Regulatory Considerations for Future Regional Air Mobility Aircraft

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Regional Air Mobility (RAM) is a term that is used to describe equitable, economical, and environmentally friendly access to air commerce at local airports. The term "regional" can imply a wide range of aircraft payload capacity and/or number of passengers carried, types of airports served, distances between aircraft origin/destination pairs, crew needs, runway lengths, required energy reserves, and much more. This paper describes the regulations and other considerations that apply to RAM operations in the conterminous United States and defines a notional set of requirements to apply to a planned NASA study on RAM aircraft sizing. These requirements include (1) a payload capacity sufficient to carry up to nine passengers or equivalent cargo, (2) nominal distance between the origin and destination of at least 100 miles, with 300 or more miles desired, (3) ability to operate from a runway that is no more than 3,364 ft in length at a density altitude of 3,100 ft, with a desire for a 2,665 ft runway at 4,100 ft density altitude, and (4) energy reserves sufficient for at least 45 minutes of operation at normal cruise power, with a desire for energy reserves that also include diversion to an alternate airport at least 50 nautical miles away. Aircraft that meet these desired capabilities will be able to provide commercial access to at least 2,507 airports in the conterminous United States without revision to airworthiness, operating, or security regulations.

I. Introduction

Regional Air Mobility (RAM) is becoming an increasingly popular term for air commerce that is accessible via underutilized airports in the current global air transportation infrastructure, many of which are not served today by commercial operations. A non-exhaustive search indicates that the RAM term entered the lexicon no later than 2019 with the launch of Georgia Tech's Center for Urban and Regional Air Mobility [1]. The term was used subsequently by Lilium [2] and the Community Air Mobility Initiative [3]. A group of individuals from NASA, industry, and academia used the term in a titular role for a paper released in 2021 [4], stating that "RAM will increase the safety, accessibility, and affordability of regional travel while building on the extensive and underutilized federal, state, and local investment in our nation's local airports." RAM has also been described as "safe, sustainable, affordable, and accessible aviation for transformational intraregional missions" and a subset of Advanced Air Mobility (AAM) [5].

The Advanced Air Mobility term has been used as an umbrella that includes both RAM and the Urban Air Mobility (UAM) concept, which came into prominence soon after the debut of Uber Elevate in 2016 [6]. Uber envisioned electric vertical takeoff and landing (eVTOL) aircraft operating within urban areas to catalyze a new era of on-demand air transportation and resolve issues associated with persistent ground traffic in cities. Although there are varying viewpoints, UAM tends to be synonymous with eVTOL aircraft operations within cities. The proposed UAM transportation networks can include existing landing facilities, including airports and heliports, but also tend to require new facilities, typically called vertiports, for passengers to embark or disembark close to dense urban areas [7]. Conversely, a core tenant of RAM is the use of existing airports that are largely underutilized, which implies vertical takeoff and landing capability is not necessary for RAM aircraft [4].

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The use of the term “regional” in Regional Air Mobility can imply a wide range of aircraft operations. This is due in part to the very arbitrary nature of the word “region,” which refers to a division or area that is ambiguously defined. Regional aircraft operations have been referenced numerous different ways, some of which are enumerated below.

- A NASA-led group identified a notional range of 50-500 miles for RAM [4], and a paper from Roland Berger and Bauhaus Luftfahrt described the RAM opportunity for trips up to 500 km (310 mi) [8].
- For passenger operations, some major air carriers offer trips between origin/destination (O/D) pairs under 500 miles on single-aisle transport aircraft like the Boeing 737 or Airbus A320.
- Additionally, there are “regional jets,” such as the Embraer ERJ series (short for “Embraer Regional Jet”). These aircraft can generally seat 30-50 passengers and are often operated by “regional” airlines under the livery of a larger air carrier, serving “spoke” routes to connect to larger airport hubs.
- The Essential Air Service (EAS) program subsidizes airlines to fly routes between some O/D pairs that lost commercial service after airline deregulation due to lower demand. Per the EAS charter [9], the EAS “was put into place to guarantee that small communities that were served by certificated air carriers before airline deregulation maintain a minimal level of scheduled air service.” The EAS overview states that this is “generally accomplished…with 30- to 50-seat aircraft, or additional frequencies with aircraft with 9-seat[s] or fewer, usually to a large- or medium-hub airport.” Many of the operators subsidized by the EAS program are considered “regional” carriers.
- In addition to these scheduled passenger operations, nonscheduled charter operators serve O/D pairs that can be considered “regional,” including recent novel entrants to the charter and private aircraft market that leverage cost-sharing or other partial-ownership models to provide these services at lower costs.
- Finally, several air cargo operations can logically be considered under the “regional” umbrella, ranging from small general aviation aircraft to widebody jets used by cargo operators to meet service commitments between “regional” O/D pairs.

The wide interpretation of the term “regional” has led to some confusion associated with the markets and missions served by, and the requirements associated with, RAM aircraft. We contributed to the development of the vision expressed in the 2021 Regional Air Mobility paper [4], and, although we cannot speak for the intent of others when they refer to RAM, we wish to disambiguate some of the driving factors associated with RAM aircraft sizing and operations for the benefit of future studies. To restate, the goal of this paper is to establish considerations for a typical RAM aircraft based on our interpretation of the RAM opportunity. These considerations are being used to establish requirements and metrics for an ongoing NASA study of RAM aircraft configurations but are not intended to limit the scope of other efforts. This paper is focused on RAM within the conterminous United States (CONUS, defined as the 48 adjoining states and the District of Columbia) to enable more concise focus on relevant statistics and regulations; however, we believe that RAM is a global opportunity and do not intend this paper’s focus on one portion of the world to be limiting. We hope it is useful to others that wish to engage in this opportunity.

II. Background

We define the core value proposition of RAM as equitable, economical, and environmentally friendly access to air commerce at local airports. RAM can leverage the extensive network of airports that exists today, obviating the need to build new takeoff and landing infrastructure for its aircraft, or may be able to leverage new facilities built to accommodate other AAM users. RAM can utilize existing airspace operations and practices or leverage ongoing technology development that may increase access and throughput in future airspace scenarios. As discussed later, RAM as we define it exists today without the need for EAS subsidies in some niche markets in the CONUS (and is an essential element of transportation and commerce in other regions of the U.S., such as Alaska).

In September 2022, the United States was home to 13,112 airports[*] (12,334 in the CONUS), of which 4,909 (4,457 in the CONUS) are designated as public use facilities [10]. Only 504 (457 in the CONUS) have Airport Operating Certificates issued under Title 14 of the Code of Federal Regulations (14 CFR) Part 139 (hereon “§139” or “Part 139”) [11],[12], which allows for a wider variety of commercial operations. In 2019, just 30 of these airports served over 73% of all enplanements, while only 98 airports accounted for 95% of enplanements. Similarly, 30 airports were responsible for almost 80% of all air cargo by weight, with 75 accounting for up to 95% of all air cargo [13]. Fig. 1 shows the geographic distribution of these airports for the CONUS.

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[*] Any facility identified as an “airport” in [10], which excludes the types “balloonport,” “gliderport,” “heliport,” “vertiport,” “seaplane base,” and “ultralight.”

