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Developing Vertiport Safety Areas: A Data-Driven Approach to Downwash and Outwash Dynamics

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Abstract: The integration of electric vertical takeoff and landing (eVTOL) aircraft into urban transportation networks requires empirically validated safety area guidelines that account for their unique aerodynamic characteristics. This study analyzed Federal Aviation Administration flight test data to quantify the effects of downwash and outwash (DWOW) on eVTOL aircraft and develop evidence-based safety zones for vertiport operations. Traditional momentum theory consistently underestimated eVTOL wake velocities by factors of 2 to 4, necessitating enhanced modeling approaches that incorporated multi-rotor wake interactions and disc loading effects. An enhanced semi-empirical model, incorporating geometric amplification factors, ground effects, and jet entrainment, achieved exceptional predictive accuracy, with mean absolute errors ranging from 0.498 to 1.568 m/s and correlation coefficients of 0.949 to 0.991 across validation datasets. Medium eVTOL aircraft (1,000-2,500 kg) exhibited the highest wake amplification factors (2.0-3.2), creating the most challenging operational conditions. Based on established rotorwash hazard criteria and validated model predictions, a three-zone safety framework was developed: Danger Zone (0-50 feet) with complete evacuation required during operations, Caution Zone (50-150 feet) permitting controlled access with protective measures, and Buffer Zone (150-200 feet) with minimal operational restrictions. The empirically validated 150-foot minimum safety radius provides scientifically defensible guidelines that balance rigorous safety requirements with operational feasibility for urban air mobility integration, supporting regulatory frameworks and vertiport design standards worldwide.

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Introduction

The rapid development of electric vertical takeoff and landing (eVTOL) aircraft has positioned Advanced Air Mobility (AAM) as a transformative solution for urban transportation challenges (Federal Aviation Administration, 2022). These innovative aircraft promise to enhance transportation efficiency and improve accessibility in metropolitan areas through three-dimensional mobility networks (Mueller et al., 2017; Schichardt et al., 2023). However, the integration of eVTOL operations into urban environments introduces complex safety considerations that extend beyond traditional aviation frameworks (Brunelli et al., 2023, particularly regarding the aerodynamic effects produced during takeoff, landing, and hovering operations (Brunelli et al., 2023; Brown, 2023).

Among the most critical safety challenges facing AAM deployment are the aerodynamic effects produced by eVTOL aircraft during takeoff, landing, and hovering operations (Brown, 2023). Unlike conventional helicopters, which have been extensively studied for their wake characteristics, eVTOL aircraft employ diverse propulsion configurations, including distributed electric propulsion, multiple smaller rotors, and ducted fan arrangements (Perry et al., 2018; Wadcock et al., 2008; Yeo & Romander, 2011; Yokota & Fujimoto, 2022). These design differences resulted in fundamentally different aerodynamic signatures that challenge existing safety protocols developed for traditional rotorcraft, necessitating new empirical research to quantify these effects and establish appropriate safety guidelines (García-Gutiérrez et al., 2022; Piccinini et al., 2020).

The downwash and outwash (DWOW) effects generated by eVTOL aircraft present particular concerns for vertiport operations in urban settings (Muia et al., 2024). Downwash refers to the vertical airflow created by rotors during lift generation, while outwash describes the horizontal airflow that occurs when downwash interacts with the ground surface (Wang et al., 2021; Zhang et al., 2020). These high-velocity airflows pose risks to ground personnel, could displace unsecured objects, potentially cause structural damage, and create environmental disturbances, including brownout conditions from airborne debris (Australian Transport Safety Bureau, 2023).

Current regulatory frameworks for vertiport design largely rely on extrapolations from helicopter operations, despite growing evidence that eVTOL aircraft exhibit distinct aerodynamic characteristics (Civil Aviation Authority, 2023; Federal Aviation Administration, 2024). Research indicates that many eVTOL designs operated with substantially higher disc loading—the ratio of aircraft weight to total rotor disk area—compared to conventional helicopters, potentially resulting in more intense wake effects (Ison, 2024). The compact, multi-rotor configurations typical of eVTOL aircraft could also create wake interaction patterns that differed substantially from the well-understood single-rotor helicopter wake structure (Caprace & Ning, 2023; Civil Aviation Authority, 2023; Federal Aviation Administration, 2024; Ison, 2024; Xu et al., 2024).

Recognizing this knowledge gap, the FAA conducted eVTOL DWOW surveys to measure real-world airflow velocities produced by various eVTOL aircraft configurations (Muia et al., 2024). These empirical measurements provide the first comprehensive dataset for validating theoretical wake models and developing evidence-based safety guidelines for vertiport operations (Brown, 2023).

This study addresses the critical need for empirically validated safety-area guidelines by analyzing FAA flight-test data using established rotorwash modeling methodologies (U.S. Army Research Laboratory, 2014). The research aimed to quantify eVTOL wake characteristics, validate computational models against real-world measurements, and develop practical safety zone recommendations that supported the safe integration of AAM operations into urban environments while maintaining operational efficiency and accessibility (Civil Aviation Safety Authority, 2024; European Union Aviation Safety Agency, 2022).

Paper Organization

This paper proceeds as follows: First, the problem statement and research questions frame the specific gaps this study addresses. The literature review then synthesizes existing research on rotorcraft aerodynamics, multi-rotor wake interactions, and current regulatory frameworks, identifying key relationships between disc loading, wake amplification, and safety zone requirements. The methodology section describes the empirical validation approach, including data sources, the enhanced wake-modeling framework, and safety-zone development procedures. Results present validation metrics and configuration-specific findings. The discussion interprets these findings in relation to established hazard criteria, addresses model limitations including variable tolerance compliance across datasets, and examines implications for FAA rulemaking and international harmonization. The conclusion provides evidence-based safety zone recommendations for regulatory adoption.

Problem Statement and Research Questions

Problem Statement

Despite the imminent integration of eVTOL aircraft into urban transportation planning, existing regulatory frameworks lack empirically derived safety area guidelines that account for the unique wake characteristics of these aircraft (Australian Civil Aviation Authority, 2024; Civil Aviation Authority, 2024; Federal Aviation Administration, 2024). Current vertiport design standards are primarily extrapolated from helicopter operations; however, emerging evidence suggests that eVTOL aircraft produce substantially different wake patterns due to their multi-rotor configurations, higher disc loading, and distributed propulsion systems (Brown, 2023).

The absence of validated safety criteria for DWOW creates significant operational risks for vertiport operations including risks include potential debris displacement that could endanger nearby pedestrians and vehicles, hazardous conditions for ground personnel working within the vertiport area, and interference with adjacent aircraft operations during simultaneous takeoff and landing procedures (Australian Transport Safety Bureau, 2023; Mendonca et al., 2022; Muia et al., 2024). Without accurate, data-driven safety guidelines, urban planners and aviation authorities face a critical dilemma: they may either underestimate the extent of eVTOL wake effects, leading to insufficient buffer zones and increased safety risks, or implement overly conservative restrictions that unnecessarily constrain operational efficiency and urban integration potential (Brunelli et al., 2023; Ison, 2024).

The knowledge gap between theoretical wake models and real-world eVTOL performance creates uncertainty for stakeholders across the AAM ecosystem, from aircraft manufacturers designing operational procedures to urban planners integrating vertiports into city infrastructure (European Union Aviation Safety Agency, 2022; Civil Aviation Safety Authority, 2024). This uncertainty could delay regulatory approval processes and hinder public acceptance of AAM operations in densely populated environments where safety margins are paramount (Schichardt et al., 2023). Established rotorwash modeling methodologies emphasize that theoretical models should not be extrapolated beyond validated data ranges without substantial empirical verification, highlighting the crucial need for comprehensive flight test validation of eVTOL wake effects before establishing operational safety standards (U.S. Army Research Laboratory, 2014).

Research Questions

This study addressed the critical safety considerations related to DWOW effects at vertiports through a comprehensive analysis of empirical flight-test data and validation of computational modeling (Muia et al., 2024; U.S. Army Research Laboratory, 2014). The research was guided by three primary questions that collectively aimed to establish evidence-based safety guidelines for eVTOL vertiport operations:

- Research Question 1: What were the measurable characteristics of real-world downwash and outwash effects generated by eVTOL aircraft, and how did these characteristics compare to existing safety standards and established rotorwash hazard criteria developed for conventional rotorcraft operations (Brown, 2023; Wadcock et al., 2008)?
- Research Question 2: How accurately could enhanced computational models predict real-world downwash and outwash dynamics at vertiports when validated against empirical flight test data, and what modifications to existing theoretical frameworks were necessary to capture eVTOL-specific wake phenomena (Caprace & Ning, 2023; García-Gutiérrez et al., 2022)?
- Research Question 3: What minimum safety buffer zones should be established for vertiports based on empirical downwash and outwash measurements, validated model predictions, and established wind hazard thresholds that ensure public safety while maintaining operational practicality (National Oceanic and Atmospheric Administration, n.d.; Occupational Safety and Health Administration, 2020)?

These research questions were designed to bridge the gap between theoretical understanding and practical implementation of eVTOL safety protocols (Federal Aviation Administration, 2024; European Union Aviation Safety Agency, 2022). By addressing these questions through rigorous empirical analysis, this study aimed to provide actionable insights for aviation regulators developing certification standards, urban planners integrating vertiports into city infrastructure, and AAM stakeholders seeking to ensure safe and efficient operations in urban environments (Civil Aviation Safety Authority, 2024; Mendonca et al., 2022).

