Achieving Resilient In-Flight Performance   
for Advanced Air Mobility through   
Simplified Vehicle Operations

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A research and development (R&D) approach is proposed for developing and validating concepts and technologies to achieve vehicle autonomy goals of Advanced Air Mobility (AAM) through Simplified Vehicle Operations (SVO). The approach applies resilience-engineering and human-automation teaming (HAT) principles to a framework for defining vehicle-based functions for the management of missions and flight trajectories, focusing initially on the en route flight domain. To achieve the SVO goal of reducing pilot training requirements and thereby increasing the pilot pool for AAM, while at the same time promoting ever-safer operations, a framework for identifying essential functions is proposed. In this framework, functions are first categorized by high-level functional purpose (*mission management, flightpath management, tactical operations,* and *vehicle control*) and then subcategorized by attributes of resilient-performing systems (abilities to *monitor, respond, learn,* and *anticipate*). The categorization by functional purpose provides structure within which HAT designs can be holistically explored and total levels of human vs. automation responsibility can be varied. The subcategorization by resilient-system attributes provides a mechanism for capturing safety-critical functions that may not be codified in current operational procedures and training curricula, particularly those where humans proactively enhance safety in currently undocumented ways. An R&D approach consisting of seven strategies is proposed in which automation engineering and human-factors communities can collaborate in the research, development, and design of an SVO roadmap to enable the ambitious objectives of AAM.

# Introduction

T

he vision for Advanced Air Mobility (AAM) of widespread, on-demand transport of people and goods throughout complex inter-urban and intra-urban environments requires an operational design that is scalable, flexible, and *resilient* if it is to accommodate demand growth safely and ultimately be economically sustainable. Achieving such resiliency calls for AAM to incorporate goals for vehicle autonomy, in which the capability for a high degree of operational independence is integrated into the vehicle’s onboard flight management functional design. The aspect of functional design addressed in this paper is the *in-flight management* of the missions and flight trajectories of AAM vehicles in various operations up to and including the highly challenging flight environment of Urban Air Mobility (UAM) [1]. The challenges these operations face are diverse and daunting: low-altitude flight over potentially highly populated areas; micro-weather unlike that common to high-altitude operations; obstructions that may be permanent (power lines), temporary (cranes), or dynamic (flock of birds); other AAM vehicles including small Unmanned Aircraft Systems (sUAS) sharing the airspace; overflight restrictions such as noise sensitive areas, schoolyards, etc.; and (among many other challenges) novel air vehicles that may or may not have a pilot onboard managing some or all aspects of the flight.

To manage these challenges in the long term, when the number of vehicle operations has grown significantly and inhabit the core regions of the most populous cities (almost certainly essential for UAM economic viability), mature AAM operations will likely rely heavily on highly automated systems for nearly all aspects of in-flight management, i.e., approaching *full autonomy*. For a vehicle operating under full autonomy, highly advanced automation manages the flight operation with independence from human operators. However, the massive amount of capital investment already pouring into the development of UAM vehicles [2] will place significant business and economic pressure to start operations as soon as possible, long before certified full autonomy is achievable. It is paramount that these initial operations prior to full autonomy be conducted safely, both for the public’s sake and for the long-term viability of UAM and the broader suite of AAM operations.

We should note here that in the current work, we use the term “automation” to refer to machine/computer technology, “autonomy” to refer to the characteristics of independence and self-governance, and “autonomous systems” to refer to automation (and potentially human-automation teams) that operates with some degree of autonomy from external control, though not necessarily without limits or external inputs. Although there are important differences between these terms and significant variations in their use in the literature, a discussion of the philosophical and practical differences are beyond the scope of this paper (for discussion see [3][4][5][6]). We also note that the references in the paper to UAM refer to the most challenging aspects of the AAM domain, likely requiring particular attention within AAM research and development (R&D). However, the concepts and proposals in this paper are generally applicable to the broader set of AAM operations, which is the focus of this paper.

In the earliest stages of AAM operations, experienced commercial pilots will likely be onboard and in command of passenger carrying flights in all but the most highly restricted settings. As demand for passenger flights increases, the scarcity of experienced commercial pilots will motivate a long-term transition towards full autonomy. In the interim period, the role of the human operator will evolve as these automation functions are gradually developed and certified. Initially, pilots onboard the vehicle would transition to performing piloting functions in coordination with onboard automation (i.e., human-automation interaction and, at later stages, human-automation teaming). Eventually, the vehicle operator may become a remote supervisor at a ground control station providing in-flight management services to a single vehicle at first, then multiple vehicles in the future (a.k.a. “m to n”) as onboard automation matures. In such Remote Supervisory Operations (RSO), the ground operator provides mission oversight without providing all the functions of a pilot at the controls. The RSO concept will require ultra-reliable ground-to-vehicle communications and must leverage a significant degree of onboard “responsible automation” performing safety critical functions. (Responsible automation is that which is certified to fully perform a specific function without any human intervention or backup.) Although RSO implementation is necessary for sUAS vehicles that cannot host an onboard pilot, the challenge of certifying such broad-reaching autonomous system functionality for passenger-carrying vehicles makes RSO less likely to be an early solution for AAM passenger-carrying operations. Lost communications must be dealt with directly in certification to ensure the onboard automation can safely manage the vehicle’s mission and flight trajectory without any human assistance during the outage. RSO that is used for early operations will likely have limited automation functionality and be highly restricted in their operations, e.g., relegated to flight over unpopulated areas.

Maintaining a human pilot onboard the vehicle for a substantial part of the transition period to full autonomy is attractive for several reasons. The communications link is much less safety-critical. Cybersecurity may also benefit by having an onboard pilot verify the legitimacy of any flight-path instructions uplinked to the vehicle. In addition, the number of onboard, automated functions initially fielded can be small with an experienced pilot onboard. Over time, as more automation capabilities are developed and certified responsible, thereby taking on a greater share of the pilot’s traditional role, the skills and performance requirements for AAM pilots can be designed to *decrease*. With this decrease comes a reduction in training costs, which in turn makes becoming an AAM pilot affordable to more people (economically essential for staffing the burgeoning fleets of AAM vehicles). This approach aligns with the concept of “Simplified Vehicle Operations” (SVO) in which automation capabilities offset the training requirements of a pilot. The SVO concept was initially proposed for General Aviation (GA) as a means to simplify the physical control of GA aircraft, thereby reducing pilot training cost and allowing more people to become GA pilots [7]. However, the SVO principle is also applicable to the transient stages of AAM leading to full autonomy, a period that may last decades. By applying SVO principles more broadly than just to simplified handling qualities, it enables using automation to simplify the pilot’s role in higher-level decision-making associated with the total operation of the flight. This paper pursues this broader SVO construct as being a necessary step to achieving full autonomy in passenger-carrying AAM vehicles.

The R&D challenge for vehicle automation supporting early AAM operations is to create a structured approach for identifying the necessary set of onboard functions to be performed by pilots and automation such that early AAM operations can be conducted safely in the extended time period prior to reaching full autonomy. As will be discussed, ongoing functional decomposition activities in the community have already begun this process by analyzing and categorizing the skill areas of pilots in current operations [7][8]. The current effort intends to extend that work by applying the principles of *resilience engineering* to illuminate the next level of detail in functional design. The resilience engineering approach is critical to achieving the level of safety required for passenger-carrying AAM operations. Resilience engineering enhances the ability of systems to succeed under varying conditions, applying the abilities to *monitor, respond, learn,* and *anticipate* [9]. The goal of this effort is to create a functional framework for exploring the human-automation design space for the transitional period of AAM, paving the way toward full autonomy. Whereas full autonomy will have the steep challenge of applying these abilities through comprehensive advanced automation, an initial system based on *human-automation teaming* (HAT) can leverage the unique abilities of both humans and automation, which may significantly open up the AAM design space for early operators [6][10]. Although many stakeholders may prefer to transition quickly to this fully autonomous state, the challenges of developing and certifying these highly automated systems (not to mention developing the certification processes and standards themselves) will act as a natural brake on this transition. Keeping the pilot in the loop through SVO provides a path forward because some onboard functions will be more amenable to certifiable automation in the near term than others will. Those that are not must remain a human responsibility or be subject to some degree of HAT.