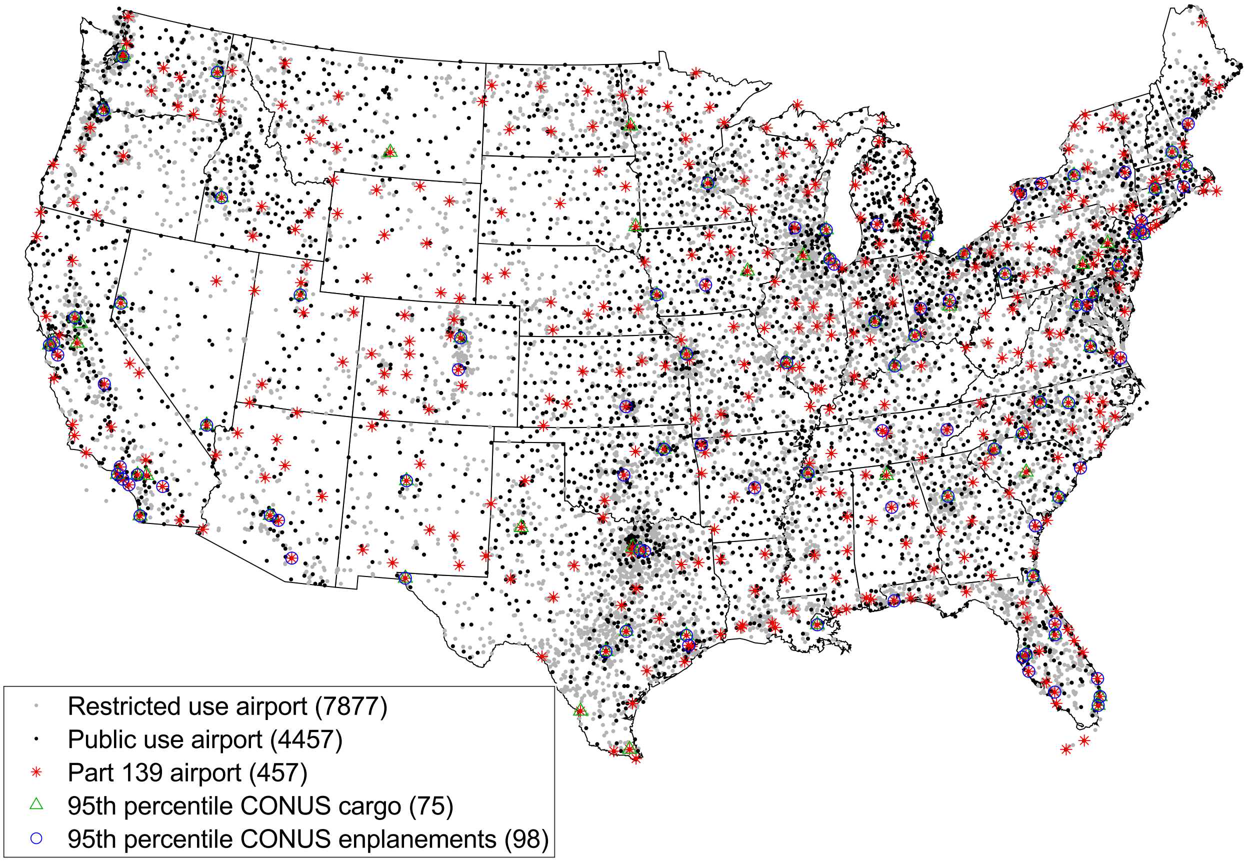

Fig. 1 Airports in the CONUS as of September 2022.

The wide distribution of airports illustrated in Fig. 1 reinforces the idea that air commerce should be physically accessible to the CONUS population. McKinsey & Co. assert that approximately 90% of the U.S. population lives within a 30-minute drive of a regional airport, whereas only 60% of the population is within the same drive time of a commercial airport [14].[†] These statistics indicate that access to air commerce is widespread but could be improved within the CONUS by leveraging more of the existing airport infrastructure.

Though airports may be reasonably accessible to the populace, they are not routinely used by the traveling public except for long-distance trips. Aultman-Hall et al. [15] characterized the travel behavior of a representative sample of 628 U.S. individuals over a one-year period for trips that included at least one overnight stay and had a destination at least 50 miles from their home. As part of their characterization of these trips (which were called "tours" in the article since they may involve multiple stops and forms of transportation), they indicated if at least one portion of the tour included travel by air [15]. The results, reproduced in Fig. 2, indicate that over 70% of these tours were between 50 and 500 miles, yet fewer than 10% of the tours between 50 and 500 miles involved any form of travel by air. Fewer than 2% of the tours between 50 and 250 miles involved travel by air. Hence, though airports may be accessible for transportation, they are not currently used very often for these regional tours.

This paper does not directly address factors associated with mode choice (e.g., whether to use air transportation or ground transportation for a tour). Rather, this paper focuses on airworthiness and operational requirements that are necessary to enable access to more of the airports in the CONUS than those that have commercial service today. Mode choice and other considerations are discussed elsewhere; for example, a comprehensive network model, which includes the impact of lower operating costs, airfares, and user transportation mode switching logic, is found in the work by Justin et al. [16].

[†] This references a third-party dataset for airport classification; it is not immediately apparent if "regional airport" refers to all public-use airports or if "commercial airport" corresponds to all 14 CFR Part 139 airports.

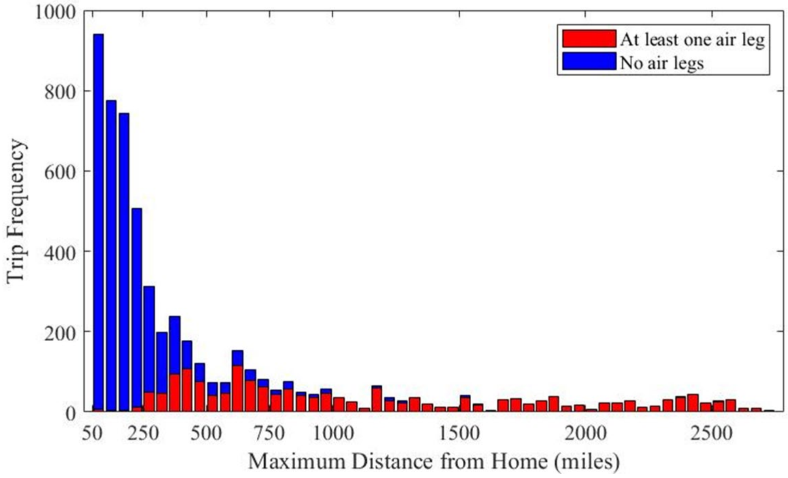

Fig. 2 Frequency distribution of maximum trip distance from home for a given overnight tour of over 50 miles for 628 individuals over one year (derived from data in [15]).

III. Key Requirements and Considerations for RAM Aircraft

The themes discussed in the prior section help to shape the driving considerations for RAM operations. RAM aircraft should service more than the current Part 139 airports if sufficient demand can be established. Time spent by travelers at the airport must be minimized, which includes the time to check in, go through security screening, board, and handle baggage. The ticket price should be low enough that the potential advantage in time saved and total cost to the traveler balances the other inconveniences associated with air travel (e.g., having to switch modes between a ground vehicle and an aircraft), whereas the cost borne by the operator should be low enough that the operator has a viable business case. The aircraft should be able to operate at small community airports in such a way to minimize actual or perceived negative impacts, particularly with respect to noise, emissions, and safety. The implications of operating at non-Part 139 airports are expanded upon in the subsections that follow.

A. Operational Paradigm

Simply having access to a certified air crew and certified airplane is generally not enough to enable access to air commerce. Although private (or some corporate) individuals may be able to operate aircraft in civil airspace under rules such as Part 91 [17], RAM includes operations accessible to the general public. The U.S. Department of Transportation (DoT) Federal Aviation Administration (FAA) Advisory Circular (AC) 120-12A [18] discusses guidelines for "whether current or proposed transportation operations by air constitute private or common carriage." This is an important factor as to whether the operating rules associated with air carriers and commercial operators apply. As discussed in AC 120-12A, "common carriage" involves four elements: "(1) a holding out[‡] of a willingness to (2) transport persons or property (3) from place to place (4) for compensation."

