UNIVERSITY AVIATION ASSOCIATION

Collegiate Aviation Review International

Volume 42 | Issue 2 Peer Reviewed Article #2

08-12-2024

# Analysis of VTOL Downwash and Outwash to Establish Vertiport Safety Standards: A Theoretical Approach

David Ison
*Washington State Department of Transportation - Aviation Division*

VTOL aircraft are expected to play a crucial role in the air transportation sector, fulfilling various use cases similar to helicopters. However, they also present a significant safety hazard, downwash, which is the concentrated and powerful airflows generated by the rotors or propellers. To mitigate downwash risks, clear communication, proper training, and the establishment of safe operating zones are essential. The study suggests that existing FAA vertiport design criteria are insufficient as they lack minimum standards for downwash and outwash safety. This study identified the dangers of VTOL downwash and developed potential mitigation strategies and basic safety guidelines. The study used existing VTOL aircraft data to calculate theoretical airflow characteristics and then compared these to wind speed comfort and safety scales. Equations based on design dimension "D" as described in existing vertiport literature were provided. In addition, equations accounting for variations in VTOL design and propulsion configurations were developed. A resultant process for determining safety zones and buffer areas around vertiports is provided. The findings of this study can assist advanced air mobility stakeholders in the development of vertiport safety guidelines and protections.

Recommended Citation:
Ison, D. (2024). Analysis of VTOL downwash and outwash to establish vertiport safety standards: A theoretical approach. *Collegiate Aviation Review International*, *42*(2), 17–40. Retrieved from https://ojs.library.okstate.edu/osu/index.php/CARI/article/view/9927/8798

## Introduction

Future vertical takeoff and landing (VTOL) aircraft are expected to play vital roles in the air transportation sector, fulfilling a variety of use cases similar to those of helicopters, including search and rescue, passenger transportation, and military operations. Also, similar to helicopters, VTOL aircraft present an often overlooked but significant safety hazard—downwash. Downwash refers to the concentrated and powerful air blast generated by the rotors or propellers of helicopters and VTOL aircraft as air is pushed downward to achieve lift. This invisible force can substantially threaten personnel and objects on the ground, particularly during maneuvers like hovering, takeoff, and landing. Downwash can cause individuals to lose balance and be knocked over, potentially leading to falls, injuries, or even being struck by loose objects. The strong winds can dislodge lightweight objects like debris, tools, or unsecured cargo, creating a projectile hazard. Additionally, downwash can cause structural damage to temporary shelters or fragile equipment. In dusty or loose soil environments, downwash can stir up significant amounts of dust, reducing visibility and creating a potentially hazardous situation for both personnel and the VTOL itself.

Although downwash is an inherent property of VTOL flight, measures must be taken to mitigate its dangers. Clear communication and signage are necessary to inform participating and non-participating personnel of the hazard. It is essential that ground personnel receive the proper training regarding downwash dangers and clear visual markers be available around the designated flight operations areas. Pilots should also undergo comprehensive training in downwash management techniques, including minimizing hover times and adjusting flight paths to minimize the impact on the ground. Establishing safe operating zones is one of the most effective ways to manage downwash risks. By implementing designated landing and takeoff areas with sufficient clearance from personnel and objects, the risk to persons and property can be minimized.

Due to the differences in downwash between VTOL aircraft and traditional helicopters, existing safety protocols may not be sufficient for the protection of persons and property from VTOL downwash. Very little data exists on the attributes and profiles of VTOL downwash, which is problematic considering the expected proliferation of VTOL aircraft operations. As such, a thorough understanding of VTOL downwash effects is crucial for further enhancing safety measures at vertiports. Research on quantifying the downwash force exerted at various distances and under different operating conditions for VTOLs is critical so that the data can then be used to refine existing safety zones and develop more precise downwash prediction models. Understanding downwash patterns can also inform the development of more effective training programs for ground personnel and pilots.

This study aimed to identify the dangers of VTOL downwash by analyzing its theoretical physical characteristics and impacts on personnel and objects. Further, potential mitigation strategies were sought to be developed. By fostering a comprehensive understanding of this phenomenon, logical standards such as safety zones or buffers can be developed to ensure a safer operating environment for those in the air and on the ground.

## Literature Review

### Background on Rotor Aerodynamics

The main rotor of a helicopter provides lift, propulsion, and control. It generates force by rotating through the air, creating a balance between lift and weight. Propulsion and control are achieved by tilting the rotor to orient this force in different directions. Basic rotorcraft design considers parameters such as the diameter of the rotor, the number of blades, the shape of the blades, and the airfoil shape.

While operating in hover out-of-ground effect (HOGE), Froude's theory indicates a connection between air speed at the rotor level squared and two parameters: the mass of the aircraft and the disc area. The speed depends directly on the mass and the rotor diameter; the heavier the helicopter, the higher the downwash speed; the larger the disc area, the lower the speed. Different helicopter designs will vary in this relationship, known as disc loading.

The induced velocity on the disc is not uniform, with more concentrated speed on the ends of the blade and as the airflow interacts with the fuselage. The unsteady airflow can form structures such as blade tip vortices, which are directly related to the hover effect of the rotor disc. Various factors, such as the size of the rotor disc, the wind direction, and the impact of the ground on the downwash, can influence wind speeds.

The Preston Model calculates the maximum speed at a given station as a function of distance in terms of rotor diameter; the further away from a reference point, the lower the speed. For an Airbus EC225 helicopter flying at an altitude equal to the distance of 1 rotor diameter above the ground, the maximum speed calculated with Froude's theory is approximately 70 mph. However, during hover, the rotor disc is not always perfectly horizontal and the axis symmetry in the diagram is not found in reality. To achieve hovering flight, the rotor must be tilted slightly due to the forces exerted on the helicopter (Airbus Helicopters, 2021).

A safety correction factor should be considered when the helicopter starts to move up vertically or stops its vertical descent, as asymmetric flows may temporarily modify the outwash. There is a minimum safety margin of 30% due to the lack of specific studies on this complex subject and the great variability of on-site conditions. Additional environmental conditions and obstacles (buildings) could also modify the outwash (Civil Aviation Safety Directorate, 2022).

The Australian Transportation Safety Board (ATSB) (2023) released a detailed report on safety risks from rotor downwash at hospital heliports. The report analyzed downwash occurrences from 2018 to 2022 to identify common factors, existing regulatory guidelines, and ways to mitigate the effects of rotor wash. Rotor wash has been shown to have a vertical component produced by the main rotor blades that support the helicopter in flight and a horizontal component due to the interaction of the outflow with the ground surface. Factors determining the strength of rotor wash include the weight of the helicopter, main rotor size, disc loading, wind, and flight path.

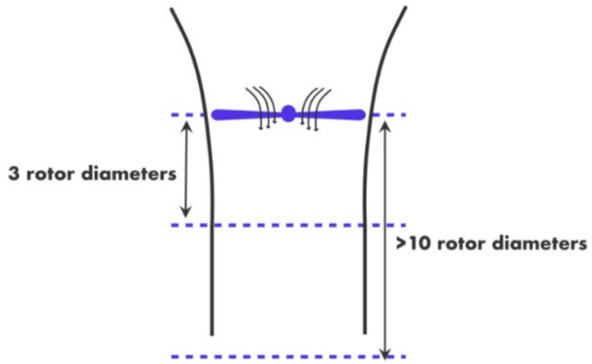
According to mathematical modeling by Airbus Helicopters (2021), the highest velocity of rotor wash occurs at altitudes equal to the length of 1 to 3 rotor diameters above the ground. Beyond this distance, high-velocity airflow dissipates due to turbulence. Researchers have also

determined that rotor wash effects are most pronounced during hover, takeoff, and landing, where they can produce localized wind strengths greater than 65 mph.
NASA researched the tuft patterns on the airframe of a full-scale UH-60L helicopter while it was hovering both within and outside the ground effect. The study revealed airframe tuft patterns at different heights above the ground, relative to the rotor, together with overlays that showed flow stability. As the helicopter descended into ground effect, the airflow grew more chaotic. The tuft patterns on the ground plane exhibited significant instability at all evaluated heights. Navier-Stokes computational fluid dynamics (CFD) simulations exposed the mechanism by which helicopter wake may induce brownout (creating a cloud of dust or dirt obstructing pilot visibility) behaviors (Wadcock et al., 2008).

