Comparative Analysis of Airspace System Accessibility for Uncrewed Aircraft Systems for Regional Operations

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***Abstract*—As part of newly developing aviation markets, fixed-wing Uncrewed Aircraft Systems (UAS) are projected to impact airspace systems and conventional air traffic in the future. The initial introduction of fixed-wing cargo UAS for regional operations is anticipated to occur at smaller under-utilized airports. Therefore, this paper assesses the integration potential of regional fixed-wing cargo UAS into the airspace system. A baseline is established to identify potential airports for UAS operations in different areas. Additionally, using 2022 data, regional aircraft eligible for future cargo UAS operations are investigated. Finally, the accessibility of these regional aircraft at the identified airports was analyzed. Based on the availability of current certified landing systems needed for initial UAS operations, the potential airports for UAS operations are compared in the areas of Germany, Texas, and California. Despite 173 identified airports for potential UAS operations in Germany, 376 in Texas, and 227 in California, only eleven of these airports provide current certified landing systems needed for initial UAS operations. However, other landing system technologies that are currently under development, such as vision-based landing systems, might support UAS accessibility at the identified airports for potential UAS operations in the future.**

Keywords—Uncrewed aircraft systems, UAS, regional air mobility, regional aircraft, air cargo, regional airport

I. INTRODUCTION

The United States (US) and Europe both have an extensive network of airports and dense airspace. Airspace in the US is, on average, denser and airports are generally busier in terms of flight movements, as well as enplaned passengers and cargo per airport, than in Europe [1]. Despite the high overall number of flight movements, many US and European airports operate under capacity because travelers and air cargo instead are consolidated into fewer, larger aircraft on high-traffic routes via major hubs [2]. In fact, only around 0.6% of all airports in the US serve 70% of passenger flights and 1.8% of all airports in Europe are responsible for 50% of air transport services [2, 3]. Moreover, most US and European local and regional airports are increasingly under-utilized [2, 4]. The introduction of next-generation air transport systems, such as fixed-wing Uncrewed Aircraft Systems (UAS), may help to revitalize traffic at these under-utilized airports [5, 6]. UAS are highly automated aircraft without pilots on board and the most promising initial use case for the development of these increasingly autonomous aircraft systems is expected to be regional air cargo operations [6].

In recent years, congestion at major hub airports, the emergence of electric and other non-conventionally powered aircraft, and a significant pilot shortage in the regional sector have created a desire to revitalize Regional Air Mobility (RAM) and to rethink the typical hub-and-spoke air cargo model [2]. Cargo UAS provide a proving ground for increasingly autonomous technologies because they will be subject to fewer regulations in terms of safety compared to operations that transport passengers. These fixed-wing cargo UAS will be either conversions of existing aircraft or new designs. To safely and efficiently integrate these fixed-wing UAS, whether they include new entrant aircraft or conversions, with conventional traffic, it is critical to consider and analyze the environment in which the UAS are operating. This paper aims to answer the questions, "What kind of airports are accessible to regional air cargo aircraft eligible for UAS operations, given current assumptions about technological capabilities, as well as where and how many of these airports are in the airspace system?" Answering these questions provides an important input to performing studies and simulations that assess the impact the introduction of cargo UAS will have on the airspace system and its different entities.

For the regional cargo UAS use case, it is likely that, initially, existing aircraft will be converted to UAS. Therefore, a previous study to obtain a baseline on current regional air cargo operations in the US and Europe determined three areas (Germany, Texas, and California) as good candidates for initial cargo UAS operations due to their large number of under-utilized airports and importance to the air cargo network. It was also found that turboprop aircraft dominate the regional air cargo network. In this paper, current air traffic and airport data from 2022 were analyzed to provide a baseline for how the introduction of fixed-wing UAS may evolve and impact airspace systems differently in different areas, by comparing Germany, Texas, and California.