Availability of RAM services to the general public[§] implies "common carriage," which pushes a RAM operator to follow the rules under Part 135 [19] or Part 121 [20]. Operations under Part 121 generally preclude operation at airports that are not certificated under Part 139 (such as §121.590); as discussed earlier, this would limit operators to 457 airports in the CONUS. Hence, to embrace the potential of all the 4,457 public use airports in the CONUS, a RAM operator needs to consider the operating rules in Part 135 in addition to the general operating rules in Part 91.

B. Passengers, Payload, and Gross Weight

A major tenet of RAM is to enable access to a larger number of airports than those certified under Part 139. This inherently limits the number of passenger seats on RAM aircraft. The applicability rules in §139.1(a) note that the airport certification rules under Part 139 apply to "**Scheduled** passenger-carrying operations of an air carrier operating aircraft configured **for more than 9 passenger seats**" and to "**Unscheduled** passenger-carrying operations of an air

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[‡] Per AC 120-12A, "A carrier becomes a common carrier when it 'holds itself out' to the public, or to a segment of the public, as willing to furnish transportation within the limits of its facilities to any person who wants it."

[§] Although many RAM-like operations may involve private carriage rather than common carriage, these use cases are not considered in this paper.

carrier operating aircraft configured for **at least 31 passenger seats**" (emphasis added). Hence, any air carrier wishing to provide commercial service to other-than-Part 139 airports is limited to aircraft seating 9 passengers or less for scheduled operations[**] and 30 passengers or less for unscheduled operations.

Airport security is another consideration for passenger capacity and payload weight. Many airports do not have facilities or personnel to enable passenger or cargo screening as required by 49 CFR §1540 [21] and §1544 [22]. Air carriers and commercial operators may need the security programs described in §1544.101 depending on passenger capacity, cargo weight, or aircraft weight. The breakpoints in programs depend on:

1) if the aircraft enplanes or deplanes into a sterile area,[††] with all operations to sterile areas requiring Transportation Security Administration (TSA) screening,
2) the number of passenger seats, with more than 30 seats mandating TSA screening, and
3) the maximum certificated takeoff weight, where the following require a security program under §1544:
    a. "all-cargo" programs for cargo-only operations above 101,309.3 pounds, and
    b. "twelve-five" programs[‡‡] for all scheduled or charter operations for cargo and passenger aircraft weighing more than 12,500 pounds.

Hence, any air carrier wishing to enplane passengers from an airport that does not have a sterile area (and, by extension, cannot deplane into a sterile area even if the destination airport is so equipped) must be operating an aircraft with a seating capacity of less than 31 passengers. Furthermore, any air carrier involved in passenger or cargo operations must not operate aircraft having a maximum certificated takeoff weight (MCTW) of more than 12,500 pounds without invoking some sort of security program at the airports of operation.

The type certification requirements for the aircraft include inflection points associated with number of passenger seats and aircraft weight. Airworthiness requirements for airplanes[§§] are divided into the Normal Category (maximum seating capacity 0-19 passengers or MCTW ≤ 19,000 pounds) and Transport Category (any airplane not certified under the Normal Category or other condition per §21.17, generally multiengine airplanes with a maximum seating capacity >19 passengers or MCTW > 19,000 pounds). The airworthiness rules for Normal Category and Transport Category airplanes are defined under 14 CFR §23 [23] and §25 [24], respectively.

The Part 23 rules were recently overhauled, moving towards performance-based rather than prescriptive rules to enable greater flexibility with changing technology [25]. As part of this overhaul, former prescriptive weight- and engine-based divisions in the rules were eliminated in favor of a risk-based approach largely focused on the maximum number of passengers. The "airplane certification levels" in §23.2005(b) are as follows:

- Level 1—for airplanes with a maximum seating configuration of 0 to 1 passengers
- Level 2—for airplanes with a maximum seating configuration of 2 to 6 passengers
- Level 3—for airplanes with a maximum seating configuration of 7 to 9 passengers
- Level 4—for airplanes with a maximum seating configuration of 10 to 19 passengers

As will be discussed in a later subsection, a major impact of selection of airplane certification level in the Normal Category (or selecting the Transport Category) is the assurance level for the aircraft system safety analysis. In addition, the airplane certification levels have a major impact on airplane performance requirements. In general, a lower certification level will have less stringent requirements for performance and safety assurance.

In summary, a RAM aircraft operating scheduled passenger service out of non-Part 139 airports will be held to at most[***] the Part 23 airworthiness rules for Level 3 airplanes (since it would be limited to 9 passengers), which would also limit its MCTW to no more than 19,000 pounds (or 12,500 pounds if the operator does not wish to implement any security program governed by 49 CFR §1544). Likewise, a RAM aircraft operating unscheduled passenger service out of non-Part 139 airports may operate with as many as 30 seats without a major security program; however, any airplane with an MCTW above 12,500 pounds, which would likely be necessary for higher seat counts, would at least

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[**] Defined in 14 CFR §139.05 as "any common carriage passenger-carrying operation for compensation or hire conducted by an air carrier for which the air carrier or its representatives offers in advance the departure location, departure time, and arrival location."

[††] Defined in 49 CFR §1540.05 as "a portion of an airport defined in the airport security program that provides passengers access to boarding aircraft and to which the access generally is controlled by TSA, or by an aircraft operator under part 1544 of this chapter… through the screening of persons and property."

[‡‡] Defined in 49 CFR §1544.101 as "a security program that meets the applicable requirements of §1544.103(c)" including "§1544.215, 1544.217, 1544.219, 1544.223, 1544.230, 1544.235, 1544.237, 1544.301(a) and (b), 1544.303, and 1544.305; and in addition, for all-cargo operations of §§ 1544.202, 1544.205(a), (b), (d), and (f)."

[§§] Defined in 14 CFR §1.1 as "an engine-driven fixed-wing aircraft heavier than air, that is supported in flight by the dynamic reaction of the air against its wings."

[***] There may be other reasons to certify under different or more stringent rules that are not discussed in this paper.

require a “twelve-five” program described in 49 CFR §1544. Such an airplane could be held to the airworthiness rules in Part 23 if the maximum seating configuration was limited to 19 passengers; otherwise, the airplane would need to comply with the airworthiness rules in Part 25. A cargo-only airplane could be held to Part 23 airworthiness rules for Level 1 airplanes if the MCTW is limited to 19,000 pounds (12,500 pounds if the operator does not wish to implement any security program governed by 49 CFR §1544). Otherwise, a cargo-only airplane could be held to Part 25 airworthiness rules and would only be subject to the “twelve-five” program in 49 CFR §1544 up to an MCTW of 101,309.3[†††] pounds.

C. Flight Crew

One challenge for the economics of RAM is that the crew cost will be amortized over fewer passengers or less cargo than larger aircraft. The aircraft manufacturer is responsible for defining the minimum crew under airworthiness rules, but the type of operation can impose additional crew requirements.

The number of flight crew required by the operating rules depends largely on the number of passengers carried and the type of commercial operation (Part 135 or Part 121). A single pilot is allowable for airplanes with fewer than 10 passenger seats per §135.99, though a second pilot is required for operations under Instrument Flight Rules (IFR), with an exception noted under the Equipment subsection below. This implies that cargo operations conducted under Part 135 may be permitted with a single pilot (if that meets the requirements for minimum flight crew from the aircraft manufacturer) and that operations under Part 135 for aircraft with 10 or more passenger seats require a second pilot. All operations under Part 121 require at least two pilots per §121.385.