Downwash generated by a helicopter hovering at four altitudes (16, 18, 20, and 25 feet AGL) was measured at two points within tree canopies. The effects of payload and hover altitude on downwash were significant, with the average downwash on the top section of canopies being significantly higher than in the middle sections at each hover altitude. Observations showed that tree branches, twigs, and leaves in canopies reduced rotor downwash. Flows varied significantly with different hover altitudes and payloads, which interactively affected the downwash. The hover altitude for generating the highest downwash for the tested helicopter was roughly 25 feet with a payload and 18 to 20 feet without a payload (Zhou et al., 2016).

Similar research has shown that downwash begins to impact the ground at a distance approximately equal to 10 times the diameter of the rotor. The maximum downwash occurs at or below a height approximately equal to 3 times the diameter of the rotor, while outwash reaches a maximum below 0.25 times the diameter of the rotor (see Figure 1) (Baculi et al., 2024; Seddon & Newman, 2011).

**Figure 1**
*Key Rotor Diameter Heights*



Helicopter wake can cause significant downwash, with velocities up to 100 feet per sec near the rotor, affecting the ground or water surfaces below and potentially leading to environmental disturbances or damage. Downwash can be estimated mathematically using Equation 1, where $V_d$ is downwash velocity in feet per second, M is the mass of the aircraft, $g$ is the gravitational constant, $\rho$ is the air density, and A is rotor disc area (Baculi et al., 2024; Leishman & Bagai, 1998):

$$V_d = \sqrt{\frac{Mg}{2\rho A}} \qquad (1)$$

Due to the Bernoulli effects, there is an amplification of downwash and outwash velocities (George et al., 1968). Testing has shown that the actual flow speeds exceed $V_d$ and can be calculated using an aircraft-specific geometric amplification factor correction. For downwash, the adjusted flow speed $V_{d(adj)}$ can be calculated with Equation 2 where $k^c$ is the geometric amplification factor (function of all the specific aspects of the aircraft's configuration, such as the size and type of the aircraft's propulsors, their relative positioning, and the altitude of the aircraft above the ground).

$$V_{d(adj)} = V_d(k^c) \qquad (2)$$

To calculate outflow velocity, $V_o$ requires the use of another formula, where $k^c$ is the geometric amplification factor, $r$ is the distance from the vehicle the flow is measured, and $\psi$ is the azimuth of the flow (Civil Aviation Authority [CAA], 2023):

$$V_o = k^c(r, \psi)V_d \qquad (3)$$

Helicopter downwash and vortices from the rotor blades can create a significant, dangerous impact on proximate aircraft operations. Numerous small fixed-wing aircraft accidents have implicated helicopter wake encounters, emphasizing the danger posed by the highly turbulent wakes during takeoff, landing, and taxiing flights in ground effect. The vortex wakes generated by helicopters can persist and pose a rolling-moment hazard to other aircraft, similar in severity to that experienced during airport approach, although the hazard diminishes after several minutes. Helicopter wake can also pose significant dangers to persons and objects on the ground due to the powerful downwash and environmental disturbances they create (Sugiura et al., 2017).

## Impact of Downwash on Heliport Operations

Helicopters are often used in confined areas near pedestrians, structures, equipment, ground vehicles, and other aircraft, leading to rotor-wash-related incidents. These incidents frequently occur when helicopters hover close to the ground during takeoff or landing. The flow field of the rotor can be described as a radial wall jet, exiting almost perpendicular to the plane of rotation of the rotor. Several incidents involving severe injury to personnel and significant damage to vehicles have occurred. The downwash of helicopters can also accelerate fine particles, damaging people's eyes, skin, and respiratory systems. Direct damage to structures can include doors being ripped off hinges, defacement and cracking of building facades and windowpanes due to deflection, and fatigue damage to structural elements (Bernardo et al., 2021).

A person's height, weight, training, and awareness directly influence the primary rotor wash risk to pedestrians. The downwash and outwash can lead to loss of balance or to being violently pushed. Urban authorities and councils are beginning to recognize the importance of pedestrian wind comfort and wind safety in city planning. Bernardo et al. (2021) recommended that stakeholders use a standardized measure, such as the Lawson Comfort Criteria, to evaluate pedestrian comfort and safety under different circumstances.

Using fluid modeling of a Bell UH-1 "Huey" helicopter, the researchers studied the downwash effect on pedestrian comfort. To ensure the most effective wake modeling, time-averaged data was used for calculations. The Blade Element Theory (BET) was used to estimate rotor forces, which are calculated based on a rotor being divided into two-dimensional sections. The fluid-modeling approach solved the Reynolds-averaged incompressible isothermal Newtonian form of the Navier-Stokes equations, including a momentum source term from the rotor disc. The "blade-tip effect" was included in the model rotor disc to account for the presence of a relatively strong secondary flow in the form of blade-tip vortices. The result is a variable, unstable flow experienced by persons as wind gusts or shear (Kidwell & Foster, 1966; Petrescu et al., 2017).

Hospital helicopter landing sites (HLSs) are often situated in built-up areas or existing hospital facilities, which exposes the public to the risk of being struck by rotor wash or objects propelled or dislodged by rotor wash. Studies have shown that 50 mph winds are unsuitable for walking, and 35 mph winds are considered the "threshold of danger" for the average population. In people over the age of 50, roughly half were displaced by a gust of 25 mph.

Between 2018 and 2022, nine of the eighteen reported rotor wash occurrences occurred near HLS. The incidents resulted in six injuries, three serious and three minor. In one incident, an elderly pedestrian was blown over by a helicopter. The pedestrian sustained minor injuries, and the pilot was unaware of the potential strength of the rotor wash. Most incident crews were unaware of the incident, and no references were found to exist for rotor wash danger or exclusion areas. Injured pedestrians were mostly 75 or older, and the locations were outside the HLS perimeter fence but within 100 feet of the final approach and takeoff area. Additionally, three events involved damage to third-party property due to debris (ATSB, 2023).

