NASA/TM–20250007128

The Viability of Digital Flight, Part 1: Establishing Accountability for Automated Self-Separation

Andrew R. Lacher and David J. Wing
NASA Langley Research Center, Hampton, VA

Ruth Stilwell
Aerospace Policy Solutions, Ft. Lauderdale-by-the-Sea, FL

William B. Cotton
Cotton Aviation, Lakeway, TX

Anna M. Dietrich
AMD Consulting, Petaluma, CA

July 2025

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

.

Available from:

NASA STI Program / Mail Stop 050
NASA Langley Research Center
Hampton, VA 23681-2199

NASA/TM-20250007128

The Viability of Digital Flight, Part 1: Establishing Accountability for Automated Self-Separation

Andrew R. Lacher and David J. Wing
NASA Langley Research Center, Hampton, VA

Ruth Stilwell
Aerospace Policy Solutions, Ft. Lauderdale-by-the-Sea, FL

William B. Cotton
Cotton Aviation, Lakeway, TX

Anna M. Dietrich
AMD Consulting, Petaluma, CA

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia

July 2025

Available from:

NASA STI Program / Mail Stop 050
NASA Langley Research Center
Hampton, VA 23681-2199

Abstract

With automation increasingly permeating nearly all aspects of aircraft design and operation, the need is growing to also automate their safe passage through airspace populated with traffic and other hazards. Today's operating modes of Visual Flight Rules (VFR) and Instrument Flight Rules (IFR) are human-centric in their methods of conflict management. Their ability to accommodate increasingly autonomous operations is quite limited and may significantly restrain growth and future operational utility. Creating an additional, digitally enabled operating mode is a paradigm shift that could unlock a new era of aviation in which highly automated aircraft operate cooperatively throughout the airspace alongside conventional (i.e., today's legacy) operations.

NASA's Digital Flight concept envisions an additional operating mode that employs automated self-separation, and which may be a more appropriate match than VFR or IFR for aircraft capable of increasingly autonomous flight. However, as a significant paradigm shift in conflict management, its viability hinges on the regulator's ability to authorize its use. The application of accountability, an accepted construct in aviation used as part of safety assurance, helps in addressing this viability question. Accountability is the obligation to answer for an action taken (or not taken) by a responsible entity. Understanding the answers to the following critical accountability questions is necessary for effective oversight by the regulator: *who* will be accountable for separation; *to whom* will they be accountable; and *for what* will they be accountable. This paper (Part 1) is the first of two that directly investigate these questions. It introduces these basic questions of accountability and discusses the first two accountability questions (*who* and *to whom*) in detail by analyzing an operator-centric scheme similar to VFR, but for automated conflict management (i.e., automated self-separation). A companion paper (Part 2) discusses the third accountability question (*for what*) in detail by introducing a new aviation performance construct: *Required Conflict Management Performance (RCMP)*.

Accountability for an outcome is different than the authority and responsibility to act, and thus the accountable party may be different than the agent which performs a given function. While authority and responsibility may be delegated to a fully automated system, accountability must ultimately reside with humans either individually or collectively (e.g., an organization). With an operator-centric, automated conflict management capability, accountability will likely shift from pilots and/or controllers to operators (i.e., organizational entity responsibility for maintaining operational control) and potentially Third-Party Service Providers (3PSPs). Accountability will be *explicitly* identified in regulations or other documented means. There may be dual lines of *explicit* accountability, especially for 3PSPs that may be accountable to both the regulator and the operator. Developers of systems and components associated with automated self-separation will have a degree of *implicit* accountability to the operators for the performance of these capabilities.

The aviation community accepts ambiguity associated with *implicit* accountability because there is confidence that post-incident processes are in place for human-centric decisions that can appropriately determine what went wrong and ensure corrective actions are taken to avoid similar incidents in the future. These processes are built around Safety Management Systems and a *Just Culture.*

The Digital Flight framework summarized in this paper, coupled with quantifiable required performance capabilities as described in our companion paper, can provide the clarity necessary for operational approval by regulators of automated self-separation (i.e., an operator-centric, automated conflict management).

Acknowledgements

The authors wish to thank the Convergent Aeronautics Solutions (CAS) Project and the NASA Transformative Aeronautics Concepts Program (TACP) for sponsoring this research on Digitally Enabled Cooperative Operations (DECO). The CAS Project Management team demonstrated excellence in nurturing paradigm-shifting thought and enabling transformative ideas to be explored without bias. We give special thanks to CAS leaders Keith Wichman, Kurt Papathakis, Gerald Welch, Todd Stinchfield, and Jennifer McHugh for making this research possible.

We thank the many dozens of participants from industry, academia, and NASA's Langley and Ames Research Centers in the CAS-led workshops on Accountability and RCMP. Your energetic and insightful contributions helped to shape and deepen the thinking encapsulated in both papers and will undoubtedly continue to further develop these topics in the community.

We thank the following peer reviewers for your time dedication, technical expertise, and thoughtful feedback on these two papers: Dr. Kyle Ellis, Dr. Husni Idris, Dr. Michael Patterson, and Kurt Swieringa.

Finally, we thank the rest of the CAS DECO research team for the extensive analyses, simulations, and flight tests that rounded out the DECO research portfolio and contributed significantly to substantiating the desirability, viability, and feasibility of Digital Flight. Along with the authors, the DECO team includes Dr. Elaine Blount, Kaleb Gould, Ana Jain, Dr. Jinhua Li, Dr. John Maris, Jerry Smith, David Thipphavong, Paul Vajda, Dr. Fred Wieland, and Harrison Wolf.

Table of Contents

Executive Summary

With automation increasingly permeating nearly all aspects of aircraft design and operation, the need is growing to also automate their safe passage through airspace populated with traffic and other hazards. Today's operating modes of Visual Flight Rules (VFR) and Instrument Flight Rules (IFR) are human-centric in their methods of conflict management, and their ability to accommodate increasingly autonomous operations is quite limited and may significantly restrain the future operational utility of these new operations. Creating an additional, *digitally enabled* operating mode is a paradigm shift that could unlock a new era of aviation in which highly automated aircraft operate cooperatively alongside conventional (i.e., VFR and IFR) operations in integrated airspace. The term *digitally enabled* here refers to leveraging digital technologies such as information services, digital connectivity and communications, and automation algorithms which maintain situation awareness (i.e., a model of the operating environment) and are capable of managing conflicts. These capabilities can be on the aircraft, on the ground, or in the cloud.

The concept of Digital Flight, documented in 2022 (NASA/TM-20220013225), offers a framework for a digitally enabled cooperative operating mode for integrated airspace. The framework could be applicable to any concept that includes cooperative operations such as Urban Air Mobility (UAM), Upper E Traffic Management (ETM), and Extensible Traffic Management (xTM). Envisioned for future use by any qualified operator of any aircraft type, the concept leverages information services, shared traffic and intent awareness, cooperative practices, and automated conflict management capabilities to provide operators with an alternative means from VFR and IFR to safely conduct their missions, eventually in all airspace classes, without the constraints and limitations of human-centered conflict management. By allowing for automated conflict management, the national airspace will benefit from the cumulative technological advancements of nearly 100 years since the first instrument flight. Automated conflict management has the potential to enable operations to scale efficiently and safely to unprecedented levels of traffic density, complexity, and operational tempo.

Digital Flight is envisioned to consist of four essential elements as follows:

- **Automated Conflict Management Capabilities** automate the critical functions of tactical separation and strategic conflict management. Six principal capabilities have been identified and are described in this paper.
- **Information Services and Connectivity** maintains a digital model of the operating environment for use by the Automated Conflict Management Capabilities.
- **Shared Traffic and Intent Awareness** involves the sharing of relevant traffic and operational intent information for use by the Automated Conflict Management Capabilities.
- **Cooperative Practices** govern the behavior of digital operations to ensure harmonized use of airspace. The Cooperative Practices would be encoded in the Automated Conflict Management Capabilities. Twelve initial Cooperative Practices have been identified and are described in this paper.

Digital Flight is a significant paradigm shift in conflict management. Its viability hinges on how the regulator will be willing to authorize its use. The application of *accountability*, an accepted construct in aviation used as part of safety assurance, may address this viability question. Accountability is the obligation to answer for an action taken (or not taken) by a responsible entity. Understanding the answers to the following critical accountability questions is necessary for effective regulatory oversight:

- ***who*** will be accountable for separation?
- ***to whom*** will they be accountable?
- ***for what*** will they be accountable?

This paper is the first of two that directly investigates these questions. It introduces these basic questions of accountability and discusses the first two accountability questions (*who* and *to whom*) in detail by analyzing an operator-centric scheme similar to VFR, but for automated self-separation. A companion paper (Part 2, TM-20250007129) discusses the third accountability question (*for what*) in detail by introducing a new performance construct: *Required Conflict Management Performance (RCMP)*. RCMP offers a structured approach for (a) authorizing operators to employ automated conflict management as the sole means for separation from traffic and hazards, and (b) specifying the minimum authorized separation based on their conflict management system performance.

A few insights emerged as the research team explored these questions. First, some ambiguity in accountability exists and is acceptable in today's human-centric system operations. Some ambiguity is likely to be acceptable in the future for increasingly autonomous processes. Second, accountability for an outcome is different than the authority and responsibility to act, and thus the accountable party may be different then than the agent which performs a given function or action. Finally, while authority and responsibility may be delegated to a fully automated system, accountability must ultimately reside with humans either individually or collectively (e.g., an organization).

With an operator-centric, automated conflict management operating mode like Digital Flight, primary accountability for conflict management will likely shift from pilots and/or controllers to operators (which in some cases is also the pilot) and potentially Third-Party Service Providers (3PSPs). The 3PSP is expected to be accountable to the operator and the operator accountable to the regulator for selecting an appropriately qualified and competent 3PSP; if 3PSP qualification mechanisms are developed, *explicit* accountability between the 3PSP and the regulator is also likely. Developers of systems and components associated with automated self-separation will have a degree of *implicit* accountability to the operators for their systems' performance of these capabilities. If the system is certified by the regulator, they will also have explicit accountability to the regulator. The research clearly distinguishes *explicit* and *implicit* accountability with the following descriptions:

- **Explicit Accountability:** Is clearly observable and well documented. Usually defined in law, regulation, stated policy, and/or formal agreements. It creates clear authority for one party to hold another party accountable. It often documents possible formal consequences.
- **Implicit Accountability:** Is implied and usually inferred from procedures, training, common practices, or social contracts with peers and does not overtly grant authority to hold another party accountable. There may be implied voluntary corrective actions. Accountability may not be clearly observable or generally understood. The community accepts that ambiguity exists.

In today's human-centric system, *explicit* and *implicit* accountability co-exist. The aviation community accepts the ambiguity associated with *implicit* accountability because there is confidence that post incident processes are in place for human-centric decisions that can appropriately determine what went wrong to ensure corrective actions are taken to avoid similar incidents in the future. These processes are built around the Safety Management System (SMS) approach and a *Just Culture* which emphasis learning over punitive action.

The Digital Flight framework summarized in this paper, coupled with quantifiable required performance capabilities as described in the companion paper, can provide the clarity necessary for operational approval by regulators of automated self-separation systems (i.e., an operator-centric, automated conflict management mechanism).

Realizing the vision of Digital Flight, or any other concept of operator-centric, automated conflict management, will ultimately require regulatory approval. To be successful, any proposal for a new operating mode must establish *explicit* operator accountability to the regulator for automated self-separation, clarify *implicit* operator accountability, and offer a measurable performance construct establishing for what the operator will be held accountable (e.g., RCMP). These components could significantly enhance the viability of a new operating mode in the eyes of the regulator and thus accelerate its authorization. This paper and its companion paper are intended to provide a foundation from which these issues can be explored further towards implementation.

1. Introduction

Aviation is at a transformative moment, with many pursuing technologies that would enable a shift towards increasingly autonomous flight [1]. Aerial missions envisioned are diverse and far reaching, including low-altitude Unmanned Aircraft Systems (UAS); air taxis in metropolitan areas; uncrewed regional cargo operations; long-endurance aircraft operating at ultrahigh altitudes; automated search and rescue missions; drones as first responders; robotic infrastructure inspection; and much more. A common thread among these proposed operations is the high degree of reliance on automated flight functions, a necessity because in the future most of these aircraft are envisioned to have no onboard pilot. Furthermore, the economics of some missions are driving fleet operators toward so-called "m:N" (pronounced "m to n") operations in which teams of "m" remote pilots supervise a larger number of "N" simultaneous flights, breaking the paradigm of having at least one pilot dedicated to each aircraft. Flight functions have been increasingly automated over decades leading to the success in automating nearly all phases of aircraft operations, including taxiing, takeoff, cruise, approach, and landing. While not ubiquitously available, steady progress is being made towards certification of these automated capabilities.

Included in these advancements are technologies to aid in operating flights in an environment with other air traffic where conflicts need to be managed, including adjusting flight paths if needed. The umbrella term for this activity is "conflict management" and is the process of limiting, to an acceptable level, the risk of collision between aircraft and hazards, including other traffic. Detect and Avoid (DAA) is a category of conflict management technology intended to replace the pilot's "see and avoid" responsibility [2]. Current DAA systems are designed for close-in tactical separation and collision avoidance, operating with short time horizons and no intent information about the intruder aircraft beyond what may be inferred from its current velocity vector.

Advancements are also being made in automating strategic conflict management, the most notable being UAS Traffic Management (UTM) [3]. While UTM is initially intended for small drones operating at low altitudes (e.g., uncontrolled airspace like Class G), many envision derivative concepts, collectively referred to as Extensible Traffic Management (xTM), that are intended for larger aircraft operating at higher altitudes in positive control airspace [4][5]. UTM technologies help to ensure that airspace volumes are not contested among participating aircraft, using a service-oriented architecture to identify and communicate potential airspace volume usage conflicts among operators for them to resolve in strategic timeframes, often before departure. The progress being made in both DAA and UTM is establishing solid foundations for creating a fully automated end-to-end conflict management capability for future operators.

