An In-time Aviation Safety Management System (IASMS) Concept of Operations for Vertiport Design and Operations

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The National Airspace System is foreseen to undergo revolutionary change with Urban Air Mobility (UAM) and its use of vertiports to transport passengers and cargo. To assure safety with UAM and more broadly with Advanced Air Mobility (AAM), the National Academies recommended an In-time Aviation Safety Management System (IASMS) that is extensible to the design and operation of vertiports. Vertiport designs will scale in several dimensions including physical size and infrastructure depending upon location and in the Services, Functions, and Capabilities required for assuring safety with increasingly complex vertiport designs and operations. These operations will be enabled by evolving technologies including electric vertical takeoff and landing (eVTOL) aircraft for passenger- and cargo-carrying commercial transportation. Within this construct, safety hazards and risk mitigations involving predictive data analytics and modeling will be used. Use cases and future challenges are examined to guide maturation of the IASMS ConOps for vertiports.

I. Introduction

The integration of Advanced Air Mobility (AAM) foreseen with the National Airspace System (NAS) includes new infrastructure involving today's airports and heliports as well as dedicated vertiports tailored for use by electric vertical takeoff and landing (eVTOL) aircraft. These eVTOLs include Uncrewed Aircraft Systems (UAS) as well as piloted and remotely piloted vehicles used by commercial operators carrying passengers and cargo operating as part of Urban Air Mobility (UAM) and UAM Traffic Management (UTM).

A vertiport has been defined as "an identifiable ground or elevated area, including any buildings, or facilities thereon, used for the vertical takeoff and landing of an aircraft" [1]. A vertiport serves as a terminal for eVTOLs transporting passengers and cargo. Within this vertiport construct, UAM will be enabled by extensive usage of autonomous systems both onboard the vehicle and on the ground at the vertiport and other takeoff and landing locations. The role of vertiports in increasingly complex operations requires highly sophisticated capabilities for airspace and surface traffic management [2].

Overall, the design and operation of vertiports will require a new approach for Safety Management Systems (SMS), an In-time Aviation Safety Management System (IASMS), that provides faster and tailored in-time safety management based on the National Academies IASMS Committee's recommendation for a safe and secure future NAS [3]. This paper describes the IASMS aligned for vertiport design and operations integrating reactive, proactive, and predictive safety methods and data to advance cohesive development of safety models and mindful application of safety intelligence. NASA previously developed an IASMS ConOps for in-time safety management that includes Part 121 commercial air carriers having the authority to operate scheduled service such as large airlines, regional air carriers, and cargo operators and have no limits on the size and type of aircraft operated; Part 135 passenger and cargo transportation that are limited in the number of passenger seats and amount of cargo permitted to be carried and includes all rotorcraft; and Part 450 space launch and reentry [4, 5, 6].

The paper is organized into several major sections. First, the future vision of the NAS is described including the design and operation of vertiports. This is followed by a description of SMS and its different components. The IASMS Concept of Operations (ConOps) is then explained with its different elements.

II. Future Visions

Future visions of the NAS foresee increasing demands for AAM to satisfy needs for operational missions involving local air mobility (LAM), regional air mobility (RAM), and UAM. These missions are enabled by new aircraft, airspace designs, and an innovative approach to integrated safety management that can scale with the expanding complexities of AAM. The design and operation of vertiports as part of UAM represents one of the most demanding challenges contextualizing the need for IASMS and helps frame its implementation for LAM, RAM, and other future possibilities.

The FAA UAS Traffic Management (UTM) ConOps 2.0 addresses UAS operations and refers to take-off and landing areas including alternate landing due to an urgent UAS condition. UTM UAS operations occur at or below 400 feet Above Ground Level [7].

The vision of the Federal Aviation Administration (FAA) for 2035 foresees an information-centric NAS (ICN) with performance-based technologies that dynamically scale for increasingly complex operations and airspace [8, 9]. The ICN concept uses both vertiport and aerodrome terms. The FAA definition of Airport in 14 CFR § 1.1 means an area of land or water that is used or intended to be used for the landing and takeoff of aircraft, and includes its buildings and facilities, if any. The European Aviation Safety Agency (EASA) defines an aerodrome as "a defined area (including any buildings, installations, and equipment) on land or water or on a fixed offshore or floating structure intended to be used either wholly or in part for the arrival, departure, and surface movement of aircraft" [10].

The ICN ConOps describes a vision for change in the NAS involving three key areas consisting of operations, supporting infrastructure, and integrated safety management. Operations will change with diverse traffic management services, enabling the increased variety and number of new vehicles, missions, and operations with a fully integrated architecture for interoperable sharing of information. Infrastructure includes broader changes beyond vertiports to include ubiquitous traffic management services that are resilient to unanticipated change involving machine learning and artificial intelligence techniques to enable the workforce to be more adaptable and flexible in off-nominal conditions. Integrated safety management involves change in tailored safety standards, flight rules, interoperable services, and in-time safety assurance.

Integrated safety management in the ICN identifies several intersections with SMS including the following considerations:

1) The use of quantitative elements for a data-driven SMS so each operator, air traffic service (ATS), and extensible traffic management (xTM) service supplier accounts for interoperability across a variety of interactions such as public versus private services, air versus ground systems, and automated versus manual control functions, all supporting increased diversity of operations.
2) Each major operator and service supplier will detail their role and how they integrate, adapt, and manage their operations to enable the collective xTM air operations to work as designed.
3) Each service supplier will address interoperability within their SMS to ensure safe interoperability with its operators and other service suppliers that includes any changes to their services and products.
4) Operators will complete required SMS analysis to assure their operations safely integrate with and adapt to changes in the operational environment of diverse vehicles, their characteristics (e.g., autonomy, performance), and missions for verifying compliance.

FAA oversight of SMS facilitates a shared understanding of the operational environment, potential risks, and effects on stakeholders. Stakeholders shown in the ICN ConOps include vertiport operators, aircraft/new entrant manufacturers, equipment providers, airport operators, and standards bodies. Evolving needs for physical infrastructure include vertiports, heliports, remote sites, and airport infrastructure in association with safety of the airspace and persons and property on the ground. New traffic management services will address operations for new entrants including access criteria for aerodromes and airspace as shared resources.

The FAA ConOps for Urban Air Mobility (UAM) poses that a UAM aerodrome meets the capability requirements to support UAM departure and arrival operations [11]. The aerodrome provides current and forecast resource availability information for UAM operations including opening/closing times and pad availability. This information is used by operators for planning flight operational intent and strategic deconfliction by Providers of Services for UAS (PSU). Aerodromes do not provide strategic deconfliction or demand capacity balancing (DCB) services. DCB can occur when the UAM corridors or aerodromes cannot support the collective Operational Intent demand, e.g., traffic congestion at an aerodrome. Aerodrome availability is accessible through the PSU or Supplemental Data Service Provider (SDSP) networks. UAM aircraft will operate between UAM aerodromes within UAM corridors. These corridors involve performance-based airspace of defined dimensions with rules, procedures, and performance requirements. UAM corridor structure and intersections would scale to enable increasing operational tempo by optimizing paths between an increasing number of aerodromes. The departure and destination aerodromes would be part of UAM flight Operational Intent. Strategic separation is based on conflict-free Operational Intent. Tactical separation within corridors is allocated to UAM operators, pilot-in-command (PIC), and Providers of Services for UAM (PSU). The UAM operator obtains current conditions as services from the PSU and Supplemental Data Service Provider (SDSP) such as aerodrome availability to determine the desired UAM Operational Intent information such as aerodrome location, corridor route, and desired departure and arrival times. The PSU analyzes and confirms a UAM operator's Operational Intent for aerodrome resource availability, consistency with current advisories and restrictions, strategically deconflicted with already established flight intent of other UAM operators, and adverse environmental conditions. SDSPs also provide supporting data on aerodrome availability and specialized weather.

The NASA Sky for All vision (circa 2050) implements increasingly dynamic automated systems involving more diverse and complex vehicles, operations, performance, missions, and vehicle systems; increased density and volume of operations; and highly integrated heterogenous collaborative and more autonomous airspace [12]. In some sense the intent is to leverage current NAS capabilities and infrastructure; however, many are not sufficient in their current design to scale for the greater tempo and complexity of operations in the future envisioned NAS.

III. Vertiport Design Concepts

A conceptualization of a Vertiport Automation System from the High-Density Automated Vertiport (HDV) ConOps is shown in Figure 1 that includes surface features, infrastructure, and airspace operations [2]. A High Density Vertiport is considered to be a vertiport that supports an increasing number of aircraft movements at or near vertiport capacity. That is, high density refers to the average number of aircraft movements needed at a vertiport to support UAM Maturity Level 4 operations.