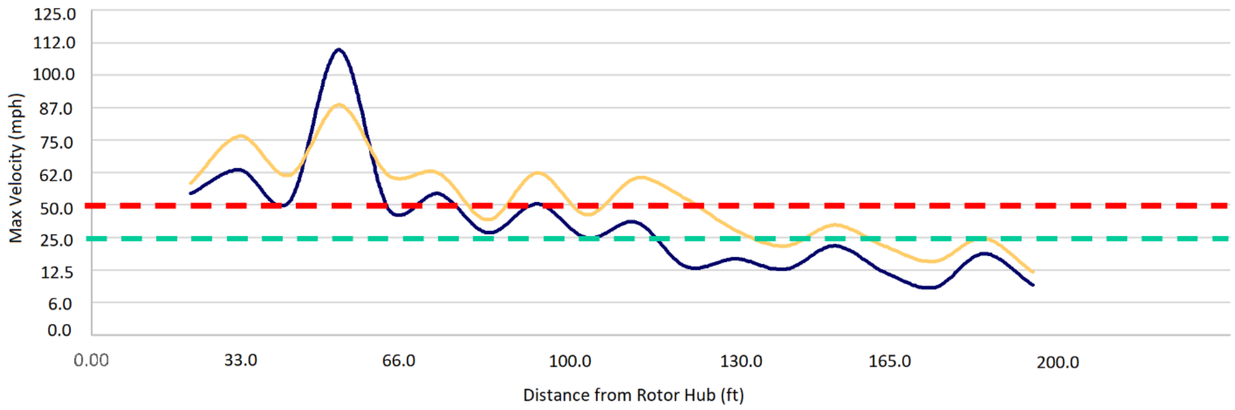
Extensive research has been conducted in the United States by the US Army to study the impact of helicopter downwash on the ground. Analysis of the effects of helicopter downwash on final approach and takeoff areas (FATOs) and hover-taxi sites can facilitate safer helicopter operations. By predicting regions with substantial wind velocity, both airports and helicopter operators can better protect people and property on and adjacent to the heliport. According to the Army's findings, it was recommended that objects and persons should be positioned at a distance equal to or greater than 2 to 3 times the diameter of the rotor (George et al., 1968). This distance allows the downwash velocity to decrease to acceptable levels. Figure 2 shows modeled data on helicopter downwash and outflow velocities. Note that the farthest distance for 50 mph was approximately 125 feet, and for 38 mph, it was approximately 158 feet (JJ Ryan Consulting, 2024). Additional data on peak helicopter rotor wash velocities was provided by ATSB (2023). On average, the range of distances where wind speeds are at or above 50 mph ranged from 26 to

125 feet; for 38 to 50 mph, the range was 72 to 167 feet, and for less than 38 mph, the distance ranged from 92 to 214 feet.

The oil industry is one of the largest users of helicopters, employing the vehicles for transportation between oil platforms and the mainland. The industry's vast experience with helicopters provides significant insights into the best practices associated with safe and efficient heliport operations. BP (2017) provides its offshore employees with training concerning the hazards of working in and around active helicopter operations. The warnings provided are noted to apply to all types of heliports. Several examples of how objects near the helipad can be damaged or cause damage were noted. One example was that a passenger exiting a running helicopter had a 10-pound bag ripped from their hands due to downwash. The bag was immediately sent flying, becoming a dangerous projectile. In another case, several 25-pound bags were blown out of a luggage holding rack adjacent to the helipad. Not only does downwash affect the helipad and its immediate surroundings, but it can also cause issues within passageways or in areas beneath the areas of operation. Moreover, if outwash is forced through tight spaces, such as a hallway, it can increase the speed of the flow due to venturi effects. Lastly, downwash and outwash have been known to violently knock people over. In some cases, persons have been pushed off of elevated structures or have been blown into objects, greatly increasing the severity of injuries (BP, 2017).

**Figure 2**

*Modeled Downwash Velocity Versus Distance from Rotor Hub*



*Note.* Adopted from JJ Ryan Consulting (2024).

## Research on New VTOL Aircraft Downwash

Although there have been numerous studies on helicopter downwash and wake, there is limited research on more complex rotorcraft configurations, such as tilt rotors and tandem rotor helicopters. Many of the emerging VTOL aircraft have been designed to have far more complex configurations than has traditionally been assessed in aerodynamic studies. Many of these VTOL designs have four, six, eight, or even more rotors arranged in various locations along the wings and tail surfaces. This radical departure from conventional helicopter aerodynamics suggests that a more complete exploration of the characteristics of VTOL outwash fields is necessary (Brown, 2022a).

Unlike singular, isolated rotors used in helicopters, VTOLs have both more airfoil blades as well as a larger total number of propulsors. Unfortunately, research is limited on the applicability of conventional rotor blade aerodynamics to multiple propeller configurations, particularly in situations when the shared aerodynamic contact between objects plays a substantial role in determining the shape and dynamics of the wake that is produced. A simulation of the aerodynamics of a quadrotor VTOL aircraft out-of-ground effects and in-ground effects showed the complex flow field produced by the four rotors. When the aircraft is in an open environment, the wakes produced by four rotors drop into the airflow underneath the aircraft, creating a cylindrical shape. Nevertheless, the wakes are susceptible to inherent instability, which hinders the organized progression of the wakes and converts them into a chaotic arrangement of vorticity. As the aircraft approaches the ground, the vortices remain around the vehicle for an extended period of time due to their intrinsic instability and their interaction with each other and the ground (Misiorowski, 2019).

Brown (2022a) noted that VTOL aircraft have substantially higher disc loading than conventional helicopters of the same weight, leading to higher downwash velocities from the propulsors. Thus, there are potential risks to ground personnel and property due to VTOL aircraft downwash, which are smaller and lighter than conventional helicopters. The resulting augmentation in downwash velocity will lead to a corresponding increase in outwash velocity. However, this assertion is complicated by various factors, such as the impact of the overall vehicle size on the intensity of the outwash, as well as the influence of the propulsor arrangement on the structure of the outwash field surrounding the aircraft. Data indicated that typical eVTOL downwash velocities are 1.25 to 2.00 times that of conventional helicopters such as the Bell 206B and the R-22. Another challenge to the characterization of VTOL downwash is the lack of geometric amplification factor data for the new aircraft, which inhibits the characterization of the salient properties of the outwash field (Brown, 2022a).

Due to the potential for higher downwash/outwash speeds produced by VTOL aircraft, they may be more susceptible to disturbing ground sediments. Operators and manufacturers must be ready to implement necessary actions to offset the potential for brownout conditions when their aircraft is close to the ground, especially when there are people, passengers, and unsecured objects and structures nearby. This may require that vertiports be paved and regularly swept (Brown, 2022a, 2022b; Chang et al., 2022).

The interaction between the wakes of the several propellers significantly contributes to creating unique flow patterns on the ground below the vehicle, which are dissimilar to those observed among typical helicopters. A higher concentration of test sensors in the testing area is required to accurately measure the outwash produced by certain VTOL designs. This will enable a more precise estimation of the velocities in the outwash region (Brown, 2022a). Interactions among wakes of different motors generate a cumulatively chaotic downwash structure (Chang et al., 2022). Stokkermans et al. (2021) examined the impact of propeller interaction on thrust, power, in-plane forces, and out-of-plane moments in side-by-side and longitudinally aligned configurations on eVTOL vehicles. The study found that interaction effects depend on the propeller angle of attack, with a drop in thrust and power of up to 30% being possible. Detrimental flow interactions will especially be important to consider as the aircraft transitions to and from vertical to forward flight. Compensation for the lost thrust through increased rotational speed resulted in power penalties of 5% to 13%. The results also indicated that downwash streams can interact in ways that can make estimated airflow speeds and directions difficult to predict (Chang et al., 2022; Stokkermans et al., 2021).

Symmetry-breaking occurs within the flow of multi-rotor aircraft when interacting with the ground, leading to small perturbations that can cause the flow to lose its original form. This phenomenon is common in the flows created by multi-rotor aircraft when interacting with the ground. One result of these interactions is the formation of highly unsteady, jet-like structures along the ground plane, known as "ground jets." These jets are the result of secondary, hairpin-like vortical structures within the outwash field. The presence of these jets can cause damage to the surroundings and can be subject to considerable meandering over time. An effect of rotor rotation can be observed in the formation of these jet-like trains of vorticity. The helical nature of these vortices tends to favor the formation of a stronger jet to the sides of the rotors that rotate outward away from the vehicle (Brown, 2022a; Civil Aviation Authority [CAA], 2023).