Flight attendants may be necessary for passenger-carrying RAM flights as well, again depending on the number of passenger seats. Per §135.107, one flight attendant is required for aircraft with a seating capacity of 20 or higher. If operating under Part 121, the number of flight attendants required is the seating capacity divided by 50 and rounded up to the nearest whole number (e.g., an aircraft with up to 50 passenger seats requires 1 flight attendant, 51 to 100 passenger seats requires two flight attendants, ad infinitum).

The minimum flight experience and ratings required by the flight crew vary based on the operating rules. Under §135.243, a pilot-in-command (PIC) of a turbojet aircraft, or any aircraft with 10 or more passenger seats, requires an Airline Transport Pilot (ATP) rating, which generally specifies a minimum of 1,500 hours of total flight experience per the ATP experience requirements in §61.159 [26]. An ATP rating (and, therefore, a minimum of 1,500 hours of total flight experience) is also required for all operations under Part 121, specifically §121.436, for both the PIC and second-in-command (SIC). However, per §135.243, pilots of non-turbojet aircraft with fewer than 10 passenger seats are only required to have a commercial pilot certificate and a minimum of 500 hours or 1,200 hours of total flight experience to fly as PIC under Visual Flight Rules (VFR) or IFR, respectively. If a second pilot is required or is acting as SIC, §135.245 states that only a commercial certificate is required, which generally relates to a minimum flight experience of 250 hours per the aeronautical experience requirements of §61.129. Accordingly, RAM operations may enable a pathway for commercial pilots to gain operational experience and build toward an ATP rating.

To summarize, an aircraft operating under Part 135 with fewer than 10 passengers that is not powered by a turbojet engine can fly with a single pilot having a commercial pilot certificate and a minimum of 500 (VFR) or 1,200 (IFR) hours of total experience, though a second pilot (with a minimum of 250 hours of experience) is required for IFR operations unless certain equipment rules are met (discussed below). Part 135 operations with airplanes that can seat 10 or more passengers require two pilots. Operations under Part 121 require two pilots, both of which must have an ATP rating (each with a minimum of 1,500 hours of flight experience). Operations under Part 135 with fewer than 20 passenger seats do not require a flight attendant, and operations under Part 121 require one flight attendant per 50 passengers or portion thereof.

D. Equipment

The number of passengers, airplane category, weight, engine type, and other factors determine what level of assurance is required for the systems and equipment installed on the aircraft. For airplanes that are certified in the Normal Category, §23.2500 includes a general requirement that the equipment and systems must “meet the level of safety applicable to the certification and performance level of the airplane,” which is a performance-based implementation of the requirements that existed in §23.1309 prior to the adoption of amendment 64 of Part 23 in 2017. The former prescriptive rules and practices in §23.1309 and the companion AC 23-1309-1E [27] are now captured in ASTM Standard F3230 [28]. In general, maximum allowable failure probabilities are assigned based on severity of the result of the failure, with “catastrophic” conditions generally leading to loss of the vehicle and of life. The classification table for required Development Assurance Level (DAL) from AC 23-1309-1E is shown in Table 1.

[†††] Also given as 45,500 kg in the regulation. The precision as stated here is the precision shown in the regulation.

Table 1 Relationship among airplane classes, probabilities, severity of failure conditions, and software and complex hardware Development Assurance Level for Normal Category airplanes, reproduced from [27]

Classification of Failure Conditions	**No Safety Effect**	**<----Minor---->**	**<----Major---->**	**<--Hazardous-->**	**<Catastrophic>**
Allowable Qualitative Probability	**No Probability Requirement**	**Probable**	**Remote**	**Extremely Remote**	**Extremely Improbable**
Effect on Airplane	No effect on operational capabilities or safety	Slight reduction in functional capabilities or safety margins	Significant reduction in functional capabilities or safety margins	Large reduction in functional capabilities or safety margins	Normally with hull loss
Effect on Occupants	Inconvenient for passengers	Physical discomfort for passengers	Physical distress to passengers, possibly including injuries	Serious or fatal injury to an occupant	Multiple fatalities
Effect on Flight Crew	No effect on flight crew	Slight increase in workload or use of emergency procedures	Physical discomfort or a significant increase in workload	Physical distress or exessive workload impairs ability to perform tasks	Fatal injury or incapacitation
Classes of Airplanes (Note 5):	**Allowable Quantitative Probabilities and Software (SW) and Complex Hardware (HW) Development Assurance Levels (Note 2)**				
Class I (Typically SRE 6,000 pounds or less)	No probability or SW and HW Development Assurance Levels Requirements	$<10^{-3}$ Note 1 P=D	$<10^{-4}$ Notes 1 and 4 P=C, S=D	$<10^{-5}$ Note 4 P=C, S=D	$<10^{-6}$ Note 3 P=C, S=C
Class II (Typically MRE, STE, or MTE 6,000 pounds or less)	No probability or SW and HW Development Assurance Levels Requirements	$<10^{-3}$ Note 1 P=D	$<10^{-5}$ Notes 1 and 4 P=C, S=D	$<10^{-6}$ Note 4 P=C, S=C	$<10^{-7}$ Note 3 P=C, S=C
Class III (Typically SRE, STE, MRE, and MTE greater than 6,000 pounds)	No probability or SW and HW Development Assurance Levels Requirements	$<10^{-3}$ Note 1 P=D	$<10^{-5}$ Notes 1 and 4 P=C, S=D	$<10^{-7}$ Note 4 P=C, S=C	$<10^{-8}$ Note 3 P=B, S=C
Class IV (Typically Commuter Category)	No probability or SW and HW Development Assurance Levels Requirements	$<10^{-3}$ Note 1 P=D	$<10^{-5}$ Notes 1 and 4 P=C, S=D	$<10^{-7}$ Note 4 P=B, S=C	$<10^{-9}$ Note 3 P=A, S=B

Note 1: Numerical values indicate an order of probability range and are provided here as a reference.

Note 2: The letters of the alphabet denote the typical SW and HW Development Assurance Levels for Primary System (P) and Secondary System (S). For example, HW or SW Development Assurance Level A on Primary System is noted by P=A.

Note 3: At airplane functional level, no single failure will result in a Catasprophic Failure Condition.

Note 4: Secondary System (S) may not be required to meet probability goals. If installed, S should meet stated criteria.

Note 5: Single Reciprocating Engine (SRE), Single Tubine Engine (STE), Multiple Reciprocating Engines (MRE), Multiple Turbine Engines (MTE)

The current version of ASTM F3230 indicates that Level 3 airplanes (as noted above, those with 7-9 passenger seats) carry similar requirements to Class III airplanes in AC 1309-1E, and Level 4 airplanes (10-19 passenger seats) carry similar requirements as Class IV airplanes.[‡‡‡] Note that a Level 3/Class III airplane requires an assurance level of no more than one catastrophic failure per hundred million flight hours, whereas Level 4/Class IV airplanes require an assurance level of no more than one catastrophic failure per billion flight hours. Similarly, for Transport Category airplanes, §25.1309 governs safety requirements for systems and equipment, including the requirement that "the occurrence of any failure condition which would prevent the continued safe flight and landing of the airplane is extremely improbable." The corresponding AC 25-1309-1A [29] defines "extremely improbable" as a failure probability "on the order of" one per billion flight hours.