This paper proposes an R&D approach to developing and validating concepts and technologies that will achieve AAM vehicle autonomy goals. The approach relies on the application of resilience engineering and HAT principles to a framework for defining vehicle-based functions for the management of missions and flight trajectories. The approach may ultimately lead to the establishment of vehicle functions within the larger AAM ecosystem, determination regarding which functions can be automated versus those that require human responsibility, and the successful design and implementation of those automated functions and human interfaces. The approach initially applies the SVO concept to the en route phase of flight as a likely starting point for R&D.

We address this topic by first defining four categories of functional purpose within flight management in relation to the vehicle’s mission and flight trajectory execution: *mission management, flightpath management, tactical operations,* and *vehicle control*. To aid in exploring the new R&D approach, the initial scope largely excludes other flight management functions traditionally performed by pilots (e.g., preflight checks, systems monitoring, passenger management). Second, the hierarchy is subcategorized by the four attributes that provide resilient system performance (*monitor, respond, learn,* and *anticipate*). Using this framework, a non-exhaustive list of candidate functions are identified, and select examples are discussed for their role in enhancing the likelihood of the vehicle’s resilient performance in flight management. These functions (and many others that will be identified through subsequent research) are then assessed as candidates for application of the SVO implementation philosophy, wherein automation supplements or supplants the responsibilities of the pilot to varying degrees, thereby reducing training requirements and expanding the pilot pool for AAM. The paper then explores the constraints and challenges of automation certification and emerging concepts of HAT, which will guide research into determining the viable design space in the SVO spectrum. Finally, an R&D approach is proposed consisting of seven strategies through which automation-engineering and human-factors experts can collaborate in designing a viable SVO roadmap toward achieving the ambitious goals of AAM.

As organized, Section II provides additional background on SVO and functional decomposition. Section III lays out the proposed primary categorization relative to the vehicle’s mission and flight trajectory execution. Section IV describes the resilience engineering approach as applied to this design space. Section V presents the resulting framework of candidate functions. Section VI discusses automation certification challenges. Section VII discusses human contributions to resilient SVO performance. Section VIII proposes the SVO R&D approach. Section IX summarizes and concludes the paper.

# Background on SVO and Functional Decomposition

## Simplified Vehicle Operations

SVO is a term adopted by the aviation community for “the use of automation to reduce the number of skills a pilot or operator of an aircraft must acquire to achieve the required level of operational safety.” [7] The goal of making aircraft easier to fly has a history as old as flight itself, but the highly tailorable control and envelope protection capabilities made possible by fly-by-wire systems has increased interest. NASA developed a fly-by-wire system called “Easy-to-Fly” (E-Z Fly) and a display system called Highway-in-the-Sky (HITS) in the 1980s and 1990s for the purpose of making aircraft safer to fly for pilots with low levels of experience [11][12]. In 2015, NASA explored the concept of On Demand Mobility (ODM) [13], a future paradigm that allows users to have immediate and flexible access to air travel. ODM relied on SVO as one of its enabling technology convergence drivers. Subsequently, the General Aviation Manufacturer’s Association (GAMA) formed a committee to coordinate the community in developing voluntary standards to advance SVO [7]. SVO received high interest from the GA community for several reasons: it may allow greater access to aviation by a future generation of pilots; it could make flying more affordable by reducing training requirements; and, importantly, it could facilitate increased safety by eliminating the most common causes of GA accidents.

The emerging AAM markets are also driving interest in SVO. Pilot qualification requirements for these future markets may limit severely the number of pilots available. Many vehicles designed to support the markets may require distributed electric or hybrid vertical take-off and landing (VTOL) capability. These potentially complex powered-lift systems will make the use of fly-by-wire systems necessary. Fly-by-wire systems can support both ease of flight over wide flight envelopes and control strategies spanning several nonconventional failure modes. They provide SVO benefits by reducing pilot training requirements. SVO may thus address pilot shortage concerns in AAM by increasing the pool of available pilots and by providing an agile response to a pilot shortage through shortened training.

SVO can also potentially define an evolutionary path toward very high levels of vehicle automation. Transformational concepts such as UAM [14] may require passenger-carrying vehicles to operate without onboard pilots to achieve large-scale operations. For long-term viability, these markets may rely on reducing the ratio of human operators to vehicles significantly below one by transitioning to RSO, and business viability may require the pilot’s seat of the small AAM aircraft to be filled with a paying customer. Under RSO, such vehicles will require highly sophisticated sensors, air-ground data exchange capability, and extensive automation. A key advantage of SVO over RSO for early operations is that it enables operations with far fewer restrictions because of the onboard pilot. The SVO philosophy seeks to reduce the human role gradually as technology matures, experience from its use is gained, and evidence of safe operations by increasingly autonomous systems is accumulated. SVO could therefore allow operators working towards full autonomy to introduce initial services in high-value markets in the near term by using onboard pilots, and then scale up their operations gradually as progress is achieved in technology, infrastructure, certification, and public acceptance.

The original focus of SVO on augmenting flight control is sometimes referred to as *simplified handling qualities*, perhaps an implicit recognition of the fact that the SVO concept may be extensible beyond this immediate step. Today’s pilots must perform many tasks beyond direct flight control and vehicle handling. Tasks under instrument flight rules (IFR) include navigation, communication with air traffic control, detection and mitigation of hazards, in-flight replanning in response to changing circumstances, and the monitoring, management, and maintenance of aircraft systems and people on board. Most of these tasks involve judgement of risk and anticipation of potential hazards before they arise. Replacing trained and experienced human operators performing these tasks with sensors and automation will require significant advances in technology. The machine-based capabilities must be proven fail-functional. For a machine-based function that is certified responsible, the operator will not be trained to serve as a backup if the capability fails. Therefore, SVO should not be thought of as a low-risk alternative to other proposed approaches to achieving full autonomy. Instead, SVO is an alternative that emphasizes employing automation technology as soon as it is mature, leveraging a collaborative teaming relationship with the human operator, and proving strengths and weaknesses from operational experience before advancing further. Because very high levels of safety will be required for passenger-carrying vehicles, SVO may be the only realistic option for near-term, passenger-carrying operations.

Evolutionary steps for SVO must be identified to implement the required technologies, procedures, and revised training requirements in a way that is compatible with the existing regulatory system. Figure 1 is a notional example of a progression path (i.e., a high-level SVO roadmap) to support the eventual AAM objective of a passenger-carrying vehicle without an onboard pilot. By establishing priorities and sequences for resolving technical, regulatory, and socio-political challenges, such progression paths may guide the community in targeting and focusing efforts efficiently. Automation technologies may be introduced first as advisory or assistive support systems, with a goal of proving reliability and availability through actual use to allow for operational credit, and eventually leading to certification as responsible automation. NASA’s *Traffic Aware Strategic Aircrew Requests* (TASAR) project applies this approach [15]. TASAR is an advisory-level application of flightpath management technology designed to eventually enable vehicle autonomy in future operations. By advising pilots of conflict-free flightpath changes for flight efficiency (e.g., saving fuel), it exercises algorithms designed for future autonomous self-separation in a non-safety-critical advisory application approvable today under current regulations. However, for the TASAR capability and the broader SVO concept to advance beyond their initial stage toward operational credit and eventual autonomy, some changes to specific regulations will be necessary, and it is likely that new methods and procedures for certification and approval will need to be developed. These authorizations will require that HAT principles and design guidelines be established, ensuring that operational safety is maintained for each step. In addition, standards may also be required for HAT and for the integration of federated human-machine systems. These new regulation, authorization methods, and standards all require a detailed understanding of the necessary functions for performing flight management.