Research by CAA (2023) discovered that VTOLs in both quadcopter-type (e.g., EHang) and lift-jet (e.g., Lilium) configurations generate maximum velocities that were two times faster than those from conventional helicopters. For lift-cruise configurations (e.g., Archer), the difference was even greater, with VTOL outflow velocities of up to two and a half times that of helicopters (CAA, 2023). An example of lift-cruise configured VTOL downwash fields is shown in Figure 3. CAA (2023) also generated outwash hazard zones for different VTOL configurations based on their findings. These are shown in Figure 4.

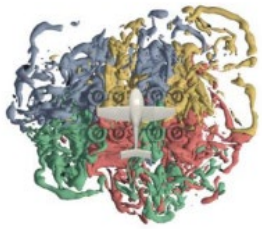
Numerical estimates show that the mean speeds in the outwash field, at a distance of 2.5 times the system reference dimension (referenced as “D,” which is the largest overall dimension of a VTOL), are at most around 0.67 times the reference velocity. However, for the helicopter with a more standard disc loading, the mean velocities were reduced to about 0.57 times the reference velocity. The observed values align with what was anticipated, and the disparity in average and maximum speeds seen in the outwash underneath the two systems may be mostly attributed to the discrepancy in disc loading between the two aircraft. The impact of the aircraft's size compared to the radius of the cylinder on the outwash measurements seems to have little effect on the average and maximum velocities generated by these specific aircraft designs. This indicates that the impact of aircraft configuration on the geometric amplification factor is notably insignificant in this specific case. However, the unsteadiness in the velocity field does not quite follow the expected pattern – aircraft with high disc loading produces a far greater root mean square velocity than what would be predicted by simply scaling it based on the induced velocity (CAA, 2023).

## Existing Guidelines

The Australian Civil Aviation Safety Authority (CASA) published *AC 91-29 v1.1*, which guides helicopter pilots and operators on suitable places to take off and land. It recommends clear final approach/takeoff (FATO) and touchdown/lift-off areas (TLOF) for hazard-free areas, no person within 100 feet (30 m) of the closest point of a hovering or taxiing helicopter, and obtaining appropriate information from owners and authorities. Rotor wash speeds can be expected at 25, 35, and 50 mph for common helicopter types, with strength increasing with increased helicopter weight. The AgustaWestland AW139, involved in nine incidents, shows that beyond the recommended 100 feet non-essential person exclusion area, rotor wash velocities can be between 35 and 50 mph (ATSB, 2023). Figure 5 shows an example of a rotor wash velocity region diagram for an AW139 aircraft.

**Figure 3**

*Simulated Downwash/Outflow for Lift-Cruise eVTOL*



Note. From CAA (2023).

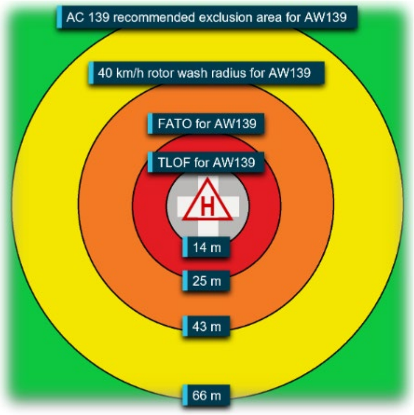
**Figure 4**

*Outwash Hazard Zones*

Note. Configurations from left to right: quadcopter, lift-jet, lift-cruise. From CAA (2023).

**Figure 5**

*AW139 Rotor Wash Velocity Regions*



*Note.* Color-coded where warmer colors depict the higher danger levels. From ATSB (2023).

The European Aviation Safety Agency (EASA) has developed a regulatory framework for helicopter downwash effects at facilities with scheduled commercial air. In EASA Member States, heliports with instrument approaches and VFR heliports at certified airports are subject to such regulations. Other public helicopter facilities are subject to individual national rules, which generally require that heliport operators maintain their facilities to applicable standards (private-use heliports are typically not regulated). The EASA has released prototype technical design specifications for vertiports that can accommodate manned VTOL-capable aircraft (Tauszig, 2023). In France, a 2009 regulation defined physical characteristics and visual aids for aviation facilities used exclusively by helicopters with one main rotor axis with an MTOW greater than 1,000 lbs. It also provides standards for obstacles to air navigation at and near these facilities (Civil Aviation Safety Directorate [CASD], 2022).

Per existing guidance, a vertiport Final Approach and Takeoff Area (FATO) is scaled based on the reference or controlling dimension “D.” A vertiport should have at least one FATO, which need not be paved. The minimum dimensions of a FATO should be the length of the rejected takeoff distance required for VTOL aircraft (RTODV) for the required takeoff procedure prescribed in the aircraft flight manual or 1.5 x D, whichever is greater. Local conditions, such as elevation, temperature, and permitted maneuvering, may have to be considered when determining the size of a FATO in accordance with EASA standards (CASD, 2022; Crespillo et al., 2023; Tauszig, 2023).

To aid in determining appropriate FATO dimensions, existing guidance recommends that VTOL aircraft manufacturers should provide the downwash velocity measured on a 2 x D circle while the aircraft is hovering at three feet above the surface in no-wind conditions. FATO design ensures safety and minimizes the impact of the surrounding environment on VTOL-capable aircraft operations. It has been recommended that a FATO should be surrounded by a safety area (SA). The SA surrounding a FATO should extend outwards from the periphery for a distance of at least 10 feet or 0.25 x D, whichever is greater (Tauszig, 2023).

Tauszig (2023) suggested facility operators can use theoretical data to determine the recommended downwash and outwash protection, but a study should consider local conditions and personal wind comfort criteria (see Table 1). If the velocity of the downwash and outwash at or within a distance of 2 x D exceeds the recommended maximum, an additional downwash protection area should be created to reduce downwash at the boundaries. Jet blast fences positioned according to local standards can also be used. An extension beyond the 2 x D circle may be necessary to account for significant mean winds. EASA also provided a table of the recommended distance from the edge of the FATO to any adjacent runway or taxiway so as not to damage nearby aircraft. This could also provide a meaningful reference for the safe distance for persons and objects (see Table 2).

In the U.S., the FAA (2012) provided guidance on heliport design in *AC 150/5390-2D.* The design standards include a heliport protection zone (HPZ) for each approach/departure corridor (See Figure 6). The HPZ begins at the FATO boundary and runs horizontally under the flight path for a distance of 280 feet. The purpose of the HPZ is to augment the safeguarding of individuals and assets at ground level. To accomplish this, heliport owners should have jurisdiction over the HPZ footprint. Such control involves the removal and ongoing maintenance of incompatible structures and activities.

The FAA released Engineering Brief (EB) 105 *Vertiport Design,* which provides design guidance for public and private vertiports and vertistops, including modifications to existing helicopter and airplane landing facilities and the establishment of new sites. It was specifically written for VTOL aircraft powered by electric motors and distributed electric propulsion, i.e., eVTOLs. The FAA will update the EB over time to address new aircraft and technologies as more performance data becomes available. The document describes the Reference Aircraft as a VTOL aircraft that combines the performance and design features of nine aircraft that are currently being developed. In the future, the FAA will create a performance-based advisory circular (AC) that focuses on the design of vertiports. This AC will specifically cover advanced operations, autonomy, various propulsion sources, density, frequency, and the complexity of operations facilities. Future guidance will also include aircraft that do not currently comply with the Reference Aircraft mentioned in the EB. It will also address the instrument flight rules (IFR) capabilities and the utilization of multiple FATOs (FAA, 2022).