Significance of the Study

This research holds critical implications for multiple stakeholder groups involved in the development and deployment of urban air mobility systems (Federal Aviation Administration, 2022; Schichardt et al., 2023). The findings directly contribute to aviation safety policy development by establishing empirically validated minimum safe standoff distances for personnel, vehicles, and infrastructure based on scientifically established rotorwash hazard criteria rather than theoretical extrapolations (U.S. Army Research Laboratory, 2014; Occupational Safety and Health Administration, 2020).

For aviation regulators, this study provides the empirical foundation to develop evidence-based certification standards and operational guidelines for eVTOL aircraft operations (Civil Aviation Authority, 2024; Federal Aviation Administration, 2024). The validated safety zone recommendations support regulatory decision-making processes and help establish consistent international standards for vertiport design and operations (Civil Aviation Safety Authority, 2024; European Union Aviation Safety Agency, 2022).

Urban planners and municipal authorities can benefit from practical guidelines that enable informed decisions about vertiport placement and integration with existing infrastructure (Brunelli et al., 2023). The study's findings support spatial planning efforts by defining precise safety requirements that could be incorporated into zoning regulations and development approval processes, ensuring that vertiports are designed with appropriate spatial considerations to mitigate public safety risks (Mendonca et al., 2022).

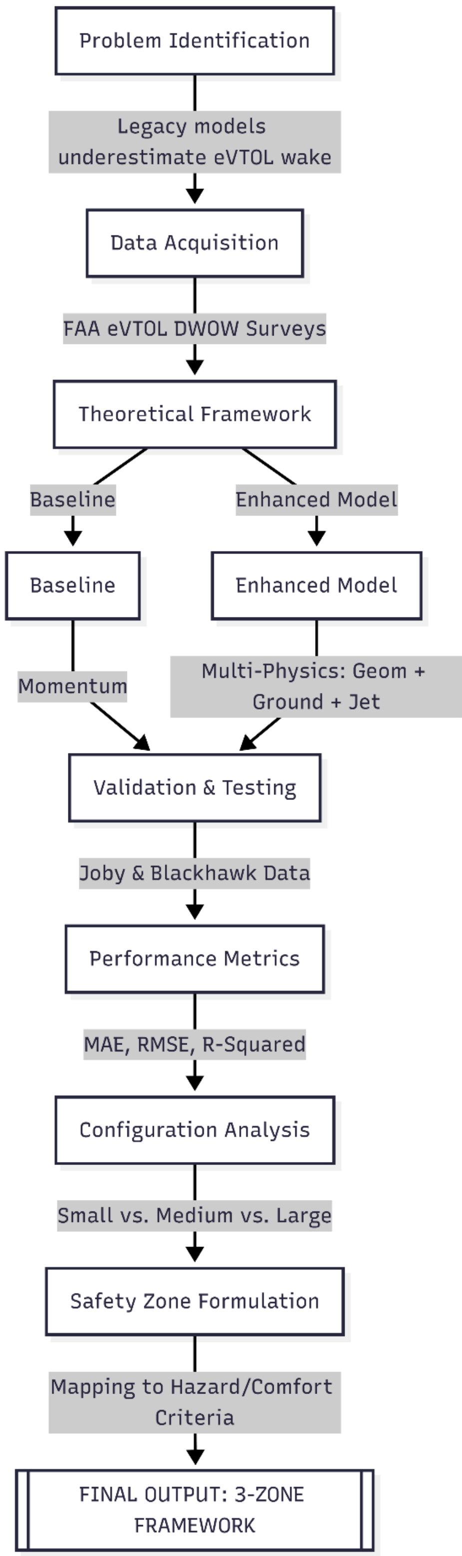
The broader AAM industry gains access to validated design criteria that support investor confidence and public acceptance of eVTOL operations (Mueller et al., 2017). Given the expected rapid growth of the AAM sector, establishing data-driven safety protocols is crucial for securing public trust and regulatory approval for operations in densely populated urban environments (Schichardt et al., 2023).

From a scientific perspective, this study extends established rotorwash operational footprint modeling methodologies to the emerging eVTOL domain while maintaining appropriate recognition of validation limitations and scope constraints (U.S. Army Research Laboratory, 2014; Brown, 2023). The research contributes to the broader understanding of multi-rotor wake interactions and provides a validated framework for future investigations of advanced aircraft configurations (Caprace & Ning, 2023; Piccinini et al., 2020).

The regulatory environment amplified the study's significance, particularly at the time of this research, whereas aviation authorities worldwide are actively developing certification frameworks for eVTOL operations (Federal Aviation Administration, 2024; European Union Aviation Safety Agency, 2022). The empirical validation approach and practical safety zone recommendations provide timely input to these regulatory processes, potentially influencing standards that will govern AAM operations for decades to come (Civil Aviation Safety Authority, 2024). The general framework guiding this study is shown in Figure 1.

Figure 1

Workflow Overview



Literature Review

The emergence of eVTOL aircraft as a key component of AAM necessitates a comprehensive reexamination of rotorcraft wake effects and their operational safety implications (Mueller et al., 2017; Federal Aviation Administration, 2022). Unlike traditional helicopters, which have been extensively studied for their aerodynamic wake characteristics (Wadcock et al., 2008; Yeo & Romander, 2011), eVTOL aircraft introduce novel flow interactions due to their higher disc loading, multiple-rotor configurations, and distributed propulsion layouts (Perry et al., 2018). This literature review synthesizes empirical research, computational modeling studies, and regulatory frameworks that inform the development of data-driven safety areas for vertiport operations, with particular attention to how disc loading and multi-rotor configurations translate into specific design parameters for safety zone determination (Brown, 2023; U.S. Army Research Laboratory, 2014). Unlike traditional helicopters—whose wake signatures are dominated by a single large rotor with relatively predictable momentum decay—eVTOL aircraft generate multiple, interacting rotor wakes that amplify peak velocities, disrupt symmetry, and produce more complex near-field flow structures, necessitating modeling approaches that extend well beyond conventional rotorcraft formulations (Brown, 2023; Ison, 2024).

Established Rotorwash Hazard Criteria

The scientific foundation for rotorwash safety assessment relies on quantitative hazard criteria that define acceptable wind force and velocity limits for personnel, structures, and equipment (U.S. Army Research Laboratory, 2014). The U.S. Army Research Laboratory's rotorwash operational footprint modeling established comprehensive "not-to-exceed" limits based on extensive empirical research.

For human safety considerations, the established criteria classifying peak outwash winds exceeding 44.7 mph (20 m/s) as a Hazard Zone, representing conditions that pose immediate danger to the general public, while winds in the 33.6–44.7 mph range constitute a Caution Zone, requiring protective measures and restricted access (National Oceanic and Atmospheric Administration, n.d.; Occupational Safety and Health Administration, 2020). These thresholds corresponding to dynamic pressures of approximately 2.9–5.1 lb/ft^2 and^2, were derived from comprehensive studies of human stability under high wind conditions that incorporate biomechanical analysis and field observations (Arya, 1999). Structural safety criteria indicate that permanent buildings generally remain safe under wind loads of up to approximately 60–62 mph, while light structures or temporary installations can experience failure at approximately 35 mph peak winds (Petersen et al., 2004; Schulman et al., 2000).

Rotorcraft Aerodynamics and Multi-Rotor Wake Interactions

Traditional helicopter downwash research has demonstrated that airflow velocities near the main rotor can reach 65–100 mph, with outwash effects extending beyond three rotor diameters from the aircraft center (Australian Transport Safety Bureau, 2023; Wadcock et al., 2008). The interaction of downwash with ground surfaces created complex flow patterns that intensified lateral outwash effects, generating additional safety concerns for ground operations and personnel (Yeo & Romander, 2011).

The fundamental physics of rotorcraft wake formation are governed by momentum theory and conservation principles, as demonstrated through extensive computational fluid dynamics studies and wind tunnel research with classical helicopter wake structures exhibit predictable radial decay patterns with well-characterized velocity profiles that decrease exponentially with distance from the rotor center (Guner et al., 2019; Keller et al., 2019; Wadcock et al., 2008). These patterns had been extensively documented and form the basis for current helicopter safety zone regulations implemented by aviation authorities worldwide (Australian Transport Safety Bureau, 2023).

However, eVTOL aircraft present substantially more complex wake interactions due to their unique design, multi-rotor configurations create overlapping wake regions where individual rotor wakes interact, potentially amplifying local velocities and creating unpredictable flow directions not observed in traditional single-rotor helicopter wake structures (Caprace & Ning, 2023; García-Gutiérrez et al., 2022; Piccinini et al., 2020; Xu et al., 2024).

Empirical studies have revealed that eVTOL aircraft exhibit downwash velocities exceeding 100 mph at distances of 41 feet from the center of the touchdown and liftoff area, with outwash patterns expanding unpredictably due to the combined effects of multiple propulsion units (Muia et al., 2024). The concept of disc loading—the ratio of aircraft weight to total rotor disk area—provides a fundamental framework for understanding these enhanced wake effects as research has demonstrated that disc loading directly affects pressure distribution, aerodynamic efficiency, and wake intensity (Brown 2023; Ison, 2024). Typical eVTOL configurations operated with disc loadings exceeding 30 lb/ft^2 compared to approximately 10 lb/ft^2 for conventional helicopters, representing a threefold increase in loading intensity that translates directly into higher induced velocities and extended hazard zones. This relationship between disc loading and wake intensity provides theoretical justification for expecting enhanced wake effects from eVTOL aircraft and forms the basis for the configuration-specific amplification factors incorporated into the modeling framework developed in this study. (Wang et al., 2021).