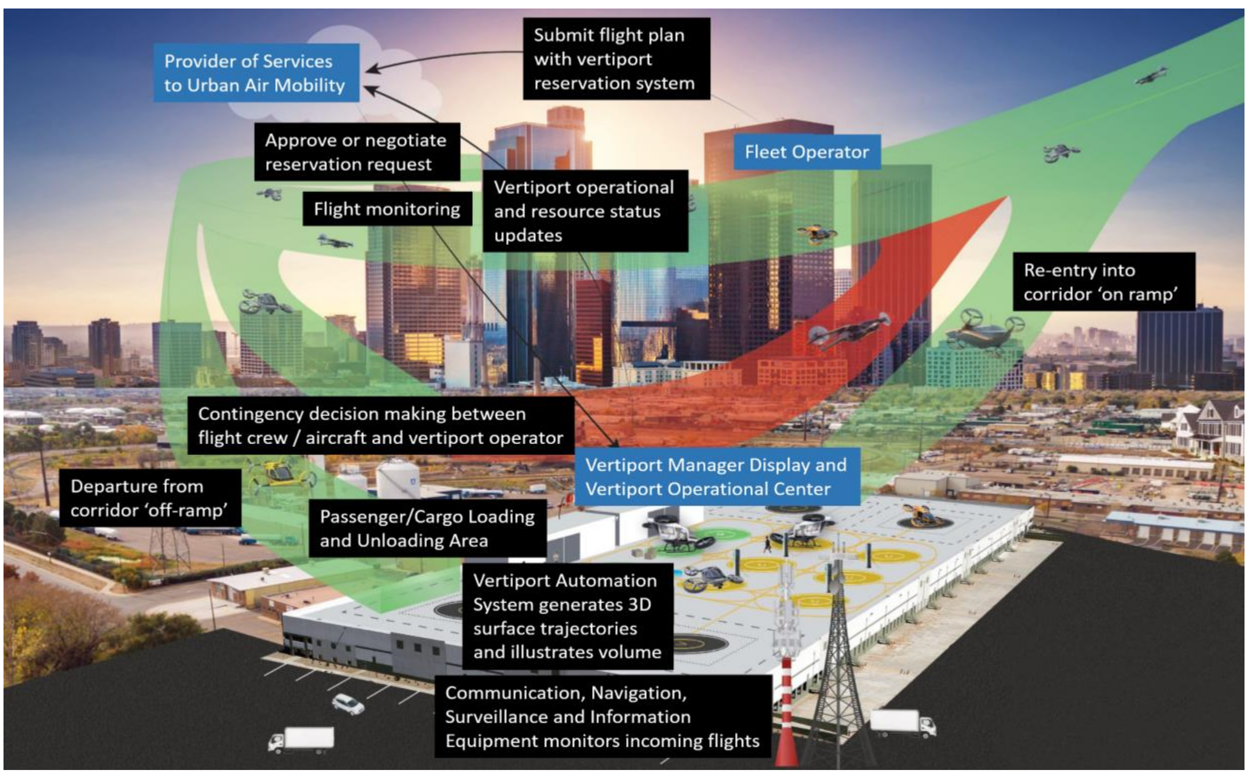


Fig. 1 Vertiport Automation System OV-1 Conceptual Diagram [adapted from 2].

Vertiport is a general term with designs scaling in size and complexity. It includes vertihub (e.g., co-located at an existing airport), vertiport (e.g., situated in an urban setting such as atop a parking garage or tall building), and vertistop (e.g., neighborhood or residential pad). A vertiplex involves multiple vertiports in a local region with interdependent arrival and departure operations.

Design of vertiports includes associated airspace involving the outer airspace Vertiport Operations Area (VOA) for high-density flight operations around vertiports and the inner airspace Vertiport Volume (VPV) surrounding the vertiport's geographic location with this terminal airspace managed by the vertiport manager, as shown in Figure 2 [2].

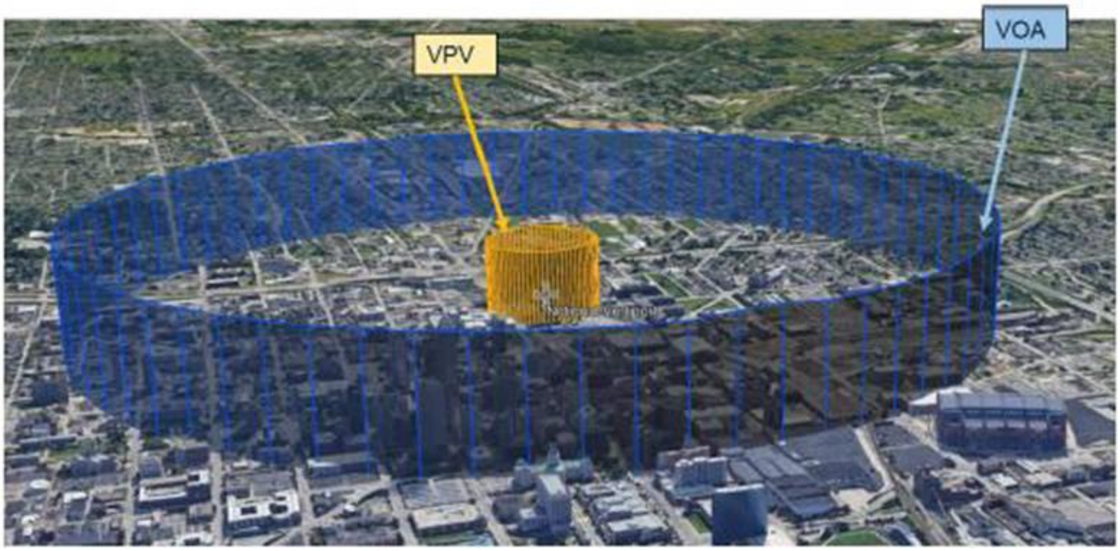


Fig. 2 Notional Representation of VOA and VPV Airspace [2].

Vertiports may be located in different operational environments involving different classes of airspace. The FAA depicted these based on different classes of airspace shown in Figure 3 along with corridors and different vehicles [11].

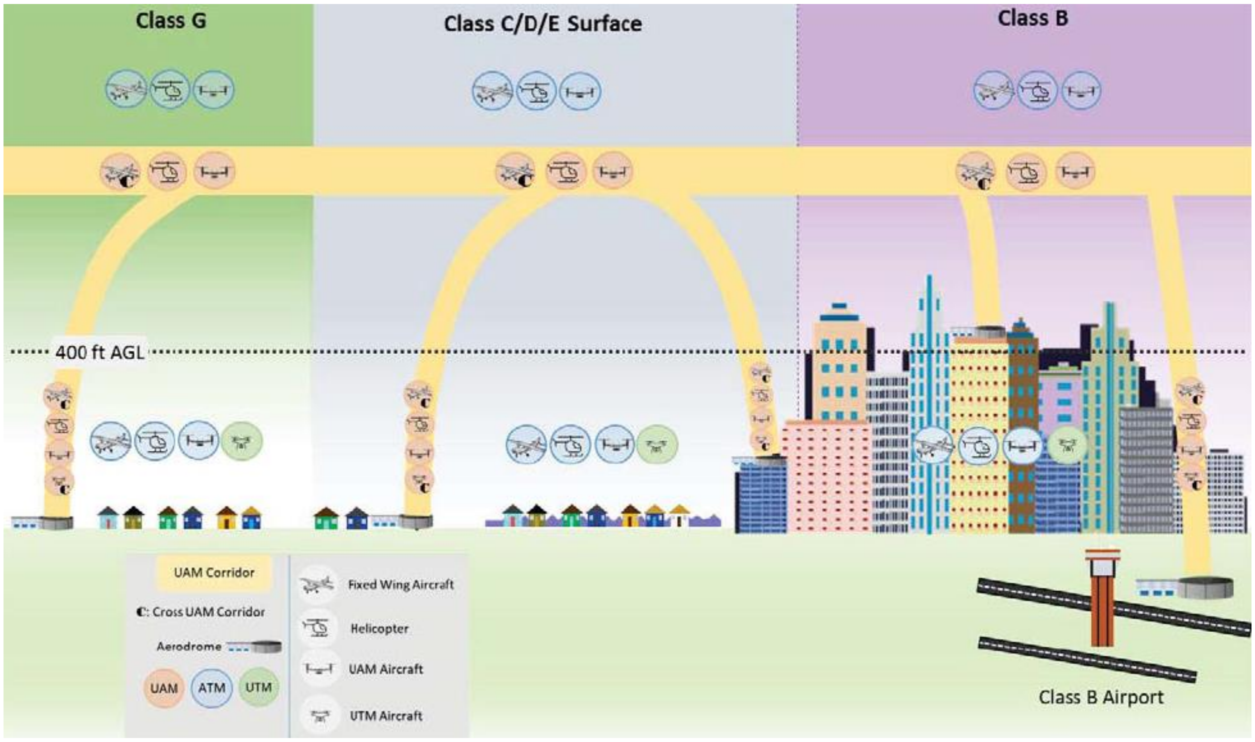


Fig. 3 FAA UAM, ATM, and UTM Operating Environments [11].