**Table 1**
*Downwash Protection Standards*

| Maximum Downwash Velocity | Type of Area |
|---|---|
| 35 mph | for areas of a vertiport traversed by flight crew or passengers, boarding or leaving an aircraft |
| 35 mph | for public areas, within or outside the vertiport boundary, where passengers or members of the public are likely to walk or congregate |
| 50 mph | for public areas where passengers or others are not likely to congregate |
| 30 mph | for public roads where the vehicle speed is likely to be 50 mph or more |
| 35 mph | for public roads where the vehicle speed is likely to be less than 50 mph |
| 50 mph | for any personnel working near an aircraft |
| 50 mph | for equipment on an apron |
| 60 mph | for buildings and other structures |

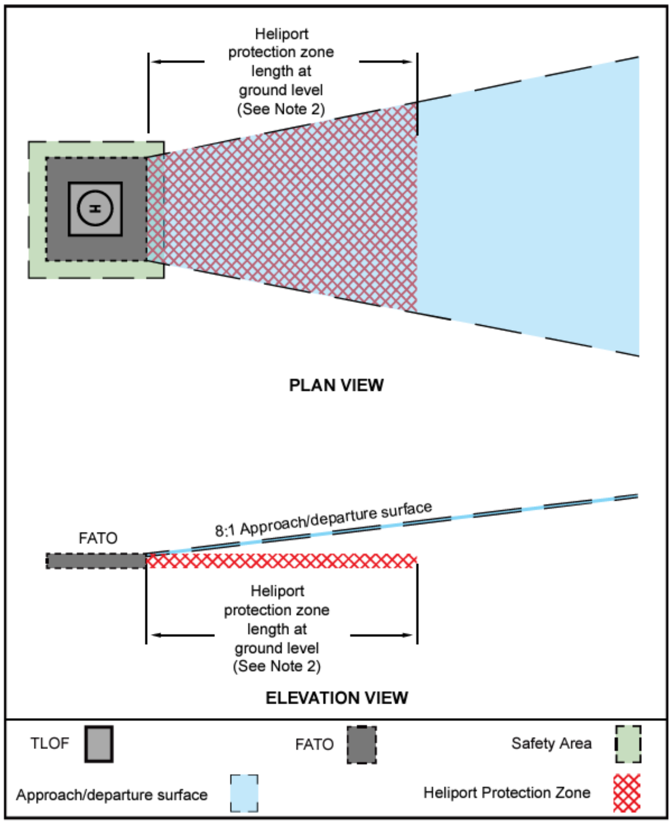
Note. Adopted from  (2023).

**Table 2**
*Recommended Distance Between FATO and Runways/Taxiways*

| eVTOL Mass | Distance from Edge of FATO |
|---|---|
| Up to but not including 7,000 lbs | 200 feet |
| 7,000 lbs up to but not including 12,700 lbs | 400 feet |
| 12,700 lbs up to but not including 22,050 lbs | 600 feet |
| 22,050 lbs and over | 820 feet |

**Figure 6**

*Helicopter Protection Zone (HPZ)*



*Note*. From *AC 150/5390-2D*

## Additional Best Practices and Recommendations

Some additional best practices and recommendations are presented in the existing literature. Conservative heliport designers have historically planned for the worst-case downwash profile for the most likely helicopter traffic to make visits. For a surface-level heliport operating exclusively light air ambulance helicopters, a minimum 100-foot downwash zone should be established, keeping it clear of people, property, or parked vehicles. If heavy or extra-heavy helicopters are used at surface level, the downwash zone should be larger, typically between 165 feet and 215 feet for the largest helicopters. As a general rule, no one and nothing should be within three rotor widths of a helicopter when it is generating lift (CASD, 2022).

Vertiport design should take into account the inherent complexity of the outwash problem, especially when it comes to planning the areas for landing and takeoff. Furthermore, it is imperative to establish operating protocols for situations when these aircraft are flown in close proximity to the ground. Overly simplistic explanations of the impact of the outwash, such as creating a circular area around the aircraft where it is unsafe to be at the closest distance, do not align with numerical simulations that indicate certain new VTOL vehicles will create unevenness in the outwash field. The scenario becomes more intricate when a variety of VTOL aircraft, varying in size, weight, and configuration, are anticipated to operate from the same site. Both the shape and strength of the outwash field created below a multi-rotor aircraft, when operated close to the ground, are likely to be particularly sensitive to the details of the aircraft's configuration (Chen et al., 2021).

Offshore helicopter operations present unique challenges due to mission demands, oil and gas exploration and production facilities, and flight environments. Industry organizations like the Helicopter Safety Advisory Conference (HSAC) and the Offshore Committee of the Helicopter Association International (HAI) have developed guidelines to reduce risks in offshore operations. These practices provide aviation and oil and gas industry operators with useful information in developing procedures to avoid hazards in VTOL operations and at vertiports. Recommended practices for offshore helicopter operations include passenger management at heliport facilities, including a designated waiting area, unloading and clearing of passengers and cargo, and supervision of unloading and loading processes. A standardized visual signal on the vertipad/vertiport can help provide a positive indication to an approaching VTOL of the status of the landing area. Clear communication procedures should be in place to connect the pilot with the ground crew and passenger handling staff (FAA, 2024).

## Scales Used to Describe the Safety and Tolerability of Wind Speeds

There are a variety of scales used to describe wind speeds and how certain velocities impact persons and objects. These scales can be used to identify wind speeds that may potentially be dangerous or harmful. The Lawson Comfort Criteria is a set of standards that quantify an individual's experience within a local wind microclimate. These criteria consider factors such as wind strength, clothing, environment, expectation, temperature, humidity, and sunshine. The criteria are based on the mean hourly wind speed, with green being acceptable, yellow being tolerable, and orange being unacceptable (see Table 3). The criteria depend on the mean hourly wind speed, with the threshold wind speed not exceeding more than 5% of the time (Bernardo et al., 2021).

**Table 3**

*Lawson Comfort Criteria*

| **Wind Effect** | **Threshold: MPH** | **Stationary** | **Walking** | **Transit (e.g., car)** |
|---|---|---|---|---|
| Calm | 0 | 🟩 | 🟩 | 🟩 |
| Felt on Face | <4 | 🟩 | 🟩 | 🟩 |
| Leaves Move | 9 | 🟨 | 🟩 | 🟩 |
| Dust Raised | 14 | 🟧 | 🟨 | 🟩 |
| Felt on Body | 18 | 🟧 | 🟨 | 🟨 |
| Hard to Walk | 22 | 🟧 | 🟧 | 🟧 |
| Trees Moving | 33 | 🟪 | 🟪 | 🟪 |
| Dangerous | 45 | 🟥 | 🟥 | 🟥 |

*Note.* Adopted from Bernardo et al. (2021).

The Beaufort Scale was initially calibrated to British Navy commander Beaufort's assessment of wind effects on a full-rigged man-of-war, identifying thirteen states of wind force and ranking them from zero to twelve. While the scale does not directly indicate the precise wind speed, it is valuable for approximating wind properties across a wide region and may be employed to predict wind conditions in the absence of wind measuring devices. The Beaufort Scale can also be used to assess and depict the impact of various wind speeds on items on land or on the ocean. In addition, the scale has been adapted to determine at which point it becomes unsafe to walk (Meaden et al., 2007; National Parks Association of New South Wales, n.d.).

