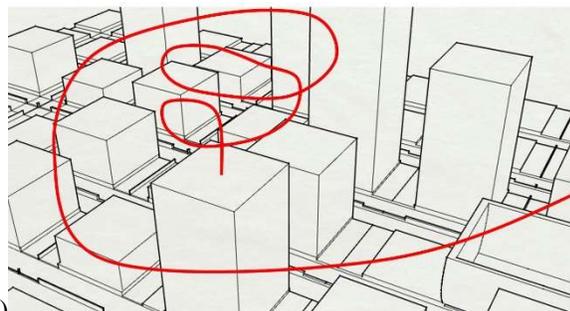
altitudes, if allowed from a regulatory perspective, the flight becomes almost “automotive” or railway-like in that the vehicle would begin to follow flight paths that would conform to city streets and other ground-transportation corridors, i.e. flying amongst the so-called “urban canyons.” A series of representative UAM maneuvers in a generic cityscape are proposed in Table 2 and in Figs. 5-6.

Table 2. UAM flight profile trajectories

#	Name	Description
Takeoff/Landing		
1	Straight-in with Bi-Linear Descent Profile	This profile can be described by three parameters: the initial descent slope, the horizontal distance from target/landing-spot, and the final descent/landing slope.
2	Right-angle bank	This profile can be described by three parameters: the speed of entry into the turn, the change in elevation during the turn, and speed of exit from the turn.
3	U-turn and/or Pirouette	Three parameters: the speed of entry into the turn, the change in elevation during the turn, and speed of exit from the turn.
4	Spiral	Parameters of interest: number of spiral (completed and partially completed) turns; height above landing/takeoff zone; entry speed into spiral; radius of entry point into spiral turn; net descent/ascent rate; net radial contraction rate of spiral maneuver.
Cruise		
1	U-turn	Assumes altitude is maintained.
2	Zig-zag	Parameters: speed of entry; initial “zig” angle; final “zag” angle; horizontal distance covered between “zig” and “zag” turns; change in altitude during course of the maneuver; speed of exit.
3	Bank Angle (90 Deg.) Turn	Assumes altitude is maintained.
4	“Hop”	Parameters: total distance (range) of “hop;” net angle of ascent; fraction of total distance covered before maximum altitude achieved; net angle of descent.
5	“Leg Yield”	Parameters: nominal cruise speed during maneuver; lateral displacement required; length of flight leg required to laterally displace (i.e. “yield”) outward and return to original trajectory.
6	“Follow the Freeways”	Parameters: a sequence of prescribed zig-zags, bank turns, and U-turns.
Emergency Procedures		
1	Aborted takeoff: loss of (partial) power	
2	Mid-flight: loss of rotor or partial power	Parameters: fraction of partial power remaining on one rotor; thrust margin above nominal 1G thrust for remaining fully functional rotor/motors; height of vehicle above ground at time of rotor/motor failure. (Refer to CFD images in Fig. 11 for partial study of problem.)
3	Aborted landing	Parameters: straight-in descent profile defined; decision point altitude and distance from target defined; climb angle during pull-out; bank-turn maneuver profile assumed/defined.
4	Immediate landing at unprepared landing site	Parameters: maximum rate of descent; maximum descent angle.



(a)



(b)

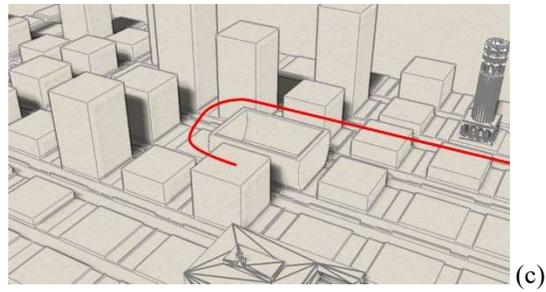


Figure 5. Landing: (a) Straight-In with Bi-Linear Descent Profile, (b) Spiral, and (c) U-Turn/Pirouette

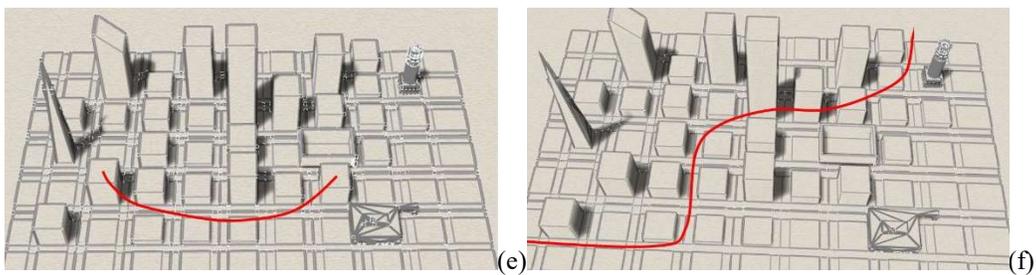
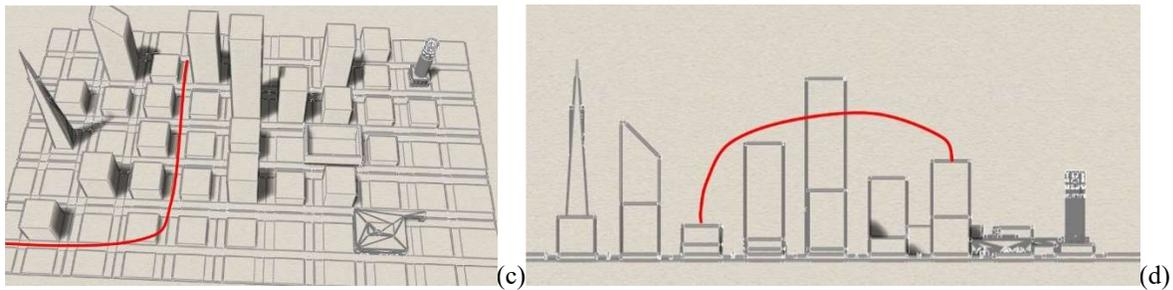
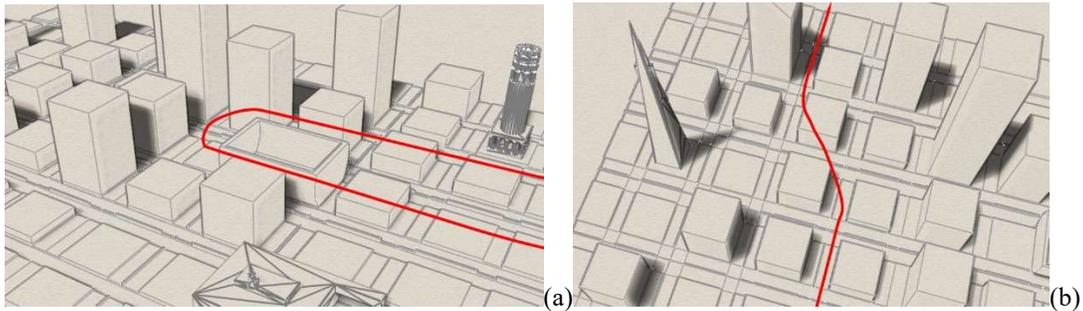


Figure 6. Cruise: (a) U-Turn, (b) Zig-Zag, (c) 90-deg. turn, (d) “Hop”, (e) “Leg-Yield”, and (f) Follow-the-Freeway

Considering only inertial loads, the resulting maximum lateral acceleration G-level for a generic level-flight banking turn (mid-turn), is shown in Fig. 7 as a function of turn-radius (m) and vehicle speed (m/s).

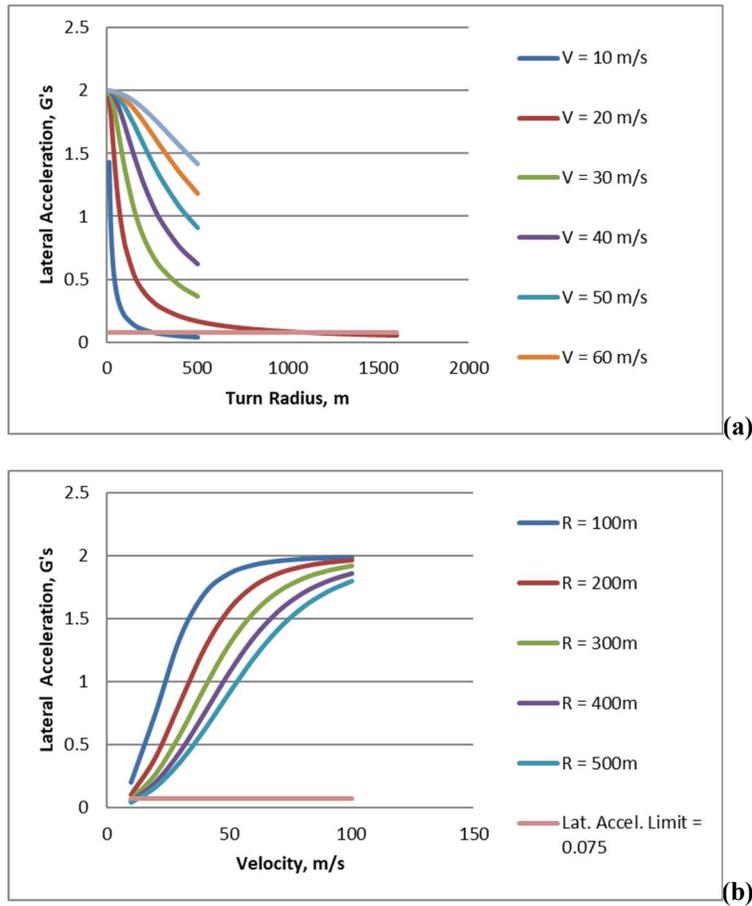


Figure 7. Maximum Lateral Acceleration for a generic level-flight Banking Turn (mid-turn): (a) families of curves for constant vehicle speed (m/s) and (b) families of curves for constant turn-radii (m)

Figure 8 considers the inverse-problem of defining the minimum turn-radii for a given maximum lateral acceleration limit imposed on the aircraft/passengers. Turn-radii less than the trend-lines in Fig. 8 will result in higher lateral accelerations than the notional limits.