There are many rules related to required equipment on board an aircraft; this subsection only addresses a few necessary items relevant to RAM operations depending on the type of aircraft and operation. As discussed in the subsections above, operations can be conducted under Part 135 with a single pilot for aircraft with fewer than 10 passenger seats. In addition to the flight time qualifications, single-pilot IFR operation also requires a functioning autopilot that meets the rules in §135.105, which states that an autopilot capable of three-axis control is required.

Another equipment discriminator that is relevant to RAM is the installation of a Traffic Alert and Collision Avoidance System (TCAS). For Part 135 operations, §135.180 states that turbine-powered aircraft with 10 to 30 passenger seats must have a TCAS system installed. TCAS installations under Part 121 are more complicated, but in general §121.356 requires some sort of TCAS installation in any aircraft with more than nine passenger seats or with a MCTW greater than 33,000 pounds. RAM aircraft with fewer than 10 passenger seats may avoid the expense of requiring TCAS and have more flexibility to leverage other automation technology that could serve a similar function.

Once again, operating an airplane with fewer than 10 passenger seats is an important inflection point for RAM equipment requirements. Such aircraft, if it has a multi-axis autopilot, may operate with a single pilot under IFR.[§§§] Aircraft with less than 10 passenger seats also are not required to have a collision avoidance system. Manufactures of such aircraft are required to show that failure of other installed equipment does not result in a catastrophic outcome in more than one per one hundred million flight hours. Airplanes with 10 or more passenger seats need at least two pilots regardless of autopilot equipage. They are required to have some sort of collision avoidance system, and the manufacturer needs to show that the installed equipment does not result in a catastrophic outcome in more than one per billion flight hours. All of these factors show that there are potential cost increases associated with onboard equipment for RAM aircraft that seat 10 or more passengers.

E. Range Considerations

Inspection of Fig. 2 indicates that the opportunity for growth in RAM largely lies in the large number of tours between O/D pairs of approximately 50 to 500 miles that are currently not served by aviation, with a heavy bias to tours under approximately 350 miles. Additionally, although RAM currently accounts for only a small portion of commercial aviation, the range distribution of these current trips can help to inform situations where the business case for RAM operations is able to close despite the challenges facing RAM economics and operations today. For example, McDonald analyzed FedEx's operations for their fleet of Cessna 208s [30], a single-engine, fixed-wing turboprop that, when configured for cargo, can carry up to about 3,000 pounds of payload. McDonald's analysis indicated that 91% of FedEx's Cessna 208 missions were under 200 miles, and nearly 99.5% of the missions were under 300 miles.

Data on RAM passenger flights can be extracted from the Airline Origin and Destination Survey database provided by the Bureau of Transportation Statistics, known as the DB1B database [31]. This database includes airfare information sampled at random for 10% of all tickets sold in the United States by carriers that serve at least 1% of domestic enplanements. This restriction alone limits the utility of DB1B for RAM data; however, some current RAM carriers "code-share" with larger air carriers, so tickets sold by those larger carriers that include a RAM flight will be captured by DB1B. The DB1B data were filtered for air carrier codes that include known RAM operators with smaller aircraft in the CONUS and further filtered to find fares attributed to a single O/D pair.[****] This represented a rare case in which a RAM flight was sold by a larger carrier via "code-share" that did not involve a flight on the larger carrier's aircraft and is the best representation of RAM operations that can be captured within the sampling limitations of DB1B. A total of 781 entries that met these criteria were found in the DB1B data from 2015-2019. Of these, 270 were flights on subsidized EAS routes, and the balance of 511 flights were on routes that were not subsidized by EAS. Only

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[‡‡‡] The DAL requirements table from ASTM F3230 is not reproduced here because this standard is copyrighted.

[§§§] There are many other requirements for single pilot IFR operation under Part 135 that are omitted here for clarity.

[****] DB1B only reports the total fare and the specific O/D pairs. It is impossible to know what type of airplane flew each leg of the route, unless there is only a single leg for the reported fare and the operator only flies a particular type of aircraft. Hence, only flights with single legs noting known RAM-like carriers were used for this analysis.

two RAM carriers were identified in this process, and both operators use aircraft that are generally configured for fewer than 10 passenger seats. The resulting cumulative distribution of trip length, shown in Fig. 3, indicates that 90% of EAS routes were under 255 nautical miles (nmi), with the longest trip at 368 nmi. The non-EAS routes were all less than 225 nmi, with 90% of routes under 167 nmi and 80% of routes under 80 nmi. Most of the non-EAS data in this sample were from three overwater routes[††††] in the northeast United States that did not have a competitive surface mode of travel in terms of travel time.

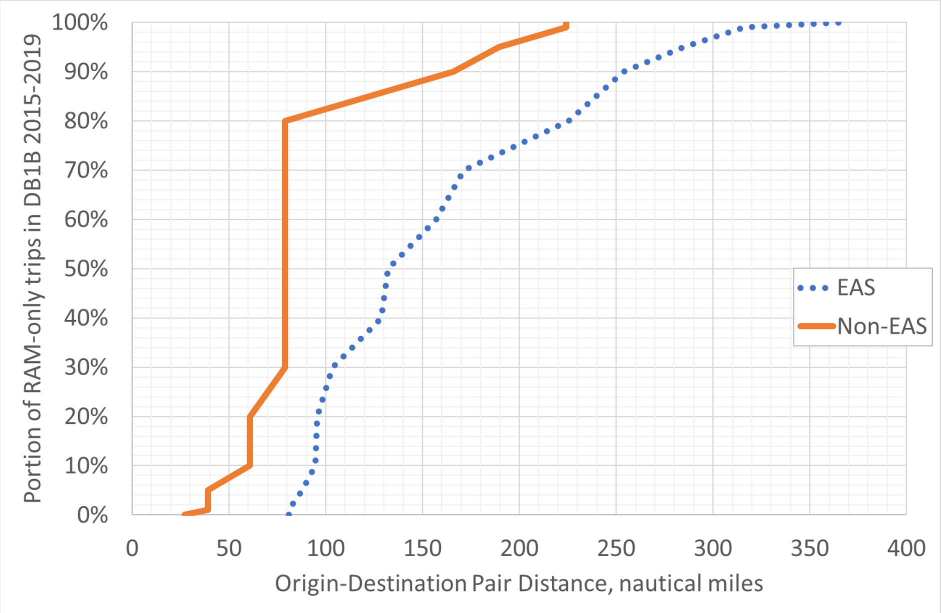

Fig. 3 Cumulative distribution of distance between O/D pairs for RAM-only flights in DB1B database.

There are other factors beyond distance between O/D pairs to consider for range capability. All aircraft are required to be operated with energy reserves, though the amount of required reserve can depend on the type of operation, time of day, and weather. For Part 135 operations, §135.209 requires that fixed-wing airplanes have enough fuel to fly to the intended destination and then continue to fly using "normal cruising fuel consumption," for at least 30 additional minutes for operations in daylight and 45 minutes for nighttime operations. For IFR, §135.223 governs reserve energy requirements, which requires 45 minutes of flight time at "normal cruising speed" and can include designation of enough energy to fly to an alternate airport with an acceptable weather forecast if the primary point of intended landing does not meet certain criteria. Part 121 operations include additional complexity associated with reserve energy requirements, but the Part 135 IFR requirements are a reasonable surrogate for mission sizing.