## Method

In this study, investigators aimed to establish safety guidelines for the protection of people and property on the ground from VTOL downwash and outwash. The study used representative VTOL aircraft data to calculate the theoretical forces and characteristics of the airflow generated during the takeoff and landing phases. This data was then compared to established wind speed scales, which categorize wind speeds based on their potential hazardous impact. By carefully analyzing this information, the researchers were able to propose a process for determining safety zones and buffer areas around vertiports.

### Data

Existing equations used to describe airflows around rotorcraft, along with data on how such flows dissipate under typical conditions, were amalgamated into formulas that theoretically describe induced flow velocities generated by VTOL aircraft. The formulas were then used to map estimated flow speeds on and around a landing site. Wind speed scales were also utilized to assist in determining speeds that are reasonable and safe for persons and property in proximity to a vertiport. In addition, an example based on the limited performance data available for an eVTOL prototype was calculated. Data for existing helicopters were also used to guide the outcomes of this study.

### Procedure

First, a consensus was established from existing literature concerning the maximum wind speeds that might be reasonable, tolerable, and safe for pedestrians to experience when standing or walking in a vertiport operational area. The same was accomplished concerning the presence and location of objects. The distance at which flow speeds dropped below the aforementioned “safe” threshold was selected for placement of a protection zone border. Additional guidance on a potential buffer zone was determined by considering the altitude at which airflow exceeding “safe” speeds would begin to interact with the ground and at what distance this would occur from the vertipad assuming a specific VTOL approach glidepath.

## Results

### Maximum Safe Wind Speed

While the speeds determined to be safe for persons to stand and walk vary slightly across different scales, the variations provide general guidance on what may be acceptable. The most conservative and protective action would be to take the lowest indicated speed as the limit for passenger and ground crew operations. The most conservative is the Lawson scale value of 18 mph. Although the scale states that 22 mph is the limit for walking without trouble, the color scale indicates that 18 mph is the upper limit of the caution range when someone is physically walking. This conservative value provides additional protection for persons over the age of 50, as recommended by ATSB (2023).

## Calculations to Determine Safety Areas at Vertiports

Using public data provided by various manufacturers, example dimensions were created to mimic one of the designs currently under flight testing. Using this data, the estimated downwash velocity for an individual rotor was calculated. The assumptions were:

- Rotor diameter = 9.5 feet
- Maximum gross weight = 4,000 lbs
- Density = Sea Level
- Number of lift rotors: 12
- Design dimension (D) = 39 feet

Under such conditions, an estimated downwash velocity was calculated to be 57 mph (using equation 1). Using a conservative outwash multiplier of 2x, the outwash velocity would approximate 114 mph ($V_{d(adj)}$). These calculations align with the findings by Brown (2022a; 2022b) and CAA (2023). As noted by Brown (2022a, 2022b), the interaction of outflows from the different rotors creates a complex airflow environment, which may result in jet-like flows in certain directions, as noted by the extensions in danger zones displayed in Figure 4. Thus, speeds in excess of 114 mph may be possible in the vicinity of these jet pathways and would be dependent on the geometric amplification factor.

The mean reduction in outwash velocity was estimated (based on Brown, 2022a, 2022b) to be 13.2% of the initial velocity for every dimension D equivalent distance or $V_{reduction} = 0.132(D)$. The new speed value is then calculated by equation 5.

$$V_{new} = V_{d(adj)} - V_{reduction} \qquad (5)$$

Therefore, for example, the estimated outflow velocity at a distance of 39 feet (1 x D) from the vehicle would be 99 mph. It should be noted that the outwash begins to expand laterally once the vehicle is within 1 x D in height and reaches a maximum when at or lower than 0.25 x D or around 10 feet. Although no guidance is yet available on how to calculate the impacts of jet flows, it was assumed that jet flows would carry further. A conservative assumed reduction of airflow speed was estimated to be at a rate of half that of normal conditions, calculated as $V_{reduction(jet)} = 0.066(D)$. These calculations and estimations provide some preliminary insight into the potential safety zone sizes for vertiports. Equations 6 and 7 can be used to determine the least conservative safe distance ($D_{safe}$). Note: The number "18" in the equation is the upper wind speed limit for pedestrians determined from the literature. Users can substitute alternative values as necessary.

$$D_{safe} = D\left[\frac{(V_{d(adj)} - 18)}{0.132(V_{d(adj)})}\right] \qquad (6)$$

$$D_{safe(jet)} = D\left[\frac{(V_{d(adj)} - 18)}{0.066(V_{d(adj)})}\right] \qquad (7)$$

As noted by Brown (personal communication, May 15, 2024), the dimension "D" is an arbitrary value and is not analogous to helicopter downwash and outwash speeds defined as functions of rotor diameter distances. Brown (2022a) recommended that downwash/outwash calculations consider variations in VTOL designs and be as conservative as possible due to the highly variable nature of VTOL wake. Brown (2022a) outlined an alternative means of estimating safe distances that consider the number and sizes of VTOL propellers. Thus, a D that takes these factors into account, $D_{cc}$, or dimension-conservative correction, should be used to calculate the most conservative safe distance. $D_{cc}$ is defined as propeller radius (*p*) multiplied by the number of propellers (*n*) (equation 8).[1]

$$D_{cc} = p \; x \; n \qquad (8)$$

For the example aircraft used in this study, the most conservative estimated outflow velocity at a distance of 57 feet (1 x $D_{cc}$) from the vehicle would be 99 mph. It should be noted that the outwash begins to expand laterally once the vehicle is within 1 x $D_{cc}$ in height and reaches a maximum when at or lower than 0.25 x $D_{cc}$ or around 15 feet. Although no guidance is yet available on how to calculate the impacts of jet flows, the same formula for calculating jet-flow reduction rate was used, substituting $D_{cc}$ for D: $V_{reduction(jet)} = 0.066(D_{cc})$. These calculations and estimations provide some preliminary insight into the potential safety zone sizes for vertiports. The most conservative safe distances for normal ($D_{c\_safe}$) and jet flows ($D_{c\_safe(jet)}$) require the substitution of $D_{cc}$ in place of D, yielding equations 9 and 10.

$$D_{c\_safe} = D_{cc}\left[\frac{(V_{d(adj)} - 18)}{0.132(V_{d(adj)})}\right] \qquad (9)$$

$$D_{c\_safe(jet)} = D_{cc}\left[\frac{(V_{d(adj)} - 18)}{0.066(V_{d(adj)})}\right] \qquad (10)$$

An approach or inner buffer area dimension formula is based upon the fact that downwash peaks begin at approximately three times the rotor diameter or D for eVTOLs represented by $3(D)$. A normal approach glideslope of 3:1 would mean that every 3 feet of distance is accompanied by a 1-foot change in height. Thus, the distance at which downwash increasingly becomes hazardous ($D_{dwa}$) would be three times the height of $3(D)$ or mathematically represented as $3\big(3(D)\big)$. The distance at which downwash begins to impact the ground ($D_{dwg}$) is 10 x the height of $3(D)$ or mathematically represented as $3\big(10(D)\big)$. Equations

---

[1] If propellers are stacked in tandem, such as on the EHang, use the number of propeller pairs instead of the total number of propellers.

11 and 12 show the least conservative approach to downwash and downwash buffer zone dimensions, respectively.

$$D_{dwa} = 3(3(D)) \qquad (11)$$

$$D_{dwg} = 3(10(D)) \qquad (12)$$

For more conservative height calculations, use $D_{cc}$ in lieu of D in equations 11 and 12. Table 4 shows the current FAA guidance for vertiport dimensions based on dimension D. For comparison purposes, Table 5 shows the least and most conservative values based upon the equations presented in this study. Based on the calculations conducted in this study, existing FAA vertiport design criteria appear to be insufficient as they lack minimum standards for downwash and outwash safety.