Fully automating conflict management requires bridging the gap between highly tactical DAA and strategic UTM capabilities. This augmentation will enable future operators to accrue the efficiency benefits of fully automated hazard separation, a function performed manually today by air traffic controllers for aircraft operating under Instrument Flight Rules (IFR). Under the IFR operating mode, separation provision considers both aircraft state and intent information and operates in timeframes generally beyond current DAA systems. In 2022, NASA published a conceptual framework in which operators could in the future employ automated self-separation in lieu of pilot-provided visual separation under Visual Flight Rules (VFR) or receiving separation services from Air Traffic Control (ATC) under IFR. The framework, referred to as Digital Flight, outlines a potential new operating mode founded on digital information and digital capabilities for automated conflict management [6]. A Digital Flight operating mode could distribute decision-making among participants who will need to have appropriate operational capabilities and comply with yet-to-be established operating practices. The paradigm shift of this digitally enabled operating mode is the leveraging of digital technologies for automated conflict management, including information services, digital connectivity and communications, and automation algorithms which maintain situation awareness (i.e., a model of the operating environment) and are capable of mitigating conflicts. These capabilities can be on the aircraft, on the ground, or in the cloud.

A key challenge to using technologies for safety-critical purposes in aviation is the need for potential changes in regulations that authorize their use. Once the technology matures and can be proven effective, paradigm-shifting concepts like automated conflict management must overcome a particularly complex challenge: *Operational Approval*. Operational approval of automated conflict management is necessary for it to be an enabler of future automated operations at scale. Since 2023, the NASA Convergent Aeronautics Solutions (CAS) Project has been exploring the desirability, viability, and feasibility of Digitally Enabled Cooperative Operations (DECO) using the Digital Flight conceptual framework [6]. This research builds upon decades of relevant research performed at NASA and elsewhere [7][8][9]. The research identified operational approval of automated conflict management by the regulator[1] as a key viability issue.

This paper and a companion paper [10] together outline a potential conceptual approach to resolving this viability issue of automated conflict management using the established aviation concept of *accountability*. Accountability is the obligation to answer for an action taken (or not taken) by a responsible entity. Applying an appropriate accountability scheme to automated conflict management may provide the necessary clarity on *who* should be accountable for automated conflict management, *to whom* they should be accountable and *for what* they should be accountable. This clarity is necessary but may not be sufficient for the regulator to be able to authorize *operators*[2] to self-separate their aircraft from other aircraft using automated capabilities without a human reversionary mode (i.e., not having pilots or controllers serving as backup). Furthermore, this authorization could apply to any operator capable of meeting the accountability requirements and could apply in any airspace in which the requirements can be met, including integrated airspace alongside traditional IFR and VFR operations. By basing its formulation on the Digital Flight Framework, which was designed for such integrated operations, the accountability structure imposed by the regulator should be able to accommodate the integration of increasingly autonomous operations and traditional operations in integrated airspace.

1.1. Purpose

The purpose of this paper is to share NASA's insight on the development of an accountability scheme as an essential step for automated, operator-centric conflict management to be authorized by a regulator. This paper describes how such a scheme could be established and explains how accountability for outcomes and performance could be determined.

1.2. Document Scope

This paper discusses a new operating mode that enables flight by reference to digital information and allows operator-centric, automated conflict management in mixed traffic environments and potentially all classes of airspace. The lines of accountability in established operating modes (IFR and VFR) define the accountability scheme for human-centric conflict management. The addition of automated conflict management raises questions of accountability that are yet to be investigated. This paper discusses the viability of automated conflict management by articulating clarity on *who* is accountable, for *what* they are accountable, and *to whom* they are accountable under a digitally enabled operating mode. A companion paper [10] details the required system performance, defining for *what* they are accountable.

1.3. Background

The aviation community is in the process of deploying new aircraft types and advanced operational concepts that are collectively referred to in this paper as Advanced Air Mobility or AAM [1][11]. There are many different concepts associated with AAM including unmanned aircraft, new types of propulsion, innovative missions, advanced business models, emerging markets, and novel locations for landings/departures. Most of the new concepts involve increasingly automated operations to the point where some new entrants are proposing operations that are primarily automated. With these operations the human is envisioned to have only an oversight role and may not be able to fully intervene (i.e., revoke authority granted to the automation). Many of these new aircraft, missions, and concepts involve remotely piloted UAS that are envisioned to become increasingly autonomous to the point where a single or small team of remote pilots (i.e., "m") could safely operate many airborne aircraft (i.e., "N") at the same time. For the purposes of

---

[1] In The United States (U.S.) the main regulator of aviation is the Federal Aviation Administration (FAA). Each country has their own aviation regulatory agency. Generically, these regulatory bodies are often referred to as a Civil Aviation Authority (CAA).
[2] For the purposes of this paper, the term operator will mean the organizational entity responsible for maintaining operational control over flight activity. Per 14 CFR § 1.1, operational control, with respect to a flight, means the exercise of authority over initiating, conducting, or terminating a flight. In the cases of a general aviation aircraft flown by an owner, the pilot and the operator are essentially the same.

this paper, we will refer to these type of operations as “increasingly autonomous flight” consistent with the terminology developed by ASTM [12][13] and the National Academy of Sciences [14].

As the community moves towards increasingly autonomous flight, the traditional roles and responsibilities of operators, pilots, and other stakeholders need to be re-examined. In light of emerging technologies and systems, it is crucial to reassess accountability, authority, and responsibility of all parties involved in aircraft operations. In 2023, ASTM performed a study on this topic that raised questions about accountability associated with the full spectrum of activities associated with operational control [15].

As part of its effort to explore operational, policy, and technical issues associated with increasingly autonomous flight, ASTM developed the following definitions for responsibility, authority, and accountability inspired by a careful review of the Code of Federal Regulations, Title 14:[15]

- **Responsibility:** The obligation to carry forward an assigned task to its successful conclusion; this is closely coupled to the authority to direct and/or take the necessary action to ensure success.
- **Authority:** The power or right to give orders and/or make decisions.
- **Accountability:** The obligation to answer for an action taken (or not taken) by a responsible entity.

Throughout this paper, we will be using the ASTM definitions for these terms.

The increased automation of aircraft systems has begun to shift how aviation systems are operated. The assumption of a pilot in direct command and control of an individual aircraft is now routinely being challenged by systems that are able to shift elements of operational decision making from humans to automated system capabilities [15]. This has significant implications for accountability.

Accountability is a mechanism by which regulators ensure desired performance in many regulated industries, including aviation [16][17]. Codifying in regulations who is accountable for actions taken or not taken eliminates ambiguity and helps guarantee that accountable parties will ensure that their behaviors are consistent with regulatory expectations, especially as they relate to ensuring safety. Through various mechanisms including the establishment of procedures and qualification and training of personnel, accountable parties attempt to ensure that their organization performs in a way that is consistent with the regulations and the expectations of desired performance. Accountable parties also ensure that the systems used are compliant with regulations for continued airworthiness. Regulations that explicitly specify who is accountable help enhance safety as well as provide a basis for any potential enforcement action that may be necessary. Therefore, concepts that shift the role of automation in decision making must eliminate ambiguity in accountability to ensure safety.

2. Accountability Questions for Increasingly Automated Systems

Exploration of the following three pillars of accountability is the main purpose of this paper, and more details will be discussed later in the paper:

- ***Who*** is accountable? – Identification of the accountable parties.
- ***To Whom*** will they be accountable? – Identification of the entity to which the accountable party is obligated to answer.
- ***For What*** will they be accountable? – Identification of the actions, behaviors, and outcomes for which they are accountable.

Identification of the party accountable for decisions is fairly clear when the decisions are made by a human. As decisions shift to automation, there is less clarity on the accountable parities. In situations with the Human-In-the-Loop[3] and the Human-On-the-Loop[4], an individual human is actively engaged and, if necessary, can revoke authority from automation and execute the appropriate course of action. For example, with today's autopilot and Flight Management Systems (FMS), the pilot delegates authority to the automation to maintain a course but must continuously monitor the execution by the automation and must take over control if the system fails to perform as desired. Accountability rests with the pilot, even though they are assisted by the automation. The pilot delegates authority and responsibility to the automation, but both are readily revokable.

As the aviation community automates more functionality, there is a point where the human will no longer have the ability to revoke authority from the automation (or even adequately monitor its functionality). The human will have high-level oversight and only be able to offer guidance, sometimes referred to as Human-Over-the-Loop[5]. There may also be situations in the future where the human delegates all authority to the automation and will have no awareness of system behavior. In such situations, the automation has full control, and the human may have no awareness of the actions being taken. The human's role is reduced to initiating and, when necessary, ceasing operations (rather than offering guidance to modify behavior). This is sometimes referred to as Human-Out-of-The-Loop[6]. Figure 1 summarizes these different roles of the human in a generic control loop. Some aviation examples are provided for clarity in the green boxes in the figure.

---

[3] Human-In-the-Loop (HITL): The human must act for the control system to perform a function. Automation may assist the human by providing or communicating information (e.g., situation awareness data) to help in the execution of actions. Some aviation examples include navigation systems that help the pilot determine the appropriate heading or avionics that help the pilot determine aircraft state [18].
[4] Human-On-the-Loop (HOTL): The human is monitoring, provides guidance and, at any time, can intervene and exert full control over the system. Automated processes have the authority to control the system and act without additional human actions. The automation systems' authority is revocable by the human at any time. Some aviation examples include autopilot and autothrottle systems [18].
[5] Human-Over-the-Loop (HOvTL): The human is monitoring and can provide guidance and oversight that will impact the control system behavior, while automated processes have the authority to act without human actions or additional authority. Effectively, the human is in a management role and cannot be in full control. Within the delegated authority, the automation acts on its own. An aviation example is RQ-4 Global Hawk's flight operations. The remote pilot can provide new guidance in terms of waypoints or heading but cannot directly provide inputs to the control surfaces [18].
[6] Human-Out-of-the-Loop (HOOTL): The human delegates all authority to the automation once the execution of the function is enabled, having no awareness of system behavior. Automated processes are in control of the system and have the authority to perform actions without the human having awareness of the actions being taken. The automation has full control once granted the authority to act by the human. The human's only role is to revoke authority and cease the function. An aviation example is a Full Authority Digital Engine Control (FADEC) system which is part of most modern jet engines and some piston engines. The automation is in control of the fuel flow, power output, and many other engine parameters. There is no manual override. If the FADEC fails, the engine fails [18].

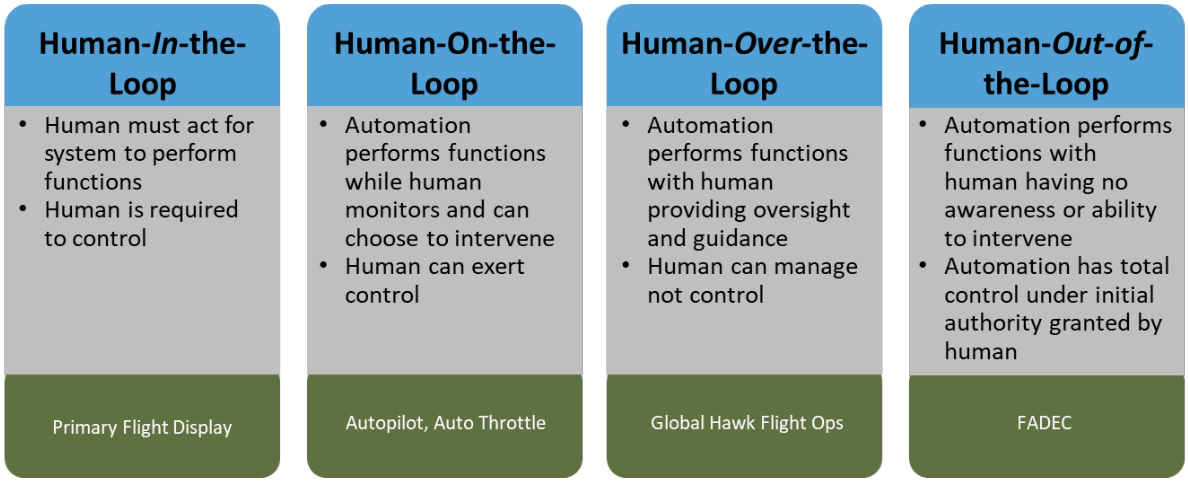

Figure 1. Human Role in the Control Loop

Generally, through rules and regulations, the regulator holds parties accountable for conforming to measurable standards and well-defined expected behaviors. Accountability exists as a mechanism to ensure required performance, expected behaviors, and desired outcomes. Effectively, accountability exists in aviation as a mechanism for achieving safety objectives.

In the current human-centered system, the pilot flying and/or the pilot-in-command (PIC), the operator (e.g., air carrier), and the Air Navigation Service Provider (ANSP) (e.g., air traffic controller) each have authorities, responsibilities, and accountabilities for ensuring appropriate behaviors that enable the achievement of the conflict management function. In the current IFR and VFR operating modes, conflict management is entirely Human-In-The-Loop, in that all final decisions on courses of action are made by humans. This is true even though humans may use and, in some cases, depend upon automation and technology to assist in the performance of their responsibilities. This highly human-centric conflict management function relies on responsible humans to determine appropriate courses of action who are accountable for the outcomes. Thus, with a human-centered system there is little ambiguity on accountability.