UAM and emerging use cases involving passenger air mobility, air cargo, and emergency services were reviewed by the National Academies UAM Airport Committee [13]. Guidance was developed for airport practitioners to understand how and where they may fit in this environment, the challenges UAM may have on current operations, the growth opportunities that AAM may present, and tools to assist with planning its use as part of safely integrating UAS into the NAS. It was assumed that Air Metro would operate first averaging three riders followed by Air Taxi with one rider. Air Taxi would necessitate a higher density of vertiport infrastructure based on a vision of ubiquitous door-to-door service. Commuter/regional flights provide inter-city connections such as between smaller communities. Vertiports may initially build on existing infrastructure such as atop parking garages or open land near highway interchanges. The National Academies UAM Airport Committee developed three use cases drawing from available market literature, as summarized in Table 1. The use cases demonstrate the potential variability in some of the vertiport services, infrastructure requirements, and operational assumptions. These use cases help to identify possible hazards and risks in the design and operation of vertiports.

Table 1. National Academies Use Cases [13].

	Passenger Transport	**Air Cargo Delivery**	**Emergency Services**
Route Network	- Air Taxi on-demand - Air Metro regular schedule/routes - Commuter/Regional Flights inter-city	UTM operations. Rural delivery may have earlier growth opportunity. Last mile deliveries are unscheduled.	Each flight has dispatch, transport, and return phases. Return time includes charging time. UTM operations.
Vehicles	Up to 4 passengers. Evolves from pilot on-board to RPIC and then autonomous.	RPIC or autonomous	Single patient, pilot, multiple medical staff, medical equipment. Evolves from pilot on-board to RPIC and then autonomous.
Vertiport Infrastructure	Sizes: Small (1 landing pad), Medium (4), or Large (12) with passenger terminal. Fast charging stations or hydrogen fueling facilities.	Located at distribution hubs. 13 cargo pads, each able to process up to 10 deliveries per hour. Neighborhood receptacles for receiving and securing delivered parcels. Large aircraft for freight containers or bulk goods	Dedicated direct access between landside and tarmac.
Operational Assumptions	11 trips per day, each 64 minutes (includes passenger loading/unloading and battery charging time of 20 minutes).	10 trips per day, each up to 30 minutes. Battery charging time averages 60 minutes.	Average mission time 130 minutes. Recharging time between 20 minutes (battery swap) and 120 minutes.

Currently, heliports are seen as the most analogous current-state model for vertiports of the future [2]. FAA AC 150/5390-2, Heliport Design, pertains to helicopters having single, tandem (front and rear) or dual (side by side) rotors [14]. Emerging eVTOL aircraft may have similarities in performance with conventional helicopters or very large tiltrotor aircraft.

The FAA Engineering Brief No. 105, Vertiport Design, provides interim guidance for the design of vertiports involving vertical takeoff and landing (VTOL) capabilities [15]. The guidance is intended for VTOLs that have ability to hover out of ground effect (HOGE) and so require smaller sizing of Final Approach and Takeoff (FATO) airspace compared to the Transport Category heliport criteria. HOGE refers to achieving hover without the benefit of the ground or a surface. The vertiport touchdown and liftoff (TLOF) pads are sized as the Controlling Dimension defined as the diameter of the smallest circle enclosing the VTOL aircraft projection on a horizontal plane, while the aircraft is in the takeoff or landing configuration, with rotors/propellers turning, if applicable. The FATO is twice the size of the TLOF, and a Safety Area that reduces risk of damage to aircraft accidentally diverging from the FATO is three times the size.

Other vertiport engineering design considerations include Visual Flight Rules (VFR) approach/departure guidance, guidance on marking, lighting, and visual aids, charging and electric infrastructure, on-airport locations for TLOF and FATO, and site safety elements such as security, turbulence, and winter weather. Arrivals and departures transit the (FATO) airspace using vertiport touchdown and liftoff (TLOF) pads. A TLOF pad could serve as a parking spot, or UAM aircraft could move to and from TLOF pads and parking spots. This movement could be accomplished such as by hover taxi or use of a tug. The FAA Engineering Brief No. 105, Vertiport Design, indicates that research needs to assess VTOL taxiing and parking needs. For example, in the interim, the guidance is that vertiports designed for ground taxiing can follow AC 150/5300-13, Airport Design, using taxiway guidelines for Group 1 aircraft [16]. For hover taxi, vertiport design should follow taxiway guidance in AC 150/5390-2, Heliport Design, for the Transport Category [14]. For parking, vertiport design should follow guidance in AC 150/5390-2 for the Transport Category. EASA recommends a taxi -route width of 1.5 the overall width of the VTOL aircraft for ground taxi and 2.0 for air taxi [10]. Other hover guidance was published as a draft Advisory Circular by the Australian Civil Aviation Safety Authority for vertiport design indicating that hover will require wider taxiways than ground [17].

As shown in Figure 3, a vertiport may be located inside the surface area of a towered airport (e.g., Class B, C, or D) so that a letter of agreement (LOA) between FAA and the vertiport may be required addressing arrival, departure, and altitude request procedures. In other cases, a vertiport may be located outside of Class B, C, or D airspace and a route could provide operations to an airport in that airspace requiring a LOA. The LOA is different from the FAA's Low Altitude Authorization and Notification Capability (LAANC) system that air traffic controllers use to control UAS operating at or near airport airspace. The LAANC system allows UAS operators to receive airspace flight authorizations in real time while providing data about their flights to other airspace users [18]. LAANC will improve airport personnel situational awareness of nearby UAS operations and by possible extension improve vertiport manager situation awareness as well.

An analysis of AAM vertiport considerations was based on collected industry viewpoints regarding the planning for and deployment of vertiports in practice [19]. These considerations included safety, siting, design, regulations, environmental impact, social acceptance, equity, and operational integration. The most demanding safety case focused on vertiports servicing a passenger-carrying eVTOL aircraft flying within a metropolitan area. This focus did not include other vehicle types (e.g., small UAS) or different missions (e.g., Regional Air Mobility).

EASA published prototype technical specifications for VFR vertiports involving manned VTOL-capable aircraft certified in the enhanced category [10]. The enhanced category (similar to performance of helicopters) provides proportionality in safety objectives while maintaining the highest level of safety in protecting third parties when flying over congested areas and when conducting commercial air transport operations with passengers. VTOL-capable aircraft certified in the enhanced category must meet the requirements for continued safe flight and landing and be able to continue to the original intended destination or a suitable alternate vertiport after a failure. In contrast, VTOL-capable aircraft certified in the basic category must meet controlled-emergency landing requirements similar to controlled glide or autorotation. EASA technical specifications included specifying the safeguarding of vertiports as a process for vertiport operators and local authorities to protect the physical environment surrounding the vertiport from development that may affect operations. Ground and air taxi-routes provide safe simultaneous operations during maneuvering of VTOL-capable aircraft. Obstacles are fixed or mobile objects located on the surface where VTOL-capable aircraft may move as well as above the surface for flight, or outside those areas but assessed as a hazard to air navigation. Obstacles can be permanent or temporary. A helicopter visual approach path indicator system should be mounted and sited as low as possible to avoid being a hazard to aircraft. VTOL-capable aircraft equipped with lithium-ion batteries may not have the capability to extinguish an onboard fire and may need to land while venting the fire overboard. The FATO location should be minimally distant to an aerodrome runway or taxiway to mitigate risk of wake turbulence encounters. EASA referred to ICAO helicopter emergency response regarding the need for rescue and firefighting equipment and services.

IV. High Density Vertiport ConOps and Assumptions

The NASA High Density Vertiplex (HDV) Sub-project is developing and testing concepts, requirements, software architectures, and technologies needed for the terminal environment around vertiports providing safety, efficiency and scalability of flight operations and includes focusing on use cases that are specific for urban operations [1]. Future concepts include Advanced Onboard Automation (AOA) for development of reference automation architecture prototypes, integration guidelines, and safety risk assessments that support increasingly autonomous and resilient operations. Scalable Autonomous Operations (SAO) is developing and evaluating concepts, prototypes, procedures, and technologies supporting operations at increased scale from a vertiport.