This paper will review previous work and establish background differences between US and European airspace in Section II. Section III will describe the derivation of a baseline and the methodology for how that baseline will be used for comparison. Using that baseline, Section IV will compare the potential for identified airports to support UAS operations by distinguishing between different Instrument Approach Procedures (IAP) needed for initial UAS operations. The final Section V presents concluding remarks and future work.

II. BACKGROUND AND PREVIOUS WORK

An airspace system can be considered as a network of different entities in controlled and uncontrolled airspace [7]. Among others, entities include airports and aviation services, procedures, and personnel managing the air traffic. When analyzing and comparing US and European airspace systems, it is important to consider the different characteristics of their Air Traffic Management (ATM) systems. The US and European ATM systems have many fundamental similarities in terms of their operational concepts. However, in Europe, 37 different national Air Navigation Service Provider (ANSP) organizations are responsible for different geographic areas, whereas in the US, airspace management is provided by one single national organization the Federal Aviation Administration (FAA) [1, 8]. Thus, ATM in Europe occurs primarily within individual European country borders. The Single European Sky (SES) initiative was introduced by the European Union (EU) in 2004 to de-fragmentize the European airspace and jointly improve efficiencies towards safety, performance, technological contribution, human factors, and airport infrastructure [8].

A. Differences in airspaces classes

Regularly, EUROCONTROL, on behalf of the EU, and the FAA jointly publish a report on "ATM operational performance comparisons between the US and Europe". The latest report published in 2019 shows that, on average, the density of operations in the US airspace of the Conterminous United States (CONUS) is higher than in Europe, because the US controls almost 50% more Instrumental Flight Rules (IFR) flights than Europe, even though its airspace is 10% smaller geographically [1]. Table I provides a comparison of airspace classes in terms of being controlled by Air Traffic Control (ATC) and the separation services provided, using Germany (GER) as a European example versus the US [9, 10, 11].

TABLE I. COMPARISON OF DIFFERENT NATIONAL AIRSPACE CLASSES

Airspace classes[a]	Controlled		ATC separation	
	GER	US	GER	US
A (Alpha)	-[b]	Yes	-	IFR to IFR *no VFR traffic*
B (Bravo)	-	Yes	-	V/IFR to V/IFR
C (Charlie)	Yes	Yes	IFR to V/IFR	IFR to V/IFR
D (Delta)	Yes	Yes	IFR to IFR	IFR to IFR
E (Echo)	Yes	Yes	IFR to IFR	IFR to IFR
G (Golf)	No	No	No	No

a. In addition to these six airspace classes, there are designated airspace areas with limitations and special use such as for military operations.

b. Unlike some other European countries, Germany does not have Class A airspace in operation. France, for example, uses Class A for the airspace around its capital, Paris. Class A airspace in the United States is not around airports at all. Rather, it incorporates the airspace between 18,000 feet and 60,000 feet.

ATC is responsible for providing separation services to aircraft by ensuring a minimum separation between the individual aircraft. In the US, airspace Classes A and B exist in which all flights must be separated by ATC, whereby only IFR flights are permitted in airspace Class A. In the only uncontrolled airspace, Class G, there is no separation of flights by ATC. Furthermore, there are additional rules for separation as in Special Visual Flight Rules (SVFR) operations when weather conditions are not within the Visual Flight Rules (VFR) limits [9, 11, 12].

Additionally, Germany operates Radio Mandatory Zones (RMZ), which are specially created for IFR approaches to airports in uncontrolled airspace. The RMZ begins on the ground (GND) and extends to the above bordering airspace Class E, which starts between 1,000 feet and 2,500 feet Above Ground Level (AGL). Within the RMZ, carrying radio communication equipment is mandatory. However, the aircraft does not require ATC clearance for its entry, but voice communication capability and radio standby [9].