**Table 4**

*Vertiport Dimensions for Example Aircraft: Available FAA Standards*

| Element | Dimension (ft) |
|---|---|
| **TLOF** | 39 |
| **FATO** | 78 |
| **Safety Area** | 117 |

**Table 5**

*Additional Recommendations Vertiport Safety Areas Dimensions: Example Aircraft*

| Formula | Least Conservative Dimension (ft) | Most Conservative Dimension (ft) |
|---|---|---|
| **Normal Flow** | 246 | 359 |
| **Approach Downwash** | 351 | 513 |
| **Jet Flow** | 492 | 720 |
| **Downwash Buffer Area** | 1,170 | 1,710 |

Note. All calculated dimensions exceed that of current FAA vertiport recommended distances.

## Discussion

The emergence of new VTOL aircraft promises a revolution in urban transportation. However, ensuring the safety of people and property on the ground from the effects of VTOL downwash and outwash is paramount. A critical component of the vertiport development process is the thorough understanding of induced airflows as a result of VTOL operations and the potential impact these may have on persons, property, other aircraft, and structures on the ground. VTOL propellers generate powerful airflows downward (downwash) and outward (outwash) during takeoff, landing, and hovering. Downwash can create strong winds that can dislodge objects, damage structures, and potentially injure people. Outwash can also pose a hazard by pushing debris or loose objects into the path of the aircraft or nearby personnel.

Currently, vertiport design regulations regarding safety area dimensions are rapidly evolving. The Federal Aviation Administration (FAA) released initial guidelines in 2022, specifying minimum dimensions for the touchdown and liftoff (TLOF) area and the final approach and takeoff (FATO) area. The European Union Aviation Safety Agency (EASA) offers similar guidelines with slight variations. The areas outlined in FAA/EASA guidelines are crucial for safe aircraft operations but do not explicitly address the need for additional protections for ground personnel and objects. Moreover, the current dimensions do not take into account the type or size of VTOL that may operate at the vertiport, although, in all fairness, such information is likely to remain unknown or uncertain over the near term. However, considering that safety requirements appear to be dependent upon the configuration and size of VTOLs, there may need to be restrictions on the type and size of aircraft that can operate at a specific vertiport depending upon the sizes of the TOLF, FATO, Safety Areas, and other designated areas of protection.

Safety areas extending beyond the FATO are vital for mitigating downwash and outwash effects. The most rational and responsible means of addressing this issue is to adopt a data-driven design approach. The dimensions of additional safety buffers should be determined based on a combination of factors. VTOL characteristics such as the size, power output, and propeller configuration of the specific eVTOL aircraft operating at the vertiport should be considered. Limits or standards for downwash and outwash should be set to help vertiport designers factor this important element into the planning process. Regulatory bodies ought to establish maximum allowable downwash velocities for different areas surrounding the vertiport, such as passenger walkways or public roads. Environmental factors should also be considered, as wind speed and direction, as well as obstructions and their geometries, can influence downwash effects, requiring adjustments to safety area size.

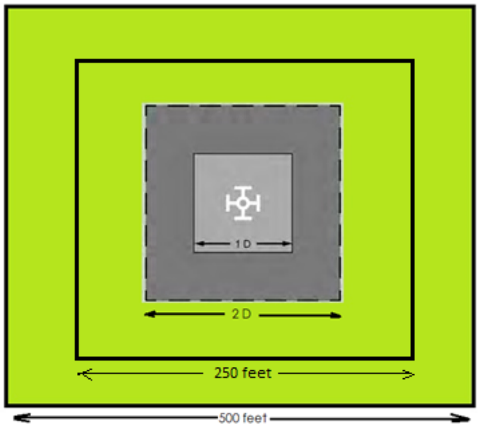
While safety is the paramount concern, it is also reasonable to expect that there be a balance between safety and efficiency. Larger safety areas undoubtedly enhance safety, but they come at a cost. Extensive land use can make vertiport development in urban areas challenging. Sizing can be optimized through computational modeling that can predict downwash and outwash patterns for specific eVTOL models, allowing for targeted safety area design. Wind mitigation structures such as strategically placed wind fences or deflectors can reduce the impact of downwash on surrounding areas. This simple design change could eliminate the need for larger vertipads and their surrounding buffers. Intelligent landscape design can also help dissipate airflows and provide additional protection for people and objects.

The findings of this study indicated that the current FAA (2022) standards may be inadequate for protecting persons and objects on and near vertiports. Moreover, the data shows that vertiport design should include downwash and outwash mitigation features. Also, designs that include means of segregating people and objects from areas influenced by airflow. This could include covered or enclosed walkways, walls, or tunnels. Areas influenced by airflow should be kept clear of unsecured objects, such as baggage and debris; items can easily become lethal projectiles if sent airborne by outwash or downwash. Consideration should also be given to the potential mix of aircraft that might operate at the vertiport because of potential differences in the characteristics of downwash and outwash. Perhaps a "worst case scenario" stance should be taken to maximize protection areas so as not to get into a situation where design features are inadequate for protecting passengers and property.

Although this study utilized theoretical data on airflows, it provides a foundation for assessing the altitudes and distances at which VTOL downwash and outwash may influence its surroundings. Available data indicated that the FAA safety area/zone dimensions are likely insufficient to adequately protect personnel and property on the ground. The least conservative safety zone dimensions (rounding up) could be defined as 250 feet for the inner safety zone, 500 feet for the outer safety zone, and 1,200 feet for a buffer zone. These values appear to be reasonable for a simple vertiport. For example, Volocopter (2024) suggested that a small vertiport could be approximately 6,700 square feet. The outer zone in this study would only occupy 2,500 square feet. A proposed basic vertiport design is shown in Figure 7. Calculating the most conservative safety zone dimensions, using Dcc could be defined as 360 feet for the inner safety zone, 720 feet for the outer safety zone, and 1,710 feet for a buffer zone. The outer safety zone would encompass just over 11 acres of land.

**Figure 7**

*Proposed Vertiport Dimensions: Least Conservative*



*Note.* The inner area is the TLOF (1 x D), the next box is the FATO (2 x D), the inner box is the inner safety area (ISA) (250 feet), and the outermost box is the outer safety area (OSA) (500 feet).

While this study provides some basic guidance on the effects of downwash and outwash on vertiports and surrounding areas, the question remains as to what types of activities or personnel would be allowed into the inner and outer safety areas. Furthermore, it must be determined when persons or objects can enter the safety areas. For example, service personnel may be permitted to begin handling the aircraft once it is on the ground and the motors turned off, but passengers will only be allowed in the areas if the propellers have stopped and the is no resulting airflow. If there are more than one vertipad, standards must be established on safe distances between pads as well as who or what might be allowed in the safety areas if an eVTOL is operating on an adjacent pad.

Another step that is necessary is to determine what land uses would be compatible with vertiports and the various distances from the vertiport that may be acceptable for such uses. This is particularly important for densely developed landscapes so as not to randomly place a vertiport that is surrounded by incompatible land uses. It is likely, however, that land use standards for vertiports will be less stringent than those for airports and will need to be flexible and customizable. For example, there could be a small buffer between the vertiport and development except in the area over which eVTOLs will approach and land at the vertipad. Land use restrictions may be applicable underneath the flight path but not in the other portions of the vicinity.