The HDV ConOps vertiport system was developed to identify relevant requirements, considerations, barriers, and enabling technologies associated with UAM Maturity Level 4 (UML-4) [2]. The ConOps defined roles and responsibilities of vertiport users, operators, and connected stakeholders, defined functional requirements and system performance criteria, and identified technology, regulatory, and research needs for vertiport operations. The ConOps developed increasingly complex use cases spanning from utility inspections representing UML-1 to urban passenger air metro service for UML-4.

Key assumptions in the HDV ConOps included:

1) The PSU, or for the purposes of this paper the Vertiport Manager, controls the VPV airspace by coordinating timing, routing, and sequencing of aircraft in AAM Corridors.
2) Air traffic involves a mix of piloted, semi-automated, and fully automated aircraft.
3) Flight crews will be remote or onboard the aircraft.
4) AAM aircraft will follow 4D required navigation performance (RNP) trajectories, potentially as tailored flight rules (TaFR) [9].

The ConOps identified ten Vertiport Automation System (VAS) Services organized into four service roles. The Vertiport Resource Management and Scheduling Service would have core responsibility for operations including vertiport configurations, business rules, community and government requirements, and strategically aligning vertiport resources as requested. The Safety role was supported by four VAS services.

1) The Aircraft Conformance Monitor tracks aircraft conformance on the vertiport surface and within the surrounding airspace for compliance with scheduled arrival and departure operations.
2) The Hazard Identification Service could receive alerts about anomalies from the Aircraft Conformance Monitor or Software Monitoring Service as well as anomalies directly detected by vertiport infrastructure sensors, and then identify hazards from these anomalies and send identified hazards to the Risk Assessment Service.
3) The Risk Assessment Service supports the vertiport SMS program by automating parts of the Safety Risk Management (SRM) process by estimating pre-identified hazard risks.

A Safety Assurance program was posed for continuous monitoring of established risk mitigation strategies and reporting on their effectiveness. Additional VAS services were identified having important intersections with the vertiport SMS.

1) The Data Management System is the central repository and database manager for the exchange of data between services.
2) The Cybersecurity Service authenticates and validates data requests from external users, between VAS services, and monitors for anomalies in VAS services for indications of security breaches).
3) The Software Monitoring Service ensures each VAS service is performing as expected and provides an assessment of operational status for each service.
4) The Surface Trajectory Service assigns taxiway and gate based on availability and provides a nominal or pre-planned 4-dimenstion (4D) surface trajectory (latitude, longitude, height above vertiport surface, and time) for aircraft surface movement.
5) The Vertiport Manager Display shows the current state of vertiport operations with sufficiently detailed information to adjust business objectives and configuration settings to help clear operational anomalies and hazards.
6) The Vertiport Automation Supplemental Data Service Provider uses a standardized interface for stakeholders to make representational state transfer (RESTful) API calls to the VAS using subscription as a means of direct communications to and from the VAS deployed at the vertiport.

V. Current Heliport Safety

Examination of safety issues related to current heliport operations provides an important perspective shaping guidance for vertiport safety [2]. All commercial helicopters operate under 14 CFR Part 135. Comparison of NTSB accident rates between Part 135 fixed wing aircraft and Part 135 helicopters shows that the rate for helicopters has increased from 2010 to 2019 while the rate for fixed wing has decreased [20]. Data from the U.S. Helicopter Safety Team (USHST) showed that U.S. fatal accidents involving low altitude operations (LALT) accounted for 15% of fatal accidents from 2009-2013 and 33% in 2018. Of these, most involved hitting wires and colliding with obstacles/objects/terrain while intentionally operating near the surface (excluding takeoff and landing phases) [21]. Heliport operators, such as hospitals, may also make changes to their facilities without FAA approval since the FAA does not regulate heliports. These facility changes may have unintended effects on the heliports. Further analysis would be needed on LALT accidents for relevance to UAM operations. Mitigations such as verifying the position of the AAM vehicles using GPS and detect and avoid technology would reduce the risk of a collision.

An example of how improper heliport operation can cause accidents occurred November 17, 2012, when two Bell Helicopters collided on a helipad near Pasadena, California resulting in substantial damage to both helicopters and five injuries [22]. The first helicopter had just departed the pad but was returning due to weather while the second helicopter was being prepared to depart. The National Transportation Safety Board (NTSB) determined the probable cause(s) of this accident to be the landing pilot's failure to maintain clearance from a parked helicopter and the other pilot's failure to park the helicopter inside of a marked parking pad. Contributing to the accident was the landing pilot's obscured visibility due to moisture on the windscreen. Although not listed as a cause, the NTSB determined that the helipad was not in conformance with AC 150/5930-2C, Heliport Design. As a result of the accident, along with their own internal review, the Pasadena Police Department made several heliport upgrades and procedural changes. NASA research is testing the Wide Area Hazard Locator for Drone Overflight (WAHLDO) that employs machine vision to monitor the assigned TLOF and provide an alert when it is occupied.

More recently, a mid-air collision between two helicopters occurred near Sea World located south of Brisbane in Australia. Based on a preliminary accident report, both helicopters were operating under visual flight rules from separate helipads located about 220 meters (about 720 feet) apart [23]. One helicopter, XKQ, was departing for a scenic flight climbing over the water. The other helicopter, XH9, was turning onto a final approach path and the pilot expected that XKQ would pass behind them. The pilot of XH9 reported not hearing a standard taxi call over the radio from the pilot of XKQ before climbing over the water. The two helicopters collided at a height of about 130 feet some 23 seconds after XKQ departed its pad. XKQ broke apart in mid-air falling into shallow water with the pilot and three passengers fatally injured and three other passengers seriously injured. The pilot of XH9 was able to land on a sandbar near XKQ. The XH9 pilot and two passengers were seriously injured, and three other passengers had minor injuries.

On November 22 of 2022 two Sikorsky helicopters (one military and one civilian) collied at Brown Field Municipal Airport (SDM) near San Diego, California [24]. The first helicopter had just taken off while the second was preparing to land. There were no injuries but both helicopters were substantially damaged. The NTSB has not issued a final report stating the probable cause.

Another example is the New York Airways, Inc. helicopter accident atop Manhattan's Pan Am Building in New York City on May 16, 1977. According to the NTSB, a metal fatigue fracture caused a landing gear to collapse, and the helicopter rolled over [25]. A rotor blade broke off, went down the side of the building, and resulted in multiple fatalities and injured on the ground [26]. As a result of this accident New York city banned all rooftop heliports. Mitigations for ground risk will be highly scrutinized for vertiports situated in an urban setting such as atop a parking garage or tall building. Today in Manhattan there are three heliports all at ground level located along the East River or Hudson River that in the future might accommodate UAS for passenger and cargo transportation. For example, the New York Downtown Manhattan Heliport/Wall Street is situated over the East River on Pier 6 with one helipad and twelve tie down helicopter parking spaced [27]. Remarks pertaining to potential hazards include birds on and in the vicinity of the heliport as well as 100-foot cranes operating near the U.S. Coast Guard ferry slip. Boats may navigate in water along the heliport pier. No flights or approaches are permitted over the adjacent FDR drive.

In addition to the examples cited above, a query of the NTSB accident database shows eight accidents in the last ten years which occurred at airports when a helicopter and a fixed wing aircraft collided [28]. These accidents caused 3 fatalities and 4 minor injuries. Final reports are available for 6 of these accidents and the probable causes cited are the pilot's failure to see and avoid the other aircraft, the failure of the pilots to maintain an adequate visual lookout, or the crew's failure to exercise the necessary vigilance and precautions and yield the right of way. In 5 of the 6 accidents the pilot of the fixed wing aircraft was at fault and in one accident the NTSB cited both the helicopter and fixed wing pilots. In 5 of the 6 accidents the fixed wing aircraft was flown under Part 91 or General Aviation rules and in one accident the fixed wing aircraft was flown under Part 135 rules.

Voluntary safety reports submitted to the NASA Aviation Safety Reporting System (ASRS) also provides data and insight into helicopter safety [29]. A sampling of 50 reports found 32 near mid-air collisions (NMAC) involving helicopters. Thirty-one of these NMACs occurred at an airport involving a helicopter and fixed wing aircraft. One NMAC occurred at a hospital helipad involving two helicopters operating for different companies who were not communicating with each other. In general, these reports pose conflicts between vertical lift aircraft and fixed wing aircraft are common. Most of these happen with fixed wing Part 91 General Aviation aircraft at smaller airports some of which do not have control towers. The primary means of deconfliction are verbal communication between aircraft and/or communication with ATC and the pilot's ability to see and avoid other aircraft. There were four examples at larger airports of Transport Category aircraft or private jets using the Traffic Alert and Collision Avoidance System (TCAS) to avoid helicopters. It is noted that ASRS reports are submitted voluntarily, and such incidents are independently submitted and are not corroborated by NASA, the FAA, or NTSB. In addition, it is held that the number of ASRS reports received concerning specific event types represents the lower measure of the true number of such events that are occurring so that with these statistical limitations in mind, the real power of ASRS data is the qualitative information contained in report narratives.