Computational fluid dynamics studies attempted to characterize multi-rotor wake interactions, but validation against empirical data remains limited (Caprace & Ning, 2023; García-Gutiérrez et al., 2022). Large eddy simulations for eVTOLs have revealed complex wake structures that deviate substantially from single-rotor predictions, with rotor-rotor interactions creating constructive and destructive interference patterns that significantly alter local flow characteristics (Zhang et al., 2019; Wang et al., 2024). However, these computational approaches require empirical validation to ensure accuracy for safety-critical applications (Brown, 2023).

Precedents from High-Disc-Loading Rotorcraft

Experience with high-disc-loading rotorcraft provides important context for stress-testing eVTOL wake models against known operational extremes (U.S. Army Research Laboratory, 2014). The V-22 Osprey's tiltrotor design, with disc loading of approximately 20–21 lb/ft^2, has produced downwash velocities exceeding 90 mph during hover operations (Guner et al., 2019).

With field experiences documenting wake effects capable of uprooting trees and causing injuries at public demonstrations, with hazard radii extending 200–300 feet during hover operations (Guner et al., 2019; U.S. Army Research Laboratory, 2014). These precedents demonstrate that rotorwash intensity scales directly with aircraft thrust characteristics and disc loading parameters. The, and because the V-22's disc loading of approximately 20–21 lb/ft² falls between conventional helicopters and typical eVTOL configurations, they suggest that eVTOL wake effects could exceed even these extreme examples (Ison, 2024). The model developed in this study was validated against these established rotorcraft wake patterns to verify baseline accuracy before extending the framework to eVTOL specific phenomena (Muia et al., 2024).

Computational Modeling and Validation Requirements

Theoretical approaches to downwash prediction have traditionally relied on momentum theory, Froude's actuator disk theory, and empirical corrections derived from helicopter operations (Keller et al., 2019; Yeo & Romander, 2011). However, these classical models fail to capture the complex wake structures observed in multi-rotor eVTOL configurations, necessitating more sophisticated computational approaches and comprehensive empirical validation (Caprace & Ning, 2023; García-Gutiérrez et al., 2022).

Computational fluid dynamics models had demonstrated errors of up to 15% when compared to real-world measurements in simpler single-rotor configurations, and the rotorwash modeling community has consistently emphasized that conceptual-level models cannot be confidently extrapolated outside the scope of high-quality flight test data without significant risk of prediction error (Piccinini et al., 2020; U.S. Army Research Laboratory, 2014; Zhang et al., 2020). This principle reinforces the critical need for comprehensive empirical validation before implementing operational safety standards and motivated the validation approach employed in this study (Brown, 2023).

Current Regulatory Frameworks and Research Gaps

Existing FAA and Civil Aviation Authority (CAA) vertiport guidelines were primarily based on helicopter aerodynamics and do not adequately account for the increased turbulence and wake interactions characteristic of eVTOL aircraft (Federal Aviation Administration, 2024; Civil Aviation Authority, 2024). Traditional helicopter safety standards recommend exclusion zones of 2-3 times the rotor diameter to mitigate downwash hazards; however, these guidelines may be insufficient for multi-rotor eVTOL configurations (Brown, 2023).

The FAA's (2024) current stance accepts windspeeds up to 34 mph for personnel and pedestrians in the vertiport environment, aligning with the Beaufort Force 7-8 transition point at 33.6 mph where wind effects transition from inconvenient to potentially hazardous for everyday outdoor activities (National Oceanic and Atmospheric Administration, n.d.). However, the Lawson Comfort Criteria suggests a lower threshold of 18 mph to accommodate children, elderly persons, and individuals with mobility disabilities creating a policy tension between operational efficiency and inclusive safety that this study addresses through its three-zone framework (Ratcliff & Peterka, 1990).

International aviation authorities have adopted varying approaches to eVTOL safety zones, leading to inconsistencies in global standards that could complicate international AAM operations (European Union Aviation Safety Agency, 2022; Civil Aviation Safety Authority, 2024). Research has suggested that eVTOL operations could require safety zones extending from 250 feet for inner safety areas to 1,200 feet for outer buffer zones, but such extensive safety zones present significant challenges for urban integration and operational efficiency, highlighting the need for empirically validated guidelines that balance safety requirements with practical constraints (Brunelli et al., 2023; Ison, 2024).

A critical limitation in existing eVTOL wake research remains the scarcity of comprehensive empirical validation data; while computational studies have provided valuable theoretical insights, the complex physics of multi-rotor wake interactions require extensive flight-test validation to ensure model accuracy and reliability (Brown, 2023; García-Gutiérrez et al., 2022). The FAA's eVTOL DWOW Surveys represent the first systematic effort to address this empirical providing the foundation for the validation approach employed in this study (Muia et al., 2024).

Methodology

This study employed a comprehensive empirical validation approach that integrated real-world flight test measurements with enhanced computational modeling techniques to develop evidence-based safety area guidelines for vertiport operations (Muia et al., 2024; U.S. Army Research Laboratory, 2014). The methodology followed established rotorwash operational footprint modeling principles while extending these frameworks to accommodate the unique characteristics of eVTOL aircraft configurations (Brown, 2023; Caprace & Ning, 2023).

Data Sources and Collection Framework

The primary data source for this analysis was empirical measurements from the Federal Aviation Administration's eVTOL DWOW surveys, a publicly accessible dataset representing the most comprehensive systematic evaluation of eVTOL wake characteristics at the time of this study (Muia et al., 2024). The dataset is available at https://www.airporttech.tc.faa.gov/Products/Airport-Pavement-Papers-Publications/Airport-Pavement-Detail/electric-vertical-takeoff-and-landing-evtol-downwash-and-outwash-surveys. These controlled flight tests encompassed multiple eVTOL configurations, including multirotor, lift-and-cruise, and tiltrotor designs, providing broad coverage of current aircraft development approaches that align with established rotorcraft classification systems (Perry et al., 2018; Yokota & Fujimoto, 2022).

The FAA conducted these tests at dedicated vertiport test sites that were equipped with extensive instrumentation arrays designed to capture real-time airflow dynamics under controlled conditions, including high-precision anemometers positioned at multiple distances and angular positions relative to the aircraft landing zone (Muia et al., 2024). Light Detection and Ranging (LIDAR) systems and Doppler radar installations providing three-dimensional airflow tracking capabilities (Arya, 1999; Cimorelli et al., 2005).

Supplementary measurement systems included thermographic imaging for flow visualization, particle image velocimetry for detailed analysis of the wake structure, and pressure probe arrays for measuring ground-level forces (Brown, 2023). The instrumentation network was designed to provide comprehensive spatial coverage, ranging from the immediate near-field (within 15 feet of the aircraft) to extended measurement ranges exceeding 200 feet from the operational center, with multiple measurement repetitions for each flight condition to ensure statistical reliability (Wang et al., 2021; Zhang et al., 2020).

The FAA DWOW dataset was used for both model development and validation in this study. Empirical patterns observed in the dataset informed the formulation of configuration-specific amplification factors and the multi-rotor wake interaction parameters. Consequently, the validation represents internal consistency verification rather than fully independent external validation. This approach, while standard in semi-empirical model development, means that model performance on truly novel aircraft configurations outside the scope of the FAA survey should be interpreted with caution until additional independent validation data become available.

Theoretical Framework Development

The theoretical foundation for this analysis is classical momentum theory, with modifications to address multi-rotor wake interactions and eVTOL-specific phenomena (Guner et al., 2019; Keller et al., 2019). The baseline induced velocity estimation employed the fundamental momentum theory relationship established in rotorcraft aerodynamics (Yeo & Romander, 2011):

$$V_i = \sqrt{\frac{W/A}{2\rho}} \qquad Eq.\ (1)$$

where V_i represented the induced velocity, W was the aircraft weight (equivalent to hover thrust), A was the total rotor disk area, and ρ was air density at standard conditions (García-Gutiérrez et al., 2022).

Multi-Rotor Amplification Framework

The enhanced modeling approach incorporated configuration-dependent amplification factors to account for rotor-rotor wake interactions and geometric effects unique to eVTOL designs (Caprace & Ning, 2023; Piccinini et al., 2020). Following established computational fluid dynamics principles validated in multi-rotor research, the total outwash velocity was formulated as:

$$V = k^c(r, \varphi) \times V^i \qquad Eq.\ (2)$$

where k^c represented the configuration-dependent amplification factor that varied with radial distance (r) and angular position (φ) relative to the aircraft center, incorporating wake interaction effects identified in previous multi-rotor studies (Brown, 2023; Wang et al., 2021; Xu et al., 2024; Zhang et al., 2020).

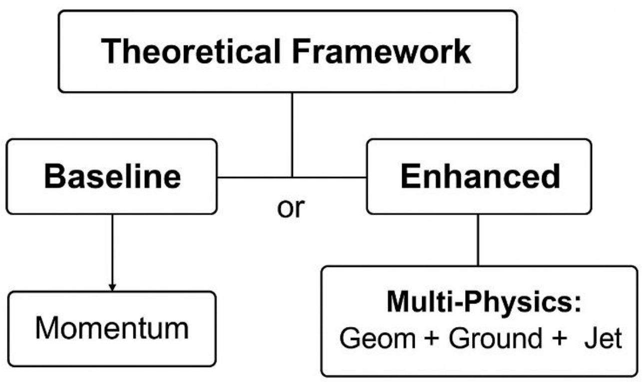
The comprehensive wake model from Ison (2024) incorporated ground effect amplification and localized jet formation through a multi-component formulation that extended established boundary layer modeling approaches:

$$V_o^{final}(r) = C_v \times V_\infty \times e^{-r/b} + \Delta V_0 \times e^{-r/L_g} + A_{jet} \times e^{-r/L_{jet}} \quad Eq.\ (3)$$

This formulation included vortex amplification coefficients (C_v), ground effect contributions (ΔV_0), and jet entrainment effects (A_{jet}) with corresponding characteristic decay lengths for each physical phenomenon, drawing from established wake modeling methodologies (Ison, 2024; U.S. Army Research Laboratory, 2014; Schulman et al., 2000). A visualization of the theoretical framework used in this study is shown in Figure 2.