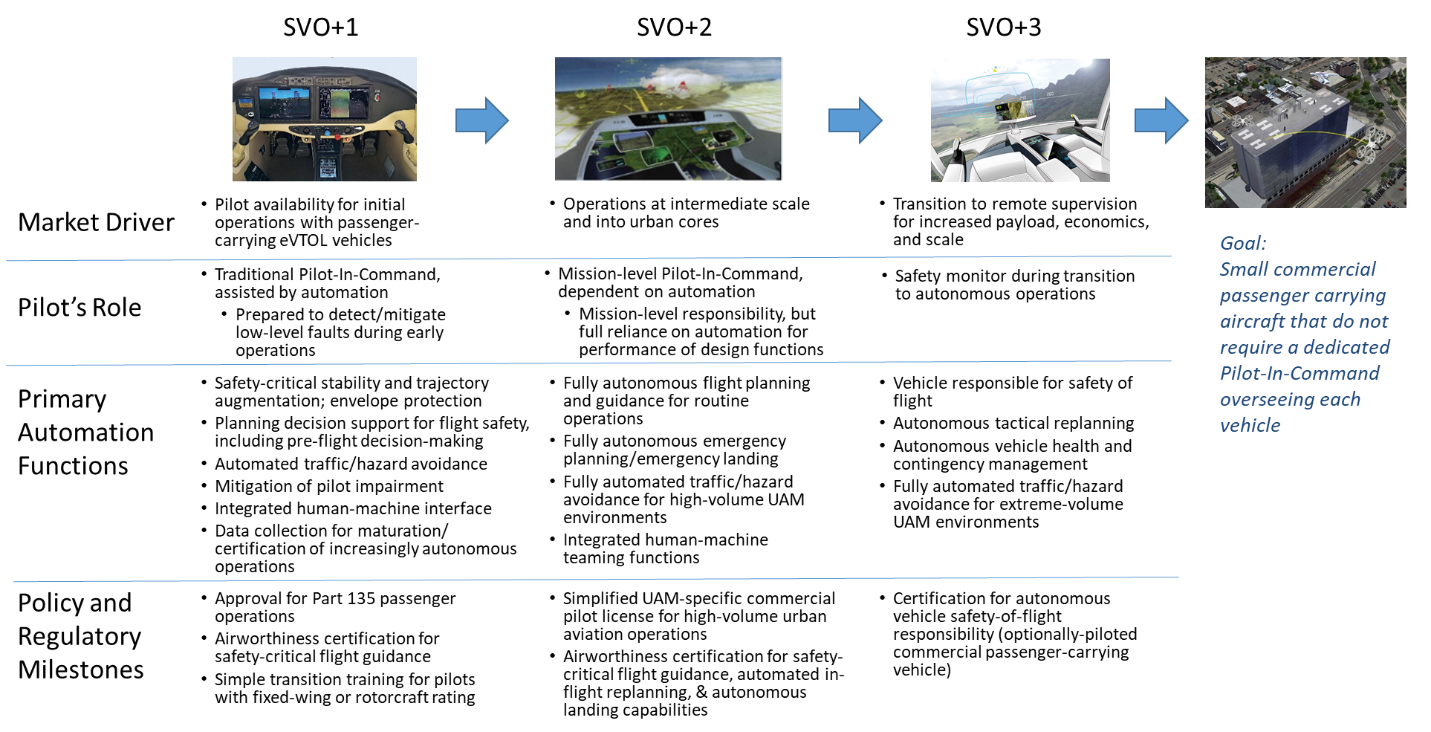


Figure 1. Notional example of SVO progression to support an unpiloted vehicle goal for AAM.

## Functional Decomposition

Decomposing flight management into specific functions that might be candidates for partial or full automation has typically been approached by analyzing the skills and responsibilities of pilots. Feary takes this approach in developing a Flight Crew Function Model (FCFM) [8] derived from the simplified model for pilot airmanship, *Aviate-Navigate-Communicate-Manage Systems*, and the Advanced Qualification Program (AQP) used by airlines and endorsed by the Federal Aviation Administration (FAA) as a method for reducing training requirements. Grouping by phase of flight, FCFM separates pilot functions that are crosscutting (i.e., relevant regardless of the type of vehicle) from those that are vehicle- and/or operation-specific. FCFM crosscutting functional categories include information integration, planning, risk assessment and decision-making, guidance and control, navigation, communication, and external hazard detection and mitigation. Vehicle-and-operation-specific functional categories in the FCFM model include systems operation, emergency procedures, inspection and test, special procedures, security procedures, and company procedures. These categories can be used to derive specific functions that must be implemented through automation for AAM.

GAMA takes a similar approach by identifying 13 pilot skill categories, each of which can be analyzed for the potential of partial or full automation [7]. These categories are aircraft handling, aircraft system emergency procedures, cockpit/passenger emergency procedures, communication, detect and avoid, navigation, planning, pre-flight inspections, risk management/decision making, systems management, takeoffs and landings, taxiing, and terminal procedures. Like FCFM, the GAMA model focuses on the pilot’s traditional role in determining what functions might be appropriate for automation.

Later in Section V, a complementary approach is taken to function identification, focusing on the application of resilience engineering principles (discussed in Section IV) to ensure an adequate capture of functions to promote a high level of safety. Next, however, we introduce a functional structure based on categories of flight management functionality, which forms the core of the proposed functional framework.

# Categorizing Flight Management Functionality

The operational domain under consideration in this paper is the post-departure, en route phase of the operation for an AAM vehicle. Thus, the flight planning is complete, the takeoff time has been coordinated with any arrival flow constraints (e.g., a reserved arrival “slot”), and the vehicle has departed and cleared the immediate terminal area of the vertiport. (This paper uses vertiport generically to refer to the departure/arrival location of the AAM vehicle, which for the challenging UAM domain will typically involve VTOL operations). Where this analysis picks up, the vehicle is airborne and executing the mission it has set out to achieve, and the conditions in which it is operating are dynamic such that replanning may be required. Though the discussion here is described for a single vehicle, it applies to all vehicles operating and interacting under the same set of rules.

When identifying the various functions that are performed in managing the airborne phase of flight, whether performed by a human pilot, automation, or HAT, we consider a categorization based on the function’s purpose in relation to the vehicle mission. For this discussion, a *mission* is defined as the safe transport of an air vehicle (typically having one or more passengers onboard, but not required for repositioning flights) to an intended destination within a set of acceptable parameters. Acceptable parameters can range from a comfortable flight (i.e., reasonable accelerations and deck angles) to arriving reasonably close to the advertised time. Successful AAM mission completion may not necessarily exclude landing at a different landing site, provided it is close to the intended destination and additional ground transportation is arranged to complete the “last mile.” This characteristic (among others) differentiates AAM operations from airline operations. AAM is more aligned with conventional charter operations except, perhaps, the number and proximity of alternative landing sites relative to the preferred destination.

In this analysis, we abstract flight management functionality into four broad categories of primary functional purpose differentiated by their mission relationship, as shown in Table 1. Only those functions envisioned to have principal residence onboard the vehicle are included in the set (whether or not similar functions also reside on the ground). Out of scope and therefore excluded from this SVO analysis are a host of other off-board functions necessary to enable AAM flights, such as fleet management, resource management, information services, and enabling infrastructure, each of which play substantial roles in the vehicle’s mission but may not be onboard or relevant to SVO. This proposed onboard functional categorization serves as our framework foundation, within which specific onboard functions can be identified and categorized based on their relationship to the vehicle’s mission. Some functions work to safely achieve the mission whereas others have the authority to suspend, redefine, or abort the mission. However, in this structure, *mission management, flightpath management, tactical operations,* and *vehicle control* all relate in some respect to the flightpath of the vehicle. Distinctions will be made in the following paragraphs with respect to their relationship to the vehicle’s mission.

Table 1. Categories of onboard flight management functionality.

|  |  |  |  |
| --- | --- | --- | --- |
| **Category** | **Onboard** | **Mission Relationship** | **Examples** |
| Mission management | Mix | Plan and revise the mission | Flight planning, completion feasibility monitoring, contingency planning, etc. |
| Flightpath management | Yes | Achieve the mission (in the most effective way) | Flight optimization, constraint conformance, conflict detection and resolution, off-path recovery planning, etc. |
| Tactical operations | Yes | Ignore the mission (until safety is restored) | Objective shedding, hazard avoidance, etc. |
| Vehicle control | Yes | Safely fly and land the vehicle (applicable to all missions) | Envelope protection, required navigation performance, emergency landing, etc. |

*Mission management* functions are monitoring the mission itself, assessing the likelihood of successful completion and preparing contingencies. Parameters of interest might include energy reserves and delivery performance, health of the vehicle (motors, automation systems, etc.), and alertness of the pilot. Mission management will also be looking at trends in the weather and delays at the destination vertiport. Any undesirable trends may warrant a replan of the mission. To that end, mission management is also maintaining and may execute a set of contingencies, ranging from alerting the pilot or the fleet manager to a problem, to executing a plan to divert. Although one can argue that some of these functions could be hosted on the ground, a safety analysis will likely dictate that most will need redundancy or primacy onboard, particularly for passenger-carrying vehicles. Pilots today perform these functions, and though assistance from the ground may be provided, it cannot be counted upon for time-critical or safety-critical decisions in a lost-communications environment. Pilots (or onboard automation) must therefore be prepared to make decisions independently and potentially promptly. Non-time-critical and non-safety-critical mission management functions could still be hosted on the ground. Moving critical functions exclusively to the ground would require significant advances in air-ground communications infrastructure that produce an ultra-reliable link.