In sum, these accidents provided insight in terms of reactive safety on helicopter accident causes and consequences. These accidents and their causes are important examples showing the need for in-time safety management as provided by IASMS. These examples reflect potential future hazards for vertiports and eVTOL operations. These accidents highlight the increased risk at vertihubs (co-located at an existing airport) especially when eVTOL aircraft are sharing airspace with less experienced Part 91 operators relying on the pilots' ability to see and avoid the eVTOL aircraft.

VI. Future Vertiport Hazards

Current heliport safety issues provide an important perspective for discussion of vertiport safety issues. Safety topics were developed as part of a wide assessment of vertiport challenges with industry stakeholders [19]. Hazards identified as part of this assessment are fixed structures such as buildings, towers, and antennas along with temporary structures such as cranes. Other potential hazards include blowing debris, urban wind shadows, visual distractions, and lost communications. Environmental hazards always exist and could include lightening, winds, downwash, electromagnetic interference (EMI), and radio frequency interference (RFI).

FAA Order 8040.6, Unmanned Aircraft Systems Safety Risk Management Policy, although written for UAS, highlights hazards that could affect AAM aircraft operating at vertiports [30]. Examples include ADS-B and GPS signal degradation and UTM failure. As part of a robust SMS, each of these hazards would need to be analyzed for risk level and possible mitigations if the risk is unacceptable. Although these same hazards could apply at other phases of flight, the proximity to the ground and other people which occurs during takeoff and landing at a vertiport adds an extra layer of complexity.

The FAA in its Vertiport Engineering Guide provided guidance including for the design of:

1) TLOF and FATO
2) Safety area
3) VFR approach/departure
4) Marking, lighting, and visual aids
5) Charging and electric infrastructure
6) On-airport vertiports
7) Firefighting
8) Security
9) Downwash/outwash
10) Turbulence
11) Weather and winter operations
12) Access to vertiports by individuals with disabilities [15].

FAA airworthiness standards related to eVTOL aircraft involve additional hazards. These involve electric engines, vectored thrust, and birds. The previously mentioned EASA prototype technical specifications for VFR vertiports noted that bird strikes are a threat to flight safety in the proximity of garbage and waste disposal sites, which can emit mephitic vapors for scavenging birds.

More broadly, hazards for airports were listed in National Academies Airport SMS Guidebook providing guidance [31, 32]. These airport hazards as adapted to vertiports are shown in Table 2.

Table 2. Example Vertiport Hazards (Adapted from National Academies Airport SMS Guidebook [32]).

Hazard Category	Main Components	Potential Consequences
Taxiway routings	Traffic control, weather conditions, communication, marking	• Routing errors with aircraft and vehicle collisions • Runway incursions
Adverse environmental conditions (night, low visibility, adverse wind conditions, precipitation)	Training and experience for adverse weather conditions, preparation and communication, visibility and lighting conditions, runway surface conditions, approach conditions	• Aircraft and ground vehicle collisions • Aircraft and vehicles running over airport workers and passengers • Aircraft overruns, veer-offs, and undershoots
Wildlife hazards (birds and other wildlife)	Fencing, wildlife detection systems and procedures, deterrent devices, wildlife management plan, training and equipment for wildlife control, minimization of attractants (through disposal of food and airport trash, garbage receptacles, and airport zoning)	• Bird and wildlife strikes to aircraft and vehicles • Loss of aircraft and vehicle control
Visual and non-visual aids for approach and landing	Adequacy and reliability, interference, runway approach area updates	• Inaccurate approach and landing • Unavailability of NAVAIDS • Collision with obstacles

		• Aircraft overruns and undershoots
Obstacles	Signage, monitoring, awareness of pilots, and air traffic control	• Aircraft collision with obstacles • Vehicle and equipment collisions
Passenger handling	Handling and control procedures, supervision, monitoring, operation of passenger bridges, operation of buses, evacuation procedures	• Vehicles striking passengers • Slips and trips • Inadvertent or deliberate damage to aircraft and equipment
Communications	Communication procedures, equipment maintenance, training	• Equipment failure • Loss of airport operations capabilities
Airport reporting (Airport Publication Information [AIP], NOTAMs, etc.)	Responsibility, up-to-date information	• Delay in operations • Runway incursions • Collisions
Apron management	Airport rules and regulations, SOPs, access control, gate assignment, ramp congestion, turnaround times, airport infrastructure, technology available, and maintenance	• Collision between aircraft and vehicles • Low capacity of infrastructure • Non-availability of emergency equipment • Delay of operations
Ground operations (marshalling, catering, towing, baggage handling, apron bridges, etc.)	Airport rules and regulations, equipment parking, SOPs, supervision, pilot blind area, personal protection equipment (PPE), training, self-maneuvering operations	• Propeller blades striking people or equipment • Jet blast displacing materials and equipment, and striking people • People and objects being sucked by jet engine intakes • Vehicles striking aircraft and/or people • Falls and falling objects
Helicopter operations	Segregation, location, and type of operations	• Helicopter blades striking people, vehicles, and equipment • Rotor wash displacing objects

VII. Aviation SMS

The IASMS ConOps derives from NASA Aeronautics Research Mission Directorate (ARMD) Strategic Thrust 5 that focuses on in-time safety assurance for aviation transformation (see https://www.nasa.gov/aeroresearch/strategy). For the Sky-for-All NAS envisioned for 2050+, the thrust addresses in-time safety assurance through domain-specific safety monitoring and alerting tools, integrated proactive and predictive technologies with domain-level applications, and in-time safety threat management.

The traditional framework of an SMS established by the International Civil Aviation Organization (ICAO) involves four components, as shown in Figure 4 [33]. The FAA provides guidance and methods for developing and implementing an SMS by Part 121 commercial air carriers in Advisory Circular (AC) 120-92B called "Safety Management Systems for Aviation Service Providers" [34]. A commercial air carrier is required to demonstrate means of compliance with the AC. Types of safety data include voluntary safety reports, recorded flight data, line observations, and maintenance records. These data are collected and analyzed to identify known hazards and emergent risks. Current day SMS operations among commercial air carriers relies on data analytics to identify anomalies, precursors, and trends in safety data collected over a period of time [4]. These approaches include reactive safety of incidents and accidents as well as proactive safety that focuses on contributions of humans to safe operations. Methods for predictive safety are being explored to identify emergent risk.

Typically, data are evaluated by data analysts and data analysis groups who produce information on patterns in data that could represent anomalies, precursors, and trends. These patterns are discussed by data analysis boards who might correlate patterns across different types of data for convergence. These safety data are iteratively reviewed by a company-wide data analysis board to understand what new safety intelligence has been gained. Actionable intelligence is used by a Company-Wide System-Safety Review Board and an Operations/Standards/Policy Board in determining the changes required to operations, policies, or standards to assure risk mitigation.

Fig. 4 ICAO SMS Framework.

VIII. Airport SMS Regulations and Guidance

The FAA developed AC 150/5200-37A, Safety Management Systems for Airports, providing guidance about developing and implementing SMS in the airfield environment [35]. The AC identifies means of compliance with applicable regulatory standards and describes how SMS supports airports in developing an explicit, proactive, and engaged process for identifying, quantifying, and managing hazards and risks.

The AC explains that Safety Assurance and Safety Risk Management (SRM) components are closely linked, as shown in Figure 5. SRM ensures hazards and their associated risks are identified, analyzed, and assessed so that necessary mitigations are designed and put in place. Safety Assurance processes then take over and use operational data to evaluate whether the mitigations are having the desired effect. Safety Assurance processes should include procedures to trigger re-evaluations of the hazard if data indicate its mitigation is not effectively reducing the risk of the hazard's outcome. For example, if an airport put in place a mitigation to decrease the likelihood of a bird strike but safety performance data showed no change after the mitigation was put in place, then the mitigation may not be effective. New hazards may also be identified through Safety Assurance processes and that information flowing to SRM to determine appropriate risk controls.