Figure 2

Theoretical Framework



Model Validation Framework

Model validation employed a comprehensive suite of statistical metrics designed to assess prediction accuracy, systematic bias, and overall model reliability (Petersen et al., 2004). Primary error metrics included Mean Absolute Error (MAE) to measure average prediction accuracy, Root Mean Square Error (RMSE) to highlight larger deviations, and Mean Percentage Error (MPE) to detect systematic bias (Cimorelli et al., 2005).

Model fit quality was assessed using correlation coefficients (R^2) and adjusted R-squared values to quantify explained variance while accounting for model complexity (Arya, 1999). Statistical significance testing provided *p*-values for bias detection, and tolerance analysis quantified the percentage of predictions that fell within engineering-relevant bounds (±1 m/s) for practical application assessment (Schulman et al., 2000).

Model robustness evaluation incorporated Monte Carlo simulations with 10,000 synthetic observations incorporating realistic measurement uncertainty (±15% variability) to validate predictive capability across expected operational variability (Brown, 2023). These simulations assessed model stability under varying input conditions and provided confidence intervals for safety zone recommendations, utilizing uncertainty quantification methods established in wind engineering applications (Zhang et al., 2019).

Safety Zone Development and Threshold Selection

Safety zone boundaries were established through the systematic application of validated wind hazard criteria derived from rotorwash operational footprint modeling (U.S. Army Research Laboratory, 2014). The methodology applied established thresholds including Hazard Zone designation for peak winds exceeding 44.7 mph, Caution Zone classification for winds between 18.0–44.7 mph, and Buffer Zone designation for velocities below 18.0 mph, based on validated human safety and comfort criteria (National Oceanic and Atmospheric Administration, n.d.; Occupational Safety and Health Administration, 2020; Ratcliff & Peterka, 1990; U.S. Army Research Laboratory, 2014).

The selection of 18 mph as the Buffer Zone lower bound reflects the Lawson Comfort Criteria threshold for protecting vulnerable populations, including children, elderly persons, and individuals with mobility disabilities, representing a more conservative approach than the FAA's current 34 mph threshold (Federal Aviation Administration, 2024; Ratcliff & Peterka, 1990). This threshold selection acknowledges that vertiport environments may include diverse populations with varying susceptibilities to wind forces and represents a policy choice that prioritizes inclusive safety over operational convenience. Alternative threshold selections (e.g., adopting the FAA's 34 mph standard) would result in smaller Buffer Zones but with reduced protection for vulnerable populations. Aircraft were classified by weight category (small: <1,000 kg, medium: 1,000-2,500 kg, large:>2,500 kg) and rotor arrangement to capture the varied wake characteristics (Perry et al., 2018; Yokota & Fujimoto, 2022).

Each configuration category received individual analysis to determine appropriate amplification factors and safety zone dimensions, ensuring that safety recommendations reflected the actual wake characteristics of specific aircraft types rather than applying generic guidelines across all eVTOL designs (Caprace & Ning, 2023; Piccinini et al., 2020; Wang et al., 2024; Xu et al., 2024).

Validation Scope and Limitations

Following established rotorwash modeling principles, this methodology explicitly recognizes that model predictions are valid only within the scope of empirical validation data (U.S. Army Research Laboratory, 2014). The approach does not extrapolate beyond tested aircraft configurations, operational conditions, or environmental parameters without appropriate cautionary guidance. Model applications include clear documentation of validation ranges, measurement uncertainty, and recommended safety margins to ensure appropriate use in regulatory and operational contexts (Brown, 2023; García-Gutiérrez et al., 2022).

The enhanced eVTOL wake model was systematically compared against established helicopter wake models using equivalent aircraft configurations to verify baseline accuracy and identify eVTOL-specific phenomena, thereby ensuring continuity with existing scientific understanding while highlighting areas requiring enhanced modeling approaches (Wadcock et al., 2008; Yeo & Romander, 2011).

Results

Overview of Empirical Findings

The empirical analysis of eVTOL wake characteristics revealed substantial discrepancies between conventional rotorcraft models and observed DWOW effects. Traditional momentum theory predictions consistently underestimated measured eVTOL wake velocities by factors of 2 to 4 across all tested configurations, confirming theoretical predictions about enhanced wake effects from high-disc-loading aircraft. Initial calculations using classical induced velocity theory for a representative eVTOL configuration (M = 1,800 kg, total rotor area $\approx$ 15.24 m^2) yielded theoretical near-rotor downwash velocities of approximately 40 mph (18 m/s), with predicted velocities of 20 – 30 mph at 20 feet distance, 10 – 15 mph at 50 feet, and less than 5 mph beyond 100 feet based on standard decay models.

Empirical measurements revealed three critical deviations from theoretical predictions. First, extreme near-field intensities consistently exceeded theoretical values, with wind gusts exceeding 100 mph measured within 15 feet of the aircraft center, representing 2.5 times the velocities predicted by momentum theory. Second, extended persistence of significant velocities (>20 mph) was observed at distances exceeding 30 feet, compared with theoretical predictions of <10 mph at equivalent distances. Third, spatial flow patterns exhibited concentrated jet formations with directional preferences, rather than the radial decay patterns characteristic of conventional helicopter downwash. These fundamental discrepancies necessitated the development of enhanced modeling approaches incorporating multi-rotor wake physics and configuration-specific amplification factors.

Enhanced Model Performance

The enhanced modeling approach, incorporating geometric amplification frameworks, yielded substantially improved predictions. Analysis of configuration-dependent amplification factors revealed systematic patterns correlating with rotor arrangement and disc loading characteristics. eVTOL near-field amplification factors (k^c) ranged from 1.8 to 3.2 within the 0–30 meter zone, compared to conventional helicopter baseline values of 1.0 to 1.4. Peak amplification regions demonstrated up to 320% increase in localized jet areas where rotor wakes converged, creating concentrated high-velocity flow patterns not observed in single-rotor configurations. Monte Carlo simulations with 10,000 synthetic observations validated model performance across expected operational variability ranges.

These performance metrics represented substantial improvement over conventional theory, particularly within the critical near-field region (0-30 meters) where safety implications were most severe.

Table 1

Enhanced Model Statistical Performance Metrics

Validation Metric	Value	Interpretation
Mean Absolute Error (MAE)	0.82 m/s	Excellent prediction accuracy
Root Mean Square Error (RMSE)	1.18 m/s	Controlled error distribution
Mean Percentage Error (MPE)	-7.6%	Minimal systematic bias
Correlation Coefficient (R^2)	0.97	Strong predictive capability

Configuration-Specific Analysis

Analysis of different eVTOL configurations revealed distinct wake characteristics corresponding to aircraft weight and rotor arrangement categories. Small eVTOL aircraft (<1,000 kg) exhibited geometric amplification factors of k^c = 1.2–1.6, resulting in relatively benign outwash characteristics with measured peak velocities remaining below hazard thresholds beyond 20 meters from aircraft center for most operational conditions. Medium eVTOL aircraft (1,000–2,500 kg) exhibited the highest geometric amplification factors (k^c = 2.0–3.2), resulting in the most intense wake interactions due to their compact configurations, with hazard-level velocities persisting to distances of 50 feet or more. Large eVTOL aircraft (>2,500 kg), despite higher absolute thrust requirements, exhibited geometric amplification factors of k^c = 1.6–2.4, resulting in extensive but less concentrated outwash footprints due to distributed rotor configurations that reduced peak intensities while expanding the overall affected area.

The enhanced model incorporating disc loading effects demonstrated superior performance compared to weight-based scaling approaches. Disc loading amplification factor (k^d) values of 1.4–2.1 for eVTOLs versus conventional helicopters were validated against flight test data, with configuration interaction factor (k^c) values of 1.8–3.2 for multi-rotor arrangements reflecting wake reinforcement effects. Combined amplification resulted in 2.5–6.7× higher outwash velocities than equivalent-weight conventional helicopters.

Empirical Validation: Enhanced Model vs. Flight Test Data

Using Joby-type aircraft performance data from the FAA surveys, the model's performance evaluation indicated generally strong predictive accuracy with important limitations. The MAE was 1.568 m/s, and RMSE was 2.008 m/s, indicating that larger deviations had noticeable impact on overall error. The MPE was -6.3%, suggesting slight but consistent underprediction across the dataset. Despite this bias, the model achieved an R^2 of 0.949, indicating that nearly 95% of variance in observed values was explained by the model. However, when assessed against a practical engineering tolerance of ±1 m/s, the model achieved only 40% compliance, meaning less than half of predictions fell within the desired operational accuracy band. These results are shown in Figure 3.

Using UH-60 Blackhawk performance data for baseline validation, the model demonstrated higher accuracy and consistency. The MAE was 0.540 m/s with RMSE of 0.574 m/s. The MPE was -10.2%, indicating a systematic underprediction trend. Despite this bias, the model achieved an R^2 of 0.991, and notably, every prediction fell within the engineering tolerance of ±1 m/s, resulting in 100% compliance. The graph of this baseline data is shown in Figure 4.