## Conclusion

In summary, this study was able to provide theoretically based equations to identify the velocity of VTOL downwash and outwash on and around vertiports. The results provide a framework for predicting downwash and outwash characteristics of various VTOL types and configurations. This information can be used to define safety zones on vertiport surfaces and in the surrounding environment. These zones should account for minimum safe distances for personnel and ground infrastructure to mitigate the risk of injury or damage from high-velocity airflows. Also, the potential for dust and debris mobilization by the downwash should be considered. The study highlighted the importance of considering environmental factors, such as wind direction and speed, in determining safe zones for VTOL operations. By incorporating these variables into safety protocols, the risk of accidents or damage can be significantly reduced.

Coupled with the guidance of the FAA and other studies, the findings of this study can assist in the development of land use compatibility standards for vertiports. Overall, this research contributes valuable insights that can improve the safety and efficiency of VTOL operations in urban environments. Additionally, the research findings can aid in the establishment of regulations and policies for VTOL operations to ensure public safety. Collaborating with industry experts and policymakers can further enhance the integration of eVTOLs into urban airspace. By fostering collaboration between various stakeholders, including industry experts and policymakers, the integration of eVTOLs into urban airspace can be streamlined. This multi-faceted approach will not only enhance safety and efficiency but also pave the way for the future of air mobility.

## Recommendations

The findings of this study logically lead to recommendations for future research. As more data becomes available on eVTOL downwash and outwash, such data should be included in standards and guidelines for vertiport design as well as local land use. This data may be sourced from simulation, but it is paramount to collect data directly from the aircraft whilst operating. By combining the findings of this study with those on vertiport safety, noise, and public sentiment, the foundation is laid to begin crafting land use compatibility guidelines and zoning standards. These are best developed under the consultation of industry experts, including manufacturers, airports, urban planners, aviation planners, and the public.

## References

Airbus Helicopters. (2021). *Safety promotion notice no. 3684-P-00: Noise and downwash considerations for ground operators.* Airbus.

ATSB. (2023). *Safety risks from rotor wash at hospital helicopter landing sites (ATSB Transport Safety Report AD-2022-001).*

Baculi, J., Nguyen, N., Okolo, W. A., & Xiong, J. (2024, July). Wake disturbance-based separation criteria study for urban air mobility aircraft. In *AIAA Aviation Forum*.

Bernardo, P., Mac Réamoinn, R., Young, P., Brennan, D., Cardiff, P., & Keenahan, J. (2021). Investigation of the helicopter downwash effect on pedestrian comfort using CFD. *Infrastructure Asset Management*, *8*(3), 133–140.

BP. (2017, March 15). *Helicopter downwash dangers* [Video]. YouTube. https://www.youtube.com/watch?v=09bvuYRKwwc

Brown, R. E. (2022a). *Do eVTOL aircraft create an inherently more problematic downwash than conventional helicopters?* Sophrodyne Aerospace.

Brown, R. E. (2022b). *Are eVTOL aircraft inherently more susceptible to vortex ring state than conventional helicopters?* Sophrodyne Aerospace.

CAA. (2023). *Understanding the downwash/outwash characteristics of eVTOL aircraft.* U.K. CAA.

Chang, M., Zheng, Z., Meng, X., Bai, J., & Wang, B. (2022). Aerodynamic analysis of a low speed tandem-channel wing for eVTOL aircraft considering propeller–wing interaction. *Energies*, *15*(22), 8616.

Chen, L., Wandelt, S., Dai, W., & Sun, X. (2021). Scalable vertiport hub location selection for air taxi operations in a metropolitan region. *INFORMS Journal of Computing*, 34, 834-856. https://doi.org/10.1287/ijoc.2021.1109

CASD. (2022). *Helicopter rotor downwash safety guidebook.* Ministère Chargé Des Transports.

Crespillo, O. G., Zhu, C., Simonetti, M., Gerbeth, D., Lee, Y. H., & Hao, W. (2023). Vertiport navigation requirements and multisensor architecture considerations for Urban Air Mobility. *arXiv preprint arXiv:2311.07487*.

FAA. (2024). *Helicopter operations – special operations.* https://www.faa.gov/air_traffic/publications/atpubs/aim_html/chap10_section_2.html

FAA. (2022). *Engineering Brief No. 105 – Vertiport design.* U.S. Department of Transportation.

FAA. (2012). *AC 150/5390-2D Heliport Design.* U.S. Department of Transportation.

George, M., Kisielowski, E., & Douglas, D. S. (1968). *Investigation of the downwash environment generated by V/STOL aircraft operating in ground effect* (p. 0149). US Army Aviation Materiel Laboratories.

Kidwell, J. C., & Foster, J. K. (1966). Engineering flight evaluation of the Bell Model 209 armed helicopter. *USAAVNTA Project*, (65–30).

JJ Ryan Consulting. (2024). *Helicopter rotor downwash – Excessive wind, FOD and brownouts, what are the risks?* https://jjryan.com.au/index.php/helicopter-rotor-downwash-excessive-wind-fod-and-brownouts-what-are-the-risks/

Leishman, J., & Bagai, A. (1998). Challenges in understanding the vortex dynamics of helicopter rotor wakes. *AIAA Journal*, 36, 1130-1140. https://doi.org/10.2514/2.510

Meaden, G. T., Kochev, S., Kolendowicz, L., Kosa-Kiss, A., Marcinoniene, I., Sioutas, M., ... & Tyrrell, J. (2007). Comparing the theoretical versions of the Beaufort scale, the T-Scale and the Fujita scale. *Atmospheric research*, *83*(2-4), 446-449.

Misiorowski, M. P. (2019). *Understanding and improvement of eVTOL UAV performance through high-fidelity analysis of interactional aerodynamics*. Rensselaer Polytechnic Institute.

National Parks Association of New South Wales. (n.d.). *Walking in different weather conditions.* https://www.bushwalking101.org/walking-in-different-weather-conditions

Petrescu, R. V., Aversa, R., Akash, B., Corchado, J., Berto, F., Apicella, A., & Petrescu, F. I. (2017). About helicopters. *Journal of Aircraft and Spacecraft Technology*, *1*(3), 204-223.

Seddon, J. M., & Newman, S. (2011). *Basic helicopter aerodynamics*. John Wiley & Sons.

Stokkermans, T. C., Usai, D., Sinnige, T., & Veldhuis, L. L. (2021). Aerodynamic interaction effects between propellers in typical eVTOL vehicle configurations. *Journal of Aircraft*, *58*(4), 815-833.

Sugiura, M., Tanabe, Y., Sugawara, H., Matayoshi, N., & Ishii, H. (2017). Numerical simulations and measurements of the helicopter wake in ground effect. *Journal of Aircraft*, 54, 209-219. https://doi.org/10.2514/1.C033665

Tauszig, L. (2023). *Prototype technical specifications for the design of vertiports – Part 1.* EASA.

Volocopter. (2024). *UAM glossary.* https://www.volocopter.com/en/blog/uamglossary-vertiport

Wadcock, A. J., Ewing, L. A., Solis, E., Potsdam, M., & Rajagopalan, G. (2008, October). Rotorcraft downwash flow field study to understand the aerodynamics of helicopter brownout. In *AHS Southwest Region Technical Specialist's Meeting Technologies for Next Generation of Vertical Life Aircraft*.

Zhou, J., Khot, L. R., Peters, T., Whiting, M. D., Zhang, Q., & Granatstein, D. (2016). Efficacy of unmanned helicopter in rainwater removal from cherry canopies. *Computers and Electronics in Agriculture*, *124*, 161-167.