*Flightpath management* is the set of functions associated with achieving the current mission in the most effective way. It acts upon “non-hazard” changes in the operating environment where successful mission completion is likely. Non-hazard changes are those that may trigger a revision to the flightpath, but they require only nominal maneuvers and can typically be achieved with a replan of a “closed” flightpath in which a complete path to destination is always maintained in the navigation system (and broadcast to external agents). The environment changes are detected in a nominal timeframe and are not physically dangerous to the vehicle if acted upon promptly. An example would be the resolution of a traffic conflict detected at some non-hazardous time to encounter.

*Tactical operations* act upon immediate hazards, but where mission completion is still likely achievable. For instance, a “pop-up” conflict with another vehicle or an airspace hazard (e.g., a flock of birds) that is detected with little time to spare may require the mission to be temporarily disregarded until the immediate hazard is resolved. Tactical operations are typically associated with shedding constraints and focusing almost exclusively on the immediate hazard. Once clear of the hazard, flightpath management functions can replan the flightpath from present position to the destination and resume “business as usual.”

*Vehicle control* involves functions associated with executing the flight to a defined flightpath but has little role in defining that path. Given that most AAM vehicle designs are novel aircraft with non-conventional flight controls, a significant degree of automation is expected to be necessary at even the earliest stages of AAM operations. The SVO challenge here will be to design the flight controls such that the vehicle either flies itself or is exceptionally easy to fly, otherwise the training requirements may rival those of today’s helicopter pilots, the training for whom can be both extensive and expensive.

# Resilient Performance for SVO

The approach taken in this research is to apply the principles of *resilience engineering* to the identification of AAM flight management functions. Resilience engineering enhances the ability of systems to succeed under varying conditions through the application of both *protective safety* and *productive safety*. Hollnagel [16] defines protective safety (also known as Safety I) as focusing on “the protection and prevention against harmful events” and productive safety (also known as Safety II) as focusing on “the system’s ability to function in a way that produces acceptable outcomes.” Thus, resilience engineering addresses both protective and productive safety by ensuring less likelihood for things to go wrong and greater likelihood for things to go right. The basis for resilient performance of a system is for it to include four fundamental abilities (excerpted from [9], p3):

* **Monitor**. Knowing what to look for, or being able to monitor that which is or could seriously affect the system’s performance in the near term – positively or negatively. The monitoring must cover the system’s own performance as well as what happens in the environment.
* **Respond**. Knowing what to do, or being able to respond to regular and irregular changes, disturbances, and opportunities by activating prepared actions or by adjusting current mode of functioning.
* **Learn**. Knowing what has happened, or being able to learn from experience, in particular to learn the right lessons from the right experience.
* **Anticipate**. Knowing what to expect, or being able to anticipate developments further into the future, such as potential disruptions, novel demands or constraints, new opportunities, or changing operating conditions.

The importance of designing for resilient performance cannot be overstated when it comes to enabling SVO for AAM. If the goal is to reduce the training and experience requirements for AAM pilot competency by augmenting (or in some cases replacing) pilot functions with automation, the combined system (pilot, automation, or HAT) should engender these qualities to ensure the highest level of safety. Even though AAM offers an airborne alternative to ground transportation, the bar for safety will likely be much higher for the new form of transportation than for the existing ground-based forms. Thus, it is useful to categorize functions not only by the flight management categories laid out in the previous section but by these resilient performance abilities as well. The next section applies this subcategorization to identify example functions that may contribute towards resilient performance of the vehicle in AAM operations.

# Functional Analysis

The approach to function identification taken in this paper, as a complement to other approaches that analyze the pilot’s role (see background discussion in Section II-B), is to focus on the perspective of achieving resilient performance of the flight and then to consider how that might be achieved under the constraints of SVO. Here, the four categories of vehicle-based flight management functionality identified in Section III (*mission management, flightpath management, tactical operations,* and *vehicle control*) are populated with applications of the resilient performance abilities identified in Section IV (*monitor, respond, learn,* and *anticipate*), and each application has one or more example functions listed. This subcategorization process may be a helpful complement to the other functional decomposition approaches (e.g., Section II-B) by identifying important functions that might not otherwise have been considered through a review of operational procedures and standardized pilot training curriculums. For instance, new functions might be illuminated that could help achieve greater safety in SVO than in piloted flight without automation. The example functions in this section are illustrative of the types of functionality that might be needed and should not be considered an exhaustive set. A detailed functional design informed by a concept of operations will be needed to establish a comprehensive list of functionality to support resilient AAM operations.

## Mission Management

The objective of mission management is to provide ongoing review of mission completion feasibility and to proactively address any perceived or emerging challenges to mission success. Such assessments are a normal part of Aeronautical Decision-Making performed by pilots in current operations and will need to be integral to HAT approaches for AAM operations as well. Table 2 gives example functions supporting mission management, subcategorized by their role in achieving resilient performance.

Table . Mission management functions aligned with attributes of resilient performance.

| **Resilience Ability** | **Application** | **Function Examples** |
| --- | --- | --- |
| Monitor | Pilot | Verify pilot is alert and engaged |
| Payload | Attend to passenger needs, cargo security |
| Energy | Track energy level, ensure adequate for completing mission |
| Power Plant | Monitor motor temperature, vibrations, etc. |
| Avionics | Confirm automation is functioning properly, not hung up |
| Communication Links | Verify connectivity via communication links and data feeds |
| Other Systems | Monitor vehicle systems (electrical, pitot-static, etc.) |
| Weather | Verify weather remains within operational limits |
| Destination | Confirm primary landing site availability |
| Alternates | Maintain list of available alternate landing sites |
| ATM System | Monitor for changes to ATM constraints applied to this flight |
|  |  |  |
| Respond | Dispatch Coordination | Consult fleet manager on preferred option for diverting |
| Constraint Revision | Renegotiate arrival slot when unable to meet assignment |
| Divert Decision | Select an alternate landing site and divert |
| Mission Abort | Abort mission and return to departure site |
| Declaring Emergency | Declare an emergency and land as soon as possible |
|  |  |  |
| Learn | Event Analysis | Identify mission-risking incursion into unexpected weather |
| Operational Adjustment | Increase protective margins around subsequent weather |
| Dissemination | Disseminate weather update among the fleet |
|  |  |  |
| Anticipate | Trend Analysis | Predict degradation rate of energy reserves  Monitor and predict arrival delay trends at destination  Extrapolate weather forecast trends |
| Contingency Planning | Prepare multiple divert plans |
| Risk Mitigation | Minimize flight time in congested airspace |
| Resource Preservation | Maximize energy efficiency through flightpath optimization |

A large part of mission management is *monitoring* the status of various systems and the operating environment against the expected situation and assessing whether any detected deviations might require a mission replan. Many questions should be periodically assessed. Is the pilot inattentive or nonresponsive? Are the batteries discharging faster than planned? Is the automation falling behind or working with erroneous or stale data? Have ground communications been lost? Is the weather approaching operational limits? Does the vertiport schedule show unavailability at the expected arrival time? Affirmative answers to these and many other questions may warrant some proactive mitigations steps or mission replanning as a response, while also being vigilant for the possibility of false alerts.

The appropriate *response* will vary depending on the severity of the situation, from alerting a human operator either onboard or on the ground, to initiating a negotiation for a revised arrival slot, to making an actual divert decision. Divert decisions may have far-reaching consequences on network operations, as both the passengers and vehicle will be displaced, and so just responding to monitored (current) data might not yield the level of resilient performance required for sustainable operations.

To increase the probability of resilient performance, mission management should also include functions that *learn* from the past and *anticipate* the future. For instance, when a mission plan for a vehicle cannot be completed, has new knowledge been gained from that situation that could be leveraged to ensure a successful replan? Can the experience be shared with other operators in real time to improve their mission success across a fleet? Similarly, applying the ability to anticipate can increase the probability of resilient performance and can be achieved in several ways. First, look for emerging signs of trouble. Are energy reserves steady or decreasing? Are arrival delays decreasing or increasing? Is the destination weather steady or deteriorating? Second, maintain a ready set of contingency plans in case the mission cannot be completed as planned. Where are the nearest vertiports with arrival capacity? What are conflict-free, minimum-energy flightpaths to those vertiports? Third, execute preemptive strategies to minimize the impact of un-forecasted disruptions, should they occur. What flightpath would preserve the most maneuvering flexibility such that disruptions (e.g., resolving a traffic conflict) can be more easily accommodated without impact to mission success? Together, these functions (and others), whether they are performed by humans, automation, or HAT, help to maximize the likelihood of mission success while maintaining readiness to adapt the mission quickly and effectively as needed to ensure a safe outcome. These functions enable mission management’s goal of ensuring that flightpath management functions have an achievable mission to execute.