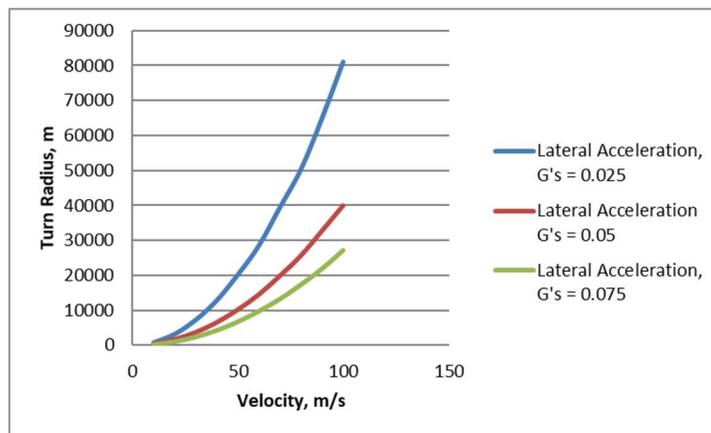


Figure 8. Minimum turn-radii yielding lateral accelerations below some proscribed set of limits for passenger acceptance

Prediction of cityscape building wakes in winds is a well-known computational problem for the civil engineering and architectural communities but it is a relatively new problem for the aviation and the rotorcraft communities (the key exception being ship/rotorcraft airwake modeling). References 8, 25, and 26 are some early work on this topic for rotorcraft and building wake interactions.

Figure 9 is an early attempt to model “complete” generic cityscapes versus the building/wake interactions for rotorcraft operating near single buildings. No rotorcraft modeling is included in the results presented in Fig. 9; later work will consider this aspect of the problem. Generating CFD solutions of complete cityscape flow fields is a very challenging problem. However, to address fundamental questions of vehicle handling qualities and passenger acceptance in terms of the bumpiness of the ride in complex flow fields, such work is necessary. Such work becomes perhaps especially critical for assessing passenger acceptance for those who are most sensitive or physically fragile.

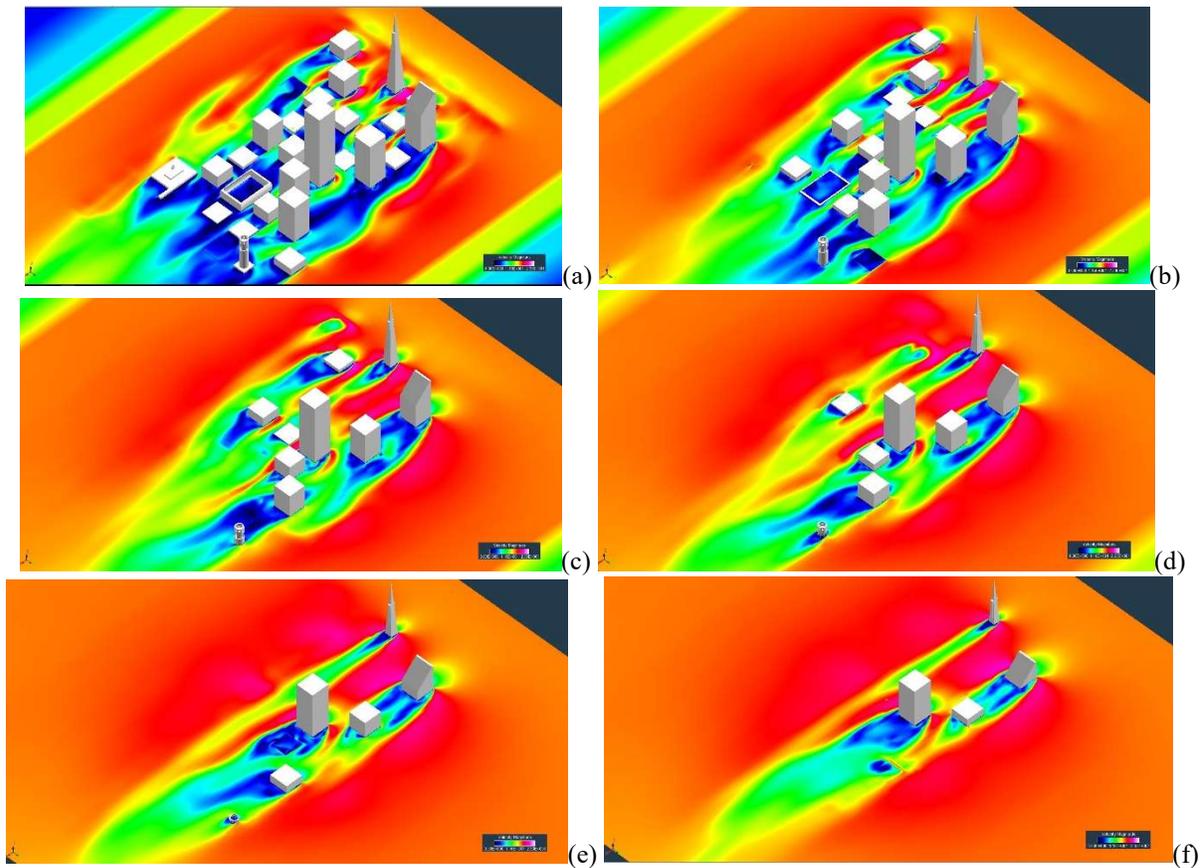


Figure 9. Challenges of all-weather operations, particularly with winds in urban canyons: (a-f) velocity magnitude contour maps at increasing heights AGL

Figure 10a-b illustrates some preliminary CFD work with respect to predicting the building wake interactions with moving (rotors only) UAM vehicles. A wind of 5m/s is blowing past a prismatic-shaped building (wind direction being shown by the yellow arrow in Fig. 10a). Behind the building, roughly mid-height above the ground, a four-rotor system is initially station keeping in the wind to the right of the building. The four-rotor system then accelerates to a constant forward-flight velocity of 2m/s and moves laterally behind the building to just past the midway point of clearing the building wake. The last time step location of the four-rotor system is highlighted by color contours of the rotor disks’ pressure differential distribution). A red Q-criterion isosurface (and a red arrow) shows the direction and distribution of the rotors’ induced velocity wakes. A grey transparent isosurface depicts the building wake (for the three-dimensional contour at 4m/s). Figure 10b shows the thrust coefficient variation as a function of time and, with the moving four-rotor system as a whole, therefore the position of the rotors moving laterally across the building wake.

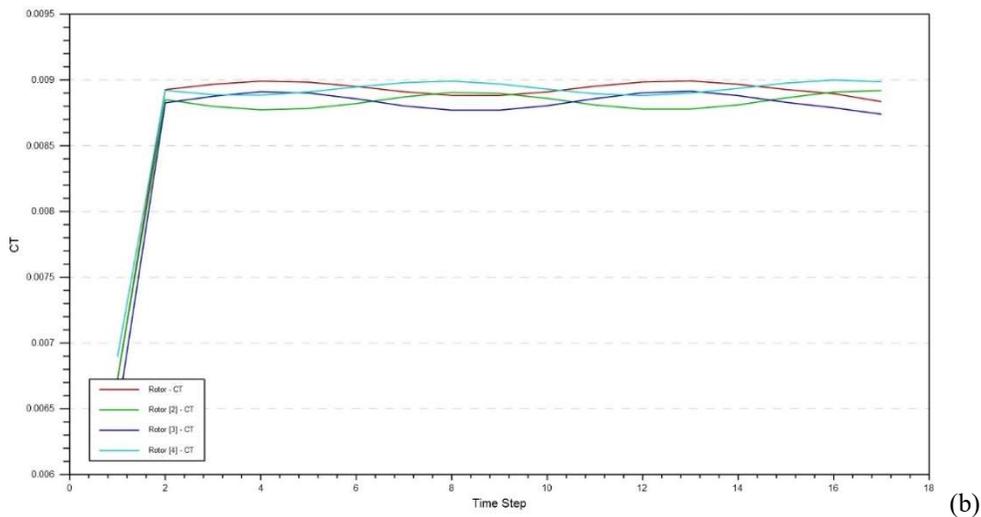
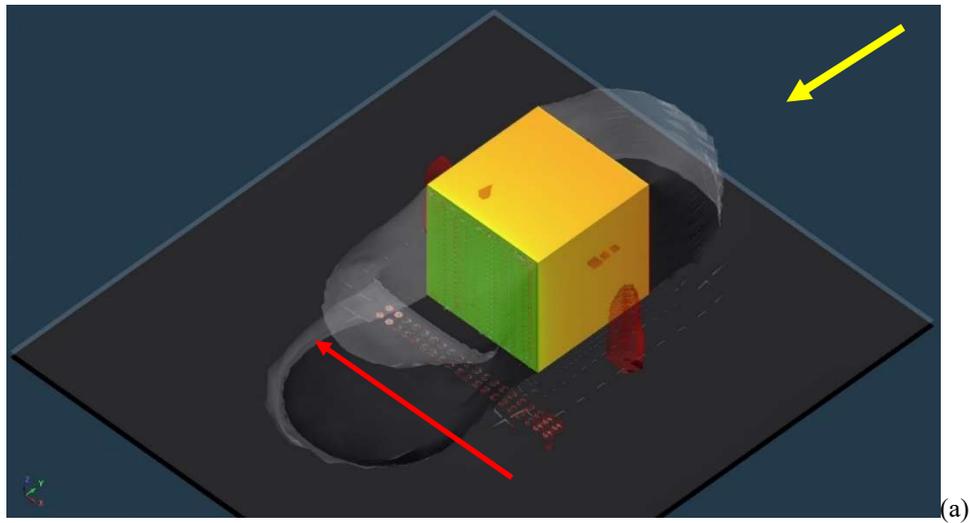