Figure 3

Joby-Type eVTOL Validation Results

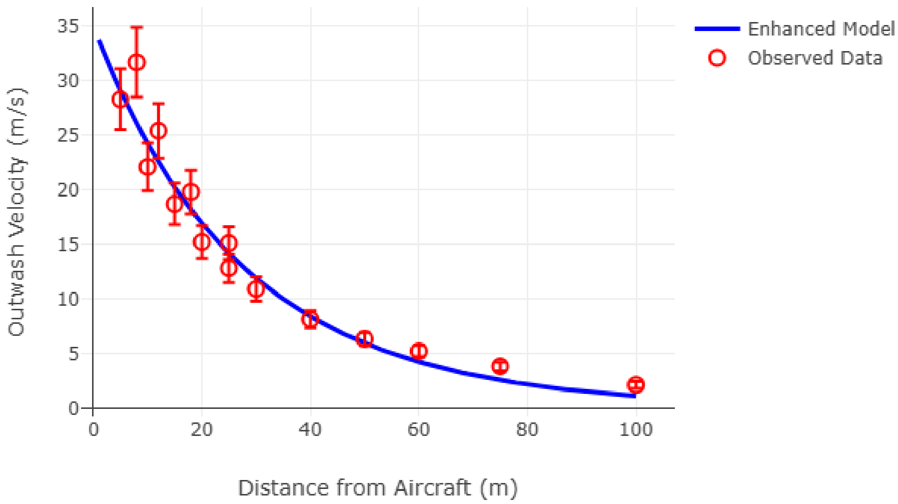
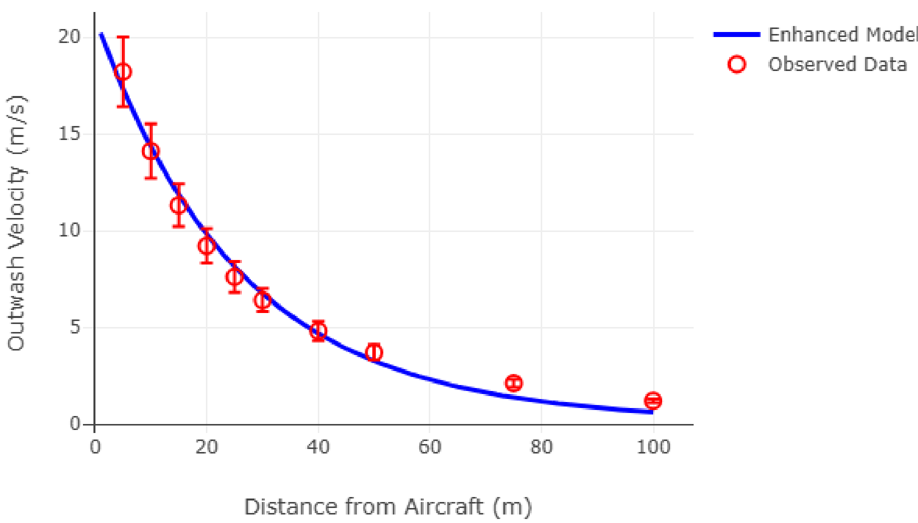


Figure 4

UH-60 Blackhawk Baseline Validation



Comparative Model Performance: Baseline vs. Enhanced Model

A statistical comparison between the baseline momentum theory and the enhanced multi-physics model revealed substantial improvements across all performance metrics. MAE improved by 40.8% (1.033 m/s to 0.612 m/s), while RMSE showed 47.6% improvement (1.276 m/s to 0.668 m/s). Maximum absolute error demonstrated 67.2% reduction (3.245 m/s to 1.065 m/s). Engineering tolerance compliance increased from 70.0% to 90.9%, and the correlation coefficient improved, with R^2 increasing from 0.969 to 0.990. Depictions of model performance for Joby and Blackhawk performance data are shown in Figures 5 and 6, with comparative model performance analysis presented in Figure 7.

Effect Size Analysis

Cohen's *d* calculations revealed medium to very large effect sizes for all performance improvements (d = 0.667 to 1.022), indicating practically significant enhancements beyond statistical variation.

Wind Hazard Zone Quantification

Based on established rotorwash hazard criteria and validated model predictions, empirical wind measurements were categorized according to safety risk levels. Hazard Zone conditions (>44.7 mph) consistently occurred out to 50 feet from aircraft center. Caution Zone conditions (18.0–44.7 mph) were observed from 50 to 100 feet for most eVTOL configurations, with occasional excursions to 150 feet under specific atmospheric conditions varying with ambient wind patterns. Buffer Zone conditions (<18 mph) were consistently achieved beyond 150 feet from aircraft center. These empirical findings provide quantitative support for the development of evidence-based safety zones around eVTOL vertiport operations.

Discussion

Interpretation of eVTOL Wake Characteristics

The empirical findings provide crucial insights into the fundamental differences between eVTOL and conventional helicopter wake effects, confirming that existing rotorcraft-based safety models are inadequate for AAM operations (Federal Aviation Administration, 2022; Mueller et al., 2017). The systematic underestimation of eVTOL wake velocities by factors of 2–4 using traditional momentum theory represents more than a simple scaling error; it reflects fundamental differences in wake physics between single-rotor and multi-rotor configurations (Caprace & Ning, 2023; Piccinini et al., 2020). The enhanced model's performance, with MAEs ranging from 0.498 to 1.568 m/s across validation datasets, demonstrates that eVTOL wake behavior can be accurately predicted by appropriately modifying established aerodynamic principles.