## Flightpath Management

Flightpath management functions focus on accomplishing a given mission within an environment of potentially dynamic conditions, constraints, and hazards. Though many flights will occur precisely as planned, every vehicle must be resilient to the possibility of perturbations or disruptions that warrant flightpath modifications to maintain safety and efficiency as the flight environment evolves. Applying the principles of resilience engineering to flightpath management will help make this possible under conditions consistent with mission completion through making nominal adjustments to the plan. Table 3 gives example functions supporting flightpath management categorized by the four attributes of systems with resilient performance.

Table . Flightpath management functions aligned with attributes of resilient performance.

| **Resilience Ability** | **Application** | **Function Examples** |
| --- | --- | --- |
| Monitor | Traffic Separation | Monitor traffic for conflicts (undetected by service provider) |
| Weather Proximity | Monitor weather hazards for proximity (unforecast development) |
| Physical Hazards | Monitor for uncharted hazards (e.g., cranes, flock of birds) |
| Visibility | Monitor real-time flight visibility for required cloud separation |
| Turbulence | Monitor ride quality for passenger comfort, airframe tolerance |
| Restricted Airspace | Monitor conformance to geo-fencing, temporary flight restrictions |
| Flightpath Constraints | Monitor conformance to arrival time slot  Monitor conformance to interval achieve-by constraint  Monitor ground track for noise constraint conformance |
| Optimization | Monitor airspace for opportunities to recover delay |
| Mission Parameters | Monitor ground links for mission parameter change |
|  |  |  |
| Respond | Conflict Resolution | Generate strategic resolution to flightpath conflicts |
| Rule Application | Apply right-of-way and other priority rules |
| Procedure Management | Revise flightpath to new arrival procedure (e.g., wind change) |
| Constraint Management | Adjust flightpath to conform to new constraints |
| Constraint Prioritization | Identify over-constraint; prioritize or relax constraints for safety |
| Plan Recovery | Replan flightpath following deviation in tactical operations |
| Flightpath Optimization | Revise flightpath to better achieve an optimization objective |
| Mission Migration | Generate new flightpath to achieve revised mission parameters |
|  |  |  |
| Learn | Event Analysis | Identify high-risk encounters (e.g., recent pop-up conflicts) |
| Operational Adjustment | Change resolution maneuver to avoid repeat-offender conflict  Add buffers to rule-breaking traffic  Replan flightpath to account for newly degraded flight controls |
|  |  |  |
| Anticipate | Uncertainty Modeling | Account for trajectory prediction uncertainty in conflict detection |
| Conflict Prevention | Identify conflict-free maneuver options before execution |
| Risk Mitigation | Avoid proximity to high-risk areas (e.g., nearby turbulence) |
| Flexibility Preservation | Plan flightpath to avoid dense traffic (mitigating their formation) |

Flightpath *monitoring* functions generally perform repeated flightpath predictions to continually assess the goodness of the current flightpath with respect to the latest information on flight objectives, flight conditions, flightpath constraints, and potential hazards via connectivity to onboard and off-board data sources. The predictions typically extend to the destination, though “look-ahead” time horizons may be applied to filter certain assessments (e.g., traffic conflict detection). Flightpath monitoring functions serve several objectives. They provide a “plan validation” function by confirming the flightpath is still the most energy-efficient route and altitude when receiving up-to-date wind data for the airspace. Simultaneously, they confirm continuing compliance with any flightpath restrictions for noise, ground safety (e.g., schoolyards), airport arrivals/departures, special events, and fixed and temporary structures. They also identify opportunities for improving flight efficiency, e.g., to increase battery reserves and minimize recharging time, or identify opportunities to reduce turbulence exposure for passenger comfort. More importantly for resilient performance, they can predict conflicts (i.e., unsafe proximity) with other vehicles or obstructions well enough in advance that only modest flightpath changes are needed, passengers are not alarmed (or even aware), and the arrival schedule is unaffected.

Flightpath *response* functions include decision-making regarding whether to continue on the current flightpath or to modify it and how. For flight optimization, the decision is optional and treated as a target of opportunity to be pursued safely or not at all. In contrast, a compelling event such as a traffic conflict may dictate a required response, depending on right-of-way or other priority assessments, and therefore flightpath changes must be implemented according to established rules of behavior. Additional monitoring is also required to ensure all vehicles involved are following the rules and to adjust the plan as necessary when noncompliance occurs.

To that end, flightpath *learning* functions can identify “rogue” vehicles that are not operating according to the rules to give them a wider berth. Similarly, “repeat offenders” for which conflicts have reoccurred several times can be flagged as needing a different response. For instance, a conflict with a vehicle (e.g., co-altitude, similar heading) that reappears following a lateral resolution maneuver for that same vehicle may warrant a strategy change to a vertical conflict resolution maneuver to break the cycle. Learning functions can help make these decisions.

Flightpath *anticipation* functions are those that try to reduce the need for future flightpath changes. Because uncertainties tend to increase with prediction distance, prediction algorithms should account for uncertainty to provide greater separation margins when early flightpath changes are made for hazards that are more distant. This should reduce the need to tweak the path later as the hazard grows nearer. Anticipation also includes pre-checking of possible maneuvers for conflicts, i.e., conflict prevention, because stumbling into a conflict by “turning without looking” will require subsequent maneuvering by one vehicle or the other, which could have been avoided. In essence, the sum effect of the resilient performance properties of flightpath management should be to minimize the need for short-notice evasive maneuvers under tactical operations.

## Tactical Operations

Even with the protection of flightpath management, additional functions supporting tactical operations will still be necessary to respond to unexpected near-term events, a key factor in increasing the probability of resilient performance. These functions address immediate hazards, which generally call for a temporary suspension of the mission until a safe operating condition is restored. Table 4 gives example functions supporting tactical operations, categorized by the four attributes of resilient performance.

Table . Tactical operations functions aligned with attributes of resilient performance.

| **Resilience Ability** | **Application** | **Function Examples** |
| --- | --- | --- |
| Monitor | Critical Data | Monitor health status of position, navigation, timing data |
| Critical Avionics | Monitor functioning of auto-pilot |
| Sudden Threats | Monitor traffic sensors for pop-up conflicts |
| Hazard Penetration | Monitor visibility for unplanned cloud penetration |
| Proximate Constraints | Monitor databases and links for unplanned geo-fence breach |
| Landing Site | Monitor landing pad for obstructions |
|  |  |  |
| Respond | Hazard Avoidance | Execute immediate escape maneuver toward safety |
| Constraint Prioritization | Prioritize constraints based on immediate hazard |
| Coordination | Communicate with intruder (if able) for maneuver coordination |
| Safety Recovery | Regain required separation and stable condition |
|  |  |  |
| Learn | Event Analysis | Observe traffic behavior relative to rules |
| Operational Adjustment | Change avoidance-maneuver tactics based on traffic behavior |
|  |  |  |
| Anticipate | Hazard Planning | Predict traffic blunders (e.g. traffic not descending as advertised) |
| Pre-coordination | Apply maneuver rules to enhance predictability |

Tactical *monitoring* functions focus foremost on detecting near-term threats as quickly and reliably as possible. As such, the algorithms will likely be independent from those supporting mission management and flightpath management. The algorithms may also be less complex to support rigorous certification. For instance, functions monitoring the vehicle’s trajectory for “Detect and Avoid” (DAA) might model only the state vectors of vehicles with simplified dynamics, leaving flightpath intent data and complex aircraft performance modeling aside for simplification. This obviously limits the utility of DAA functions to close-in hazards, making them insufficient as the sole means for traffic separation. Other types of monitoring may check on the health of fundamental components necessary for quick and reliable response, such as navigation sensors, the autopilot system, and potentially the pilot.