Figure 10. CFD predictions of quadrotor-type vehicle (rotors only) flying behind a building, in a wind, in the buildings wake: (a) orthogonal view and (b) time variation in thrust coefficients flying through the wake

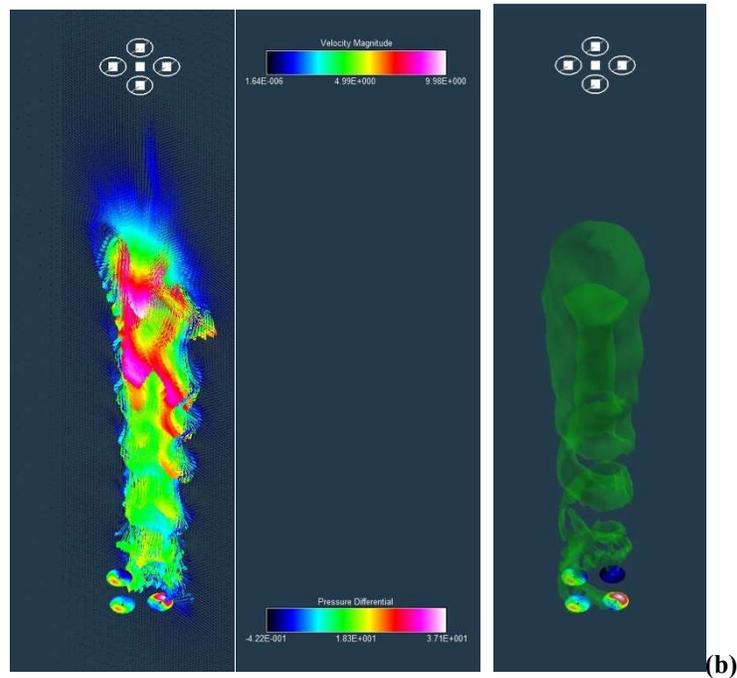
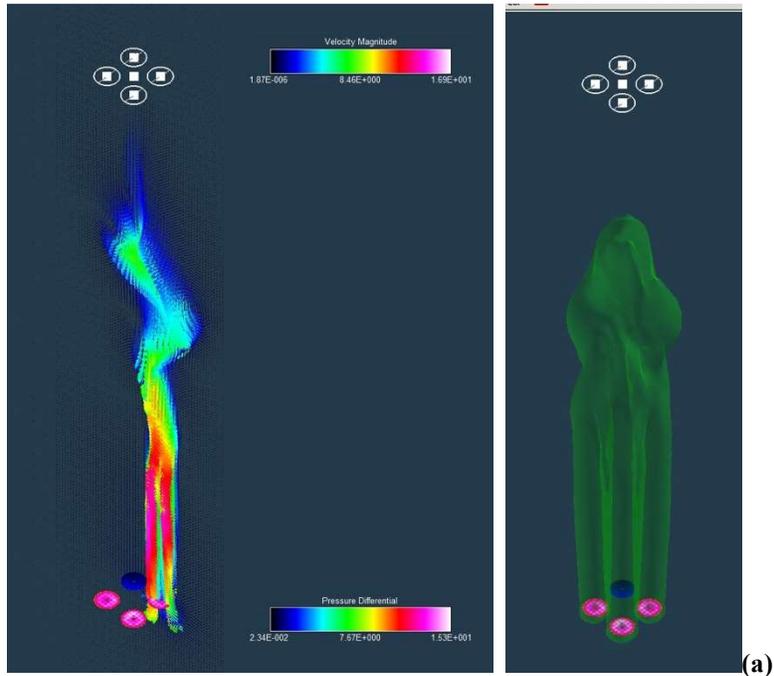
Accessibility for UAM Vehicles

For standard/conventional access/egress is it sufficient to merely meet the current standards of access/egress of conventional commercial transport aircraft, or should significant improvements be made? For inflight emergencies and emergency egress, do new types of automated onboard/internal assistance equipment need to be developed? Does current and/or contemplated design requirements provide for enough room/accommodation for mobility devices and other assistance aids (e.g. service dogs), or room for caregivers/assistants? Is adequate thought being directed towards the definition and development of novel access/egress at vertiport stations: “people movers,” automated jetway/docking systems, and mobile robotic “passenger seats” that can autonomously transport passengers to and from vertiport gates and the interior of the aerial vehicles?

A Brief Examination of Emergency Landings in the Context of Accessibility

The following is a brief examination of the results of the uncontrolled descent of a four-rotor vehicle due to a motor/rotor failure. References 26 and 27 briefly illustrate the challenges inherent in such uncontrolled descents.

The influence of five parameters can be examined with the uncontrolled descent CFD modeling: (a) vehicle tilt/bank angle during descent, θ_B ; (b) radius of the descent spiral, R_S ; (c) rate of spin about the spiral axis, Ω_S ; (d) the rate of rotation about the vehicle center-of-gravity during descent, $\Omega_{c.g.}$; and (e) the overall descent velocity, V_D . A baseline uncontrolled descent condition is defined as: $\theta_B = 10$ Deg.; $R/R_S = 0$; $\Omega_S R_S / (\Omega R) = 0$; $\Omega_{c.g.} / \Omega = 0.1$; and $V_D / (\Omega R) = 0.1$.



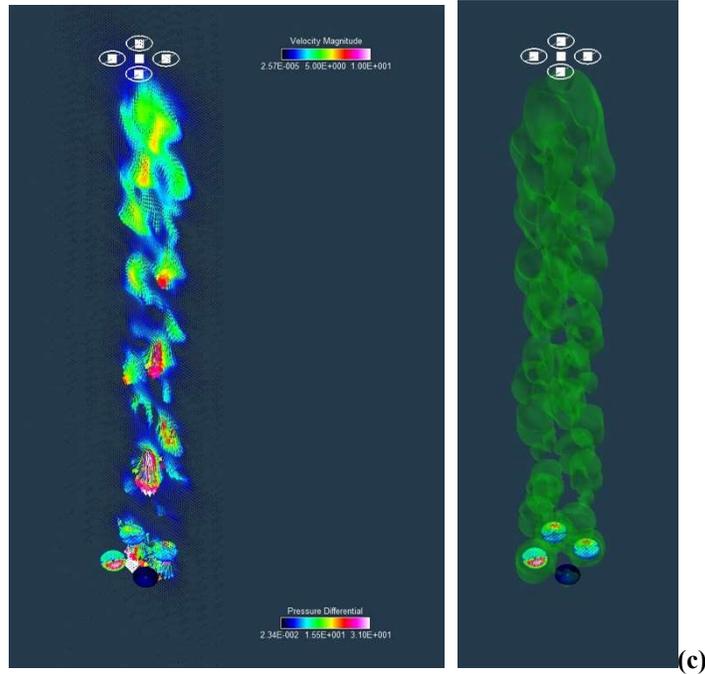


Figure 11. Incremental build-up of descent profile complexity -- CFD (Rotors-only) Prediction of Various Prescribed Uncontrolled Descent Profiles: (a) no rotation (straight-down descent) of vehicle; (b) “flat-pitch” ($\theta_B = 0$) rotation; $\Omega_{c.g.}/\Omega = 0.1$; or $\Omega_{c.g.} = 2500$ Deg/sec); (c) “tilted/banked over” ($\theta_B = 10$) rotation; $\Omega_{c.g.}/\Omega = 0.1$

CFD coupled with simulation plus innovations in providing for emergency propulsion thrust augmentation and anti-torque options will all be necessary to provide for safe emergency descent for all passengers (and people on the ground). Emergency anti-torque has to date focused on providing redundancy in propellers/rotors and motors. This is likely not feasible for vehicles with four or less propellers/rotors. However, going to higher propeller/rotor counts could yield aerodynamically inefficient vehicle configurations in forward-flight. Other emergency anti-torque options should be considered.