The actual air distance traveled and associated total energy requirements can include non-direct routing for airspace or weather avoidance, as well as impacts from winds aloft. Crawford et al. captured these factors from actual flight track and weather data for three RAM operators in different regions of the United States (two in the CONUS and one in Hawaii) [32]. Their data analysis indicates that actual distance traveled for flights under approximately 200 nmi can be 20-40% higher than the great circle distance of the O/D pairs, though the (admittedly limited) data for O/D pairs above 200 nmi indicates less than 5% of additional distance over the great circle distance. As expected, they found that the actual weather impact on energy requirements for operation (VFR, IFR with no alternate airport, or IFR with alternate airport) varied greatly by region, season, and time of day. In the most extreme combination of factors, they noted that the actual and forecast weather at time of dispatch would have required IFR reserves on up to 50% of the trips, with about half of those requiring reserve energy for an alternate airport. They also determined that winds aloft tended to be no higher than about 30 knots on these routes, which again varied by region.

Adequately summarizing the range requirements for all RAM operations is difficult, but for vehicles sized for fewer than 10 passengers or equivalent cargo, the considerations above can provide guidance into current use cases. These aircraft tend to fly missions on routes with an O/D distance of less than 300 nmi, and the majority of O/D pairs in geographically constrained RAM markets are less than 100 nmi. Nominal range should consider non-direct routing, increasing distances by 20-40% for O/D pairs under 200 nmi, with a small nominal penalty for distances greater than

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[††††] These O/D pairs were all in Massachusetts: Boston to/from Nantucket, Martha's Vineyard, or Provincetown.

200 nmi. Presuming IFR operation is desired, RAM aircraft need to carry enough energy for an additional 45 minutes of operation at normal cruise power, as well as energy to travel to an alternate airport. Although statistics have been difficult to gather for today's niche RAM operations, our informal discussions with RAM operators indicate that an alternate range of at least 50 nmi is a reasonable starting point and is consistent with the exploratory demand studies by Justin et al. [16], though this should be further refined in future studies.

F. Speed, Trip Duration, and Altitude Capability

The speed at which a RAM aircraft travels can impact productivity, throughput, and passenger convenience. It also can impact aircraft energy use (and therefore cost, range, and endurance), engine power level, and aircraft weight. Flight speeds are suggested (or in some cases required) by the manufacturer, and selected by the operator, to provide an appropriate balance of capability and cost. There are many considerations in selection of an appropriate cruise speed. Given that many aircraft operating characteristics related to speed are also related to altitude, consideration should be given to the altitudes at which the aircraft can operate as well.

As noted above, RAM aircraft (particularly those with fewer than 10 passenger seats or equivalent cargo) tend to travel shorter distances compared to transport aircraft. Depending on the aircraft climb capability, a RAM aircraft may spend much of its mission at lower altitudes than larger commercial jet traffic. The operating rules in §91.117 limit the speed of all aircraft to 250 knots below an altitude of 10,000 ft mean sea level (MSL). In addition, the airworthiness rules for Normal Category airplanes include a discriminator at this speed; namely, §23.2005 defines "high speed" airplanes as those with a maximum structural cruising speed of more than 250 knots calibrated airspeed (or, for those required to operate by Mach number, those with a maximum operating Mach number of greater than 0.6). Airplanes that are certified to these higher operating speeds have increased airworthiness requirements, including those for performance, structural strength, design, and equipment.

Although it does not directly impact speed, §92.211 discusses requirements for the provision of supplemental oxygen to crew and passengers, which depend on altitude. The requirements start at 12,500 to 14,000 ft MSL for the crew members (depending on duration at altitude), and by 15,000 ft MSL all passengers are required to be provided with supplemental oxygen. Although operating rules do not explicitly describe pressurization versus supplemental oxygen, the airworthiness rules in §23.2320 outline performance-based requirements for the airplane cabin physical environment, which trace to airworthiness standards now in ASTM F3227 [33] (formerly in §23.841 prior to August 2017). These standards indicate that cabin pressurization systems are necessary for operation above 25,000 ft MSL. Transport Category airplanes with pressurized cabins are required to maintain a pressure equivalent to an altitude of 8,000 ft MSL or less at the aircraft maximum operating altitude per §25.841.

Air traffic management considerations may also impose limits on practical flight altitudes. Operations in Class A airspace, which begins at 18,000 ft MSL and extends up to 60,000 ft MSL, must be performed under IFR and are required to have an air traffic control (ATC) clearance, among other requirements per §91.135. Since most RAM flights are likely to cover short ranges, from a performance perspective it is not likely reaching 18,000 ft MSL would even be desired for many flights; however, for those that would ideally reach such altitudes, the duration of time in Class A airspace is likely to be very short. Therefore, it is not likely that RAM flights would receive the required ATC clearance to enter Class A airspace (due to increasing controller workload and providing separation from larger transport category airplanes).

Passenger comfort is another consideration for altitude and speed. A traveler who is used to the traditional aircraft cabin environment of transport category airplanes may experience additional discomfort in unpressurized cabin environments that exceed the equivalent pressure of 8,000 ft MSL. Additionally, passengers may find oxygen masks or cannulas undesirable, so cabin pressurization may be an important feature for passenger comfort. This can be especially important in mountainous regions, where higher surface elevations may lead to increased operating altitudes for terrain clearance and navigation aid reception.

Another consideration for altitude impact on passenger comfort is ride quality. Smaller aircraft operating at lower altitudes may be subjected to increased turbulence effects due to gusty winds. While no specific guidelines are given in this paper, designers of RAM aircraft should consider the effect of wind gusts at low altitude on ride quality [34].

Flight time on aircraft that do not have a lavatory on board, which is common for smaller airplanes, should be limited. One current RAM operator indicates that flight times should be limited to 99 minutes or less [35]. As such, range may be limited by speed in addition to the energy requirements described above.

Once again, inflection points emerge from altitude and speed requirements. Shorter-range RAM missions may be limited to 250 knots due to the amount of time spent at low altitude (below 10,000 ft MSL), and airworthiness requirements increase for aircraft with maximum certified operating speeds greater than 250 knots or Mach 0.6. For operation at higher altitudes, particularly in mountainous regions, aircraft have supplemental oxygen requirements for crew starting at 12,500 to 14,000 ft MSL and for passengers at 15,000 ft MSL. Cabin pressurization may be highly desirable for flights above 8,000 ft MSL, and it is necessary for operations above 25,000 ft MSL. Air traffic management considerations are likely to limit RAM operations to remain below 18,000 ft MSL. Finally, aircraft speed may be a factor for aircraft range on aircraft that are not equipped with an onboard lavatory.

G. Runway Environment

RAM envisions providing enhanced access to air commerce for more communities by leveraging far more of the existing network of airports than are currently used for most commercial operations. The runway environments of these airports may be more limiting than the airports used today for large commercial passenger and cargo aircraft. These differences include runway length available for takeoff and landing, runway surface type, runway lighting, and runway navigation aids. Additionally, the environment in the vicinity of the runway, such as atmospheric characteristics (varying climates and geographies), winds, obstacles, and terrain, can also impact the suitability of the runway environment for aircraft operations.

Runway surface conditions can change the required runway length to accelerate for takeoff or decelerate after landing. Unimproved surfaces, such as turf or sod, may not be suitable for operation after extensive precipitation due to mud or flooding, and these surfaces are more susceptible to erosion and wear that may damage aircraft landing gear. Although RAM operations can use unimproved surfaces, for this paper and our planned subsequent studies, we consider only airports with hard-surfaced runways.