Tactical *response* functions will focus on immediately and safely mitigating the hazard, which in complex situations might even include choosing to retain only those constraints that are most critical for safety. For instance, a pop-up conflict with another vehicle might dictate a temporary incursion into unoccupied noise-protected airspace, whereas avoiding a fixed structure might warrant a brief loss of required separation with another vehicle. Tactical response functions must continue to provide guidance until a safe operating condition is reestablished, at which point flightpath management functions can reestablish the vehicle on a route to the destination to complete the (temporarily suspended) mission.

Because certification requirements may dictate that functions for tactical operations be deterministic, there may be limited opportunities to apply the resilient performance abilities of *learning* and *anticipation* in this domain. Anticipation functions might apply trajectory prediction to determine if a given maneuver will trade one hazard for another and therefore perhaps recommend a different course of action altogether. It might also apply the principle of “implicit coordination” which establish the rules for complementary maneuver directions between two vehicles in a close-in conflict without requiring direct communication. Learning functions might observe the tactical behavior of the intruding vehicle to ensure it is following the prescribed procedure and to take evasive action if it is not.

## Vehicle Control

Vehicle control functions are distinct from the previous functions in that its focus is to safely operate the vehicle to a defined path rather than define the parameters of the path itself. However, the abilities associated with resilient performance still apply, and given the unique types of emerging AAM vehicles, many or all of them may have to be fully automated to not rely on the pilot at all. Table 5 gives example functions supporting vehicle control, categorized by the four attributes of resilient performance.

Table . Vehicle control functions aligned with attributes of resilient performance.

| **Resilience Ability** | **Application** | **Function Examples** |
| --- | --- | --- |
| Monitor | Guidance System | Monitor guidance system for anomalies to flightpath conformance |
| Control System | Monitor control system for anomalies affecting stable flight |
| Stable Flight | Monitor conformance to stable flight |
| Nav. Performance | Monitor conformance to required navigation performance |
| Performance Envelope | Monitor proximity to flight envelope boundaries |
|  |  |  |
| Respond | Control Strategy | Apply appropriate set of controls for condition of vehicle |
| Upset Recovery | Apply flight controls to recover from disturbance |
|  |  |  |
| Learn | Adaptive Control | Generate adaptive control laws for condition of vehicle |
| Performance Modeling | Revise performance model for degraded mode operations |
|  |  |  |
| Anticipate | Performance Prediction | Detect early deviations from nominal aircraft performance |
| Risk Mitigation | Mitigate non-participant casualty risk preemptively |

*Monitoring* and *response* functions for vehicle control of these non-conventional, multirotor, distributed-electric or hybrid VTOL aircraft will almost certainly be fly-by-wire and fully automated [17]. Given their safety criticality, these functions will likely require the highest level of certification. If employing distributed electric propulsion, loss of a single rotor would be accounted for in basic system design, with lifting and propulsive functions redistributed to the remaining functional rotors. Loss of multiple rotors may require advanced *learning* functions that identify controllable modes “on the fly” to recover positive control and attempt a safe landing. *Anticipation* functions may be able to choose maneuvers that minimize risks to persons and property below.

In this section, we have applied the principles of resilience engineering to identify candidate functions that support in-flight management of the vehicle trajectory with the intent of increasing the probability of resilient performance under dynamic and uncertain conditions including unexpected lost communications. This non-exhaustive list of candidate functions illustrates the breadth and complexity of functionality at all levels of flight management likely needed to produce the level of safety expected for AAM. In conventional flight operations, the responsibility for most of these functions is borne by the Pilot-in-Command (PIC). To achieve the goals of SVO, in which increasingly autonomous systems offset some of the training requirements of pilots, these autonomous systems will need to be designed, developed, and matured to a sufficient level of safety performance to be certified as “responsible” for performing their intended functions. Reaching this level of certification will be both challenging and time-consuming. By retaining a pilot onboard, SVO affords the opportunity to apply innovative HAT concepts to maximize resilient performance before full autonomy is achievable. The following two sections introduce the issues associated with certification and HAT for SVO.

# Certifying Autonomous Systems for SVO

Certifying complex, autonomous software technologies to be responsible for specific functions (i.e., to perform to safety-critical specifications with no reliance on the pilot as a backup) is largely uncharted territory. Although the current certification process has set a remarkably high standard for aviation safety, applying the process to safety-critical flight systems is generally expensive, slow, and unsuited for handling non-deterministic automated systems. As increasingly complex and novel autonomous systems are introduced in support of the SVO concept, the certification process for safety-critical technologies will need to adapt significantly to achieve an appropriate level of resilient performance to meet public expectations for safety. Meanwhile, as complex automated systems begin to take over pilot responsibilities for SVO, regulations for pilot certification will need to adapt accordingly to reduce training requirements.

As mentioned earlier in this paper, GAMA has proposed a path forward for SVO pilot certification that takes a modular approach to pilot proficiency by breaking down the various pilot functions into skill categories [7]. Each skill category represents functions that are currently handled by the pilot but will eventually transition to automation. With FAA support, this appears to be the likely near-term process for SVO pilot certification. Although this represents a clear vision for the pilot, the certification process for SVO automation is still uncertain.

Several efforts are underway to address the issue of certifying autonomous, safety-critical, flight systems [18][19], but it appears the solution will not be as straightforward as SVO pilot certification. Technology certification is complicated by introducing new automation to perform safety-critical functions that, up to this point, have only been handled by the pilot and many of which are non-deterministic. Considering the four abilities contributing to resilient performance (*monitor, respond, learn,* and *anticipate*), monitoring functions may generally lend themselves best to deterministic processes, given a well-established and fixed set of parameters to monitor. Response functions may also be generally suitable for deterministic processes for expected events, although the need to respond to unexpected events may present a challenge. The ground collision accident of an experimental electric VTOL aircraft provides an example [20]. In this accident, a software error triggered by a preflight misconfiguration of the vehicle resulted in degraded flight controls that degraded further in transition to hover. To minimize damage, the PIC decided to respond with a forward landing (rather than vertical) for which the vehicle was not designed or approved. Thus, an unexpected event led to an improvised response. Whereas this response was not anticipated and relied on the pilot’s real-time judgment and experience, even more likely to require non-deterministic methods are the resilience engineering abilities to learn and anticipate, given that they are involved with the unexpected to an even greater degree.

One possible approach for introducing and certifying new technologies, including non-deterministic functions, is to document over an extended operational period their proven, reliable use in service in non-safety-critical roles. This method progresses the technology through four certification stages: *advisory, assistive, operational-credit,* and *responsible*, as shown in Figure 2 using the example of Enhanced Flight Vision Systems (EFVS) [21]. First, the new technology serves as an advisory system, either providing supplemental information or operating strictly during emergencies (i.e., when the system can only improve the situation). After sufficiently demonstrating that the technology is capable of an advisory role in service, it can then be certified as assistive technology (i.e., safety enhancing). In an assistive role, the technology provides certified accurate data to the pilot. While it matures in service over time, the pilot remains primary for safety. After potential regulatory changes and further demonstration of enhanced safety, the system can be certified to provide operational credit with the pilot backing up the proven technology. EFVS has reached this stage of certification [22]. The final step of certifying automation as responsible technology, which designates the system with primary responsibility for safety, has not yet been accomplished in practice but will be critical to enabling the goals of SVO.