Within the different airspace classes there are further differences between Germany and the US such as the altitude AGL to which airspace extends. In the US, Class D, for example, typically covers the airspace from GND to 2,500 feet AGL [10]. In Germany, Class D airspace can reach 10,000 feet Mean Sea Level and is utilized as a Controlled Traffic Region (CTR) at 32 public airports and airfields in controlled airspace [9]. In the US, however, Classes B, C, and D are utilized as controlled airspaces around airports depending on the level of flight activities (with Class B airspace being used for the busiest airports). Additionally, some less-busy, towered airports in Class D airspace in the US become non-towered at less traffic-intensive times, such as late evening or night, and move to Class E or G airspace accordingly. For example, Waco Regional Airport (KACT) is a Class D airspace between 1200-0600 Universal Time Coordinated and is Class E when the tower is not operating. For simplicity, airports with a physical air traffic control tower receiving separation by ATC will be counted as "towered" in this study, although some airports might not always have this tower operational.

B. Differences in network and distribution of airports

Looking at the year 2022, the prior trends of US airports being busier than their European counterparts, as investigated in [1], can be observed by comparing the most recent annual data from Eurostat, the statistical office of the European Union, and the US Bureau of Transportation Statistics on commercial flight movements with passengers and/or cargo on board (all operations[1]), enplaned passengers, cargo-only flight movements, and enplaned cargo in metric tonnes (t) for the 34 busiest main European and US airports in Table II [13, 14].

TABLE II. MEDIAN VALUES BASED ON 34 MAIN AIRPORTS BY COMMERCIAL MOVEMENTS IN 2022

Median value at main airports	Europe	United States
All operations flight movements[a]	140,566	300,489
Enplaned passengers	18,752,120	30,750,214
Cargo-only[b] flight movements	4,433	9,906
Enplaned cargo (t)[b, c]	141,206	198,554

a. Flight movements refer to the sum of an arrival and departure for all national and international commercial flights that are both scheduled and non-scheduled.

b. Cargo consists of both freight and mail. "Cargo-only" flights have no passengers.

c. Enplaned cargo on board cargo-only flights.

Although Table II indicates that the main airports in the US are busier on average, Europe's airports have a higher number of IFR flights per active runway and airports operate

[1] The air cargo on board of "all operations flight movements" is either cargo-only (no passengers transported), belly freight (cargo transported in the lower deck of the passenger aircraft), or combi freight (split of the main cabin of the aircraft to separate passenger seats and cargo area).

closer to their capacity limits than in the US. In 2022, 8,302,587 IFR flights were operated in Europe (based on the 27 states of the European Union plus Norway and Switzerland) with 35.8% of IFR flights (2,971,433) in France and 32.7% of IFR flights in Germany (2,712,552) [15]. In the US, 15,416,640 IFR flights were handled by the FAA in FY2022[2] [16]. 13.7% of the IFR operations in the US took place at just three airports: Atlanta (KATL), Chicago O'Hare (KORD), and Dallas-Fort Worth (KDFW).

Generally, it can be observed that there are a considerable number of under-utilized airports in the US and Europe, which may be candidates for initial UAS operations. In the US, about 70% of passenger flights are operated from just 30 airports (operated in the relatively busy airspace Class B), although there are over 5,000 public US airports [2]. In Europe, a similar phenomenon exists with over 2,500 less busy airports [3, 4]. Likewise, air cargo traffic is primarily oriented around hub-and-spoke operations, namely through major international hubs [5, 17, 18]. Smaller airports are responsible for feeder traffic to the hub-and-spoke system or for point-to-point flights, with many of these less-busy airports focused on passenger transport rather than air cargo [5, 18].