IV. Some Vehicle Concepts that provide Accommodation

There is a general standard (e.g. Ref. 24) within the public transit community called the “common wheelchair.” A “common wheelchair” description defines a weight and a size set of requirements for passengers requiring wheelchair: ≤ 30 inches (0.76m) in width; ≤ 48 inches (1.22 m) length (measured 2 inches (0.05 m) above ground); ≤ 600 lb (273 kg) when occupied. This “common wheelchair” standard, though, does not reflect the wide-range of wheelchair mobility options now available to the public. In particular, ever more capable (and heavy) electric wheelchairs have been introduced to the market. Additionally, emerging “exoskeleton” mobility options have largely unexplored public transportation implications; can passengers wearing such exoskeletons sit in unmodified passenger seating or will some tailored solutions need to be defined and provided for in public transit systems.

A key consideration in developing accessible small-passenger-carrying urban aerial mobility vehicles is the means for providing easy and safe access/egress for passengers and their support aids/network. Among the possible access/egress design features that might be developed include: (1) a sliding door and ramp on the side of the vehicles; (2) a “gull-wing” door and ramp such as used on high-performance sport cars; (3) a rear-loading integral ramp/empennage-structure (similar to military cargo planes); (4) front loading via the fuselage nose pivoting open (such as used for the “super guppy” type transport aircraft used for in-development spacecraft cargo); (5) all-access

doors that pivot open on all sides of the vehicles; (6) “transforming” structures to radically change the vehicle’s geometry and “openness” while on the ground; (7) modular ground/air mobility units (the “New Nomads” concept, Ref. 11, and the “Pop-Up” Airbus/Italia concept, Ref. 12); (8) garage/rollaway doors that conform when closed to the fuselage outer-mold-lines; (very speculative) in-situ assembly or self-assembly of vehicle around passengers. Some of these access/egress design options could potentially radically impact the overall vehicle configuration. Landing gear height has to be kept to an absolute minimum to keep ramp complexity and weight to a minimum for the vehicles. This might entail the incorporation of landing gear that can raise and lower while on the ground. Rotors and lifting surfaces have to have a spatial geometry and/or clearance height such not to provide an undue impediment for accessible access/egress – both during standard loading and unloading of passengers as well as emergency egress.

Adaptive environmental conditioning might be required: (1) tailored heating and air conditioning; (2) tailored humidity control; (3) pressurization levels; (4) oxygen levels; (5) lighting/sounds levels; (6) acceptance/reassurance level of voice- and other annunciation-communication to/from passengers to the onboard and remote autonomous systems (how informed do the passengers want to be with regards to flight status?); (7) acceptance/reassurance level of augmented/virtual-reality mapping of the passengers’ visual/audio environment (do the passengers want to feel like they are flying/in-control of an aircraft or do they want to feel like they are in a (potentially more comforting) non-aviation environment); (8) electrical and data bandwidth support for mobility and service aids (e.g. inflight electrical charging of electric wheel chair batteries and/or real time data relay of wearable and/or implanted medical technology and/or health monitoring devices).

Adaptive flight-control/maneuver-limiting might be required: people with more fragile physiologies should not be submitted to the same acceleration/deceleration levels as people with no disabilities or health problems.

To what extent will remote monitoring of onboard cabin activity be allowed? How can seizures, cardiac, and/or respiratory crises be observed and monitored if only a single passenger is onboard the vehicle (or, if more than one passenger, the other passengers are ill-equipped to provide aid or emergency notification)?

A. Accessibility for UAM Vehicles Access/Egress

Next, possible design approaches to loading and unloading passengers to maximize accessibility will be discussed. There are several possible vehicle/overall-system-of-systems conceptual design implementations. It is unlikely that there is one “best” solution for all vehicles for providing access/egress for those with accessibility needs. Further, the safety and ease of access and egress during both normal operations and emergencies must be tempered by vehicle weight, drag, and structural design considerations. UAM vehicles with electric propulsion are still facing significant design challenges just from a vehicle aeroperformance/propulsion perspective; striving to provide acceptable accessibility for all passengers may compound the challenge but, ultimately, is a worthy and necessary endeavor.

The most conventional approach to the providing accessibility is illustrated in Fig.12, i.e. providing for sliding side doors for vehicle with a portable/movable external ramp or lift.

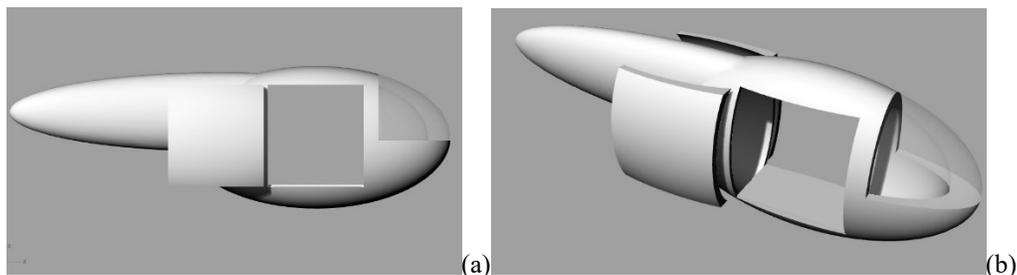


Figure 12. Sliding side doors for vehicle with portable/movable external ramp or lift.

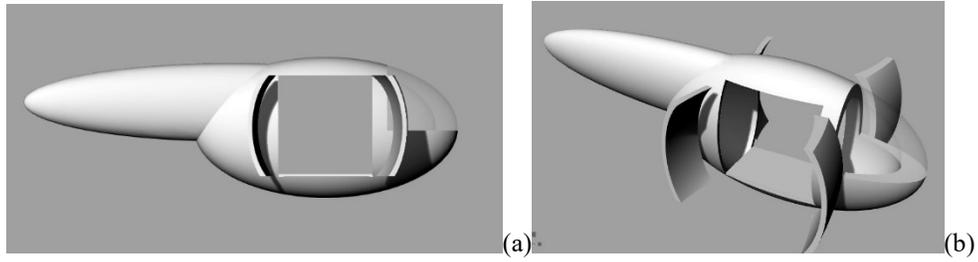


Figure 13. Cupboard-type doors with portable/movable ramp or lift.