The FAA Airports SMS AC states that safety issues can be identified through the airport's hazard reporting system, airport self-inspections, maintenance activities, or manager or tenant meetings. In addition, the evaluation of certain activities or events may identify safety issues including airport accidents or incidents, airfield changes (including geometry, construction, conversion from movement to non-movement areas, airfield procedures, and pavement marking modifications), irregular operations or events, winter weather operations, tenant operational changes (including new servicing equipment and aircraft using airport), and ramp operations (including use of ramp for activities not originally intended). SRM addresses the identification of hazards and establishing controls. The airport should consider the worst credible outcome (harm), which is the most unfavorable condition that is considered possible. In identifying hazards, airports should strive for reasonable assessments that cite credible outcomes. Not all hazards could technically result in a catastrophic accident. The airport should leverage quantitative or real-life examples of outcomes based on the hazard. Using examples from airports of similar size and operations may help add credibility. Based on the worst credible outcome of each hazard, the airport uses qualitative and/or quantitative methods to rate the severity and likelihood levels of that outcome. These levels would typically be unique to each airport since they are how management defines what constitutes acceptable and unacceptable levels of risk. The airport would develop these levels commensurate with its operational needs and complexity.

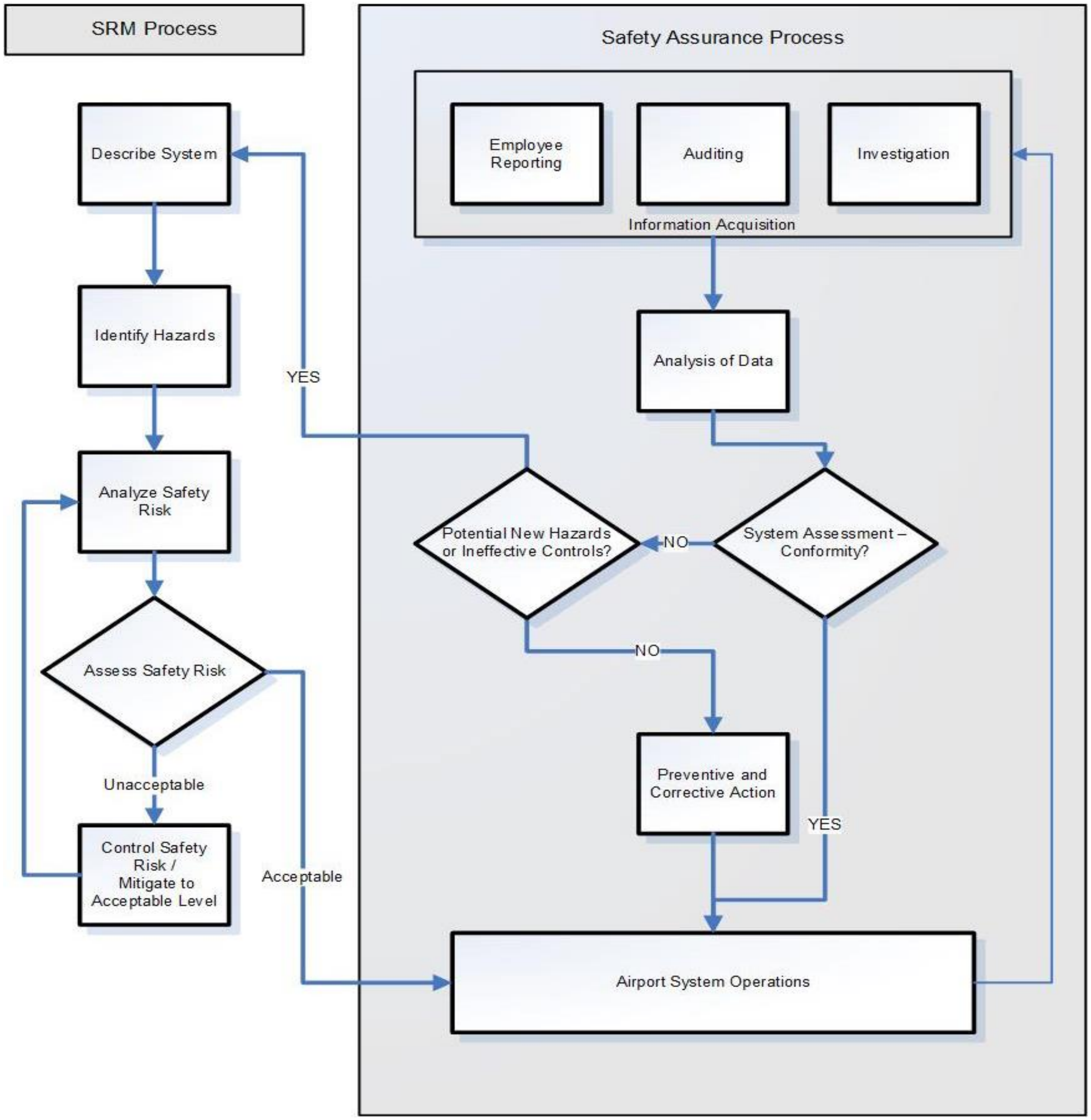
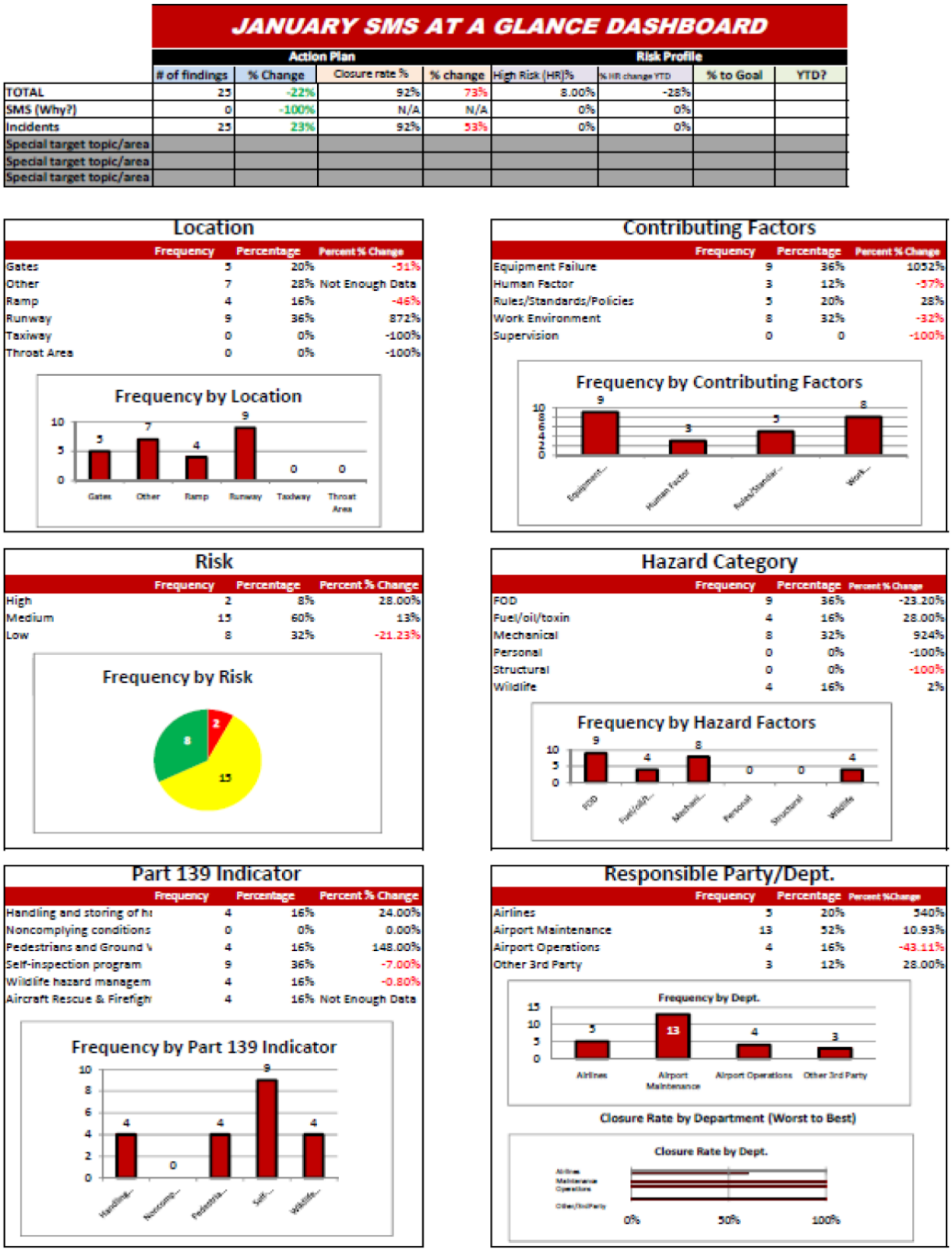


Fig. 5 FAA SMS for Part 139 Airports Showing SRM/Safety Assurance Relationship (from [35] Figure 5.2).