Previous analysis has shown that the aircraft flying into the airports likely to be used for the introduction of cargo UAS are small, fixed-wing aircraft, also known as regional aircraft [19]. The term *regional aircraft*[3], in this work, refers to fixed-wing aircraft that have a payload <9 tonnes and a Maximum Takeoff Weight (MTOW) <25 tonnes, regardless of propulsion type. The analysis of the potential for regional air cargo operations for UAS has also shown that most of domestic[4] cargo flight movements by regional aircraft were operated within a flight distance under 1,000 kilometers [19]. 94% of the domestic cargo-only flight movements by all aircraft in Europe and 97% of the domestic cargo-only flight movements by regional aircraft in the US were operated within this flight distance. Likewise, this definition of a regional flight distance is in accordance with NASA's definition of RAM, in which regional flights are conducted in ranges between 50-500 nautical miles (93-926 kilometers) [20].

The same analysis proved that a higher number of flight movements by smaller regional aircraft in the US (e.g., Cessna 208 Caravan) are used to transport an equal amount of cargo (3.7 versus 3.9 million tonnes) relative to Europe [19]. Considering regional turboprop aircraft types, larger aircraft are used in Europe, such as the ATR 42, ATR 72, and Embraer EMB 120. Compared to the US, almost 60% of all European cargo flight movements are operated over longer regional flight distances between 300 and 700 kilometers. However, in the US, over 60% of cargo flight movements by regional aircraft are operated between 0 and 300 kilometers in flight distance.

Despite its high number of small commercial airports and the by far highest amount of intra- and extra-European cargo flight movements compared to any other European country, Germany had fewer than 400 domestic cargo flight movements by regional aircraft in 2021 [19]. This number indicates that Germany is a potential country for the introduction of regional cargo UAS via the introduction of new flight routes.

The same analysis has shown that California and Texas appear to be well suited for regional fixed-wing cargo operations in the US [19]. California, a large, populous state in the western US of similar size to Germany, and Texas, another large, populous state, in the south central portion of the US, have a similar percentage of intra-state cargo flight movements being performed by regional aircraft (i.e., eligible for potential UAS replacement). Both Texas and California also have important large cargo sorting hubs. However, the share of airports by sizes relevant for cargo UAS operations is different in the two US states. California has a high share of *small*[5] airports (73 *small* airports, more than any other US state, save Alaska[6]) whereas Texas has the highest share of medium-sized airports (that Eurostat refers to as *other* airports) compared to any other US state. These *other* airports, being busier than the *small* airports, may present more challenges with respect to the integration of cargo UAS. In this context, according to Eurostat, Germany has 141 *small* public, commercial airports with the majority being under-utilized [13]. The three areas, Germany, Texas, and California are relatively busy in terms of total number of cargo flight movements compared to other US states and European countries (see Table III).

TABLE III. AIR CARGO FLIGHT MOVEMENTS IN 2021 [19]

Air cargo flight movements	Germany	Texas	California
Total[a] by all aircraft	157,764	98,007	178,792
Intra-state[b] by all aircraft	15,816	44,504	138,180
Total by regional aircraft	9,870	18,575	28,370
Intra-state[a] by regional aircraft	392	15,026	27,952

a. Refers to cargo flights within the US and to intra- and extra-European cargo flights.

b. Intra-state refers to cargo flights within a US state and within Germany.

Likewise, the investigated areas have a significant share of less-busy airports relevant for the introduction of initial UAS operations, namely *small* and *other* airports. However, Germany has a comparatively low share of domestic cargo flight movements by regional aircraft that have the potential to become UAS by replacing current flight routes. California and Texas, on the other hand, might be prime locations with the required airport infrastructure as well as current air cargo routes for the replacement by UAS [19].

III. METHODOLOGY OF THE ANALYSIS OF AIRSPACE SYSTEM CHARACTERISTICS

The methodology section describes the baseline that is applied to identify potential airports for UAS operations in

[2] FY2022, or Fiscal Year 2022, was Oct. 1, 2021, to Sept. 31, 2022.

[3] Note that, in [19], *regional aircraft* referred to only piston and turboprop aircraft. The term has been expanded to include jet aircraft in this work because there is a strong desire by industry to expand beyond just turboprop aircraft into larger jet aircraft.