Similarly, some RAM operations may only occur during the day, but maximum flexibility is afforded in a lighted runway environment that allows for operation at night. In analyzing the existing airport network, we consider only airports with runway lights when establishing available field lengths for RAM operations. Although a similar argument can be made for airports to have an instrument approach, we do not consider this a requirement for the field length analysis for several reasons. First, an increasing number of airports offer instrument approaches enabled by global navigation and surveillance systems; second, less infrastructure is required to establish new approaches as needed than is required for installing runway and taxiway lights; and finally, some RAM operations may be feasibly performed purely under VFR and thus not need an instrument approach.

Of the 4,457 public use airports in the CONUS, 3,504 have hard-surfaced, lighted runways [10]. These data indicate that, of the 3,504 aforementioned airports, 95.2% have a takeoff distance available of at least 2,600 ft, whereas 94.0% have at least this amount of landing distance available.[‡‡‡‡] The cumulative distribution of maximum available landing distance for different types of airports is shown in Fig. 4.

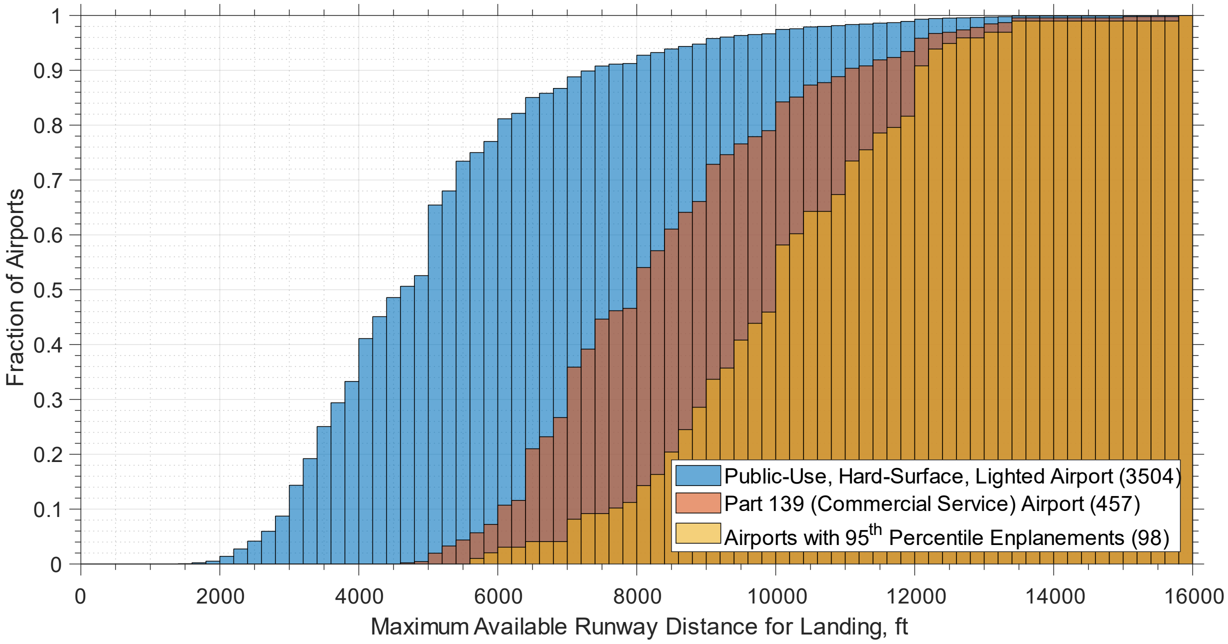

Fig. 4 Cumulative distribution of maximum available runway distance for landing.

[‡‡‡‡] The difference between the two is largely due to displaced thresholds on some airport runways – a displaced threshold is not available for landing but is available for use during takeoff.

Aircraft manufacturers are required to provide the estimated runway length requirements for takeoff and landing in a variety of different environments, which may include extremes in parameters that impact air density, such as air temperature and altitude. Most operational speeds are described in terms of a reference weight and calibrated airspeed. As air density decreases, true airspeed increases (for a given calibrated airspeed), which can increase the runway used to accelerate/decelerate to a specified calibrated airspeed associated with takeoff or landing operations. Additionally, aircraft propulsion systems can experience thrust or power lapse with decreased air density and/or increased true airspeed, which can increase required takeoff distance with density altitude. Often, the runway environment is equated to a density altitude, which is pressure altitude corrected for nonstandard temperature. Since airports have known latitude, longitude, and elevation, the maximum expected density altitude can be captured versus field length. The density altitude for each airport was estimated by first finding the maximum temperature for each airport location from the 2010-2020 U.S. Climate Normals [36]. Then, the density altitude was calculated by applying this maximum estimated temperature[§§§§] to the reported airport field elevation. The corresponding landing field length data discussed above is then compared to density altitude in Fig. 5. These data show some of the relationships between density altitude and landing field length; for example, 75% of these airports have a landing field length of at least 2,665 ft below a maximum density altitude of 4,100 ft, and 50% have a landing field length of at least 3,364 ft below a maximum density altitude of 3,100 ft.[*****]

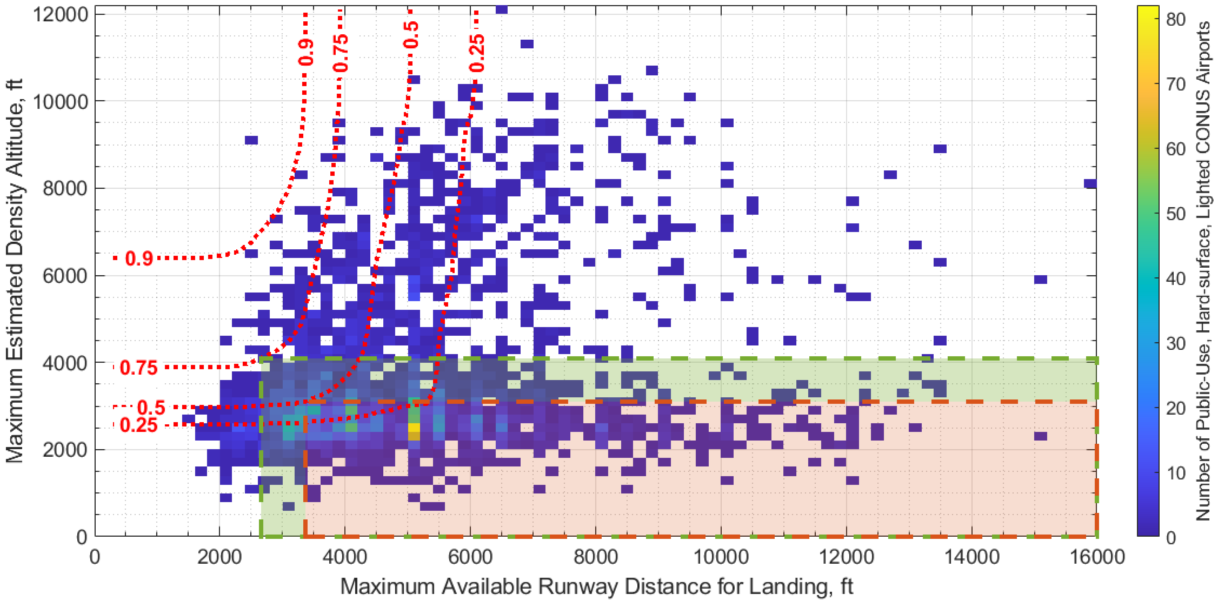

Fig. 5 Distribution of landing runway length and maximum density altitude. Contours indicate the joint probability of a runway with a given landing distance or longer at or below the specified density altitude, as shown with the highlighted rectangles for the 50th and 75th percentile values described in the text.