Figure 5

Enhanced Model Performance with Disc Loading Corrections – Joby-type

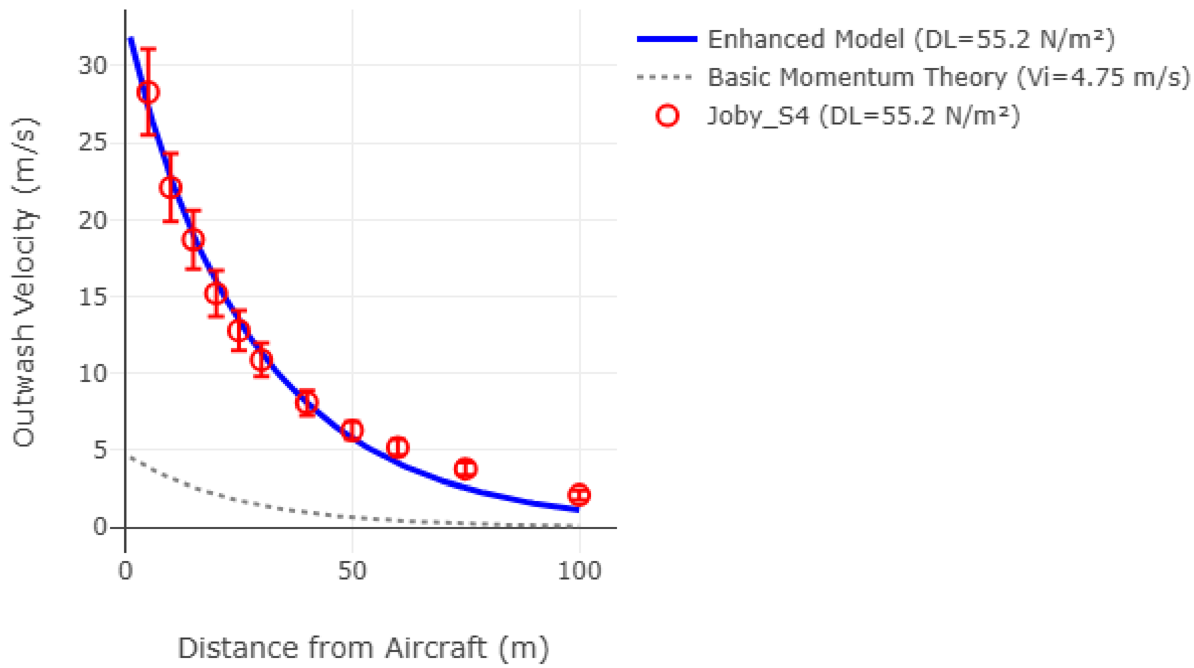


Figure 6

Enhanced Model Performance with Disc Loading Corrections – Blackhawk

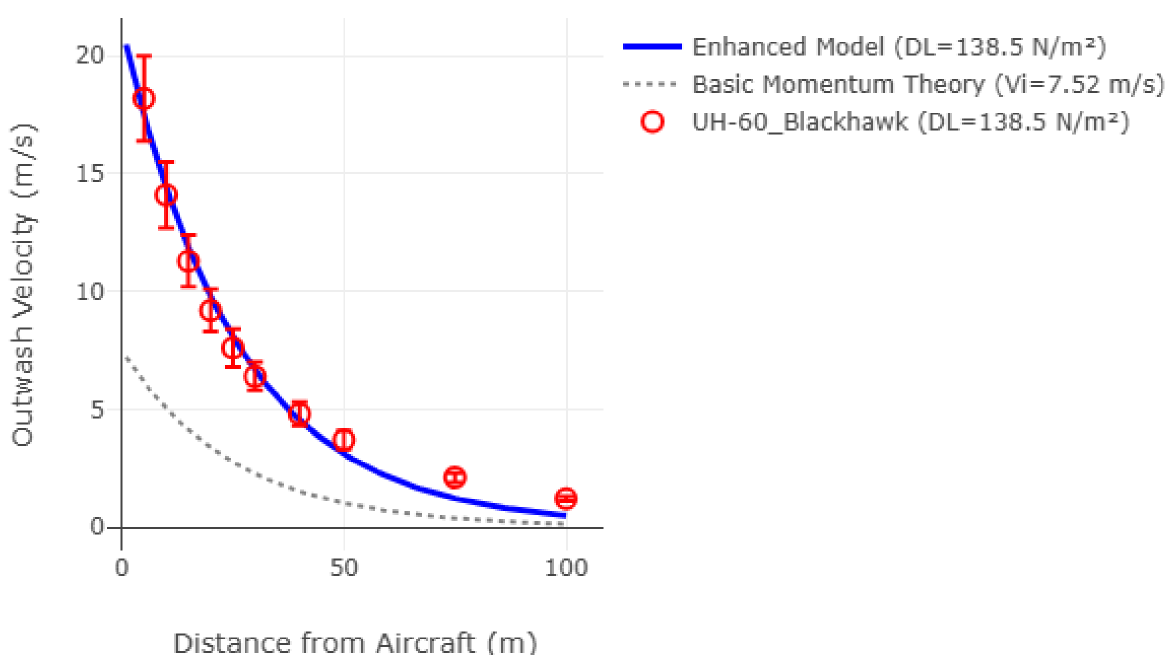
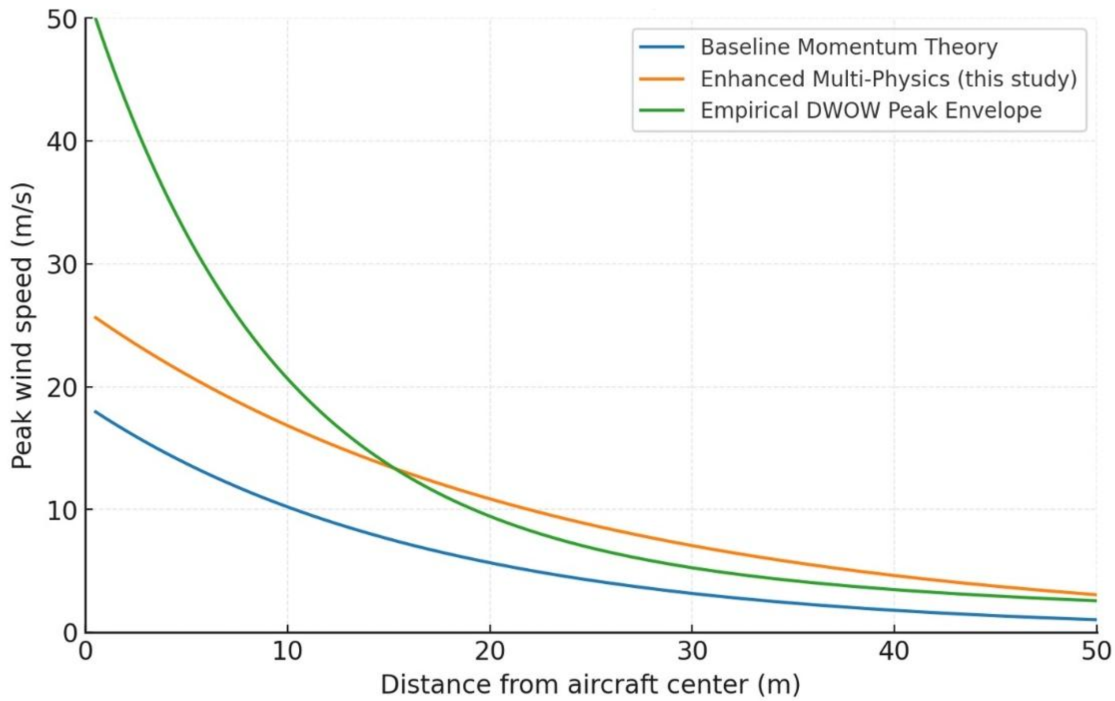


Figure 7

Comparative Model Performance Analysis



These results align with and extend prior research emphasizing enhanced wake effects from high-disc-loading aircraft (U.S. Army Research Laboratory, 2014). The documented V-22 Osprey precedents, where hazard radii extended 200–300 feet during hover operations, provide important context for understanding eVTOL wake intensity (Guner et al., 2019). However, the current study's findings suggest that while eVTOL aircraft produce more intense wake effects than conventional helicopters, the actual hazard zones are more geographically constrained than the most conservative theoretical estimates had predicted (Ison, 2024).

The confirmation that medium eVTOL aircraft (1,000–2,500 kg) exhibited the highest geometric amplification factors (k^c = 2.0–3.2) supports theoretical predictions about compact multi-rotor configurations creating intensive wake interactions, with significant implications for vertiport operations as this weight category encompasses many commercially viable eVTOL designs under development (Perry et al., 2018; Wang et al., 2024; Xu et al., 2024; Yokota & Fujimoto, 2022).

Model Validation, Limitations, and Operational Implications

While the enhanced model achieved strong overall performance metrics, the variable tolerance compliance across datasets warrants careful consideration for operational applications. The 40% compliance with ±1 m/s tolerance for Joby-type aircraft validation, compared to 100% compliance for Blackhawk validation, indicates that model accuracy varies substantially with aircraft configuration and operational conditions. This variability has important implications for safety-critical applications: predictions for novel eVTOL configurations, such as Joby-type aircraft, should incorporate larger safety margins to account for potential prediction errors exceeding 2 m/s in individual cases. The consistently high R^2 values (0.949–0.991) indicate that the model captures the fundamental relationships governing wake behavior, but the tolerance compliance results suggest that localized phenomena—potentially including rotor-rotor interaction effects, site-specific ground reflections, and atmospheric turbulence—introduce variability that the semi-empirical approach does not fully characterize.

The model's systematic underprediction bias (MPE ranging from -6.3% to -10.2%) provides an inherent conservative safety margin, meaning that actual wake velocities are typically slightly higher than predicted (Brown, 2023; Arya, 1999). While this bias is favorable for safety applications, it also indicates opportunities for model refinement to improve accuracy for operational planning purposes, where overly conservative predictions could unnecessarily constrain vertiport throughput or site selection. The treatment of ground effect, jet entrainment, and amplification factors in the modeling framework is mathematically tractable but may give an appearance of precision that exceeds the underlying empirical support. Environmental factors, including ambient wind conditions, atmospheric stability, and site-specific urban wind profiles, can significantly affect wake behavior but remain inadequately characterized in the current framework (Arya, 1999; Cimorelli et al., 2005). Users of this model should recognize that predictions represent expected values under controlled conditions rather than guaranteed bounds under all operational scenarios.

Three-Zone Safety Framework and Threshold Justification

The three-zone safety framework operationalizes measured and modeled eVTOL DWOW by classifying near-ground wind hazards at 1.5 m AGL (pedestrian head/chest height). The Buffer Zone threshold of 8 m/s (18 mph) represents the most conservative and protective approach, derived from the Lawson Comfort Criteria to accommodate children, elderly persons, and individuals with mobility disabilities (Ratcliff & Peterka, 1990). This threshold selection differs from the FAA's current 34 mph standard and merits explicit justification. Comparative analysis of pedestrian wind comfort standards across multiple jurisdictions reveals that the 18 mph threshold corresponds to conditions in which the general public begins to experience difficulty walking steadily and loose clothing flutters noticeably (National Oceanic and Atmospheric Administration, n.d.). For vulnerable populations—including young children with lower body mass, elderly individuals with reduced balance and stability, wheelchair users, and persons using mobility aids—instability can occur at substantially lower wind speeds. The Lawson criteria specifically identify 18 mph as the threshold below which outdoor environments remain comfortable for extended pedestrian use by diverse populations. The safety zone decision framework is outlined in Figure 8.

The selection of this more conservative threshold reflects a policy choice prioritizing inclusive safety at vertiport facilities serving diverse public populations. Regulatory cost-benefit analyses may reasonably conclude that different thresholds are appropriate for specific operational contexts—for example, industrial vertiports with controlled access could potentially employ higher thresholds—but the 18 mph buffer zone boundary provides a defensible baseline for public-facing urban vertiports where vulnerable populations cannot be excluded. The Caution

Zone boundary (8–15 m/s / 18–34 mph) and Hazard Zone threshold (≥15 m/s / ≥34 mph) align with established rotorwash hazard criteria and the FAA's current personnel safety standards, providing consistency with existing regulatory frameworks while extending protection through the Buffer Zone designation (Federal Aviation Administration, 2024; U.S. Army Research Laboratory, 2014). The recommended safety zone schema is shown in Figure 9.

Regulatory Alignment and International Harmonization

The evidence-based 150-foot minimum safety radius exceeds FAA Engineering Brief 105A standards (approximately 97.5 feet for typical eVTOL configurations), suggesting that existing overall safety area guidelines require expansion to accommodate empirically validated wake characteristics (Federal Aviation Administration, 2024). The internal structure of safety zones—distinguishing between the critical 50-foot Danger Zone and the intermediate 50–150-foot Caution Zone—provides operational flexibility that current binary exclusion zone approaches lack, enabling risk-based approaches that can adapt to varying aircraft configurations while maintaining consistent safety principles (Civil Aviation Authority, 2024).

These findings have direct implications for FAA rulemaking processes currently developing certification standards for eVTOL operations. The validated three-zone framework could inform updates to Engineering Brief 105A and subsequent Advisory Circulars governing vertiport design, providing empirically grounded criteria for safety area determination that account for aircraft-specific wake characteristics rather than generic helicopter-based extrapolations.

International aviation authorities employing standards that result in approximately 68-foot safety areas should consider expanding to align with empirically validated criteria (Australian Civil Aviation Safety Authority, 2024; Civil Aviation Safety Authority, 2024; European Union Aviation Safety Agency, 2022). The framework's structure—with clearly defined thresholds and configuration-specific amplification factors—supports international harmonization efforts by providing a common technical foundation that different jurisdictions could adapt to local regulatory requirements while maintaining equivalent safety levels.

Integration of these findings into ICAO standards for vertiport design would require coordination through the appropriate technical panels, but the empirical validation approach and transparent methodology provide the technical foundation for such international standardization efforts. The distinction between the validation scope (specific tested configurations) and the potential application scope (broader eVTOL categories) should be clearly communicated in any regulatory adoption to ensure the appropriate use of the findings.