[4] Domestic refers to flight movements within the US or within a European country.

[5] According to Eurostat, *small* airports are defined as airports with <15,000 annual passenger units (where one passenger unit corresponds to either one passenger or 100 kilograms of cargo); *other* airports have <150,000 to ≥15,000 annual passenger units, and *main* airports >150,000.

[6] While Alaska is a potentially very interesting use case for cargo UAS, the choice was made to study in depth only states in the CONUS, as those results would likely be more applicable to other US states.

different areas. The IAP needed for initial UAS operations at the potential airports are introduced before concluding with the data sources used for this study.

A. Derivation of a baseline for analysis

To assess how the introduction of UAS may evolve and impact airspace systems in different areas, a baseline of accessible airports for potential UAS operations needs to be identified. First, potential airports are defined based on the air transport services they provide. In a second step, potential airports are classified based on their annual number of IFR flight movements to identify less busy airports. Finally, a cutoff regarding the maximum number of flight movements at an airport is applied to provide a baseline of potential airports for the introduction of UAS in different areas, namely Germany, Texas, and California.

In Germany, airports and airfields are collectively referred to as *aerodromes* by the German air navigation service provider, Deutsche Flugsicherung (DFS). Here, DFS distinguishes between *airports*, which "require protection by a construction protection area in accordance with § 12 of the Air Traffic Act", and *airfields*, which do not. The construction protection area ensures that the construction of buildings within a radius of 1.5 kilometers radius around the airport reference point, as well as on the take-off and landing areas and safety areas, require approval by the aviation authority [21]. For simplicity, and to better align with FAA terminology, both airfields and airports will, in this paper, be referred to as *airports*.

It is likely that the introduction of cargo UAS will initially occur at publicly accessible airports with less busy air transport services [22]. Due to this factor and the added difficulty of interacting with military aircraft, private [7] airports, as well as military and military-public joint-use airports are excluded from consideration. Therefore, only *public* airports will be analyzed. Public airports can be further distinguished by whether they provide commercial and/or non-commercial air transport services. Eurostat defines commercial air transport operators and commercial purposes as "scheduled or non-scheduled air transport services, or both, which are available to the public for carriage of passengers, mail, and/ or cargo" [23]. The FAA defines airports with "commercial services" as airports that are publicly owned "with at least 2,500 annual enplanements and scheduled air carrier service" [24]. In this study, the term *public airport* will refer to airports that are publicly accessible (regarding potential UAS operations), regardless of if the airport currently has commercial operations. For example, Heringsdorf Airport (EDAH), despite its relatively few (688) IFR flight movements in 2022 is a public airport because it is publicly accessible for use by both commercial and general aviation aircraft [9].

According to DFS, Germany operates 15 towered International Airports of which four serve as so-called *Hub* airports, six as *International Access Airports 1* (IAA1) and five as *International Access Airports 2* (IAA2). In addition to the 15 towered International Airports, DFS defines 20 more towered airports as *Regional Airports* [25]. In 2022, the four German *Hub* airports (Berlin EDDB, Frankfurt EDDF, Dusseldorf EDDL, and Munich EDDM) had a median of 222,483 IFR flight movements followed by the IAA1 with a median of 77,145 annual IFR flight movements. In total, the *Hub* Airports and the IAA1 accounted for 87.7% of all annual IFR flight movements of all the towered airports in Germany. Looking at the IFR flight movements of IAA1, Cologne/Bonn Airport (EDDK) was the busiest IAA1 (119,117) and Nuremberg Airport (EDDN) the least busy (35,714). The IAA2 had a median of 11,909 annual IFR flight movements with the highest number of annual IFR flight movements operated at Bremen Airport (EDDW) with 19,423 IFR flight movements and Erfurt Airport (EDDG) as the least busy with 2,865 annual IFR flight movements. The subsequent category of airports by DFS are so-called *Regional Airports* with a median of 6,483 annual IFR flight movements in 2022. The most IFR flights operated at a *Regional Airport* was at Dortmund Airport (EDLW) with 21,476 annual IFR flight movements and Schwerin-Parchim Airport (EDOP) being the least busy *Regional Airport* with one single annual IFR flight movement.