***Accountability:** The obligation to answer for an action taken (or not taken) by a responsible entity.*

Regulators require accountable parties to answer for actions taken or not taken in a timely fashion to learn, understand, and improve safety in future operations. Clear lines of accountability promote safety of the National Airspace System (NAS), by ensuring actors have an unambiguous understanding of roles and requirements; when requirements are not met, regulators can take corrective action with accountable parties using tools that may or may not include enforcement action. It is also important to separate *accountability* from *liability*. Liability is a legal determination that may include financial or other legal penalties. Liability is the legal obligation to pay a claim for bodily injury or property damage (as consistent with 14 CFR §440.3). Liability is not determined by aviation regulations but by the tort system[7]. It should be noted that the regulators themselves are also accountable to others. In the United States (U.S.), the aviation regulator is the Federal Aviation Administration (FAA). The FAA, an agency of the Department of Transportation, is authorized by and is subject to Congressional oversight and, through Congress, is accountable to the American public. This accountability is evident after a safety incident or major disruption when

[7] The tort system is a legal framework that deals with civil wrongs or injuries, allowing individuals to seek compensation for losses caused by others' actions or omissions.

FAA executives are compelled to testify in Congressional hearings to answer for actions taken or not taken by the agency. Section 7.1 discusses the regulator's accountability to Congress in a bit more detail.

Aviation serves as a model for other safety-critical sectors, demonstrating the value of a culture focused on constantly improving the safety of the system. The Safety Management System (SMS) approach is defined by FAA as "the formal, top-down, organization-wide approach to managing safety risk and assuring the effectiveness of safety risk controls. It includes systematic procedures, practices, and policies for the management of safety risk" [19]. The International Civil Aviation Organization (ICAO) Annex 19 details SMS standards and recommended practices for the management of safety risk in air operations, maintenance, air traffic services, aerodromes, flight training, and design and production of aircraft, engines, and propellers [20]. The aviation safety culture includes elements of what is often referred to as a *Just Culture*. *Just Culture* is a system that promotes transparency, accountability, and learning from errors in a way that encourages open communication and reporting of safety concerns [21]. A *Just Culture* encourages individuals to self-report safety concerns, errors, observations of unsafe situations, etc. so that the entire community can learn from precursors of potential incidents and opportunities to fix systemic issues can be identified and implemented. *Just Culture* creates an atmosphere of trust [22]. Accountability is thus about safety improvement, not about punitive actions. The aviation safety culture, a *Just Culture*, and SMS have been a model for many other safety-critical sectors including healthcare, nuclear energy, rail transportation, etc.[21]

3. Need for Conflict Management

A key to aviation's ability to accommodate increasing numbers of increasingly autonomous flight operations at scale, without disrupting legacy operators, is the incorporation of automated conflict management by appropriately equipped operators. This is a premise that has driven much of the research chronicled in this paper.

Conflict management limits, to an acceptable level, the risk of encountering hazards, including collisions among aircraft. Hazards that an aircraft needs to avoid include other aircraft (or traffic), terrain, weather, wake turbulence (produced by other aircraft), incompatible airspace activity (often defined by an airspace constraint), and, when on the ground, taxiing aircraft, surface vehicles, and other obstructions on the apron and maneuvering area [23]. It should be noted that conflict management and air traffic management are not the same thing. Air Traffic Management (ATM) is defined by ICAO as, "The dynamic, integrated management of air traffic and airspace — safely, economically and efficiently — through the provision of facilities and seamless services in collaboration with all parties" [23].

Conflict management is an element of ATM that may be provided as an air traffic control service for IFR flights and for VFR flights in certain airspace classes. Pilot-provided conflict management through see and avoid relies on ATM-designed airspace to determine where VFR flight (following established procedures) is safely permitted; but it is not dependent on ATM facilities and services. Operator-dependent conflict management based on digital information may depend on ATM facilities, including surveillance, information, and communications facilities, but may be less dependent on ATM services than those operators using air traffic control services. This reliance on ATM has consequences for the accountability framework. The techniques used for accomplishing conflict management determine pilot qualifications, aircraft equipment, procedures, and operating condition requirements, as well as air traffic controller procedures, training, and qualifications. Regulators define requirements for applying these techniques in formal regulations often referred to as flight rules [24].

Throughout aviation's history, there have been two primary methods for managing conflicts among aircraft. These are differentiated by the locus of authority, responsibility, and accountability for conducting the actions associated with keeping aircraft sufficiently separated to ensure collision risk remains within an acceptable level. They are as follows:

- **A user-centric conflict management scheme exemplified by VFR:** With this method, authority, responsibility, and accountability for actions are distributed among the pilots operating in the airspace. Decisions are based on subjective criteria (e.g., "unless well clear" [25]) relying upon the pilot's judgement as to the potential risk of collision. There are few technology capabilities required and there is little sharing of operational intent. It is advisable to communicate on a Common Traffic Advisory Frequency (CTAF) to share intent, especially near an airport or in a traffic pattern [26]. There are some optional technologies available that can assist in the visual acquisition of traffic, like cockpit displays of traffic information (CDTI) which show the location of most, but not all, aircraft in the vicinity by leveraging Automatic Dependent Surveillance – Broadcast (ADS-B) and Traffic Alert and Collision Avoidance System (TCAS) technologies. Regardless, whether the pilot is assisted by technology or not, this method requires vigilance by the pilot, and all decisions for hazard avoidance actions are made by the pilot. This method also requires the visual detection of traffic; thus, operations are limited by weather conditions and aircraft must remain sufficiently clear of clouds [27]. In addition to atmospheric conditions, performance of this method is inherently limited by the pilot's vision, situational awareness, perception, cognitive ability, and the geometry of encounters. Although the residual collision risk has not been calculated, the aviation community, the regulator (i.e., FAA), and the flying public have generally found the historic safety performance to be acceptable. However, recent midair collisions have increased public scrutiny of this method [28][29][30].
- **A service-centric conflict management scheme exemplified by IFR:** With this method, authority, responsibility, and accountability for actions associated with the separation of specific aircraft primarily rests with the individual air traffic controller as delegated by the ANSP. For any given volume of airspace (e.g., sector), separation service-related decisions are centralized with the sector controller. Decisions are based on

objective criteria to apply appropriate separation minima[8] that are clearly specified. The controller relies on significant technology and automation, including surveillance systems (as well as the altimeters, transponders, and ADS-B transceivers on board the aircraft), radar data processing, flight data processing, two-way radio communication systems, traffic displays, and other ATM automation technologies. Regardless of the technology aids available, the controller is the decision-maker using their situation awareness, perception, and cognitive skills. A rigorous training and qualification process ensures desired performance of the human air traffic controller [31]. Aircraft operating under this method are not able to freely maneuver and require specific controller approval (i.e., clearances) of any flight path modification.[9] Reliable communication between controllers and pilots is essential for this service-centric scheme to be effective. This method is limited by surveillance technology, radio frequency congestion and availability, and the cognitive workload of controllers. These inherent limitations define sector capacity. Although the separation minima are clearly defined and losses of separation are documented and reported, the residual collision risk has not been quantified.

3.1. Operating Mode

This paper defines operating mode to encompass the totality of requirements for which an operator is accountable (below). To ensure the safety of flight operations, all flights must have an operating mode. Depending upon the operating mode, there may also be requirements on the ANSP and perhaps others.

Operating Mode: *Procedural and technical requirements as defined in approved regulations, policies, procedures, and training materials by which a regulator holds an operator accountable for safe operations.*

Globally, two routine operating modes are in widespread use for civil aircraft and are routine for pilots and controllers: VFR and IFR. While these operating modes are often referred to by the flight rules that define them, there are more detailed requirements regarding conflict management procedures contained in official publications, such as the Aeronautical Information Manual [26] and FAA Order 7110.65 on Air Traffic Control procedures [32]. In addition to the two routine modes, several specialized operating modes are in use for specific operations that are incompatible with the VFR and IFR operating modes. These specialized modes are limited to specific types of aircraft or types of operations or operators; and can be limited to specific airspace classes or geographic regions. Most of the specialized operating rules are prescribed in the Code of Federal Regulations (CFR). A few examples are as follows:

- Moored Balloons / Kites / Amateur Rockets / Unmanned Free Balloons 14 CFR Part 101 [33]
- Ultralight Vehicles 14 CFR Part 103 [34]
- Parachute Operations 14 CFR Part 105 [35]
- Small Unmanned Aircraft Systems 14 CFR Part 107 [36]

The FAA is expected to release a Notice of Proposed Rulemaking (NPRM) for unmanned aircraft operations beyond visual line of sight (BVLOS) of the pilot. Visual observation of the unmanned aircraft is currently required by the existing rules for small, unmanned aircraft operations [36]. As of the preparation of this report, the new BVLOS rule is embargoed; however, the NPRM is expected to include a new operating mode to be defined in a new Part 108 of the CFR. This new Part and its associated operating mode are a welcome addition by the aviation community and will enable a host of BVLOS missions that will be benefit to the aviation community and the general public. This new Part

[8] The ICAO Global Air Traffic Management Operational Concept defines separation minima as “the minimum displacements between an aircraft and a hazard that maintain the risk of collision at an acceptable level of safety” [23].
[9] There is an exception provided in 14 CFR § 91.3 for a pilot in command to deviate from controller clearances during “an in-flight emergency requiring immediate action…to the extent required to meet that emergency.”

108 is another example of a specialized operating mode that applies to a set of narrowly defined flights and operating areas.

The proliferation of specialized operating modes adds unintended complexity to airspace operations. Achieving integrated operations with existing, stable, routine operating modes supports the development of an equally stable routine operating mode for flight operations using highly automated conflict management across a breath of envisioned increasingly autonomous flight operations. This additional operating mode (i.e., Digital Flight) may also apply to appropriately equipped legacy operations.

In addition to the operating modes codified by specific regulations in the CFR, U.S. military and other public aircraft can operate in U.S.-managed flight information regions (FIR) using a procedure where the Military-authority Assumes Responsibility for Separation of Aircraft (MARSA) [26]. Internationally, "state-operated" (e.g., national security or law enforcement activity) can assume the risk of operating outside the regulatory standards provided they do so with "due regard" for the safety of civil air traffic [37]. These procedures are created to accommodate missions where standard separation is not possible (e.g., aerial refueling) or where mission security would be compromised following standard IFR procedures.

It is notable that in the U.S., remotely piloted public-use (e.g., military and security) aircraft have been flying under IFR in integrated airspace for more than two decades. Regulations and provisions for civil-operated remotely piloted IFR flights to operate routinely (i.e., without waivers and/or exceptions) are still being developed.

The existing operating modes (i.e., the two routine and the many specialized operating modes) are all human-centric, with humans having the final authority and responsibility for actions using human perception and judgement. The human may be assisted by automation technology to help gather, display, and share information; however, it is the human who is the final decision-maker. This provides a clear line of accountability.

Remotely piloted aircraft systems (RPAS) and the standards and recommended practices developed for them retain human-centric conflict management [38]. For small UAS operating under 14 CFR Part 107, the remote pilot is responsible for conflict management [36]. Accountability is unchanged because the decision-making process is not transferred to automated systems. These provisions do not accommodate automated flight operations without human reversionary modes. While the small UAS rule [36] enabled a variety of commercial applications and other civil operations (e.g., drone as first responder), the operational limitations of remaining in visual line of sight of the remote pilot limits applicability for a broader set of operational missions.

The adoption of Part 107 illustrates the value in regulatory certainty and was developed in response to sudden and tremendous growth in demand for small UAS. The small UAS approach was one of accommodation, not integration. For increasingly autonomous operations to benefit in the same way, integration into mixed use airspace is required. Restricting access to airspace was a fundamental tool to mitigate the safety risk of small UAS, but is an unreasonable restriction for AAM. Particularly for AAM operations using existing runways used by legacy aircraft for take-offs and landings and/or AAM operations that involve transporting passengers. The growth projections for AAM warrant a more inclusive and proactive approach than the reactionary experience of small UAS. Similarly, integrating AAM as IFR flights could require significant modification to the stable and well understood instrument flight rules. Limiting AAM to IFR, may strain the ATC system (placing additional burdens on existing users). IFR may have significant capacity limitations especially when considering existing separation minima. See Section 4.2 for further discussion. Restriction of AAM operations to IFR may also preclude remotely piloted m:N operations in which a single remote pilot oversees multiple remotely piloted aircraft. Human-centric conflict management is inherently limited (i.e., has a finite capacity) by radio frequency congestion and controller workload.

3.2. Conflict Management Overview

As defined by ICAO, "conflict management will limit, to an acceptable level, the risk of collision between aircraft and hazards" [23] including other traffic. ICAO defines three layers of conflict management in their Global Air Traffic Management Operational Concept (GATMOC) (See Figure 2) [23]:

- **Strategic Conflict Management:** Reduces the need for separation provision to a designated level. Strategic conflict management includes airspace organization and management, demand and capacity balancing, and traffic synchronization. Strategic conflict management can be thought of as the processes that ensures conflicts can be safely addressed using tactical conflict management tools and procedures. Strategic conflict management is not intended to eliminate the need for further conflict management actions, but to reduce the need to apply the second separation provision layer. Often strategic actions occur prior to departure, but they are not limited to pre-departure, particularly in the case of longer-duration flights but usually on the scale of 10s of minutes to hours or even days.

- **Separation Provision or Tactical Conflict Management:** Is the tactical process of keeping aircraft away from hazards by at least the appropriate separation minima. Separation provision or tactical conflict management can be thought of as the process that identifies and resolves tactical conflicts (i.e., potential loss of separation between aircraft and hazards based upon their current position and intended flight paths in the next few seconds to tens of minutes). The tactical conflict management process ensures aircraft remain away from hazards including other traffic by the appropriate separation minima.
- **Collision Avoidance:** Activates when the "separation mode has been compromised" to ensure a collision with a hazard is avoided.

As shown in Figure 2, the spatial and temporal scope (i.e., the conflict horizon[10]) of strategic conflict management is the broadest. Conversely, collision avoidance tends to consider only very short time horizons and potential collision threats in the immediate vicinity.