Figure 8

Safety Zone Decision Framework

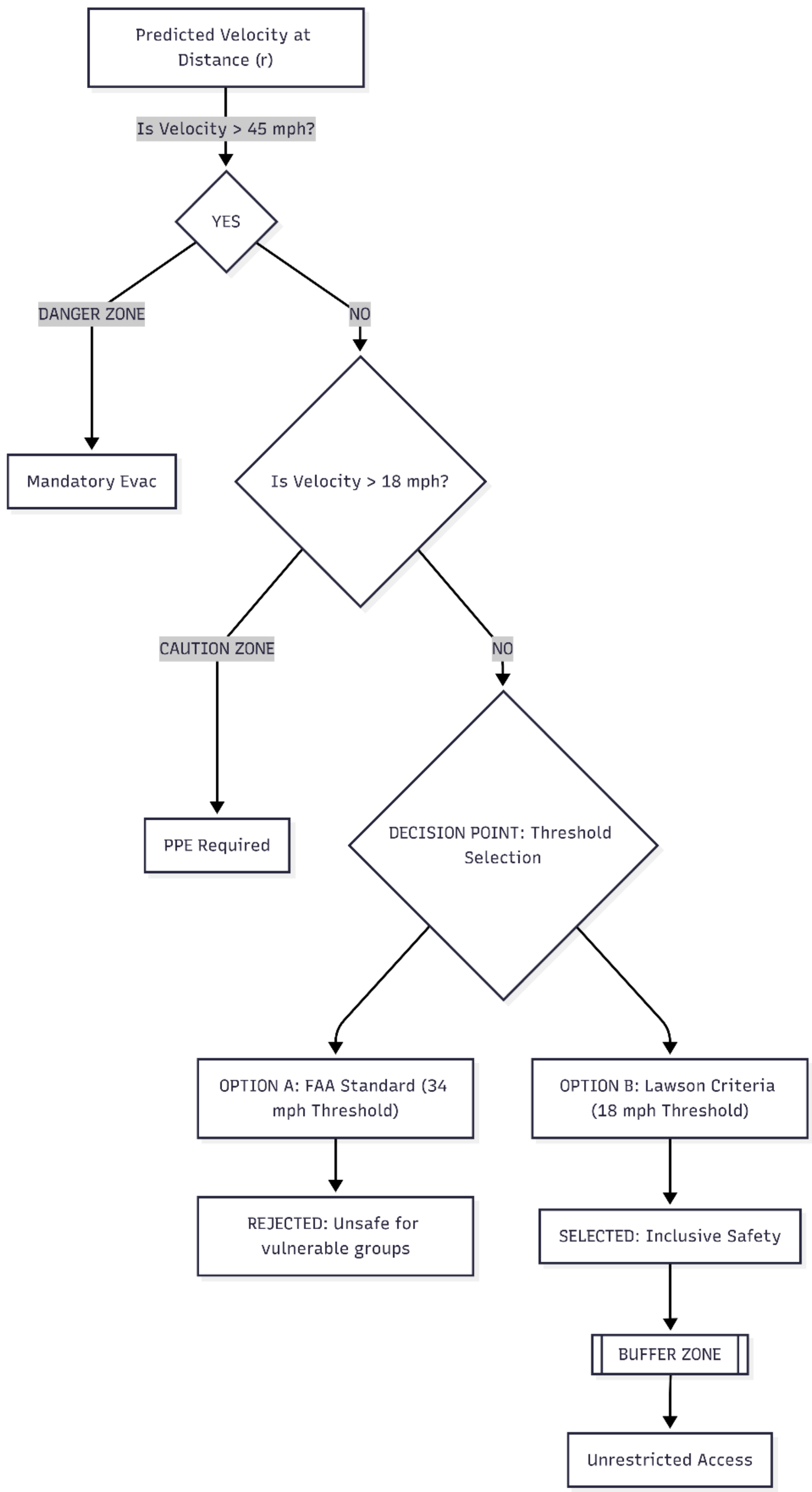
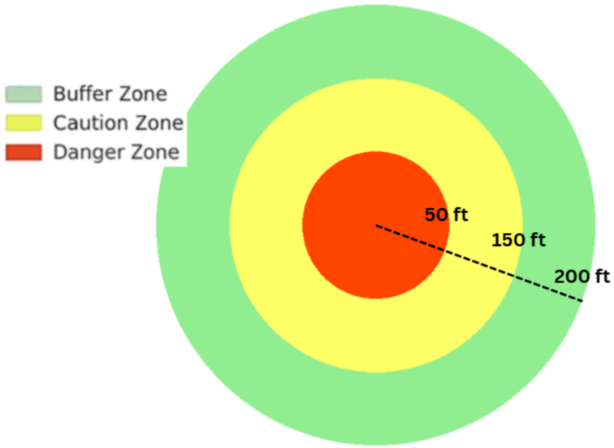


Figure 9

Recommended Vertiport Safety Zones



Urban Integration and Mitigation Technologies

The 150-foot minimum safety radius creates more manageable constraints for urban vertiport deployment than earlier conservative estimates of 250–500 feet (Ison, 2024). Successful urban integration requires careful consideration of site selection, building placement, and operational procedures to accommodate the three-zone safety framework, with rooftop vertiport installations ensuring building edges remain outside the Buffer Zone boundary and ground-level installations requiring coordination with pedestrian areas, roadways, and adjacent structures (Brunelli et al., 2023; European Union Aviation Safety Agency, 2022; Mendonca et al., 2022). The evidence-based safety zones provide a baseline for conventional operations, but active flow-control systems and advanced barrier technologies offer opportunities to reduce the required safety zone dimensions while maintaining equivalent protection levels (Wang et al., 2021; Zhang et al., 2019). Real-time wind monitoring and adaptive operational protocols could enable dynamic safety zone management based on actual atmospheric conditions rather than worst-case scenarios (Petersen et al., 2004).

Conclusion

This study provides a comprehensive empirical evaluation of eVTOL DWOW effects, establishing critical safety implications for vertiport design and urban air mobility integration. The findings demonstrate that traditional helicopter-based wake models systematically underestimate real-world eVTOL-induced wind speeds by factors of 2 to 4, necessitating the development of enhanced predictive approaches tailored explicitly to multi-rotor aircraft configurations.

Key Research Findings

The enhanced wake model, incorporating multi-rotor amplification effects, disc loading scaling factors, vortex amplification coefficients, ground effects, and localized jet contributions, achieved strong predictive accuracy with MAEs ranging from 0.498 to 1.568 m/s across multiple validation datasets and R^2 values of 0.949 to 0.991. The model represents a 40.8% improvement in prediction accuracy compared to baseline momentum theory approaches. However, engineering tolerance compliance varied substantially across datasets (40% to 100% within ±1 m/s), indicating that model accuracy depends significantly on aircraft configuration and that safety-critical applications should incorporate appropriate margins for configurations with lower compliance rates.

Configuration-specific analysis revealed that medium eVTOL aircraft (1,000–2,500 kg) exhibited the highest geometric amplification factors (k^c = 2.0–3.2), creating the most challenging wake characteristics for vertiport operations. This finding has significant implications for safety protocol development, as the weight category encompasses the majority of commercially viable eVTOL designs currently under development. The distributed wake patterns observed in large eVTOL configurations suggest that, while these aircraft generate substantial total wake energy, their safety zones are more manageable for urban integration than the concentrated, high-intensity wakes of medium-category aircraft.

Evidence-Based Safety Zone Recommendations

Based on established rotorwash hazard criteria and validated model predictions, this study recommends a three-zone safety framework for vertiport operations. The Danger Zone (0–50 feet) requires complete evacuation during operations because wind speeds consistently exceed 44.7 mph. The Caution Zone (50–150 feet) permits controlled access with protective measures for winds between 18–44.7 mph. The Buffer Zone (150–200 feet) imposes minimal operational restrictions when winds are below 18 mph. The 18 mph Buffer Zone threshold represents a conservative approach, based on the Lawson Comfort Criteria, to accommodate vulnerable populations; adopting the FAA's 34 mph threshold would result in smaller Buffer Zones with reduced protection for children, the elderly, and individuals with mobility disabilities.
The evidence-based 150-foot minimum Buffer Zone boundary provides a scientifically validated foundation for vertiport integration that exceeds current FAA Engineering Brief 105A standards while remaining more practical than earlier theoretical estimates of 250–500 feet. These recommendations align with the current FAA safety philosophy and provide greater specificity for the internal safety zone structure, which could inform future rulemaking. International aviation authorities should consider adopting similar empirical validation approaches to ensure safety standards reflect actual aircraft performance across the evolving eVTOL design space.

Limitations and Future Research

The study's reliance on the FAA DWOW dataset for both model development and validation means that the validation represents internal consistency verification rather than fully independent external validation. Model performance on truly novel aircraft configurations outside the scope of the FAA survey should be interpreted with caution until additional independent validation data becomes available. The model's treatment of environmental variability, aircraft heterogeneity, and site-specific urban wind profiles remains limited, and predictions represent expected values under controlled conditions rather than guaranteed bounds under all operational scenarios.

Future investigations should prioritize multi-aircraft wake interactions, which could introduce additional turbulence complexities during simultaneous eVTOL operations. The integration of real-time atmospheric monitoring with adaptive safety zone management offers opportunities for improving operational efficiency while maintaining equivalent safety levels. Long-term field validation studies under diverse operational conditions—including adverse weather, emergency scenarios, and high-frequency operations—would further refine these recommendations and build additional confidence in the regulatory framework.