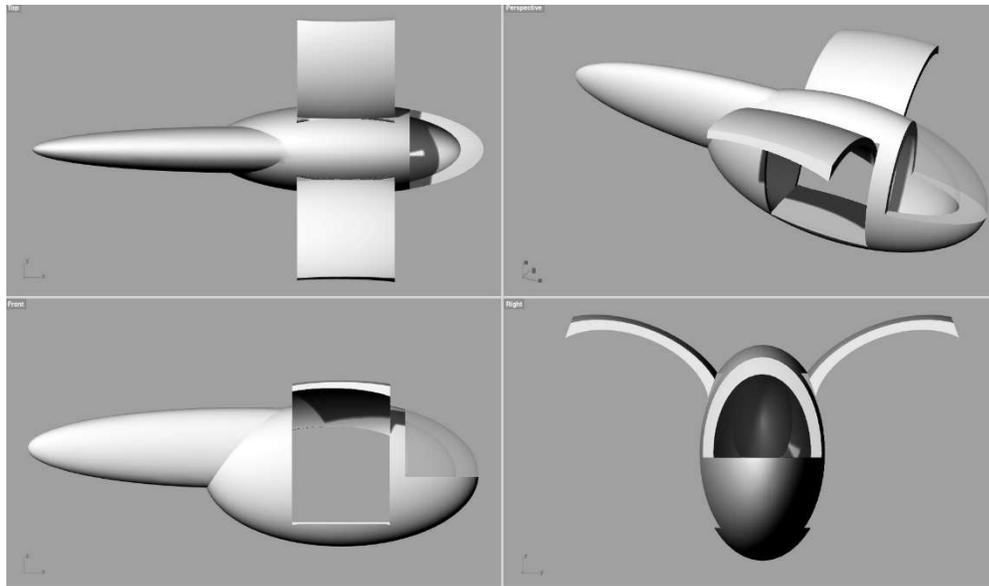


Figure 14. “Gull-wing,” “butterfly,” or “scissor” doors and passenger loading

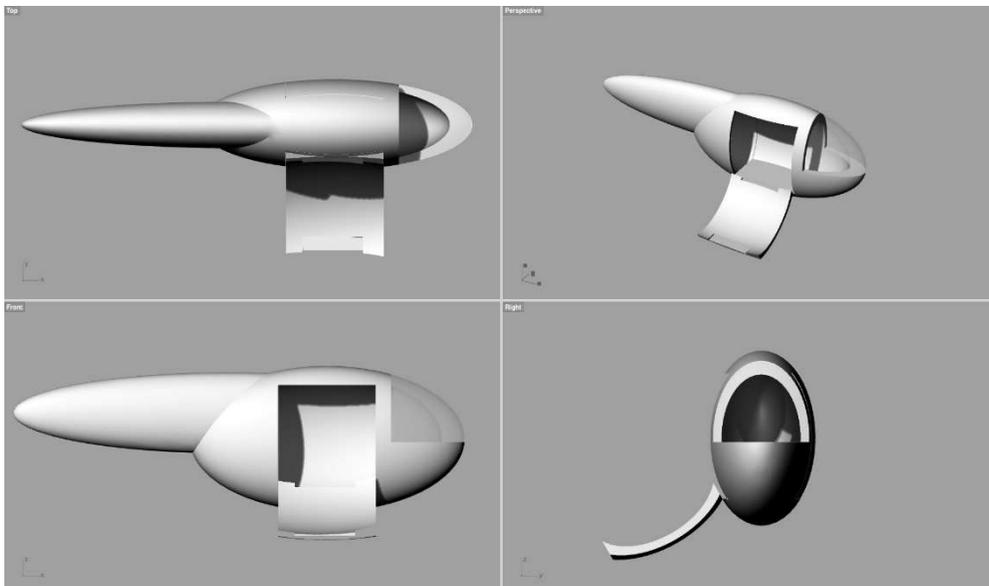


Figure 15. Door ramp passenger loading

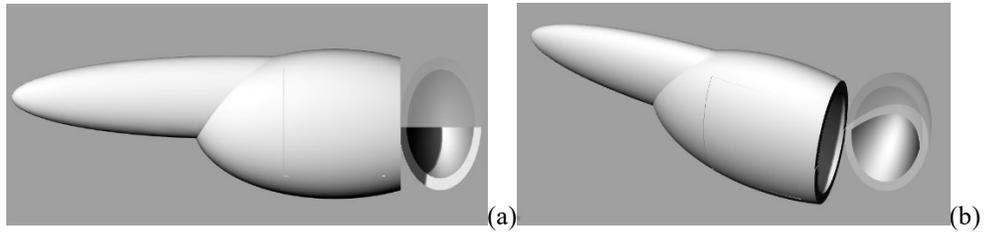


Figure 16. Loading from the Nose (or, alternatively, the Tail) of the Vehicle

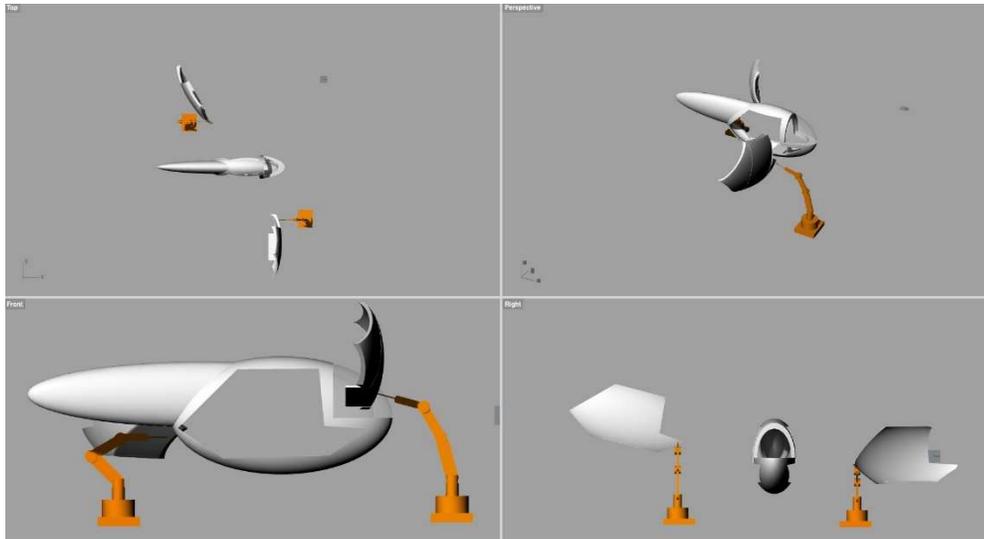
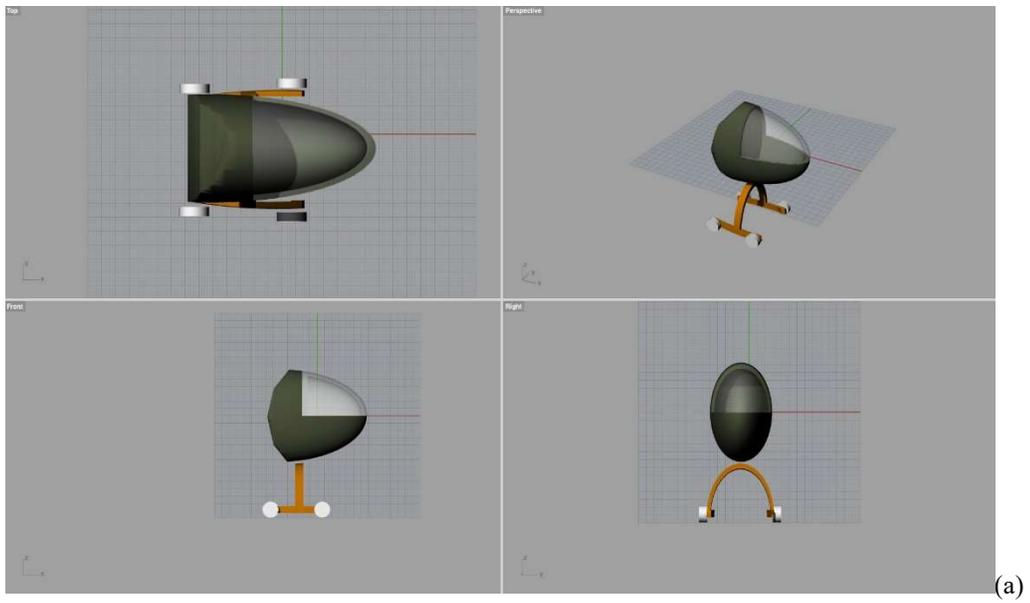


Figure 17. Loading by means of rapid robotic assembly of vehicle side panels



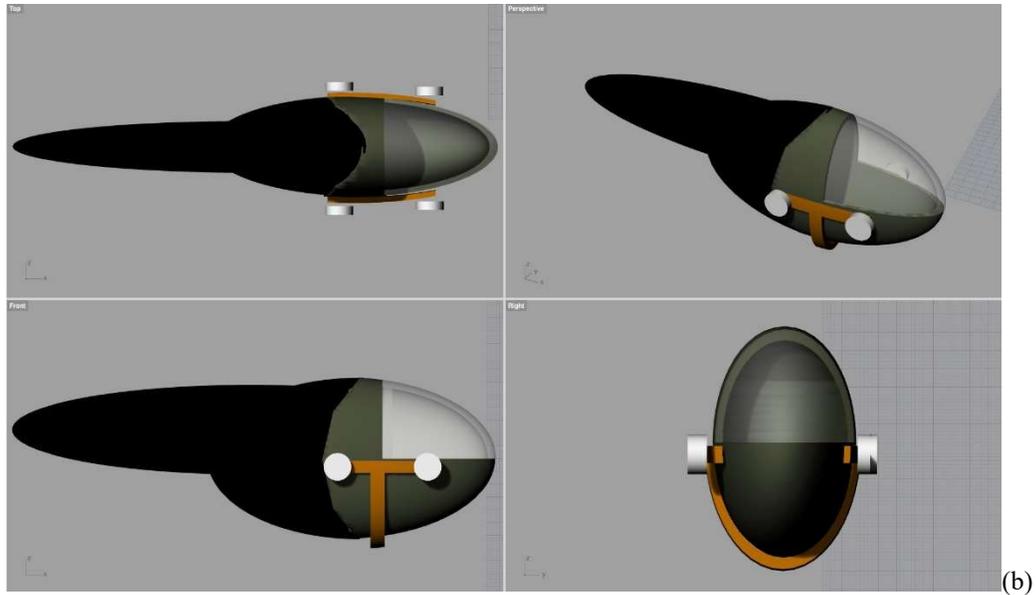
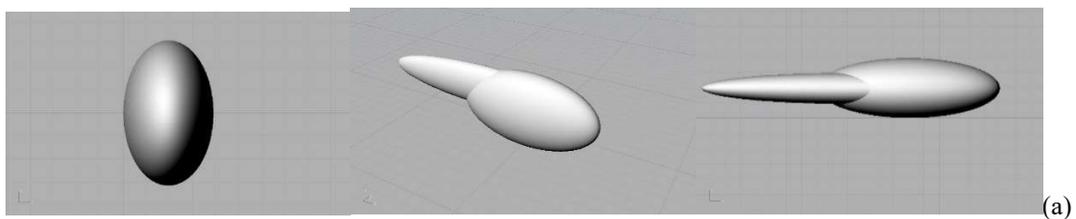


Figure 18. Loading by means of assembly/transfer of multimodal transportation subsystems/vehicle elements

All of the above passenger access options have vehicle design implications and vehicle weight consequences. Unlike perhaps automotive or rail transit systems, aviation assets are very weight sensitive with respect to overall vehicle performance. UAM vehicles relying on (all- or hybrid-) electric propulsion will be especially sensitive to vehicle weight. Additionally, there are fleet operations implications as well. For example, should all vehicles in the UAM fleet conform to the same accessibility standards or should a subset of the fleet be dedicated to provide such support. One potential attribute of such a subset of the fleet is that they could perhaps have relaxed requirements for electric propulsion, i.e. use fossil-fuel-based propulsion, so as to compensate for the heavier and potentially higher drag vehicles required for higher levels of (accessibility) support. A secondary consideration is the possible implication of reconfigurable and/or modular cabin interiors that can be tailored on need to support passenger accessibility. This same cabin interior reconfigurability may also be required to support on-need conversion of vehicles for passenger-carrying to that of cargo-carrying. Future work should attempt to derive detailed weight equations for various different types of passenger loading, unloading, and cabin reconfigurability mechanical implementation options that could be used for vehicle sizing during conceptual design.