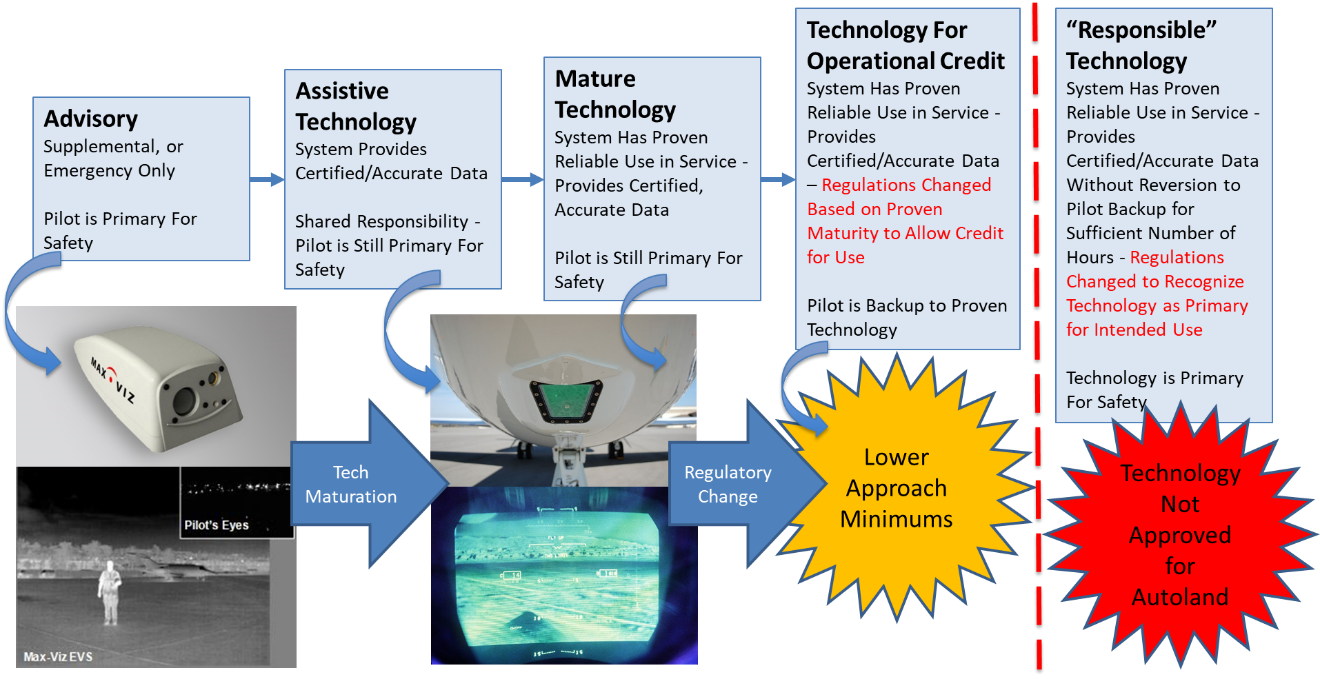


Figure 2. Example of a methodical process for technology potentially progressing to higher levels of certification. Reproduced from [21] with permission and does not represent FAA policy.

Although this path to regulatory approval can be applied in many cases, it will not be suitable for all functions identified by the resilience-engineering framework. Some functions cannot be effectively demonstrated in an advisory or assistive role due to their infrequency of use (e.g., Hazard Avoidance). Others require new operating authorities to be in place or otherwise cannot be easily demonstrated in a non-AAM operational environment (e.g., Conflict Resolution, Rule Application). Different techniques and adaptations of the certification process for SVO automation will therefore need to be determined on a case-by-case basis. For instance, sUAS operations might be a suitable venue in some cases for accumulating a record of operational performance for functions not requiring an onboard pilot. Ultimately, the implication for SVO is that some functions will transition more quickly to fully responsible automation than others based on varying maturity levels, methods of certification, and opportunities to collect evidence of operational performance. This in turn will drive the SVO roadmap, i.e., the steps through which SVO progresses toward full autonomy.

As more functions move from pilot to automation, there needs to be consideration for treating the pilot as a vital component of overall system resiliency. The pilot’s contributions to safety are not limited to these functions alone [23], so it will be important to look at the total vehicle system (i.e., automation and pilot) from a resilience engineering perspective to determine how to maximize the probability of resilient performance in SVO. As more automation is introduced, the interaction of the pilot with the automated systems must be addressed, because more automation can lead to increased confusion for the operator, particularly as different manufacturers deploy similar automated systems. Recently observed in the automotive industry, a single advanced automated function (adaptive cruise control) was found to have as many as 20 unique names across manufacturers, many of which did not well represent the function [24]. The SVO vision could benefit from regulations on human-system interfaces that, where appropriate, standardize functions, controls, displays, and even naming across all manufacturers to provide a more suitable environment for the pilot to work effectively with numerous automated functions across multiple vehicle designs.

# Human Contributions to Resilient SVO Performance

The purpose of the proposed framework is to provide a method to structure human-automation trade space discussions in a manner that urges the AAM R&D community to consider how functions contribute to resilient performance. However, it is not intended to lead to another MABA-MABA analysis (Men-Are-Better-At/Machines-Are-Better-At; e.g., [25]). Indeed, MABA-MABA analyses can give the impression that technology and humans have fixed strengths and weakness, which provides a plausibly oversimplified method on which to base function allocation decisions [26] (see [27] for an alternative perspective). A lesson that is reported repeatedly (and often relearned) is that automation does not simply replace the human; it changes the human’s tasks in unexpected and unintended ways [28]. No matter the function assigned to technology, even highly automated system performance cannot be well predicted by the functionality of the technology alone.

The product of the proposed framework in this paper is the identification of functions to increase the probability of resilient performance of in-flight trajectory management in AAM SVO operations. The next challenge is to propose viable SVO design concepts to accomplish these functions, which includes assignment of some functions to automation. Unfortunately, the human-automation interaction literature is replete with examples that illustrate the “pitfalls of automation” [29]. One such pitfall is *out-of-the-loop unfamiliarity*, where a human operator has a diminished ability to detect automation failures and intervene effectively in a timely manner [30]. Causes have been attributed to lack of feedback from passive monitoring [29], poor situation awareness [30], vigilance [31], and complacency [32]. There is a clear desire in the AAM community to adopt increasingly autonomous systems (e.g., [14]), yet this strategy runs the risk of introducing out-of-the-loop unfamiliarity issues encountered in other similarly highly automated domains. Indeed, although referring to highly automated ground vehicles, Hancock’s maxim holds in the context of SVO for AAM as well: “If you build vehicles where drivers are rarely required to respond, then they will rarely respond when required.” ([33] p. 485).

A related pitfall is clumsy automation, which refers to automation that tends to make easy tasks easier and hard tasks harder. For example, flight management systems (FMS) tend to make the low-workload phase of flight easier (e.g., straight/level flight, routine climb), whereas the high workload phases tend to be more difficult, such as preparation for landing, where pilots must time-share among landing procedures, ATC communications, and programing the FMS [29]. Because the easy task is highly automated, the operator has a diminished ability to respond effectively in off-nominal/difficult situations (i.e., out-of-the-loop unfamiliarity) and has impoverished skills and lack of experience to respond appropriately. Often these pitfalls are the result of acting on the *ability* to automate some functions, leaving the human with the “leftover” aspects of the tasks that were too difficult to automate or too challenging to certify. These issues are indicative of a “machine-centered” approach to system design that often neglects the human at the expense of safety, sometimes excising an important contributor to resilient system performance (i.e., the human). Even if a machine-centered approach to SVO development is not intended, the urgency of achieving early AAM operations may exasperate the tendency to take these shortcuts to an early operational capability that invokes these same problematic issues.

The purpose here is not to cast blame on past design strategies. Clearly, there is a tendency in the human factors and ergonomics community to sometimes exaggerate the pitfalls of the automation narrative, without recognizing that increased automation, in many domains, has delivered on the promises of increased efficiency, safety, and economic advantages [34]. However, the human’s capacity to significantly increase the likelihood of resilient performance should also be recognized. Holbrook et al. provide a compelling analysis of what goes right in everyday “nominal” civil aviation operations because of consistent human interventions in highly automated procedures [23]. The authors highlight the numerous ways that humans greatly increase the probability for resilient performance (see also [35]). Proposed AAM design concepts should support the ability for a system (used broadly to include both technology and human components) to *monitor, respond, learn,* and *anticipate*, and those abilities should manifest from a thoughtful analysis for how humans and technology can work and think better together [6]. An emerging concept that embodies this perspective is HAT.

The concept of HAT adopts the perspective that the benefits of increasingly autonomous technologies will more likely manifest when humans and technologies partner as a team, which is defined as “a distinguishable set of two or more agents who interact, dynamically, interdependently, and adaptively toward a common and valued goal/objective/mission” ([36] p. 7). Here an important distinction illustrates the capability to fundamentally shift from human*-*automation *interaction* strategies to human-automation *teaming* strategies. Whereas current-day automation is typically designed to accomplish pre-specified steps to achieve a limited set of outcomes, increasingly autonomous systems are characterized by the ability to independently assume more complex functions, with less human intervention overall, and for longer periods of time [33], as well as with potentially greater degrees of freedom. It is these increasingly sophisticated characteristics of autonomous systems that may allow more complex teaming principles normally associated with human teams to become applicable to human-technology partnerships, which is often absent in simple human-automation interactions (e.g., it is difficult to imagine how a pilot is teaming with an FMS in any meaningful way). This is not to dismiss the calls for collaborative and complementary pairings between humans and automation that have been issued over the years (e.g., [26][37]). Instead, the HAT concept opens the human-automation trade-space even further to incorporate more sophisticated pairing strategies. Moreover, resilience includes the capacity to amend some or all of the system goals to achieve a workable result [35], which implies that HAT should possess some degree of autonomy. The emerging concept of HAT offers a potentially fruitful avenue to the AAM R&D community to increase resilient performance in SVO. Although more work is required, several researchers are beginning to report theoretical frameworks and empirical evidence supporting the HAT concept (see [5] for a recent review).