The FAA AC for Airports SMS addresses scaling of SMS with airport operators of small airports using simple methods for conducting the processes within the SMS. Medium and large airports may require more detailed processes within the SMS.

Just as with the new regulation requiring airports to implement an SMS, vertiports will address challenges with adapting SMS to fit their particular circumstances. The FAA AC for Part 139 Airports SMS provides guidance for the four components of SMS established by ICAO as previously discussed. This includes an example of an SMS dashboard as shown in Figure 6. This example shows safety data organized in different categories including percentage of change and closure rates by different departments. The example's Part 139 Indicator poses that some data were collected using a self-inspection program, and it is not clear what data might be sourced from a hazard reporting system, self-inspections, maintenance logs, and other possible methods for monitoring safety pertinent to airports SMS.



	Action Plan				Risk Profile			
	# of findings	% Change	Closure rate %	% change	High Risk (HR)%	% HR change YTD	% to Goal	YTD?
TOTAL	25	-22%	92%	73%	8.00%	-28%		
SMS (Why?)	0	-100%	N/A	N/A	0%	0%		
Incidents	25	23%	92%	53%	0%	0%		
Special target topic/area								
Special target topic/area								
Special target topic/area								

Location

	Frequency	Percentage	Percent % Change
Gates	5	20%	-51%
Other	7	28%	Not Enough Data
Ramp	4	16%	-46%
Runway	9	36%	872%
Taxiway	0	0%	-100%
Throat Area	0	0%	-100%

Contributing Factors

	Frequency	Percentage	Percent % Change
Equipment Failure	9	36%	1052%
Human Factor	3	12%	-57%
Rules/Standards/Policies	5	20%	28%
Work Environment	8	32%	-32%
Supervision	0	0	-100%

Risk

	Frequency	Percentage	Percent % Change
High	2	8%	28.00%
Medium	15	60%	13%
Low	8	32%	-21.23%

Hazard Category

	Frequency	Percentage	Percent % Change
FOD	9	36%	-23.20%
Fuel/oil/toxin	4	16%	28.00%
Mechanical	8	32%	924%
Personal	0	0%	-100%
Structural	0	0%	-100%
Wildlife	4	16%	2%

Part 139 Indicator

	Frequency	Percentage	Percent % Change
Handling and storing of h	4	16%	24.00%
Noncomplying conditions	0	0%	0.00%
Pedestrians and Ground V	4	16%	148.00%
Self-inspection program	9	36%	-7.00%
Wildlife hazard managem	4	16%	-0.80%
Aircraft Rescue & Firefigh	4	16%	Not Enough Data

Responsible Party/Dept.

	Frequency	Percentage	Percent %Change
Airlines	5	20%	540%
Airport Maintenance	13	52%	10.93%
Airport Operations	4	16%	-43.11%
Other 3rd Party	3	12%	28.00%

Fig. 6 Example SMS Dashboard [35].

The FAA AC for Airports SMS and AC for Part 121 commercial air carriers SMS together reflect the range of known possibilities for SMS that will need to be further explored to understand and define the envelope for vertiport SMS and IASMS. Helicopter operations such as at heliports and hospitals provide an important reference point on possibilities for vertiports.

IX. Need for In-time Safety Management

The need for in-time safety management is rooted in the wide variation of vertiport operator size and complexity of operations that necessitates the development of tools and processes to quickly mitigate risks and hazards effectively and economically. IASMS enables safe introduction of advanced technology to achieve a higher level of complexity in design and operations and help ensure that systems safely perform as intended. IASMS augments today's SMS with faster in-time hazard identification, risk assessment, and alerting. IASMS builds on today's SMS by providing features addressing future UAM safety needs. These needs are reflected by the following advancements as emphasized in the FAA ICN ConOps:

1) Accelerate the responsiveness of IASMS for in-time safety assurance and alerting in addressing hazards in-time.
2) Provide tailorability and accessibility of IASMS services to meet mission requirements and performance standards.
3) Ensure interoperability in utilization of resources with IASMS across operators, vehicles, service suppliers, and architectures.

Addressing these three needs will provide improved speed and characterization of vertiport and vertiport-system wide risk identification to augment existing SMS processes for risk management and safety assurance. Implementation of IASMS presumes that the safety business case calibrates the balance between safety and efficiency of operations for ensuring the economical return on the investment and assuring in-time safety management.

The technology roadmap for IASMS in some sense mirrors the planned evolution of the Aviation Safety Information Analysis and Sharing (ASIAS) system used by Part 121 commercial air carriers and others who partner in sharing and analyzing data to assess and understand common safety concerns [36]. Today's ASIAS, called ASIAS 1.0, treats data within their methodological silos (e.g., recorded flight data, de-identified voluntary safety reports) with an architecture distributed across the carriers and a central repository. Transitioning to ASIAS 2.0 involves an integrated production system involving processing higher volumes of data and analysis with automated capabilities to fuse disparate data sources. ASIAS 3.0 will expand to new communities with additional data and improved operating processes. Transformed collaboration will provide more agile, innovative interactions. Predictive analytics and advanced tools will identify emerging risks.

X. Basis for Safety Intelligence

IASMS integrates reactive, proactive, and predictive safety systems and their respective methods and data. Together these systems support development of safety intelligence, which ICAO defines "an outcome of the process of analyzing safety data and safety information to support decision-making" [37]. Triangulation of these safety systems to safety intelligence leverages what we already know or will be able to know about hazards and mitigating risks.

Reactive safety responds to events and intends to mitigate safety events after the hazard has occurred. Reactive safety is based on accident and incident investigation review boards identifying causal and contributing factors and possible mitigations. The system, including the human operator, acts quickly and efficiently in response to undesirable incidents minimizing damage from critical safety situations. This necessitates high quality decision making in reaction to safety data showing threats and risk.

Proactive safety intends to identify system/human behaviors that lead to a hazard occurrence, that is, stop the hazard event before it happens. The objective is to identify root causes before they lead to a hazard occurrence. By identifying risks from historical or latent data from past accidents or incidents or other safety concerning events, underlying causes of unsafe conditions can be detected. Proactive safety includes human contributions to safety in which the safety culture encourages human operators to mitigate deviations from normal operations before they might lead to unsafe conditions. Airports and the different workforces can learn from all operations and so facilitate human contributions to safety.

What differentiates proactive SMS from reactive SMS is the use of aviation leading indicators to directly assess underlying factors and precursors to create a range of acceptable safety performance, and a framework for future risk exposure, mitigations, and safety assurance. Reactive and proactive safety management work collectively to address both detected and previously undetected safety events, and continuously monitor and assess actionable safety data to identify root causes that may lead to more timely mitigation and/or prevention of a specific event occurrence.

Predictive safety involves detecting and mitigating a potential risk as determined from patterns identified in normal operational data (i.e., not accident data) to prevent an accident that has not yet happened but may probably occur if left unaddressed. Predictive SMS identifies previously unknown or emergent risk identified through data analytics applied to large data sets. Predictive safety management attempts to identify all possible risks in different scenarios based on both observed and hypothesized situations/circumstances in order to anticipate future risk controls, risk mitigation options, safety assurance, and organizational needs. Importantly, predictive SMS is complementary to, and not a replacement for both reactive and proactive SMS; that is, they are intended to work collectively to enhance airline safety.

Operators of vertiports in the future, like operators of airports today, will coordinate with fleet operators, aircraft crews, service providers, and others in developing and applying safety intelligence to prevent the next accident from happening, to ensure that the absence of accidents does not mean the presence of safety, to understand and leverage human contributions to safety, and to promote learning from all operations.

XI. Data Analytics

Vertiport operators will collect different types of safety data depending upon the methods employed. Challenges with safety data have been characterized as four V's. First, the Variety of data spans numerical types such as involving numerical values (continuous/binary), forecast and actual weather data, vertiport/airport meta data, GPS/radar track data, voice and digital vertiport/pilot/USS/ATC communications, and textual safety reports (e.g., ASAP, ASRS). Next, the Volume of data streams will be large such as weather data involving the FAA NAS-wide Corridor Integrated Weather System (CIWS) having about 2.7 TB. The Velocity of data represents the rate at which data are collected. The velocity of CIWS data is about 233 GB/month, and for radar tracks across 47 facilities (en route and terminal) about 35 GB/month compressed or 268 GB/month uncompressed. Lastly, the Veracity of data represents its fidelity relative to incomplete or missing data, duplicate data, or reused flight identifiers (call signs or computer identifications). Together these data considerations represent the challenges vertiport operators will contend with in selecting, tailoring, and scaling SMS methods to their particular operations.