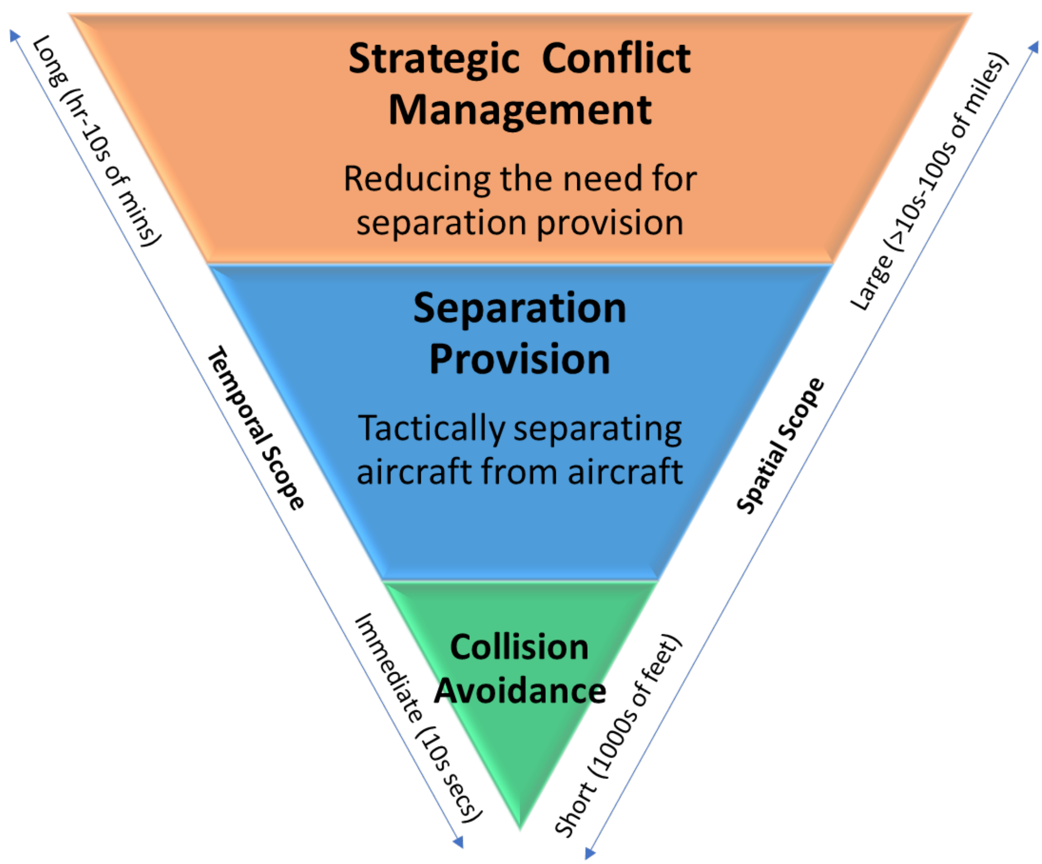

Figure 2. Simplified Model of ICAO Conflict Management Layers

[10] The ICAO GATMOC defines the "conflict horizon" as the "extent to which hazards…are considered" [10]

The separator is the agent responsible for separation provision ensuring that the distance (or time) between aircraft and hazards meet or exceed the defined separation minima. The separator must be clearly defined prior to the commencement of separation provision (i.e., predetermined) [23]. The ICAO GATMOC document makes it clear that the ATM system should minimize restrictions on airspace users; therefore, the predetermined separator should be the airspace user, unless safety or other design considerations require a separation provision service [23].

"…the predetermined separator will be the airspace user, unless safety … requires a separation provision service." – ICAO GATMOC

As we consider automating conflict management, we need to consider automation components for all three layers of conflict management defined by ICAO. The community's work to date in automating conflict management has focused on introducing automation to the strategic conflict management layer (e.g., UTM) [39] and the collision avoidance layer (e.g., TCAS [40] and DAA). Considerable research and development have been associated with the development of DAA capability. Developed to mirror "see and avoid" requirements using digital rather than visual information, DAA tends to straddle the tactical conflict management and collision avoidance layers. DAA systems rely upon surveillance information that is limited to current position and velocity. DAA may rely on a historical track to estimate heading and groundspeed. DAA, as conceived today, does not have access to traffic intent information. The limited surveillance range and heading/velocity information results in a tactical conflict management capability that tends to be constrained from tens of seconds to one or two minutes. In contrast, human-centric air traffic control services leverage intent information (i.e., flight plans and controller clearances) and can employ a longer time horizon (minutes to 10s of minutes) for tactical conflict management.

A tactical conflict management solution that addresses procedures and accountability in the middle, or tactical conflict management, layer is only partly addressed by current automation efforts (i.e., DAA standards and solutions). Addressing automation capabilities that leverage operational intent (including as the intent is altered) completes the tactical conflict management layer and could unlock significant efficiencies and scalability in airspace utilization. This is a significant missing piece between UTM and DAA and is the focus of much of the research shared in this and its companion paper [10].

Much of the community research on technologies associated with automated tactical conflict management has focused on technical and operational feasibility. This paper discusses underlying questions of accountability and viability from a regulatory oversight perspective.

4. Motivation for a New Operator-Centric Operating Mode

As indicated above, the ICAO GATMOC clearly states that the preferred separator should be the airspace user, which would tend to favor an operator-centric operating mode, unless safety or other considerations would warrant a service-centric operating mode (i.e., air traffic services). When the IFR operating mode emerged, technology capabilities associated with traffic surveillance, communications, and information were limited. There were no real technical capabilities for operator-to-operator exchange of information (other than ad-hoc voice communications) or for the operator to access system information, like flight data or radar data. This centralized access to information dictated that an service-centric conflict management operating mode (i.e., air traffic control services) was required to ensure the safe and efficient flow of traffic in complex airspace with high operational tempos. Today's technologies that enable system and intent information to be shared among operators creates an opportunity to expand operations in the same way that instrument flight created an opportunity to expand flight beyond visual conditions.

In the U.S., the FAA published concepts associated with the emerging operations of new entrants, each of which tends towards an operator-centric approach [3][4][5][41][42]. The FAA concepts are often described under the umbrella of eXtensible Traffic Management (XTM), as shown in Figure 3, and have the following characteristics in common:

- Place responsibility for conflict management on the operator
- Require information sharing among operators
- Depend upon third parties to provide information services
- Rely upon automated decision-making
- Expect cooperative operating practices to be defined by the aviation community and approved by the regulator

Figure 3. FAA Operational Concepts Associated with New Entrants [3][4][5][41][42]

Internationally, there are also significant efforts to define a future operational mode that has many of the characteristics listed above. These include concepts from Eurocontrol for U-Space [43] and Civil Air Navigation Services Organization (CANSO) [44].

4.1. Why Automated Conflict Management

The aviation community is pursuing increasingly autonomous flight operations because they are projected to:

- Reduce operational costs by reducing personnel costs, which in turn increases public access to air mobility.
- Enable business and operational scalability by reducing operational costs.
- Have the potential to improve safety by reducing variability in human performance of controllers and pilots.

It is beyond the scope of this paper to examine the validity of these motivations. However, it is believed that today's human-centered approaches to conflict management, especially tactical conflict management, are incompatible with increasingly autonomous flight operations. If the aviation community is automating the bulk of functions associated with flight operations, it seems consistent that the functions associated with conflict management should be automated as well. Although logical, this is no small matter. For over two decades the unmanned aircraft community has been attempting to create a technology equivalent to the safety intent of the requirement for the pilot to "see and avoid" [2]. The community has expanded the term DAA to include not just the sensing function but also the automated functionality of maneuvering to avoid detected traffic. Although standards have been developed [45] and accepted by the regulator [46][47], there has only been limited operational implementation via regulator-approved waivers. It is expected that the new regulations enabling BVLOS operations will rely heavily upon DAA technology. The current DAA standards, approvals, and mature prototypes are associated with a variety of surveillance sources; however, they are limited to current position, heading, and velocity and are restricted to a conflict horizon of tens of seconds. Current DAA standards and prototypes do not consider operational intent or planned trajectories.

The operational structure of ATC capabilities and procedures are incompatible with fully automated flight, as ATC is largely dependent upon voice communications between the pilot and the controller. This limitation was evident in a recent NASA-sponsored working group, which considered barriers to routine operation of multiple aircraft by a single or small number of remote pilots (i.e., multi-aircraft operations). The working group identified airspace integration as a significant barrier based on the following [48]:

- ATC interaction (which mainly occurs via voice communications) may be a limiting factor in the number of aircraft a single remote pilot can simultaneously manage.
- The remote pilot may not be able to maintain the necessary situation awareness to safely monitor multiple aircraft and interact with multiple controllers on different radio frequencies at the same time, including switching their attention among aircraft as needed.
- The remote pilot may not be able to manage the cognitive effort and maintain the necessary focus on individual aircraft necessary to maintain operational control and determine whether they can comply with controller instructions.
- If a pilot were in communication with multiple controllers simultaneously, there is a potential for the remote pilot to confuse aircraft or controllers as they respond to revised clearances and/or ATC instructions.
- Latency in communications, the need to potentially repeat communications, and delays in remote pilot response/action may have a cascading effect on traffic management efficiencies (i.e., place constraints on ATC's ability to be responsive, potentially requiring increased spacing buffers), possibly resulting in reduced capacity.

Despite significant advances over time in technology available, ATM remains a human-centric decision process and there have been limited changes in the separation minima. There are also benefits to automating the conflict management functions, which involve complex decision processes requiring a large amount of highly dynamic and static information. When compared to a human-centric decision process, automated decision processes can often be conducted faster and more precisely, reliably, and consistently. Automated processes can also incorporate increasingly complex information (e.g., probabilistic information) and individualistic tailoring. For example, if using automated conflict management, every pair of aircraft could have different required separation minima based upon the performance capabilities of each aircraft involved and the operating environment. Using human-centric decision processes, the ability to tailor separation minima is possible but more limited (i.e., the human may be able to select between a handful of potential separation minima, while an automated system could select between thousands of potential pairwise combinations) [27].

4.2. Why Focus Upon an Operator-Centric Operating Mode

As stated in the ICAO GATMOC, the preferred pre-determined separator is the aircraft operator to "minimize restrictions on user operations" [23]. This is one of many reasons to focus on exploring an operator-centric conflict management operating mode. This is also consistent with the discussions of a NASA-industry working group exploring options to address the challenges of routinely accommodating highly automated multi-aircraft operations in integrated airspace (i.e., non-segregated airspace). The NASA-industry working group discussed the concept of technology-enabled VFR-equivalent operations [48]. The concept is that technology will enable operations that satisfy the safety intent of the VFR operating mode with procedures that are generally equivalent. Although a VFR equivalent flight enables operation by reference to digital information, it stops short of capitalizing on the operational improvements that are obtained by integrating operational intent.

As an operator-centric, automated conflict management operating mode would not require ATC separation services. Responsibilities for ATC could be identical to those for VFR; thus, no significant changes to ANSP infrastructure or procedures are anticipated. The lack of a significant impact on the ANSP increases the viability of being able to incorporate a new operating mode.

Given that capabilities for complying with an operator-centric operating mode are primarily the responsibility of the operator and that decision-making is distributed among operators, such an approach can scale with traffic growth. This assumes of course that these new entrants will be capable of complying with the required conflict management capabilities and operational procedures.

5. Digital Flight Concept: Operating Mode Employing Automated Self-Separation

In 2022, NASA shared a concept for a broad operator-centric, conflict management operating mode, often referred to by the shorthand *Digital Flight* [6]. Digital Flight is a concept for employing distributed, automated conflict management that takes advantage of shared traffic situation awareness and operational intent information, improved communications, shared information services, and automation of conflict management capabilities. The concept for a Digital Flight operating mode is to augment, not replace the existing routine operating modes of IFR and VFR. Rulemaking is beyond of the scope of this paper and the DECO research, but many in the community are talking about the possibility of establishing a corresponding “digital flight rule” [49][50]. It is the intent that this new routine operating mode would be able to integrate with and harmonize with the existing operating modes. Digital Flight would be an option for any operator who can comply with the operating practices and conform to the required performance capabilities. This will enable a variety of flight missions to be covered by a single set of operating rules and standardized practices to ensure interoperability and accountability.

The operator of a Digital Flight may be a remote pilot at a ground control center; a person monitoring and authorizing an autonomous flight to take place; or an onboard PIC. In each case, a regulator-approved, automated conflict management system, associated data sources, and enabling technologies is employed by the operator to carry out this safety-critical function during operations. The required capabilities could be implemented in systems that are located on the aircraft, in the ground control station, distributed in the cloud, or any combination of these. The operator is responsible for employing and maintaining an approved automated conflict management system and accountable to the regulator for outcomes from its use in an acceptable manner. This will include complying with their regulator-approved Operational Specification, also known as an OpsSpec [51].

Digital Flight: *A future operating mode for integrated airspace in which flight operations are conducted by reference to digital information, with the operator ensuring flight-path safety through cooperative practices and automated self-separation enabled by connected digital technologies and automated information exchange.*

Digital Flight operations require that the operator is responsible for ensuring automated conflict management systems are sharing operational intent, maintaining traffic awareness, appropriately connected to information services, and that their aircraft follows the conflict resolution guidance developed by the separation algorithms. For increasingly autonomous operations, flight control systems will have the authority to execute the required maneuvers without human engagement consistent with established procedures. In the case of operations with an on-board pilot, the pilot may be directly involved with executing the maneuver based upon guidance from the automation system. The requirement to follow the automation guidance will be similar to how a pilot is accountable for complying with ATC clearances and instructions per 14 CFR §91.123 [52]. Critical conflict management decisions could be automated in nominal operations, yet an operator-centric accountability scheme will exist similar to VFR. Relying upon human execution responsibility in off-nominal situations is not preferred from either a safety or efficiency perspective but may be employed as an intermediate step to gain necessary experience with fully automated aircraft systems.