B. Accessibility Implications for Cabin Geometry

Cabin width will be a key parametric consideration in designing accessible UAM vehicles. The more cabin room for a given number of passengers, plus the more rectangular in form of the cabin interior, are all desirable features from an accessibility perspective. The chief downsides of providing this additional volumetric space as well as a better cabin interior form factor is increased vehicle weight, reduced aerodynamic performance, and overall vehicle acquisition cost.



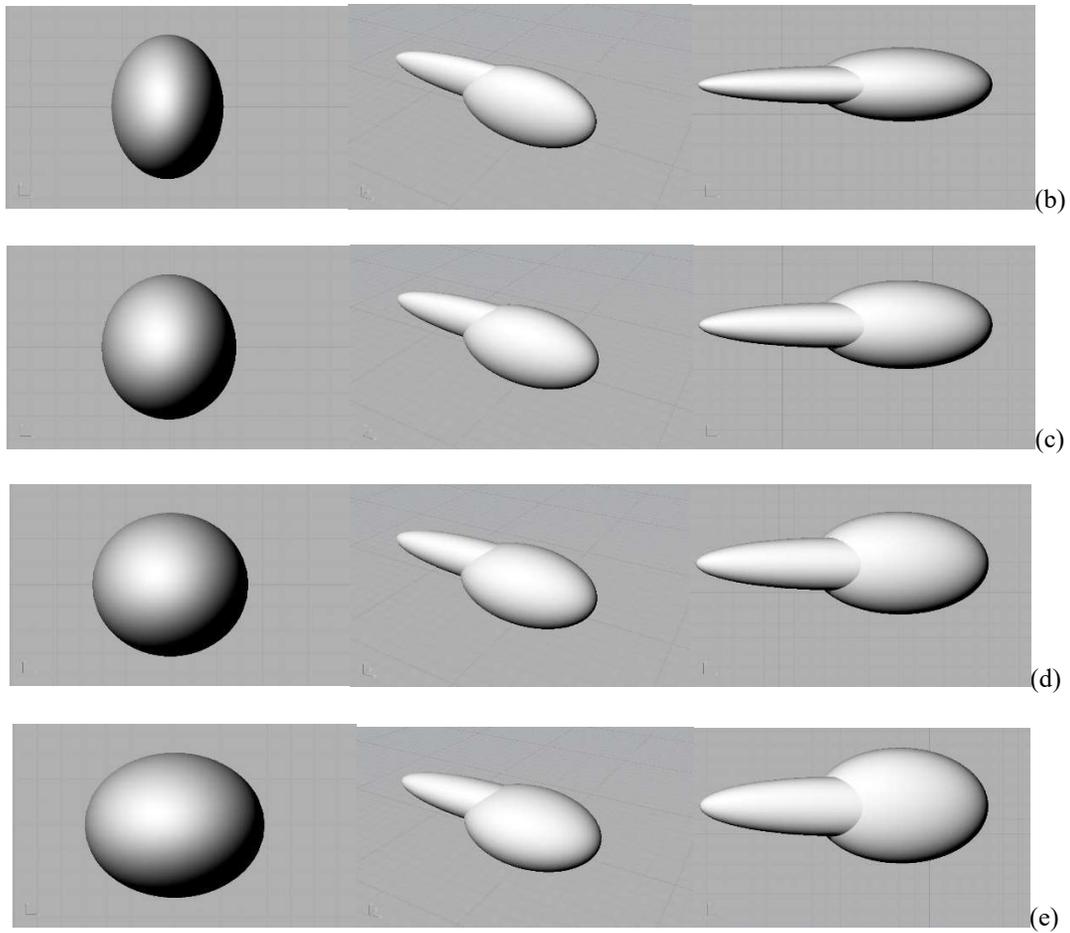


Figure 19. Parametric Sweep of Cabin/Fuselage Cross-sectional Width: (a) scale multiplier of vehicle (and therefore cabin) width = 1; (b) scale = 1.25; (c) scale = 1.5; (d) scale = 1.75; (e) scale = 2.0

Figures 20 and 21 summarize the CFD results for the configuration shown in Fig. 19.

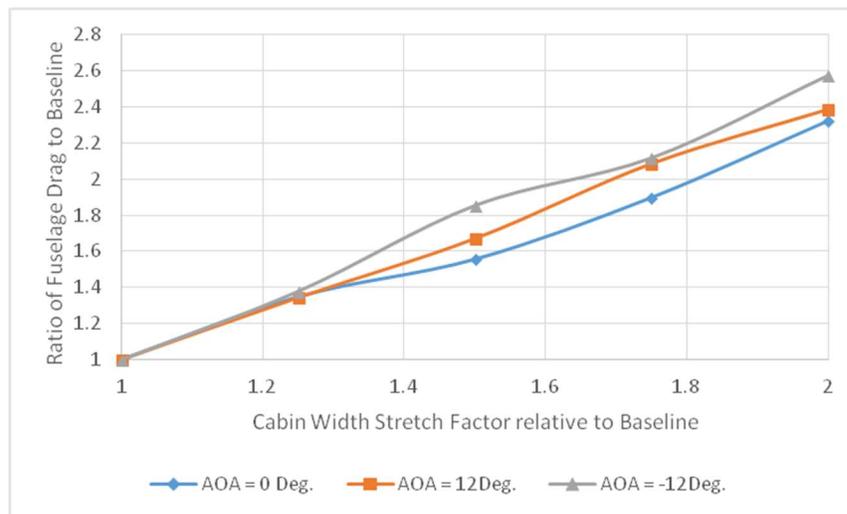
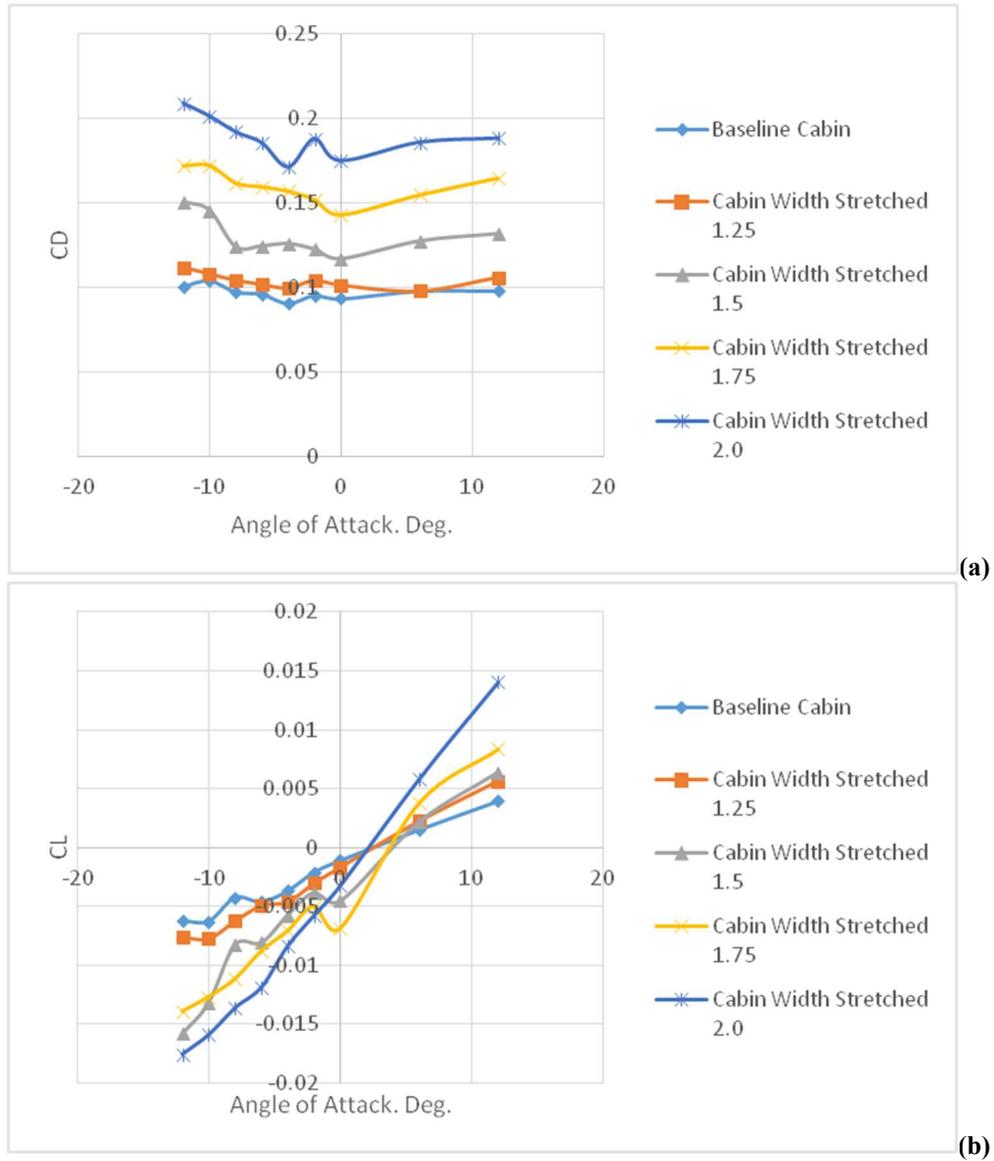


Figure 20. Fuselage Drag Trend with Cabin Width (AOA=0Deg.)