The vertiport operator will need to determine what safety methods will be used and how safety data will be collected and analyzed. Some methods involve manually collecting data (e.g., transcribing written safety reports) and other methods support automated collection (e.g., weather and maintenance data). An architecture would provide a framework by which automated Services, Functions, and Capabilities (SFCs) could collect, fuse, and analyze the data. SFCs represent what data will be fused and how it will be analyzed using data analytics. SFCs may provide initial risk analysis although the human analyst will retain final decision making. SFCs would provide alerting when a risk threshold is reached and could provide a recommendation for risk mitigation. The architecture and SFCs would be scaled according to vertiport size and complexity, i.e., tailored safety as described in the FAA ICN ConOps.

The objective is to rapidly discover patterns in data that may predict negative outcomes before the next safety event occurs. The potential for emergent hazards and risks necessitates innovative data analytical solutions involving ML/AI that can distinguish between proactive methods that build on precedent and predictive methods, which currently are not resident or have limited application for airport safety management. SFCs comprising the mitigation function could alert the human operator about a hazard, suggest possible mitigation priorities for human decision-making and action, or automatically intercede and disrupt the sequence of causal and contributing factors. SFCs could also quickly inform system design as emergent hazards are identified to establish effective controls.

SFCs can be characterized as part of operational systems or IASMS across multiple layers of the architecture, as shown in Figure 7. Examples of NASA-developed reference SFCs include 3rd party risk assessment service using cloud-based services to mitigate risk from flying over people, advanced weather risk models involving safeguard updates for HDV areas, radio frequency (RF) interference monitoring and modeling, airspace conformance, and contingency management.

Increasingly complex aviation safety issues necessitate new analytic methods and tools to identify complex patterns and detect emergent risks. Machine Learning (ML) as part of data science provides techniques to fuse and interpret complex patterns in data that might otherwise appear insignificant. The improved speed and characterization of system-wide risk identification could augment existing SMS processes for vertiports in supporting risk management and safety assurance.

One significant limitation is the lack of requisite advanced data analytical SFCs designed for big data analytics that can uncover hidden or latent safety risks that traditional reactive and proactive approaches do not effectively address. Using ML can overcome limitations with current SMS data analytics that do not yet possess sufficient capability to continuously learn from high volume safety data. Predictive SMS involves faster modelling and predicting of future outcomes, more refined safety decision-making, and enhanced safety intelligence.

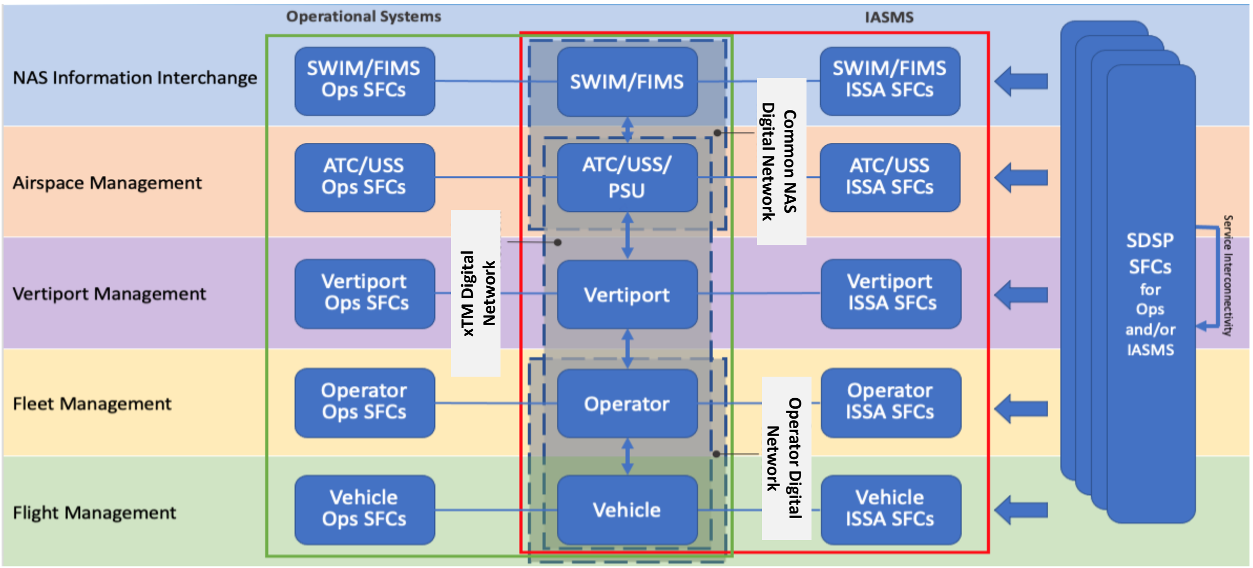


Fig. 7 SFCs as Part of Operational Systems and IASMS.

By effectively transforming their SMS to an IASMS, airports will be able to analyze operational data and shorten review and decision-making cycle times more effectively. In-time decision making will be enabled by ML that will automatically detect and elevate critical risks for immediate attention. As decision makers gain confidence and trust with the IASMS, subsequent concerns may emerge for safety critical decisions that have been characterized as "use, misuse, disuse, and abuse" [38]. That is, data analysts and safety managers may over time drift toward over-relying on automation to detect problems or placing too much trust on automation so as to not guard against false alarms. The human will remain the central decision maker with vertiport IASMS using data analytics to inform effective safety management. Data visualization will facilitate the data analyst and safety manager in identifying and using actionable data for risk mitigations.

XII. Operational Scenarios

Operational scenarios represent opportunities to demonstrate IASMS safety management in vertiport operations [1, 2]. These scenarios represent a range of vertiport operations and operational conditions.

A. HDV Operational Scenarios

Detailed nominal and off-nominal scenarios described how the vertiport automaton system (VAS) would operate from the user perspective. Scenarios were described for baseline nominal operations including passenger gate-to-gate and cargo gate-to-gate [2]. Each scenario was decomposed into operational phases involving pre-flight, taxi for takeoff, climb and cruise, approach, and land, taxi, and unload. Variations were included such as for maintenance after arrival. Off-nominal vignettes were also described including:

1) Missed approach due to weather
2) Late/early arrival at a vertiport with reservation negotiation
3) Vertiport infrastructure failure
4) Communications failure between the vertiport, PSUs, fleet operators, aircraft and flight crew, or air traffic control
5) Physical or cybersecurity breach on the vertiport

The urban passenger scenario involved high traffic density, mixed VTOL traffic, multiple vertiport variants, and some autonomy in vertiport and aircraft operations considering weather and high-density route structure. This included additional automation on conformance monitoring, anomaly detection, and surface trajectory replanning for off nominal or contingency scenarios, and collaboration such as for allocation of TLOF slots.

B. Advanced Onboard Automation Test Case

A test case as part of HDV's Advanced Onboard Automation (AOA) addressed the role and integration of onboard autonomous systems as part of off-nominal testing. A key scenario was an aircraft that just after departure encountered an emergency requiring an immediate return to the vertiport. Related systems included airspace management, ground control, and fleet management, and how these integrate with vertiport automation systems to ensure safe high-density future operations [13].

C. Interactions Between General Aviation and eVTOL aircraft at Low Altitude

Current FAA rules mandate that no aircraft may operate below1000 feet of the highest obstacle in a congested area and 500 feet above the surface in other than a congested area (14 CFR § 91.119). It is anticipated that most vertiports would operate in congested areas and without proper deconfliction the vertical separation between eVTOL and general aviation aircraft may not meet safety requirements. To meet the safety and efficiency needs of the future, all vehicles in low-altitude airspace may be expected to share some level of position and intent data via an integrated information environment [9]. Historically, low altitude general aviation operators have opposed regulations requiring new equipment as the costs exceed the benefits [39]. Portable devices may reduce the cost to an acceptable level.

XIII. Summary and Future Challenges

In sum, the NAS is envisioned to undergo significant evolution that includes the use of vertiports as terminals for eVTOLs transporting passengers and cargo as part of UAM. To assure safety with vertiports in the context of the FAA ICN ConOps, the IASMS would be tailored to scale with increasingly complex designs and operations. The IASMS would be interoperable between different fleets, aircraft, service providers, and vertiports to align with different missions, airspace requirements, and performance standards. The IASMS would provide in-time safety assurance providing alerting for detected hazards and using data analytics to model emergent risks.

Among future challenges is integrating IASMS SFCs in vertiport design and operations to spur development of novel system models, tools, and architectures. Innovative methods, procedures, and techniques will support the design, integration, and implementation of a human-system integrated IASMS capable of predictive data analytics for "in-time" risk mitigation and safety assurance. To meet these future challenges, research will be needed such as to assess use of non-traditional safety data and design of data exchange architectures.

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