Multiple Digital Flights operations sharing the same airspace may encounter each other. These conflicts could be resolved through implicit coordination[11] or cooperatively through direct communication between the automation systems in both aircraft, resulting in more efficient flight paths (smaller separation values than those established for IFR operations today) and less use of airspace.

[11] By following the same Cooperative Practices and having shared situational awareness, manuvers will be expected and predictabile without direct coordination.

Automated conflict management for Digital Flight will be enabled by four essential elements, regardless of the type of aircraft or operation. As shown in Figure 4, these essential elements are Information Services and Connectivity, Shared Traffic and Intent Awareness, Cooperative Practices, and Automated Conflict Management Capabilities.

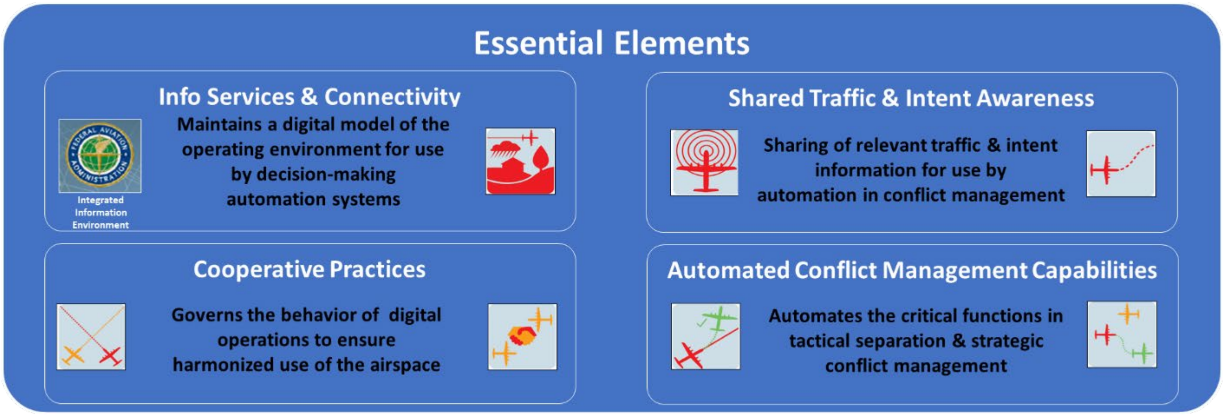

Figure 4. Essential Elements of the Digital Flight Operating Mode

The four essential elements identified in Figure 4 are mutually dependent upon each other and work together to realize the capabilities necessary to ensure that a distributed, automated conflict management operating mode can be realized. Many of these elements are discussed in other concepts in the aviation community, including concepts from the FAA [3][4][5][41][42], industry [49], and international organizations [43][44]. The DECO research introduces a critically important ingredient that helps eliminate barriers towards concept viability: operator-centric accountability for automated conflict management. By introducing clarity regarding who the regulator will hold accountable for meeting conflict management performance requirements, the aviation community will have a mechanism for ensuring safety.

More information about the approach to defining performance requirements of automated conflict management can be found in a companion NASA Technical Memorandum on Required Conflict Management Performance (RCMP) [10].

5.1. Automated Conflict Management Capabilities

The heart of the essential elements is the automation system used by the operator to ensure safe separation from all hazards. Inputs to this automation come from sources both internal and external to the operator. External information includes airspace/facility status; traffic situation and intent information; flow constraints; and environmental condition updates, which may come from the ANSP, other aircraft, or third-party information service providers. These sources are each accountable for the quality of the information provided and its dissemination in accordance with applicable standards. Information Services and Connectivity are discussed further in Section 5.2.

The operator is responsible for ensuring the separation automation is approved and maintained in accordance with applicable regulations and to act upon its flight guidance in a timely fashion. The automation software would be approved through processes and to standards accepted by the regulator, and the software must be kept up to date through an approved maintenance operation.

Encoded in the automation will be a set of Cooperative Practices (which are discussed in Section 5.4) that are developed by the aviation community and endorsed by the airspace regulator. Some Cooperative Practices may be described in FAA regulations (i.e., 14 CFR), FAA procedures (e.g., Aeronautical Information Manual), or FAA orders that offer guidance on approval of operator-planned practices. Additional details may be described in industry consensus standards which are in turn authorized by the FAA.

The role of the Automated Conflict Management Capabilities will be to accurately reflect these Cooperative Practices in a full set of automated algorithms that appropriately conform to the approved standard practices. The DECO research identified six different Automated Conflict Management Capabilities. Three align with separation provision (i.e., tactical conflict management), and three align with strategic conflict management. Table 1 lists the six principal capabilities (PC) and the corresponding operational outcomes for which there must be clarity on accountability. The rest of this section describes each PC in more detail.

Capability	Operational Outcome
PC1: Operator Self-Separation	Enables Digital Flight operators to provide their own separation from all other traffic to include VFR, IFR, and other Digital Flight operations, as well as other hazards, in lieu of visual procedures and ATC separation services.
PC2: Shared Separation	Enables Digital Flight operators to share intent information with other operators to distribute or share the separation role equitably and safely following accepted Cooperative Practices. Enables reduced minimum separation minima relative to PC1.
PC3: Pairwise Coordinated Separation	Enables Digital Flight operators to explicitly coordinate separation actions and tailor pairwise separation minima for each encounter, creating the potential for further reducing minimum separation minima and enabling even greater efficiency gains relative to PC2.
PC4: Constrained Resource Collaboration	Enables Digital Flight operators to collaborate with resource managers (e.g., ANSP) in traffic synchronization (e.g., arrival metering) and demand-capacity balancing (e.g., flow programs, weather reroutes)
PC5: Self-Organization	Enables Digital Flight operators to organize their flight paths as needed, absent centralized coordination (i.e., without a central resource manager that provides sequencing or scheduling)
PC6: Self-Limiting Density & Complexity	Enables Digital Flight operators to sustain safe operations by managing (e.g., delaying, reducing, or rerouting) their own operations to ensure operational complexity does not constrain self-separation capabilities.

Table 1. Summary of Six Principal Capabilities Associated with the Digital Flight Operating Mode

Tactical Principal Capabilities

PC1, Operator Self-Separation is the most basic of the Automated Conflict Management Capabilities and provides conflict detection and resolution that result in appropriate separation from hazards, including other aircraft (i.e., primarily VFR and IFR flights) without additional information other than current position and an estimate of the velocity vector. Both cooperative (e.g., Mode C, ADS-B, and TCAS) and non-cooperative surveillance sensors (e.g., phased array radar) will provide information on surrounding traffic. Automation applies computational speed and precision to track potentially large numbers of flights and other hazards including terrain, weather, protected airspace, etc. Similar to VFR, the responsibility for maintaining appropriate separation from other traffic is distributed to each Digital Flight operator. The operator will ensure that the aircraft remains sufficiently separated from IFR traffic to avoid disrupting their flight path or impacting controller workload. While the capability to self-separate is heavily dependent upon surveillance information and automation algorithms, the functionality is independent of other sub-systems (e.g., connectivity to third party service providers).

PC2, Shared Separation occurs when two or more flights are sharing accurate position and intent information with each other so that decision agents have common information regarding any conflict. Flights will implicitly cooperate by following accepted Cooperative Practices (e.g., that determine which aircraft in an encounter has the right of way), ensuring that separation can be maintained with efficiency. The sharing of intent information will likely enable separation minima to be reduced and false alerts and unnecessary maneuvers reduced significantly. For example, an aircraft that is turning that appears to present a conflict which will be eliminated as the aircraft intends to complete a turn. The sharing of intent information coupled with implicit cooperation extends the planning horizon, reduces total maneuvering, and increases flight efficiency.

PC3, Pairwise Coordinated Separation enables operators to explicitly coordinate separation actions and tailor separation minima for each specific encounter. Aircraft in the encounter will need to directly exchange data in near-real-time to coordinate maneuver actions. This ability to directly coordinate maneuvers creates an opportunity to potentially further reduce separation minima and may offer greater efficiency gains when compared to just PC1 and PC2. Separation minima can also be tailored to each pairwise encounter based upon each participants' performance capability as defined in specified requirements. This pairwise coordination is the central topic to our companion paper [10]. Pairwise separation minima can also consider other factors (e.g., wake turbulence spacing requirements) besides conflict management performance capabilities.

Strategic Principal Capabilities

PC4, Constrained Resource Collaboration enables Digital Flight operations to comply with time-of-arrival and interval management instructions associated with traffic flow management initiatives put in place to synchronize traffic flows and balance demand and capacity. This will facilitate the operational integration of Digital Flight operations with IFR traffic flows into major airports and in highly congested airspace. The implementation of time-based flow management initiatives would facilitate the operator's ability to comply without controller-issued clearances reflecting flow management instructions.

PC5, Self-Organization is the capability for Digital Flight operators to organize their flight paths in the absence of a resource manager or centralized coordinator (i.e., without centralized sequencing or scheduling) to structure flows to constrained resources. This is similar to how pilots of VFR flights at non-towered airports enter into and organize a traffic pattern by sharing intent (via CTAF) and following established procedures in a distributed fashion. This capability is likely to be applicable in situations where there are structured flows to make efficient use of runways at non-towered airports, constrained airspace around severe weather, traffic coordination at airspace boundaries, etc.[53] Cooperative practices will be essential in establishing the expected distributed behaviors that will ensure the appropriate behavior emerges. There are numerous examples of complex behavior emerging from relatively few simple well-crafted rules [54][55][56][57]. Self-organizing into structured flows reduces conflicts and higher-risk encounter geometries (e.g., head-on encounters) as well as ensuring efficient use of available capacity at runways and in constrained airspace.

PC6, Self-Limiting Density & Complexity is the capability for an operator to monitor traffic density and complexity, determine when self-separation capabilities could potentially be over-constrained, and choose flight paths or delay operations to reduce these limits, including potentially avoiding the complex region altogether. This ensures that operational flexibility will remain to adjust flight paths to address tactical separation conflicts which may arise. This capability is highly dependent upon understanding the performance of the other five Automated Conflict Management Capabilities [10] and awareness of the traffic situation and planned intent associated with a given operational area.

5.2. Information Services and Connectivity

In September 2021, the FAA released a vision for the future operations of the NAS which espoused the notion of info-centric operations [41]. The FAA's goal is to take NAS operations to the "next level of safety and efficiency" in the next decade by "leveraging the information and connectivity revolution" as they integrate some truly revolutionary technologies, like autonomous vehicles [41]. Closely aligned with the FAA's vision is the Digital Flight essential element Information Services and Connectivity. Information is central to a digitally enabled operating mode in which conflict management is automated. The FAA vision for information services introduces the concept of Third-Party Service Providers (3PSP) to include organizations other than the ANSP, regulator, or operator that provide information and services essential to the safe operation of an aircraft[12]. This allows operators to access commercially provided essential information and connectivity among operators and with the ANSP to realize the info-centric vision. Information services may include traffic situation awareness, traffic intent, resource status, airspace constraints, hazard information, winds, weather, surveillance, and other aeronautical information. More active information services may include authentication, approvals, compliance monitoring, conflict detection, restriction management, flight planning, etc. Connectivity to these information services may be required through an operations center or by the aircraft itself.

[12] SkyGrid, a Boeing Joint Venture, recently publicly released a 3PSP operational concept [58].

Aircraft may require some level of aircraft-to-aircraft connectivity to directly exchange information that enables some of the Automated Conflict Management Capabilities that explicitly coordinate maneuvers (e.g., PC3: Pairwise Coordinated Separation).

Operational safety and efficiency would be enhanced by striving towards a *common operational picture* where, as the foundation for distributed decision-making, all operators draw from compatible operational information, including weather, traffic, intent, and aeronautical information. Distributed decision-making is most effective when there is shared situation awareness. Although it is difficult for all agents to have identical information in a distributed, highly dynamic system, the purpose of information services and connectivity in part is to strive towards what is realistically achievable, given computational and communication latency.

The concept of a *common operational picture* is based upon the military notion where a single set of relevant operational information is shared by more than one entity. In the military usage, a common operational picture facilitates cooperative planning and combined execution and assists with obtaining shared situation awareness. The term "common" applies to all involved agents, from the highest commander to the lowest soldier to the attached airman. "Operational" refers to actual, preferably real-time, status and developments. "Picture" refers to a single, combined, representation of the environment, forces, and actions. Taken together, a common operational picture enables both the lowest soldier and the highest commander to independently and immediately sense and act collaboratively to achieve the predefined mission and commander's intent. To achieve cooperative distributed decision-making on the battlefield, a common operational picture is a necessity [59].

A major function of the 3PSPs is to contribute towards the common operational picture for increasingly autonomous aircraft operations.

5.3. Shared Traffic and Intent Awareness

Shared Traffic and Intent Awareness can produce significant operational gains for participating Digital Flight operators. Shared operational intent data will compliment shared aircraft state data to create an accurate representation of surrounding traffic and their expected future state. This information is a highly dynamic component of the common operational picture discussed in Section 5.2.

In cases where electronic conspicuity is not mandated or otherwise cannot be relied upon (e.g., for some VFR traffic that are not participants in cooperative surveillance), traffic situation awareness information may come from non-cooperative methods such as radar, acoustic, or electro-optic sensors located on the aircraft or positioned elsewhere as part of a shared surveillance network. In either case, intent information for these aircraft is unavailable. Traffic situation awareness and intent information for other aircraft may be received directly from the other aircraft from transmission such as ADS-B OUT and Mode S transponder returns. Other sources of traffic and intent information may include FAA surveillance and rebroadcast services or from third party service providers. The sending party is accountable for maintaining the source of this information in accordance with applicable standards and regulations. If a link is used in its transmission to the using party, the provider of that link is accountable for the link's performance.