The takeoff and landing distance available for RAM aircraft depends largely on the airports that are desired to be accessible, the aircraft's passenger capacity, and the pertinent operational regulations. Scheduled passenger service in aircraft with more than nine passenger seats would limit access to the 457 CONUS Part 139 airports. We believe that RAM requires access to far more airports, and operation at 3,504 public-use airports in the CONUS with hard-surfaced runways and lighting is plausible for Part 135 operations in aircraft with less than 10 passenger seats. At least[†††††] 2,507 of these airports have 2,665 ft or more of runway available for landing at a maximum density altitude

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[§§§§] The data for maximum reported temperature from 2010-2020 was reported over a resolution of about 1/24 of a degree in latitude and longitude. Because of this, density altitude for 161 of the 3,504 airports could not be resolved. Higher spatial resolution and inclusion of some percentile of temperature will result in some changes to the density altitudes shown here.

[*****] These percentages merely refer to count of airports above the listed field length and below the listed maximum density altitude; they do not purport to indicate operational suitability, which is a far more detailed evaluation.

[†††††] The data used to estimate temperatures resulted in the inability to resolve density altitude for 161 of the 3,504 airports, so these figures are based on the 3,343 airports for which density altitude estimates could be determined.

of 4,100 ft or less, and at least 1,671 have 3,364 ft of runway available for landing at a maximum density altitude of 3,100 ft or less. These runway summary statistics should not be taken directly as field length requirements; the airworthiness rules have several additional performance requirements associated with failures during the takeoff run, initial climb, and landing approach that are not described in this paper (such as requirements for critical loss of thrust). Furthermore, operators may be inclined to keep some additional margin over these figures.

IV. Summary

This paper identified several of the regulations and considerations impacting the design of aircraft that could be used for Regional Air Mobility. Although several different use cases could exist within RAM, we chose to focus on a subset of characteristics that could be applied to an aircraft regularly operating at more than just the 457 Part 139 airports in the CONUS; specifically, we considered requirements for an aircraft that could access up to 3,504 hard-surfaced, lighted, public-use airports in the CONUS. The considerations for requirements of a RAM aircraft are summarized in Table 2, and the operational considerations of RAM aircraft are summarized in Table 3.

Table 2 Summary of RAM Aircraft Requirements

Description	Value	Implication
Maximum Passenger Seating	≤ 9	Scheduled passenger operations under 14 CFR §135 possible
		Enables Certification Level 3 under 14 CFR §23 (Normal Category)
		Single-pilot operations possible under 14 CFR §135 (rather than 2 otherwise); multi-axis autopilot required for single-pilot IFR operations
		Pilot-in-command requires only commercial certificate (unless turbojet) with at least 500 hours total time for VFR operations (rather than 1,500)
		Pilot-in-command needs only commercial certificate (unless turbojet) with at least 1,200 hours total time for IFR operations (rather than 1,500)
		Collision avoidance system not required
	≤ 19	Enables certification Level 4 under 14 CFR §23 (Normal Category) rather than §25 (Transport Category)
		No flight attendant required
	≤ 30	Unscheduled passenger operations under 14 CFR §135 possible
		Collision avoidance system not required for non-turbine-powered aircraft
		No security program required under 49 CFR §1544 other than based on certified takeoff weight
Maximum Certified Takeoff Weight	≤ 12,500 lbs	Enables operation at airports without a security program under 49 CFR §1544 (subject to requirements associated with # of passenger seats)
	≤ 19,000 lbs	Enables certification under 14 CFR §23 (Normal Category) rather than §25 (Transport Category)
	≤ 33,000 lbs	Collision avoidance system not required for non-turbine-powered aircraft (subject to requirements associated with # of passenger seats)
	≤ 101,309.3 lbs	Reduced security program required for all-cargo operations
14 CFR §23 (Normal Category)	Level 3 (≤ 9 passenger seats ≤ 19,000 lbs)	Development Assurance Level for critical hardware and software of 1 failure per 100 million flight hours for catastrophic failures (otherwise 1 per billion per Level 4 or §25 Transport Category)

Table 3 Operational Considerations for RAM Aircraft

Description	Value	Implication
Operating Rules	14 CFR §135	Public passenger operation possible at airports other than 14 CFR §139 airports (only 457 in CONUS vs 4,457 public-use airports)
Distance between O/D pairs	100 nmi	Meets current niche RAM markets with constrained geography
	300 nmi	Meets majority of current RAM markets
Non-direct distance between O/D pair	20-40%	For O/D pairs under 200 nmi
	5%	For portion of O/D pair distance over 200 nmi
Reserve mission energy	30 min at normal cruising speed	VFR day reserve requirement
	45 min at normal cruising speed	VFR night reserve requirement
		IFR reserve requirement if no alternate airport required
	50 (to be refined) nmi alternate + 45 min at cruising speed	IFR reserve requirement if alternate airport required (forecast weather at destination does not meet certain criteria)
Maximum operating speed	250 knots calibrated airspeed or less	Speed limit for all operations under 10,000 ft MSL
		Enables certification under low-speed criteria in 14 CFR §23 (also $M \leq 0.6$ if aircraft uses Mach)
Maximum flight time	99 min	For aircraft without an onboard lavatory
Maximum operating altitude	8,000 ft MSL	Maximum cabin altitude for pressurized aircraft under 14 CFR §121
	12,500 ft MSL	Crew must use supplemental oxygen if operating more than 30 min
	14,000 ft MSL	Crew must use supplemental oxygen regardless of operating time
	15,000 ft MSL	Passengers must be provided with supplemental oxygen
	18,000 ft MSL	Class A airspace begins; additional air traffic management requirements
	25,000 ft MSL	Pressurized cabin required for Normal Category airplanes (14 CFR §23)
Runway environment	2,665 ft runway at 4,100 ft density altitude	Accounts for 75% of public use, hard-surfaced, lighted CONUS airports per maximum temperature observed from 2010-2020
	3,364 ft runway at 3,100 ft density altitude	Accounts for 50% of public use, hard-surfaced, lighted CONUS airports per maximum temperature observed from 2010-2020

These considerations show that non-turbojet RAM aircraft that have fewer than 10 passenger seats with an MCTW of 12,500 pounds or less maximizes access to airports, since such an aircraft would not be required to operate at an airport certified under 14 CFR §139 nor be required to operate under the security rules of 49 CFR §1544. Such an aircraft could operate scheduled service under 14 CFR §135 and could be certified under the airworthiness rules in 14 CFR §23 Normal Category airplanes with certification level 3. It could be crewed by a single commercial-rated pilot with no flight attendant. The aircraft could operate under IFR if equipped with a capable autopilot, the critical installed equipment and software could be certified to a DAL that is 10 times lower than that for an aircraft capable of carrying more passengers, and no collision avoidance system would be required. Although this paper does not explicitly characterize market forces, an aircraft sized to a nominal mission range of at least 130 nmi may capture niche transportation markets,[‡‡‡‡‡] and if mission range were expanded to 365 nmi, the aircraft could handle the vast majority of today's RAM passenger and cargo missions. An energy reserve suitable for operating 45 minutes at normal cruise speed plus a 50 nmi diversion to an alternate airport would be adequate for RAM operations under IFR. A maximum operating speed of 250 knots calibrated airspeed or less with a maximum flight time at maximum range of 99 minutes is recommended. Sizing the aircraft to operate from a 2,665 ft runway at a density altitude of 4,100 ft is also suggested to enable regular operation from at least 2,507 CONUS airports.

[‡‡‡‡‡] Assumes 30% non-direct routing for distances up to 200 nmi, the midpoint of the 20-40% range found from Crawford et al. [32].

Acknowledgments

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