# Proposed R&D Approach

Proceeding with system design for AAM SVO requires an R&D approach that brings together the automation engineering and human-factors communities into a collaborative space where they can work collectively to achieve the ambitious vision and goals of AAM SVO. We believe this collaborative approach is more likely to produce operationally viable designs that achieve high levels of resilient performance than a strictly technology-centric or human-centric evolution (e.g., automating functions starting with those we know how to automate; off-loading the pilot starting with the hardest-to-train functions). By taking a true community-teaming approach to the design (thereby emulating the HAT system itself), we can better control that each step in the SVO roadmap is actually achievable, certifiable, and trainable, while maintaining the highest levels of safety expectation, as each step is put into service. To that end, we propose the following seven strategies to conducting R&D for AAM SVO.

### Expand SVO beyond flight controls to include all in-flight operations and decision-making

Although originally envisioned as a means to make aircraft easier to fly, the SVO concept can and should be applied more broadly to making it easier overall to operate the flight. Extending beyond simplified flight controls, this expanded SVO concept includes operational decision-making and other responsibilities. As shown earlier, flight management responsibilities can be categorized by functional purpose relative to the vehicle’s mission and flight trajectory execution: *mission management, flightpath management, tactical operations,* and *vehicle control*. Each of these levels contain functions that today are the full responsibility of the PIC and require substantial pilot training, but in SVO can be redesigned to reduce those training requirements. When applied to all in-flight functions including decision-making, the net effect of this approach may be a substantially streamlined pilot role that makes training to become an AAM pilot a realistic option to a wider population.

### Apply resilience-engineering principles to identify critical flight management functions

Many approaches are available for identifying the individual functions involved in flight management, from a systematic procedural analysis of the flight from take-off to landing, to dissection of the FAA Airman Certification Standards. These approaches are valid and should be pursued, but we advocate augmenting them with the application of resilience engineering to invoke the principle of productive safety (i.e., Safety II) in the design of SVO. According to resilience engineering, systems capable of resilient performance include the abilities to *monitor, respond, learn,* and *anticipate*. As discussed in the paper, this approach may help identify important functions that might otherwise not emerge through standard functional decomposition analyses. In addition, it may help bring forth the critical human contributions to productive safety that may not be codified in operational procedures and training curricula. The functions identified in this paper are only a starting point to illustrate the approach’s potential. A detailed functional analysis informed by a concept of operations will be needed to generate a comprehensive list of functionality to support resilient-performing AAM operations. However, rather than targeting a complete list at the outset, we anticipate that functions will continually emerge throughout ongoing R&D in essentially a spiral development process.

### Approach all functions from an HAT design perspective

Although it will be tempting to look for “low hanging fruit” functions to automate, we propose that the design of *every* identified function be considered first from the perspective of HAT. How might two collaborating agents, each having unique strengths to contribute (i.e., those of machines and humans), implement this function in a collective way such as to increase the probability of resilient performance? The two agents could be thought of as a flight crew, with the human initially in the captain’s role as the responsible party (i.e., PIC) but with duties distributed between them to reduce the pilot’s burden and to allow for team benefits such as crosschecking. In an SVO roadmap evolution, some of those duties performed by automation would accumulate into larger functions for which the automation is eventually certified as the responsible party, thereby permanently offloading the pilot of the responsibility (and the required training). This HAT-driven design approach to SVO would retain pilot involvement broadly across all functions, reducing the probability of out-of-the-loop unfamiliarity, until such time that the permanent handoff to automation can be safely made.

### Conduct HAT R&D within each flight management functional categorization

Given the breadth of the human-automation design space in SVO, determining viable design points for the various functions will require a significant amount of research, much of which by the nature of HAT will need to include complex human-in-the-loop simulations and flight tests. A challenge to conducting such expensive research on individual functions are their large quantity and diverse nature (this paper alone lists more than 75 example functions). The challenge also affects development, including software architectures, algorithms, and user interface (UI) design. Our recommendation is to consider organizing R&D by the flight management categories presented in this paper: *mission management, flightpath management, tactical operations,* and *vehicle control*. It may even be advisable to approach UI and procedure design according to this structure as well, where each category (with its unique relationship to the vehicle mission) is designed holistically, rather than function by function. (Additional research into safely transitioning between functional categories will also need to be included.) While making more efficient use of limited R&D resources, this approach may also lead to a more unified design at each level to the pilot’s benefit, especially as they transition between vehicle types. Research metrics at all levels should include those focused on resilient performance, the ultimate design goal.

### Develop expandable/adaptable system architectures to support HAT research and SVO evolution

Equal in importance to functional design is the system architecture. It must be flexible and expandable to support not only new functions identified in the course of research but also changing priorities among functions as HAT designs evolve along the SVO roadmap. A modular approach with clearly defined, standard interfaces would both enhance these properties and better support certification throughout the SVO roadmap as new capabilities are added, others are possibly retired, and certain functions graduate to responsible automation. Prolific data exchange between functions (and between air and ground systems) should also be considered in the architecture design, as not all of the cross-flowing information needs will have been identified at the outset.

### Define certification maturity paths for all automation and autonomous system capabilities

To support the goals of SVO (where automation and HAT are applied to offset the training requirements of pilots), new technologies will need one or more viable paths to certification as responsible automation. As discussed in this paper, a promising (though potentially lengthy) path involves maturing the technology through the advisory, assistive, and operational-credit stages through in-service documentation of performance at lower criticality levels. Other paths will need to be considered as well, such as leveraging sUAS platforms and operations, but a function without an identified path to certification is unlikely to ever reach the responsible automation stage.

### Define pilot training and certification strategies commensurate with evolving automation systems

Similarly, the pilot’s evolving role should be thoughtfully considered as well. At each stage in the SVO roadmap, the pilot’s role will be defined by a collection of responsibilities that will need to be trained as a package (e.g., different levels of SVO pilot certification). Here the flight management functional categories (*mission management, flightpath management, tactical operations,* and *vehicle control)* may be useful again, where a holistic design approach may enable simultaneously reducing pilot training requirements across all functions of a given category as automation capabilities increase, without compromising the goal of achieving resilient performance. This may help prevent the pilot being assigned a highly distorted set of responsibilities that may be difficult to train, let alone execute.

These seven SVO R&D strategies, when taken together, provide a proposed framework in which the communities of automation engineering and human-factors specialists can collaborate on exploring the viable design space for SVO at each stage of its maturity along the SVO roadmap. We hope this approach resonates and inspires a coordinated R&D effort across the industry to advance AAM methodically toward operational reality.

# Conclusion

This paper proposes an R&D approach to developing and validating concepts and technologies to achieve vehicle autonomy goals of Advanced Air Mobility through Simplified Vehicle Operations. The approach applies resilience-engineering and human-automation teaming principles to a framework for defining vehicle-based functions for the management of missions and flight trajectories, focusing initially on the en route flight domain. To achieve the SVO goal of reducing pilot training requirements and thereby increasing the pilot pool for AAM, while at the same time promoting ever-safer operations, a framework for identifying essential functions is proposed. In this framework, functions are first categorized by high-level functional purpose (*mission management, flightpath management, tactical operations,* and *vehicle control*) and then subcategorized by attributes of resilient-performing systems (abilities to *monitor, respond, learn,* and *anticipate*). The categorization by functional purpose provides structure within which HAT designs can be holistically explored and crosscutting levels of human vs. automation responsibility can be varied. The subcategorization by resilient-system attributes provides a mechanism for capturing safety-critical functions that may not be codified in current operational procedures and training curricula, particularly those where humans proactively enhance safety in currently undocumented ways. An R&D approach consisting of seven strategies is proposed in which automation engineering and human-factors communities can collaborate in the research, development, and design of an SVO roadmap to enable the ambitious objectives of AAM.

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