Operators participating in digital operations (i.e., Operator-centric, automated conflict management) are responsible for sharing traffic information and intent in accordance with applicable standards and regulations. They are ultimately accountable for the performance of their systems by maintaining and operating equipment correctly.

Conformance monitoring is an important component of ensuring appropriate performance of participating operators. Operators should be monitoring their own performance as a part of safety assurance (see Section 6). As Digital Flight operators share their intent, they may also share their conformance state for use by other Digital Flight operators in determining if a response is needed. For instance, an aircraft might share "0.5 nmi left of course; correcting course" to indicate to others their own awareness and actions. There may also be system level conformance monitoring that is performed as part of an In-time Aviation Safety Management System (IASMS), which will be discussed further in Section 6.

5.4. Cooperative Practices

Automated Conflict Management Capabilities will embed in software algorithms a set of Cooperative Practices[13] (abbreviated as CP) to promote harmonized use of the shared airspace and most efficiently and fairly perform functions associated with separation and airspace integration. The Cooperative Practices themselves must be standardized especially when they govern coordinated procedures to be employed by aircraft associated with multiple operators. The Automated Conflict Management Capabilities will perform the separation functions without a human decision-maker directly overseeing their operation and without a human in a reversionary role. Therefore, to ensure required safety performance, the automation must adhere to the required performance in all scenarios and environments encountered during its operation. The specific Cooperative Practices will be defined by the aviation community and approved by regulators. The DECO research has postulated twelve types of Cooperative Practices as a potential starting point for consideration. More detailed descriptions are required, and further research may identify additional Cooperative Practices. The Cooperative Practices developed by the DECO team are listed in Table 2.

ID	Cooperative Practice	Purpose
CP-A	Share and Update Intent	Increase predictability, efficiency, stability, and safety
CP-B	Take Timely Action	
CP-C	Consider Intent When Changing Intent	Minimize disruption to existing operations
CP-D	Defer to VFR and IFR Aircraft	
CP-E	Navigate with Intended Precision	Increase airspace capacity, reduce actionable conflicts
CP-F	Apply Pair-Appropriate Separation	
CP-G	Respect Right-of-Way Among Digital Flight Aircraft	Distribute separation burden, increase safety
CP-H	Coordinate Maneuvering Among Digital Flight Aircraft	
CP-I	Coordinate with ATC in Controlled Airspace	Facilitate airspace integration, minimize controller workload, minimize disruptions
CP-J	Join in Appropriate Flow Management	
CP-K	Avoid Active Protected Airspace	
CP-L	Comply with Established Operating Procedures	

Table 2. Summary of an Initial Set of Digital Flight Cooperative Practices

[13] As used in this document, the notion of "Cooperative Practices" is virtually identical to the concept of "cooperative operating practices" discussed in FAA documents [4][5][6][41][42]. The DECO team uses the term "Cooperative Practices" and the abbreviation CP to avoid confusion with the abbreviation COP that is widely used in the command-and-control community to mean common operational picture (see Section 5.2).

6. Accountability and Safety Assurance

Accountability is an essential element of SMS, the ICAO endorsed standard methodology for safety in aviation. SMS is defined as “a systematic approach to managing safety, including the necessary organization structures, accountability, responsibilities, policies, and procedures” [20]. Responsibility and accountability are referenced as distinct items in this definition. Responsibility is tied to the execution of a task or activity (and can be delegated) while accountability is for someone be answerable for the outcome of a decision or action (and cannot be delegated) [19].

SMS is comprised of organizational components to ensure the prevention of accidents. Safety management moves beyond the concept of punitive consequences and incorporates safety risk management and safety assurance into repeatable, proactive processes [60]. The four components of SMS are Safety Policy, Safety Assurance, Safety Risk Management, and Safety Promotion.

Safety Assurance is the monitoring and analysis to ensure the performance of the safety risk management processes to prevent the development of situations that may result in an accident. This preventative approach is designed to promote continuous improvement in safety performance. Accountability in safety assurance is taking ownership and being answerable for one’s actions or decisions. While there may be consequences for the individual when the outcomes are negative, including certificate action, the concept of accountability is distinct from that of liability (see Section 2). The Just Culture principle underlines the motivation to learn to improve safety of future operations. For the purposes of safety management and safety assurance, accountability is the important concept.

Safety Assurance cannot be achieved without a clearly understood and transparent accountability structure. The requirements of a safety assurance process include audits and evaluation, data analysis, and system assessment [62]. These processes evaluate both system and human performance and provide insight and analysis to improve safety performance for the purpose of preventing accidents. The emerging concept of IASMS, originally proposed by NASA and adopted by the National Academies[63], is being explored as part of the NASA Aeronautics Research Mission Directorate portfolio. IASMS seeks to move from the reactive cycle of SMS based on data collected over time to one that increases responsiveness by utilizing system wide safety data to provide in-time alerting and mitigation strategies [61]. The construct of an IASMS for the U.S. that relies on automated data collection is endorsed by the National Academies in its report, “In-time Aviation Safety Management: Challenges and Research for an Evolving Aviation System” where the committee makes the following recommendation [62]:

> *“The concept of real-time system-wide safety assurance should be approached in terms of an in-time aviation safety management system (IASMS) that continuously monitors the national airspace system, assesses the data that it has collected, and then either recommends or initiates safety assurance actions as necessary. Some elements of such a system would function in real time or close to real time, while other elements would search for risks by examining trends over a time frame of hours, days, or even longer.”*

The means of monitoring in a Safety Assurance model drives engineering requirements, processes, and training, each of which have independent layers of accountability. The purpose of the Safety Assurance approach is to identify and address deficiencies in the safety risk management process. It is not limited to the operational level and may identify deficiencies at the standards, training, certification, or programmatic levels where accountable individuals may or may not maintain a professional certification. The structure of hierarchical accountability allows the certificated individual at the operational delivery of conflict management to rely on the outcomes of the work of accountable persons along the safety chain[14]. For example, the air traffic controller is accountable to apply the appropriate separation standard; however, the determination that the separation distance in that standard is safe has been made by an accountable entity at another stage of the safety risk management process. In the case of a safety event related to the separation standard (e.g., wake turbulence upset), the safety assurance process would not only examine the applicability of the standard and recommend appropriate changes but should also evaluate the processes used in determining the applicability of given separation standards between aircraft types.

---

[14] Sequence of events that lead to a potential incident or accident. Avoiding incidents and accidents is about interrupting the sequence of events or breaking the chain.

An aviation safety culture is necessary for the Safety Promotion component of an SMS. Safety Promotion includes training, communication, and reporting systems within the workforce [60]. While consequences for failure within the safety chain are appropriate, a safety culture views those consequences as corrective rather than punitive in nature. The non-punitive approach (i.e., *Just Culture* as described in Section 2) is recognized as a critical step in the safety assurance process particularly in safety reporting. The value in the ability of humans to identify deficiencies that may lead to safety lapses is realized when there is a willingness to report. Systems perceived as punitive, discourage reporting, and may allow deficiencies to go unrecognized until later in the safety chain when the opportunity to correct or recover is more limited. The administrators of a safety reporting system have an implicit accountability to the reporters to evaluate the identified safety issues and inform the appropriate entities who are accountable for taking corrective action.

Accountability for outcomes occurs throughout the safety management process and has consequences for conflict management. The issue of accountability is not confined to the interaction between pilot and controller. It is essential to analyze accountability throughout the decision-making processes in the conflict management function, particularly at the points where humans interact with automation, and to ensure that the accountability assigned to the human is appropriately applied at the point where the human interaction had the ability to affect the outcome.

7. Hierarchical Accountability

The concept of hierarchical accountability in aviation operations is not new. Aircraft maintenance provides a straightforward example. Before a flight can depart, the pilot is accountable to ensure that any required maintenance items are complete and that they are operating an airworthy aircraft. However, the pilot does not directly inspect or supervise the maintenance to be done. There are many parties involved as the following examples demonstrate:

- The pilot is accountable to ensure there is a sign-off by a licensed mechanic in the logbook.
- The aviation mechanic is accountable for completing the work consistent with the requirements of their license and the operator's requirements.
- The operator is accountable for hiring qualified staff and training them.
- The operator is accountable for maintaining appropriate records to demonstrate that the proper maintenance has been completed.
- At a Part 121 airline, the flight dispatcher and the PIC are accountable for ensuring that the aircraft assigned to a planned flight has the necessary records to show that all required maintenance has been completed and that there are no items on the minimum equipment list (MEL) that are past due inspection and/or maintenance.
- The regulator is accountable to ensure the licensing process is adequate to ensure competency.

For air carriers, these responsibilities and accountabilities are documented in the Operational Specification, or OpsSpec [51], prepared by each operator and approved by the regulator. Each party in the accountability chain [63] relies on the presumption that the previous accountable person is competent and qualified by virtue of the position they hold. The structure of trust is built on these established accountability frameworks.

7.1. Regulator Accountable to Congress and the American People

In the U.S., the top level of aviation accountability is to the American public. It is at this level that the policy framework is established. The U.S. Congress, who are accountable to the voting public, authorizes, provides a mission mandate, appropriates funding, and provides oversight to the Federal agency (i.e., the FAA) responsible for safety oversight of aviation (i.e., the regulator). Public attention or concern can be a triggering event for additional legislation that provides specific guidance to the regulator. A relatively recent aviation example is the Colgan Air crash in 2009 that resulted in Congressional requirements for the FAA to mandate a minimum amount of experience for air transport pilots [64]. Catastrophic events can also trigger major changes related to accountability. For example, in 1996, the Valujet crash highlighted concern for the FAA's so called "dual mandate" to both promote the aviation industry and serve as its safety regulator.[65] The perception that the requirement to promote the industry could be at odds with the safety mandate led to reform as Congress removed the 1958 language requiring the FAA to promote the aviation industry in the 1996 FAA Authorization. In 2020, in response to the fatal crashes of the Boeing 737-Max, Congress enacted changes to the aircraft certification process. Ultimately, the regulator (i.e., the U.S. FAA) is accountable to the public as represented by the Civil Government (i.e., the U.S. Congress).

Top-level operational entities will be accountable to the regulator.

Certificated organizations (e.g., air carrier or operator) and certificated persons (e.g., pilot, controller, mechanic, flight dispatcher) are explicitly accountable to the regulator. The accountability structure is explicitly tied to the certificate and the standards and practices developed. As the licensing structure applies to both the organization and the individual, there exists a construct of dual hierarchical accountability. Under this structure, a licensed person is accountable to both the regulator and the employing licensed organization. Conversely, the licensed organization is accountable for the actions of its licensed employee. The license is the primary mechanism to assure accountability throughout the safety chain. This construct of trusted accountability also allows for contracted services where a licensed organization, like Maintenance, Repair, and Overhaul (MRO) providers, are accountable to both the customer (e.g., air carrier or operator), who may also be a licensed entity, and to the regulator. In contracted services, both the service provider and the entity that contracts for the service are accountable to the regulator for the outcome of the contracted service. See Figure 5.

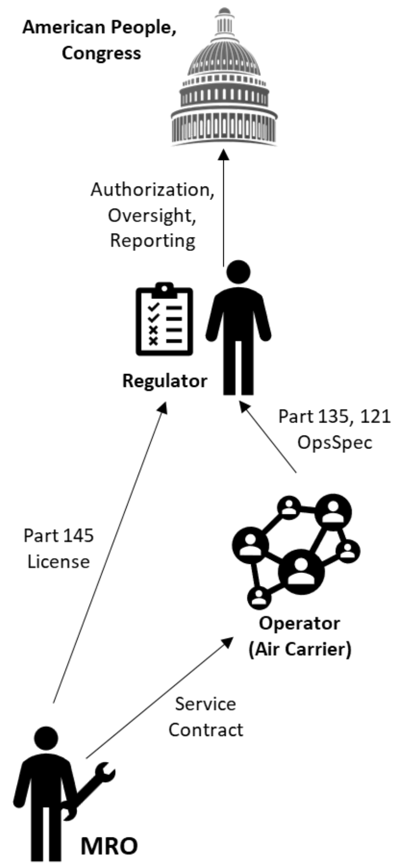

Figure 5. Dual Accountability of the MRO (i.e., Third Party Service Provider) to the Regulator and to the Operator

7.2. The Conflict Management Function May Have a Dual Hierarchical Accountability Structure

Under IFR, the air traffic controller is accountable to issue an air traffic clearance that ensures an aircraft will be safely separated; the pilot is accountable to comply with the clearance; aircraft maintenance is accountable to ensure the aircraft and avionics are in operational condition to execute the prescribed maneuver; and the operator is accountable for hiring and training programs to ensure staff are appropriately qualified and trained. This is the organic hierarchical accountability structure for human-centric conflict management.

As we contemplate shifting to an operating mode with distributed, automated conflict management dependent upon the sharing of operational intent and information services from one or more 3PSPs, an appropriately defined hierarchical accountability structure is needed. The FAA has publicly indicated that they are considering approving and licensing 3PSPs of information services such as UTM Service Suppliers (USS) under a new 14 CFR Part (i.e., Part 146) [66]. Thus, for automated conflict management, there may be three entities with top-level accountability directly to the regulator: the operator, the pilot-in-command, and the 3PSP. Similar to the MRO example, the 3PSP providing information services for conflict management may have dual accountability to both the regulator and the operator with whom they contracted to provide the service. See Figure 6.