Note that in Fig. 21a-c the drag coefficient is nondimensionalized with the zero angle-of-attack maximum frontal area. The lift and pitching moment coefficients are nondimensionalized by the fuselage “wet area.” Further, the pitching-moment coefficient “length-scale” is the cabin height, which is held constant for all the cabin configurations studied.



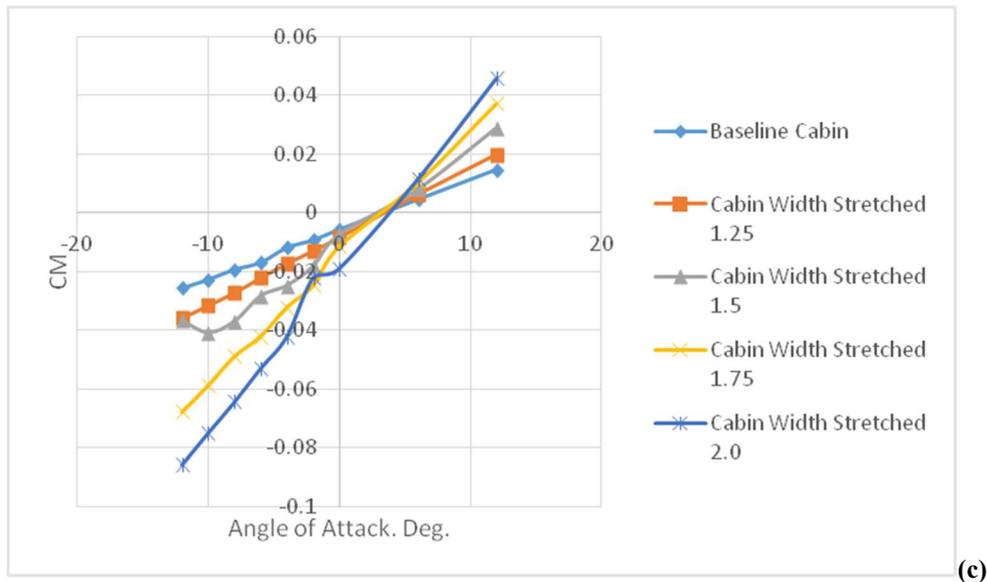


Figure 21. Fuselage Drag, Lift, and Pitching Moment Coefficients as a Function of Angle-of-Attack (for various different (“stretched”) cabin/fuselage cross-sectional widths)

In the Fig. 22 weight trend, it is assumed that fuselage weight is proportional to the fuselage “wet area” which is, in turn, derived from estimates from fuselage CAD models.

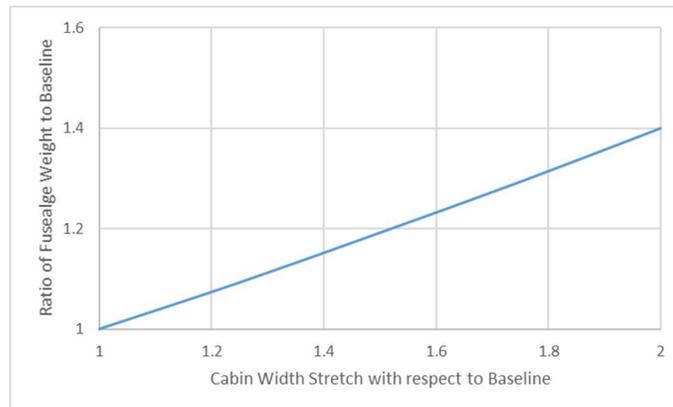


Figure 22. Fuselage weight as a function of cabin/fuselage cross-sectional width

Reflecting the above results (particularly Figs. 20 and 22), as anticipated, there is clearly going to be weight and drag penalties for stretching small vehicle cabin widths to provide for increased passenger accessibility accommodation in cabin interiors. Despite such penalties, though, it is argued that reasonable vehicle performance compromises are acceptable in achieving greater accessibility.

Tailoring the cabin cross-sections to be less circular or elliptical might be beneficial in a number of ways. It is postulated that a more rectangular cabin cross-section is perhaps more acceptable from an accessibility perspective. A parametric series of cabin shapes are presented next in Fig. 23 illustrating going from an elliptical cross-sectional to a more rectangular (albeit with rounded-edges). (The area ratio of A/A_R ranges from $\pi/4$ for a circular or elliptical cross-section to a value of one for a fully rectangular cross-section. There are many ways by which a “box” like cabin can be transformed from a circular or elliptical cross-section. In this particular parametric series,

the sides and bottom of the initial elliptical cross-section is “trimmed” by an increasing percentage, leaving flat faces for the sides and bottoms; then the vertical dimension of the overall vehicle is “stretched” so that the total vertical cabin height is kept constant. This approach, though simple and results in an increasingly “box” like cabin with increasing trimming, has a secondary consequence/influence of stretching the vertical dimension of the tail boom.)

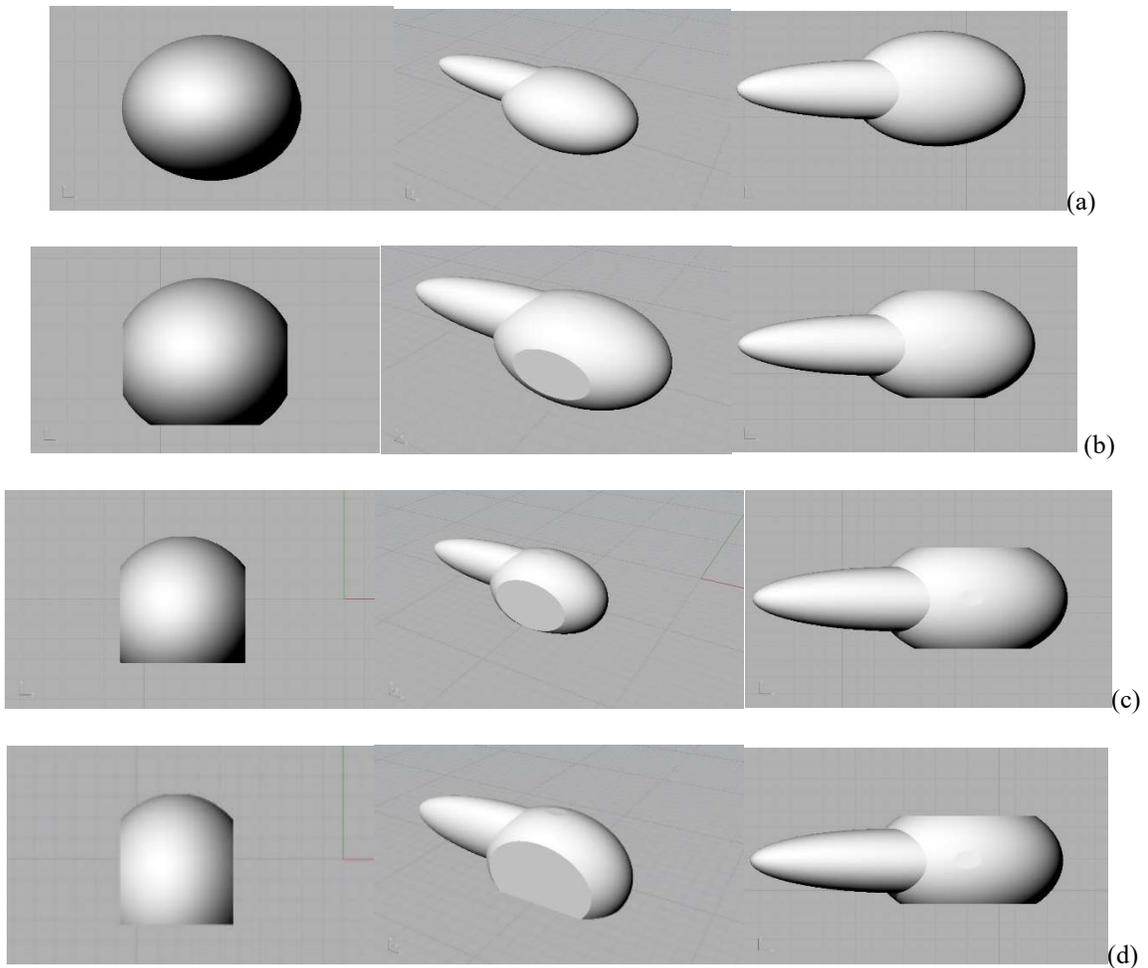


Figure 23. Parametric Sweep of Cabin/Fuselage Contour: (a) $A/A_R=\pi/4$, (b) $A/A_R=0.84$, (c) $A/A_R=0.88$; (d) $A/A_R=0.9$