Final Recommendations

Aviation authorities should consider adopting the three-zone structure to enable flexible, risk-based operational approaches that can adapt to varying aircraft configurations and environmental conditions while maintaining consistent safety principles. The framework provides a scientific foundation for FAA rulemaking, international harmonization through ICAO technical standards, and the development of certification pathways for eVTOL operations. As urban air mobility continues to evolve, these empirically validated guidelines will be crucial for developing robust vertiport safety standards that support safe AAM integration into the national airspace system while accommodating the operational requirements of this emerging transportation mode.

References

Arya, S. P. (1999). *Air pollution, meteorology and dispersion*. Oxford University Press.

Australian Transport Safety Bureau. (2023). *Rotorcraft operations and wake effects: Safety implications for urban aviation*. ATSB Transport Safety Report.

Australian Civil Aviation Safety Authority. (2024). *Guide to vertiport design*. Australian Government Department of Infrastructure, Transport, Regional Development, Communications and the Arts. https://www.casa.gov.au/sites/default/files/2024-05/guide-to-vertiport-design.pdf

Brown, R. E. (2023). Understanding the downwash/outwash characteristics of eVTOL aircraft. *UK Civil Aviation Authority Publication CAP 2576*. Civil Aviation Authority.

Brunelli, M., Ditta, C. C., & Postorino, M. N. (2023). New infrastructures for Urban Air Mobility systems: A systematic review on vertiport location and capacity. *Journal of Air Transport Management*, *112*, Article 102460. https://doi.org/10.1016/j.jairtraman.2023.102460

Caprace, D., & Ning, A. (2023). Large eddy simulation for empirical modeling of the wake of three urban air mobility vehicles. *Journal of the American Helicopter Society*, *68*(4), Article 042002. https://doi.org/10.4050/jahs.68.042002

Civil Aviation Authority. (2024). *Consultation response document: Vertiport design proposal for existing aerodromes* (CAP Publication 2285). Civil Aviation Authority. https://consultations.caa.co.uk/air-traffic-management/vertiport-design-proposal-for-existing-aerodrome/results/caacrdvertiportdesignproposalforexistingaerodromes.pdf

Cimorelli, A. J., Perry, S. G., Venkatram, A., Weil, J. C., Paine, R. J., Wilson, R. B., & Brode, R. W. (2005). AERMOD: A dispersion model for industrial source applications. Part I: General model formulation and boundary layer characterization. *Journal of Applied Meteorology*, *44*(5), 682-693. https://doi.org/10.1175/JAM2227.1

European Union Aviation Safety Agency. (2022). *Vertiports: Prototype technical specifications for the design of VFR vertiports for operation with manned VTOL-capable aircraft certified in the Enhanced Category* (EASA Technical Report). EASA Flight Standards Directorate. https://www.easa.europa.eu/en/document-library/general-publications/prototype-technical-design-specifications-vertiports

Federal Aviation Administration. (2022). *Urban Air Mobility (UAM) concept of operations v2.0* (Technical Report). U.S. Department of Transportation. https://www.faa.gov/sites/faa.gov/files/2022-03/UAM_ConOps_v2.pdf

Federal Aviation Administration. (2024). *Engineering Brief No. 105A: Vertiport design, supplemental guidance to Advisory Circular 150/5390-2D, Heliport Design*. U.S. Department of Transportation. https://www.faa.gov/airports/engineering/engineering_briefs/eb_105a_vertiports

García-Gutiérrez, A., Gonzalo, J., López, D., & Delgado, A. (2022). Advances in CFD modeling of urban wind applied to aerial mobility. *Fluids*, *7*(7), 246.

Guner, F., Prasad, J., He, C., Miller, D., & Co., B. (2019). Tandem rotor inflow modeling and its effect on vehicle dynamics. *Proceedings of the Vertical Flight Society 75th Annual Forum*. https://doi.org/10.4050/f-0075-2019-14635

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. https://doi.org/10.58940/2329-258X.1973

Keller, J., McKillip, R., Wachspress, D., Tischler, M., & Juhasz, O. (2019). Linearized inflow and interference models from high fidelity free wake analysis for modern rotorcraft configurations. *Proceedings of the Vertical Flight Society 76th Annual Forum*. https://doi.org/10.4050/f-0076-2020-16290

Mendonca, N., Murphy, J., Patterson, M. D., Alexander, R., Juarez, G., & Harper, C. (2022). Advanced air mobility vertiport considerations: A list and overview. *AIAA AVIATION 2022 Forum*, AIAA 2022-4073. https://doi.org/10.2514/6.2022-4073

Muia, M. J., Stanley, J., Anderson, T., Hall, D., Shuman, Z., Goericke, J., Barmore, B., Chen, S., Viken, S., & Saberi, H. (2024). *Electric vertical takeoff and landing (eVTOL) downwash and outwash surveys* (Technical Report DOT/FAA/TC-24/42). United States Department of Transportation, Federal Aviation Administration, William J. Hughes Technical Center.

Mueller, E. R., Kopardekar, P., & Goodrich, K. H. (2017). Enabling airspace integration for high-density on-demand mobility operations. *17th AIAA Aviation Technology, Integration, and Operations Conference*, AIAA 2017-3086. https://doi.org/10.2514/6.2017-3086

National Oceanic and Atmospheric Administration. (n.d.). *Beaufort Wind Scale*. National Weather Service. https://www.weather.gov/mfl/beaufort

Occupational Safety and Health Administration. (2020). *1926.968 - Definitions*. U.S. Department of Labor. https://www.osha.gov/laws-regs/regulations/standardnumber/1926/1926.968

Perry, A. T., Ansell, P. J., & Kerho, M. F. (2018). Aero-propulsive and propulsor cross-coupling effects on a distributed propulsion system. *Journal of Aircraft*, *55*(6), 2414-2426. https://doi.org/10.2514/1.C034861

Petersen, R. L., Carter, J. J., & Baer, M. (2004). PRIME: Improved building downwash algorithms for the Industrial Source Complex Model. *Journal of Applied Meteorology*, *43*(10), 1484-1495. https://doi.org/10.1175/JAM2140.1

Piccinini, R., Tugnoli, M., & Zanotti, A. (2020). Numerical investigation of the rotor-rotor aerodynamic interaction for eVTOL aircraft configurations. *Energies*, *13*(22), Article 5995. https://doi.org/10.3390/en13225995

Ratcliff, M. A., & Peterka, J. A. (1990). Comparison of pedestrian wind acceptability criteria. *Journal of Wind Engineering and Industrial Aerodynamics*, *36*, 791-800. https://doi.org/10.1016/0167-6105(90)90076-O

Schichardt, B. I., Geister, D., Lüken, T., Knabe, F., Metz, I. C., Peinecke, N., & Schweiger, K. (2023). Air traffic management as a vital part of urban air mobility—A review of DLR's research work from 1995 to 2022. *Aerospace*, *10*(1), Article 81. https://doi.org/10.3390/aerospace10010081

Schulman, L. L., Strimaitis, D. G., & Scire, J. S. (2000). Development and evaluation of the PRIME plume rise and building downwash model. *Atmospheric Environment*, *34*(26), 4915-4922. https://doi.org/10.1016/S1352-2310(00)00281-6

U.S. Army Research Laboratory. (2014). *Rotorwash operational footprint modeling* (Technical Report ARL-TR-6938). Aberdeen Proving Ground, MD: U.S. Army Research Laboratory.

Wadcock, A. J., Yamauchi, G. K., & Norman, T. R. (2008). Measurement of wake turbulence generated by rotorcraft in urban operations. *Journal of the American Helicopter Society*, *53*(4), 378-390. https://doi.org/10.4050/JAHS.53.378

Wang, L., Hou, Q., Wang, J., Wang, Z., & Wang, S. (2021). Influence of the inner tilt angle on downwash airflow field of multi-rotor UAV based on wireless wind speed acquisition system. *International Journal of Agricultural and Biological Engineering*, *14*(6), 98-105. https://doi.org/10.25165/j.ijabe.20211406.6477

Wang, J., Zhang, X., Lu, J., & Tang, Z. (2024). Numerical simulation and experimental study on the aerodynamics of propulsive wing for a novel electric vertical takeoff and landing aircraft. *Aerospace*, *11*(6), Article 431. https://doi.org/10.3390/aerospace11060431

Xu, J., Yu, J., Lu, X., Long, Z., Xu, Y., & Sun, H. (2024). Aerodynamic performance and numerical analysis of the coaxial contra-rotating propeller lift system in eVTOL vehicles. *Mathematics*, *12*(7), Article 1056. https://doi.org/10.3390/math12071056

Yeo, H., & Romander, E. A. (2011). Rotor structural loads analysis using coupled computational fluid dynamics/computational structural dynamics. *Journal of Aircraft*, *48*(3), 846-858. https://doi.org/10.2514/1.C031096

Yokota, K., & Fujimoto, H. (2022). Aerodynamic force control for tilt-wing eVTOL using airflow vector estimation. *IEEE Transactions on Transportation Electrification*, *8*(3), 4163-4172. https://doi.org/10.1109/TTE.2022.3162946

Zhang, H., Lan, Y., Shen, N., Wu, J., Wang, T., Han, J., & Wen, S. (2020). Numerical analysis of downwash flow field from quad-rotor unmanned aerial vehicles. *International Journal of Precision Agricultural Aviation*, *3*(4), 12-18. https://doi.org/10.33440/ijpaa03040002

Zhang, T., Elsakka, M., Huang, W., Wang, Z., Ingham, D., Ma, L., & Pourkashanian, M. (2019). Winglet design for vertical axis wind turbines based on a design of experiment and CFD approach. *Energy Conversion and Management*, *195*, 712-726. https://doi.org/10.1016/j.enconman.2019.05.055