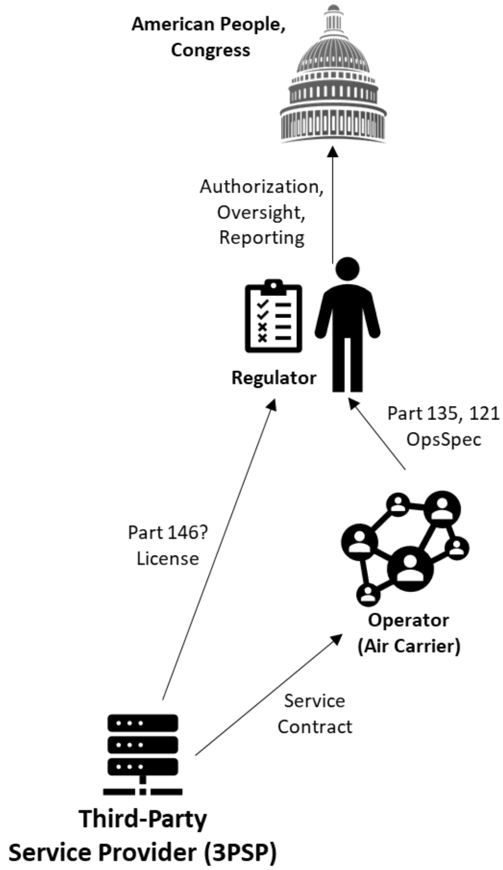

Figure 6. Potential Dual Accountability of Information Service Providers (i.e., 3PSP) which are Essential for Automated Conflict Management Capabilities

8. Explicit and Implicit Accountability

It is accepted practice within the aviation community that both explicit and implicit accountability exist. For our research we clearly distinguish the two with the following descriptions:

- **Explicit Accountability** is clearly observable, well documented, and usually defined in law, regulation, stated policy, and/or formal agreements, creating an explicit authority for one party to hold another party accountable. It often documents possible formal consequences.
- **Implicit Accountability** is implied and usually inferred from procedures, training, common practices, or social contracts with peers and does not overtly grant authority to hold another party accountable. There may be implied voluntary corrective actions. Accountability may not be clearly observable or generally understood. The community accepts that ambiguity exists.

Accountability is outcome based. Within a safety culture, both explicit and implicit accountability play important roles. An examination of the process of accident investigation provides important insight into the concept. In determining the causal factors of an aircraft accident, missed opportunities to prevent the accident (i.e., an action not taken) are identified. Although these may not be declared as a "cause" of an accident, each missed opportunity to prevent an accident can be perceived as contributory, since prevention is the goal of effective safety systems. While causal factors are the basis for explicit accountability, the contributory factors may illustrate implicit accountability. A clear example of this principle is found in the development of Crew Resource Management (CRM). Several high-profile accidents highlighted the shortcomings of a hierarchical structure in which decisions of the individual with explicit accountability (the Pilot in Command) went unchallenged [67]. The development of CRM clarified that other crew members with knowledge of a safety risk are implicitly accountable for not having communicated that information. This implicit accountability goes beyond emergency situations and includes safety reporting as a critical component of a positive safety culture.

Increasingly automated and distributed operations are driving a need for clarity on accountability especially for separation provision or tactical conflict management. For human-centric tactical conflict management, who is accountable for the outcomes is straightforward. However, with an automated conflict management capability, decision-making and execution is performed by systems that are human designed and operate with human oversight but without direct human engagement. That is, the human has a management role and would have limited visibility into the system's decision-making processes and little opportunity to intervene or override the system because they have incomplete information.

Accountability is a central piece of the regulatory and "social contract" landscape for aviation today and likely into the future. As increasing levels of autonomy and automation are implemented, moving decisions from human actors to systems and processes (centralized or distributed), new, unambiguous structures for assigning accountability are needed. The shift in accountability associated with automated self-separation is the single greatest difference between existing flight rules and future Digital Flight operations.

Clarity in *explicit* accountability currently comes from laws, regulations, policies, and other formal, legally binding agreements. *Implicit* accountability is somewhat intentionally ambiguous, ultimately residing with one of a few "top-level" individuals or organizations (i.e., the Pilot in Command, the air carrier/operator, and the ANSP/controller) and dependent on professional judgement. This combination of clarity and ambiguity is acceptable in a human-centric process due to the high degree of reliance on human decision making and existing confidence that in the aftermath of an accident or incident an appropriate determination of accountability and corrective actions can be established based on the specifics of the event. In general, in the U.S., society seems less comfortable with ambiguity and failure associated with technology than with people [68]. As decision making and other functions are moved from individuals to automated systems, the human-centric ambiguity will likely cease to be acceptable and becomes a potential barrier for the implementation of automated self-separation and other increasingly distributed and interconnected technologies and operations.

Explicit accountability can be tied to the ability to take enforcement action. However, an effective safety culture requires more complex interactions among the accountable actors. This introduces the concept of implicit accountability. It is within this construct that safety professionals are accountable to each other. For example, in VFR operations, pilots are implicitly accountable to each other for following rules of the road and established procedures and conventions (e.g., traffic patterns).

The controller is implicitly accountable to the pilot to issue clearances that do not place an unnecessary burden on the pilot. Although the pilot has the authority to refuse a clearance, the pilot is explicitly accountable to the controller to comply with a clearance that does not compromise safety of flight per 14 CFR 91.123. A pilot who does not comply with a controller instruction can be reported to the regulator for a “pilot deviation.” A pilot can also raise a complaint regarding a controller’s or another pilot’s actions that can be referred to the regulator for action.

Conflict management is the application of rules, standards, and practices to achieve a safety outcome. Each person in the safety chain is tasked with responsibility for this outcome. This is a point where we can draw a distinction between responsibility and accountability. Although overall responsibility can be shared, accountability is tied to individuals or entities along the safety chain for specific functions or actions. This would remain true for increasingly autonomous flight operations and operator-centric, automated conflict management.

9. Explicit and Implicit Accountability in Automated Self-Separation

With a highly automated, operator-centric conflict management operating mode, both *explicit* and *implicit* accountability will need to be identified within the hierarchical accountability structure that will be defined by the regulator. As indicated above, with highly automated, interconnected, and distributed operations, accountability for actions taken or not taken is not necessarily self-evident. There is a need to balance *explicit* accountability with the burden of holding new operations to a more prescriptive measure of accountability than the ambiguity that is acceptable in human systems. Finding the right balance is important because creating too high a measure of explicit accountability may hinder progress without necessarily increasing safety.

9.1. Explicit Accountable to the Regulator

An operator authorized to employ automated conflict management must be *explicitly* accountable to the regulator as a mechanism for the regulator to assure the public that the operation is safe. The regulator defines the requirements through regulations, recognized standards, and other formal documents, and they compel a prospective operator to prove their qualification through the operational approval process. They can also issue formal consequences to the approved operator for non-compliance. Requiring adherence to a specified performance level would be the means by which the regulator could hold the operator accountable, thus ensuring operations are conducted within an acceptable level of risk.

A new operational concept employing novel approaches to conflict management would not be viable without this clarity. Having a new operating mode comprehensively addressing a wide range of potential operational missions and aircraft types avoids having multiple and potentially conflicting accountability structures which could be either a burden or a source of unintended ambiguity for both operators and regulators.

Similarly, if third parties are authorized by the regulator to provide information services that are critical to the conflict management function (especially the tactical conflict management or separation provision layer) they too will likely have *explicit* accountability to the regulator.

9.2. Implicit Accountable to Other Operators

Under the user-centric accountability scheme (described in Section 3), automated conflict management will be a distributed function. As with distributed human operator-centric flights (i.e., VFR), operators are *implicitly* accountable to each other. Operator-centric operations are interdependent, implying a social contract for cooperative behavior. If one operator fails in their role (e.g., non-conformance to the Cooperative Practices), it impacts other operators as they may need to compensate for the degraded state. This is true whether conflict management is human-centric or automated. Operator accountability to each other is implied by the Digital Flight framework, including the need to follow Cooperative Practices and adhere to required performance associated with the automated capabilities. As long as the aircraft's flight control system is in compliance with the guidance of or boundaries established by the automated conflict management system, the operator will be meeting their responsibility and their accountability is satisfied. Regulators may receive complaints from operators about other operators who fail to follow the Cooperative Practices, and the regulator could hold the non-compliant operator explicitly accountable.

9.3. Implicit Accountable to the ANSP

Operator accountability to the ANSP is necessary for operations in ANSP-controlled airspace. With operator-centric, automated conflict management, the operator is accountable for deconflicting with IFR traffic. If the operator fails to adhere to the Cooperative Practices (e.g., does not conform to shared intent, does not appropriately join in flow management), it impacts the ANSP as they may need to compensate for a degraded state. If the operator of a Digital Flight does not appropriately maintain the necessary separation from an IFR flight, the ANSP may need to intervene. *Implicit* accountability here is to the ANSP since the ANSP is responsible for the IFR conflict management function. Thus, if the operator does not behave as expected, they have created a burden on the ANSP similar to the violation of the social contract with another operator as described in Section 9.2. This is a peer-like relationship. The ANSP may in turn inform the regulator of the non-compliance. Again, the regulator could hold the non-compliant operator *explicitly* accountable.

This is analogous to how an operator (i.e., the pilot) is implicitly accountability to the ANSP in today's operations. If a pilot fails to follow ATC instructions, they may be told to "call this number" upon landing. If the ANSP is not satisfied with the explanation, they can refer the situation to the regulator who can formally hold the operator accountable (i.e., explicit accountability).

9.4. Accountability of Developers

The aviation regulator develops regulations, establishes accepted procedures, and formally accepts industry consensus standards. Developers of systems and components in turn work towards confirming that their products are in compliance with these regulations, procedures, and standards. The regulator formally confirms this compliance through the certification process, a form of explicit accountability. This will be true of the Automated Conflict Management Capabilities associated with operator-centric, automated conflict management. While the operator is accountability for the outcomes of automated self-separation, developers of systems and components that comprise the automated self-separation integrated system will have a degree of *implicit* accountability to the operators for the performance of the capabilities. As the system is certified by the regulator they will have *explicit* accountability to the regulator. There is also implicit accountability of the regulator and the industry that develops standards to the aviation community and flying public for the quality and accuracy of those requirements to achieve the safety objectives.

10.Summary: Accountability for Automated Self-Separation

AAM is a revolution in aviation that introduces an emerging transportation system using increasingly autonomous aircraft with advanced technologies promising safe, efficient, and affordable travel. Scaling automated flight to become a viable mode of transportation will likely require a shift towards automated conflict management.

A key pillar of SMS, the ICAO-mandated safety framework implemented by regulators around the world, is Safety Assurance which uses accountability as a mechanism by which a regulator can ensure safe operations. As a safety-critical function, automated conflict management will require clarity on accountability. An operator-centric accountability scheme (i.e., self-separation) is a logical extension of the existing human-based operating mode of VFR. To establish clarity on accountability, three primary questions need to be explored:

- *Who* is accountable?
- To *Whom* are they accountable?
- For *What* are they accountable?

To appropriately answer these questions, this paper and a companion paper [10] consider several key concepts. First, ambiguity in implicit accountability exists in human systems and is likely to be acceptable in the future. Second, accountability is different than the authority and responsibility to act and thus the accountable party may be different than the agent who executes a given function. Finally, while authority and responsibility may be delegated to a fully automated system, accountability must ultimately reside with humans either individually or collectively (e.g., an organization).

With an operator-centric, automated conflict management capability, primary accountability will likely shift from pilots and/or controllers to operators and potentially 3PSPs. The 3PSP is expected to be accountable to the operator and the operator accountable to the regulator for selecting an appropriately qualified and competent 3PSP; if 3PSP certification mechanisms are developed, explicit accountability between the 3PSP and the regulator is also likely.

To answer the question of "for what?" an entity is accountable, functional allocation of roles and responsibilities for increasingly autonomous operations needs to be conducted with greater resolution than is traditionally necessary from an accountability perspective in human-centric operations. The perception of shared accountability is the result of a function not being sufficiently decomposed; this can lead to confusion, safety assurance gaps, or scapegoating and should be addressed until a clear accountable entity is identified for each function. The result is hierarchical accountability. The answer to "for what" an entity is accountable may shift more to an oversight, qualification verification, and planning activity set rather than a real-time implementation set of actions. Similar to how a PIC today is accountable to ensure that a preflight inspection was completed but may not be the one performing the detailed inspection, the responsibility to conduct an action may be more frequently removed from the entity accountable for its outcome with automated self-separation. Ultimately, the accountable party is responsible for ensuring that the Automated Conflict Management Capabilities are configured to perform as required by a defined set of required performance standards. Discussion of required conflict management performance is discussed in detail in the companion paper [10].

In today's human-centric system, *explicit* and *implicit* accountability co-exist. The aviation community accepts the ambiguity associated with *implicit* accountability because there is confidence that post-incident processes are in place for human-centric decisions that can appropriately determine what went wrong to ensure corrective actions are taken to avoid similar incidents in the future. These processes are built around SMS and a *Just Culture.* The Digital Flight framework summarized in this paper, coupled with quantifiable required performance capabilities as described in our companion paper [10], can be the basis of the clarity necessary for operational approval by regulators of automated self-separation systems (i.e., operator-centric, automated conflict management).

Realizing the vision of Digital Flight, or any other concept of operator-centric, automated conflict management will ultimately require regulator approval. To be successful, any proposal for a new operating mode must establish *explicit* operator accountability to the regulator for automated self-separation, clarify *implicit* operator accountability, and offer a measurable performance construct establishing for what the operator will be held accountable (see companion paper [10]). These components could significantly enhance the viability of a new operating mode in the eyes of the regulator and thus accelerate its authorization. This paper and its companion paper [10] are intended to provide a foundation from which these issues can be explored further towards implementation.

11. References

[1] U.S. Department of Transportation, *Advanced Air Mobility Interagency Working Group*, https://www.transportation.gov/aamiwg, Accessed May 6, 2025.

[2] Title 14 Code of Federal Regulations, §91.113, *Right-of-way rules: Except water operations*.