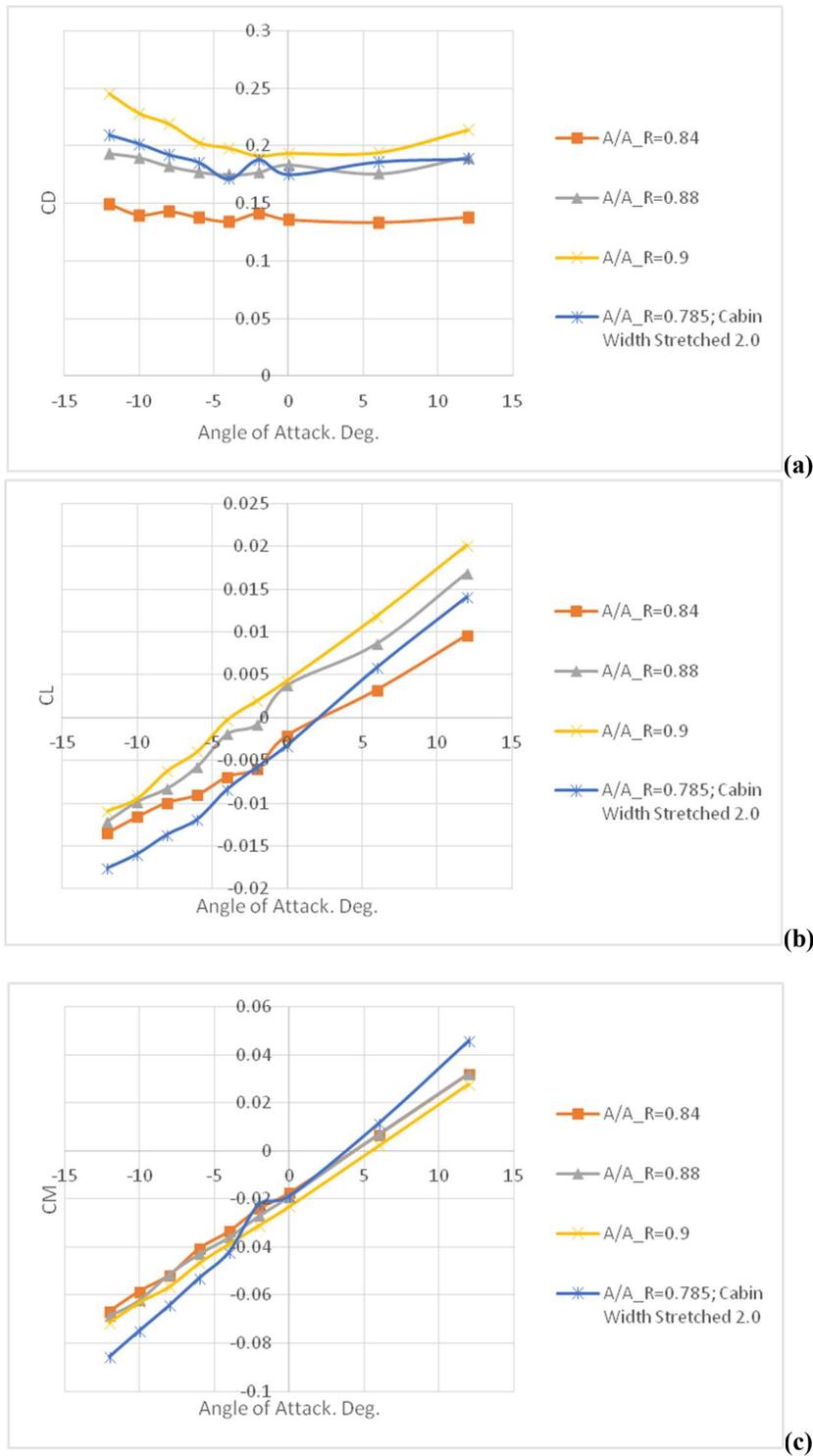


Figure 24. Fuselage (a) Drag, (b) Lift, and (c) Pitching Moment Coefficients as a Function of Angle-of-Attack for various different “Box” (Non-elliptical) Cabin cross-sections

Drawing on analogies with rail and ground public transportation vehicle cabins, a more “box” like UAM cabin might yield a more passenger-friendly cabin, especially for those with accessibility challenges. Additionally, more

box-like cabins might also allow designing lower profile (in height) landing gear or, maybe, no landing gear at all (with fuselage bottom edge used for contact during landing). These are assumptions that should be tested by performing passenger acceptance testing with cabin mockups. From a vehicle aerodynamic perspective, as seen in the initial results of Fig. 24, the area ratio A/A_R seems to have a mixed influence on vehicle drag; a more box-like cabin doesn't always result in increased drag. The $A/A_R=0.84$ case had the lowest drag of the four configuration studied.

C. Accessibility Implications for Vehicle Size and Onboard and External Assistance Equipage

Smaller Vehicles:

As some of the earlier discussion might suggest, incorporating design features to enhance accessibility for small one or two passenger vehicles could be a considerable design challenge entailing, in part, the adoption of some fairly radical vehicle configurations and, perhaps, technologies. Increasing cabin size and changing their geometry to be more box-like and, therefore, more like rail and ground public transportation vehicles could significantly increase vehicle weight and drag. It is already debatable as to whether all-electric propulsion can meet realistic UAM mission profiles; making these small vehicles more accessible will be an even greater challenge. But, just because something is a challenge doesn't mean the effort shouldn't be attempted. Providing acceptable levels of accessibility could mean that larger passenger capacity vehicles may need to be included in the UAM fleets. It also may be that vehicles providing high levels of support for accessibility may have to focus on hybrid-electric vehicles rather than those with all-electric propulsion. These are open design questions outside the scope of this paper but they are questions that should be tackled in the not too distant future.

Larger Vehicles:

Larger vehicles perhaps present a better opportunity to incorporate design features to enhance accessibility, as compared to smaller vehicles. One example of this is that larger vehicles can more easily and flexibly accommodate changes to cabin interior layout configurations to accommodate wheelchairs and other assistive equipment upon need. Further, larger vehicles inherently have larger capacity to accommodate more interior assistance equipment (e.g. actuated ramps, lifts, access doors).

Internal and External Assistance Equipment:

During normal operations, for UAM networks comprised of full-featured vertiport stations and operating fleets of fairly large vehicles, one can anticipate that such stations would provide a substantial amount of support both through station-staff assistance and automated system external assistance equipment to safely and efficiently load and unload all passengers into the UAM vehicles, including those with accessibility needs. It becomes more challenging when smaller vehicles are considered, or when partial-featured stations and/or informal landing zones are regularly employed. In these cases, a greater amount of reliance on automated onboard/internal assistance equipment must be integrated into the vehicle designs. Finally, though, if one considers accessibility equipment requirements from an emergency landing perspective, it is clear that a considerable amount of innovation will be required to devise and implement automated onboard/internal assistance equipment for all vehicles, available on-demand at all times. Whereas today's passengers on commercial aircraft can depend on equipment operate by highly trained cabin crew, UAM vehicles/networks of the future very well may not have such crew to rely on during normal operations and emergencies. Autonomous flight may be essential for successful UAM fleets/networks but automation applied to passenger equipment for both normal operations and emergencies is also vital.

V. As an Aside: Accessibility Considerations with respect to Cargo/Delivery Drones (aka vertical lift UAVs)

Though proposed cargo VTOL UAVs or delivery drones will not have the parallel accessibility issue for access/egress into the vehicles themselves there very well may be similar accessibility challenges to the ground infrastructure and operations of such vehicles to personnel and consumers/end-users.

There may well be dedicated cargo vertiport stations but there is also the likelihood that both cargo and passengers will be serviced at the same vertiports. Further, it is not unrealistic to anticipate that primarily passenger transport eVTOLs will also carry small amounts of high-value third-party cargo in addition to passenger luggage or other belongings. Or, that upon demand, cabin interiors can be converted back and forth between passenger transport and cargo transport for the same aircraft for different flights.

As UAM and cargo/delivery-drone business models mature, vehicle designs and design requirements will also mature. It is vital that would-be UAM providers remain engaged with would-be cargo/delivery drone providers so that ideally a unified technical/operational approach can be taken to address both sets of potential markets. In all these discussions, though, it is important to keep in mind the unique needs of those with accessibility needs. Whether, it is providing for safe and efficient transport on the aircraft themselves or providing for safe and acceptable pick-up of their delivered packages, it is vital that all citizens gain the benefits of these new/emerging aviation sectors.

VI. Concluding Remarks

Historically, NASA has developed vehicle reference designs as aids to help identify and develop new technologies to enable further advancements in the aviation industry. As enthusiasm has grown for the concept of urban aerial mobility, as prototype designs start to be realized, as market/application strategies begin to mature, it is reasonable to pause ever so briefly if need be and consider those who might benefit greatly from this emerging transportation capability but who are also perhaps most at risk for not being adequately accounted for by the designers, developers, marketers, business leaders, and municipal governments that seek to realize such metropolitan aerial transportation systems. It only takes a brief survey of a number of the aerial vehicles being proposed to realize that providing accessibility for such vehicles will be a challenge. Now is the time, when most if not all these vehicles are only paper airplanes or early prototypes, to encourage the rotorcraft and eVTOL communities to refine their designs, missions, and market strategies to make UAM accessible to everyone.

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