[3] Federal Aviation Administration (FAA), *Concept of Operations v2.0: Unmanned Aircraft Systems (UAS) Traffic Management (UTM)*, FAA, Washington, DC, March 2020.

[4] Federal Aviation Administration (FAA), *Urban Air Mobility (UAM): Concept of Operations v2.0*, FAA, Washington, DC, April 2023.

[5] Federal Aviation Administration (FAA), *Upper Class E Traffic Management (ETM): Concept of Operations v1.0*, FAA, Washington, DC, May 2020.

[6] Wing, D., Lacher, A., Ryan, W., Cotton, W., Stilwell, R., Maris, J., and Vajda, P., *Digital Flight: A New Cooperative Operating Mode to Complement VFR and IFR*, NASA/TM-20220013225, NASA Langley Research Center, Hampton, VA, September 2022.

[7] Drouilhet, Paul, *Electronic Flight Rules (EFR)-A Concept for Enhanced Freedom of Airspace*, SAE Technical Paper 800735, March 1980.

[8] Wing, David J., and William B. Cotton. *Autonomous Flight Rules-a Concept for Self-Separation in US Domestic Airspace*, https://ntrs.nasa.gov/api/citations/20110023668/downloads/20110023668.pdf, No. NASA/TP–2011-217174, Hampton, Virginia, November 2011.

[9] Sievers, T. F., Geister, D., Schwoch, G., Peinecke, N., Schuchardt, B. I., Volkert, A., & Lieb, T. J., *DLR Blueprint – Initial ConOps of U-Space Flight Rules (UFR)*, https://www.dlr.de/en/fl/media/publications/reports/2024/dlr_blueprint_ufr_conops.pdf, Accessed 4 December 2024, DLR Institute of Flight Guidance, March 2024.

[10] Wing, D., Lacher, A., Cotton, W., Stilwell, R., and Dietrich, A., *The Viability of Digital Flight, Part 2: Requiring Performance for Conflict Management*, NASA/TM-20250007129, NASA Langley Research Center, Hampton, VA, July 2025.

[11] National Academies of Sciences Engineering, and Medicine, *Advanced Aerial Mobility: A National Blueprint,* 2020, https://nap.nationalacademies.org/catalog/25646/advancing-aerial-mobility-a-national-blueprint, Accessed 21 February 2025.

[12] ASTM, Inc., *Standard Terminology for Aircraft*, F3060-25, May 2025.

[13] ASTM, Inc., *Autonomy Design and Operations in Aviation Terminology and Requirements Framework*, Technical Report 1, 2019.

[14] National Academies of Sciences Engineering, and Medicine, *Autonomy Research for Civil Aviation: Toward a New Era of Flight*, 2014, http://nap.edu/18815, Accessed 13 May 2025.

[15] ASTM AC377, *Roles and Responsibilities for Operational Control in the Age of Increasingly Autonomous Flight*, 2023, https://www.astm.org/about/white-papers, Accessed 14 May 2025.

[16] May, P.J., *Regulatory Regimes and Accountability*. Regulation & Governance, 1: 8-26. https://doi.org/10.1111/j.1748-5991.2007.00002.x, Accessed 14 May 2025.

[17] Woods, David D. *Conflicts between learning and accountability in patient safety*. DePaul Law Rev. 54, 2004, https://via.library.depaul.edu/cgi/viewcontent.cgi?article=1404&context=law-review, Accessed 14 May 2025.

[18] Lacher, A.R., Ren, L., Maroney, D. R., Schulenberg, C., and Daniels, J. *Dimensional Role Analysis: The Role of Humans and Automation for Increasingly Autonomous Aviation Systems*, Integrated Communication, Navigation and Surveillance Conference (ICNS), Herndon, VA, USA, 2023.

[19] Federal Aviation Administration, *Safety Management Systems (SMS)*, https://www.faa.gov/about/initiatives/sms, Accessed 16 June 2025.

[20] International Civil Aviation Organization (ICAO), *Annex 19 - Safety Management, 2nd Edition*, July 2016.

[21] Dekker, Sidney, *Just Culture: Balancing Safety and Accountability*, Ashgate Pub Company. 2007.

[22] Reason, James, *Managing the Risks of Organizational Accidents*, Ashgate Publishing, 1997.

[23] International Civil Aviation Organization (ICAO), *Global Air Traffic Management Operational Concept*, Doc 9854, ICAO, Montreal, Québec, Canada, 2005.

[24] Code of Federal Regulations, Title 14, Part 91, *General Operating and Flight Rules*.

[25] Code of Federal Regulations, Title 14, §91.113, *Right-of-way Rules: Except Water Operations*.

[26] Federal Aviation Administration, *Aeronautical Information Manual (AIM)*, https://www.faa.gov/air_traffic/publications/atpubs/aim_html/, Accessed 16 May 2025.

[27] Code of Federal Regulations, Title 14, §91.155, *Basic VFR weather minimums*.

[28] Husain, Sohail, *Making Sense of the DCA Midair Collision: Insights from the NTSB Investigation*, Eno Center for Transportation, March 28, 2025, https://enotrans.org/article/making-sense-of-the-dca-midair-collision-insights-from-the-ntsb-investigation/, Accessed 16 May 2025.

[29] Lewis, Russell, *There's a serious safety issue,' investigators say following DCA midair collision*, National Public Radio, March 12, 2025, https://www.npr.org/2025/03/11/nx-s1-5324543/ntsb-dca-mid-air-collision-american-black-hawk, Accessed 16 May 2025.

[30] Cervantes JR., Fernando, and Gonzalez, Daniel, *Two dead after small planes collide mid-air near Marana airport in Arizona, officials say*, USA Today, Feb 19, 2025, https://www.usatoday.com/story/travel/2025/02/19/marana-arizona-plane-crash/79207852007/, Accessed 16 May 2025.

[31] Federal Aviation Administration, *Air Traffic Controller Qualifications*, https://www.faa.gov/air-traffic-controller-qualifications#:~:text=Training%20requirements&text=After%20graduating%20the%20academy%2C%20individuals,becoming%20a%20certified%20professional%20controller., Accessed 16 May 2025.

[32] Federal Aviation Administration, Order JO 7110.65BB, *Air Traffic Control*, 20 February 2025.

[33] Code of Federal Regulations, Title 14, Part 101, *Moored Balloons, Kites, Amateur Rockets, and Unmanned Free Balloons*.

[34] Code of Federal Regulations, Title 14, Part 103, *Ultralight Vehicles*.

[35] Code of Federal Regulations, Title 14, Part 105, *Parachute Operations*.

[36] Code of Federal Regulations, Title 14, Part 107, *Small Unmanned Aircraft Systems*.

[37] U.S. Department of Defense, *Use of International Airspace by U.S. Military Aircraft and for Missile and Projectile Firings*, DoD Instruction 4540.01, 2 June 2015.

[38] International Civil Aviation Organization, *Annex 6 Part IV - Remotely Piloted Aircraft Systems*, 2024.

[39] Virginia Tech MidAtlantic Aviation Partnership, *Uncrewed Aircraft Systems (UAS) Traffic Management (UTM) Implementation in the United States (US) - Initial Operationalization Report*, 18 March 2025.

[40] Federal Aviation Administration, *Introduction to TCAS II, Version 7.1*, 28 February 2011, https://www.faa.gov/documentlibrary/media/advisory_circular/tcas%20ii%20v7.1%20intro%20booklet.pdf, Accessed 27 May 2025.

[41] Federal Aviation Administration, *Charting Aviation's Future Operations in An Info-Centric National Airspace System*, FAA, Washington, DC, Sept 2022.

[42] Federal Aviation Administration, *Initial Concept of Operations for an Info-Centric National Airspace System*, FAA, Washington, DC, December 2022.

[43] Sievers, T. F., Geister, D., Schwoch, G., Peinecke, N., Schuchardt, B. I., Volkert, A., & Lieb, T. J., "*DLR Blueprint – Initial ConOps of U-Space Flight Rules (UFR)*, DLR Institute of Flight Guidance, March 2024, https://www.dlr.de/en/fl/media/publications/reports/2024/dlr_blueprint_ufr_conops.pdf, Accessed 4 December 2024.

[44] Complete Air Traffic System (CATS) Global Council, *Conops for Future Skies*, April 2025.

[45] RTCA, Inc., DO-365C *Minimum Operational Performance Standards (MOPS) for Detect and Avoid (DAA)* Systems, Washington, DC, September 2022.

[46] Federal Aviation Administration, *Technical Standard Order-C211 – Detect and Avoid Systems, 25 September 2017*, https://drs.faa.gov/browse/excelExternalWindow/2507451EFFF4AC09862581AE004F95B1.0001, Accessed 27 May 2025.

[47] Federal Aviation Administration, *Technical Standard Order-C212 - Air-to-Air Radar (ATAR) for Traffic Surveillance*, 22 September 2017, https://drs.faa.gov/browse/excelExternalWindow/481537DD66D6F62C862581AE0050191E.0001, Accessed 27 May 2025.

[48] Lacher, Andrew, *Considerations for Airspace Integration Enabling Early Multi-Aircraft (m:N) Operations*, National Aeronautical and Space Administration, March 2025, https://ntrs.nasa.gov/api/citations/20250002264/downloads/NASA-TM-20250002264.pdf, Accessed 29 May 2025.

[49] Boeing Wisk, *Concept of Operations for Uncrewed Urban Air Mobility Version 2.0*, https://wisk.aero/wp-content/uploads/2023/12/Concept-of-Operations-for-Uncrewed-Urban-Air-Mobility-v2.0.pdf, 2023, Accessed 12 May 2025.

[50] RTCA, Forum for Digital Flight: Enabling Future Operational Concepts in the National Airspace System for All Airspace Users, https://www.rtca.org/wp-content/uploads/2023/12/RTCA-FDF-White-Paper_FNL-1.pdf, 20 December 2023, Accessed 10 June 2025.

[51] Federal Aviation Administration, Order 8900.1, *Flight Standards Information Management Systems,* Accessed 30 May 2025.

[52] Code of Federal Regulations, Title 14, §91.123, *Compliance with ATC Clearances and Instructions*.

[53] Jain, A., Idris, H., Clarke J.P., and Delahaye, D., *Adaptive Traffic-Following Scheme for Safe Separation and Orderly Control of Distributed Multi-Vehicle Systems,* ATRD Symposium, Prague, Czech Republic, June 2025.

[54] Lacher, Andrew, Cook, Stephen, Ryan Oksenhorn, *Emergent Autonomy – A Step Toward Assurance*, IEEE DASC 2021.

[55] Mitchell Waldrop, *Complexity: The Emerging Science at the Edge of Order and Chaos*, Simon & Schuster.; January 1992.

[56] Eamonn O'Toole, Vivek Nallur, and Siobhan Clarke, *Towards Decentralized Detection of Emergence in Complex Adaptive Systems*, IEEE 8th International Conference on Self-Adaptive and Self-Organizing Systems, 2014.

[57] Craig Reynolds, *Flocks, Herds and Schools: A Distributed Behavioral Model*, SIGGRAPH '87: Proceedings of the 14th Annual Conference on Computer Graphics and Interactive Techniques. Association for Computing Machinery. pp. 25–34, 1987.

[58] SkyGrid, *Concept of Operations for Third-Party Services: Supporting the Airspace Integration of Advanced Air Mobility*, Version 1.0, 2024, https://www.skygrid.com/wp-content/uploads/2024/12/SkyGrid-Concept-of-Operations-v1.0-2.pdf, Accessed 11 June 2025.

[59] U.S. Army, Field Manual (FM) 3-0, *Operations,* October 2022, https://irp.fas.org/doddir/army/fm3-0.pdf, Accessed 9 June 2025.

[60] Federal Aviation Administration, *Safety Management System Components*, 11 September 2024, https://www.faa.gov/about/initiatives/sms/explained/components#safety_assurance, Accessed 25 June 2025.

[61] National Aeronautics and Space Administration, System Wide Safety Project, Aeronautics Research Mission Directorate, *In-Time Aviation Safety Management Systems*, 11 April 2023, https://ntrs.nasa.gov/api/citations/20230005340/downloads/IASMS_FAASWSRTT_04112023.pdf, Accessed 25 June 2025.

[62] National Academies of Sciences, Engineering, and Medicine, *In-time Aviation Safety Management: Challenges and Research for an Evolving Aviation System*, Washington, DC., 2018.

[63] Lacher, Andrew R., Wing, David J., Jinhua, Li, Stilwell, Ruth, and Cotton, William B., *Considering an Accountability Chain for a Digitally-Enabled Cooperative Operating Mode*, 2024 Digital Avionics Systems Conference (DASC), IEEE, 9 September 2024.

[64] Air Line Pilots Association, International, *Putting Public Safety Over Politics and Preserving The 1,500-Hour Pilot Training Rule*, https://www.alpa.org/news-and-events/air-line-pilot-magazine/public-safety-over-politics, August 2023, Accessed 19 June 2025.

[65] Langewiesche, William, *The Lessons of ValuJet 592*, The Atlantic Monthly Magazine, March 1998, https://www.faa.gov/sites/faa.gov/files/2022-11/langewiesche.pdf, Accessed 12 July 2025.

[66] RTCA SC-228, Summary of Plenary #41, RTCA Paper No. 106-24/SC228-117 Hybrid Meeting 9:00 AM EDT, May 3, 2024, https://www.rtca.org/wp-content/uploads/2024/08/228sum-41.pdf, Accessed 11 June 2025.

[67] Green, P., From *Tragedy to Safety: How accidents shaped crew resource management in aviation*, GlobalAir.com, 23 May 2024.

[68] Lacher, Andrew R, *Applicability of Lessons Learned from Aviation Safety Management System for Automated Vehicles*, Automated Vehicle Symposium, AUVSI/TRB, San Francisco, CA, July 2016.