For the US, the FAA distinguishes between primary airports classified as *Hub* (large, medium, and small) and *Non-hub* airports, as well as between non-primary airports classified as *National*, *Regional*, *Local*, *Basic*, and *Unclassified* (limited activity) airports [24]. Primary airports are airports with commercial services that handle more than 10,000 passenger boardings annually. The categorization of US airports also includes special facilities such as seaplane bases or heliports, though those are excluded from this analysis. Additionally, as in Germany, the US operates military-civil joint-use airports, which, as discussed previously, will be excluded.

In this study, the baseline of accessible airports for potential UAS operations refers to the term *potential UAS airports*. *Potential UAS airports* include: 1) Public towered airports with annual IFR flight movements percentages under 2.2% for the given area (country/state) and 2) Public non-towered airports.

The <2.2% value was selected because the least busy IAA1 airport (EDDN) had 2.2% of the total annual IFR flights in Germany. Using this cutoff includes the five towered IAA2 and the 20 towered *Regional Airports*, as defined by DFS. Additionally, there are numerous airports in Germany that are non-towered and for which there is no record of IFR and VFR flight data provided by DFS. It can be assumed that these non-towered airports have fewer flight movements than the towered airports and thus are also included in the definition of *potential UAS airports* in this study. In Germany, there are 183 public airports (32 towered) with 173 being *potential UAS airports* (22 towered).

In Texas, there are a total of 2,080 airports (394 of which are public use) with 210 commercial airports included in the NPIAS (48 being towered). California has a total of 899 airports (246 available for public access), with 188 commercial airports included in the NPIAS (57 being towered). Adapting the <2.2% cutoff for towered US airports, Texas has 376 *potential UAS airports* (40 being towered) and California has 227 *potential UAS airports* (43 being towered) [26]. For the year 2022, Fort Worth Alliance Airport (KAFW) was the busiest *potential UAS airport* in Texas with 48,119 annual IFR flight movements and Palm Springs International

[7] German airports are distinguished by their type of operating obligation. German airports with no operating obligation (because they are privately owned) are called special airports and special airfields. Only the operator and, upon request, third parties are allowed to operate on them.

Airport (KPSP) was the busiest *potential UAS airport* in California with 47,982 annual IFR flight movements.

B. Introduction of IAP for initial UAS operations

IAP are used to land in Instrument Meteorological Conditions, in which visual landing is not possible. It is anticipated that UAS will utilize IAP to land at airports. However, no regulations yet exist that specify required IAP for UAS. Nonetheless, when integrating UAS into the airspace system, it is important to consider other air traffic participants in the airspace as well as the availability of enabling procedures and technologies for initial UAS operations, such as needed IAP present at airports.

RTCA, Inc. highlights the need for autoland systems for UAS in its Guidance Material and Considerations for Unmanned Aircraft Systems (RTCA DO-304A, Section 2.4.6) [27]. Although autoland systems not based on ground based navigational aids would provide the most operational freedom for UAS, Instrument Landing System (ILS) Category (CAT) III systems, are the only current systems that enable autoland[8]. Therefore, until such time as alternative systems are developed and certified, it is assumed that for future fixed-wing UAS operations at airports, the most likely current IAP for UAS is ILS CAT III. Although other landing systems, such as vision-based landing systems [28], are also in development, only currently certified systems are considered in this work [29]. ILS CAT III are the most stringent IAP that exist today and require the highest level of technology of all the IAP. For ILS CAT III approaches, autoland and rollout control systems are needed to control the approaching aircraft. For more information about ILS categories, see [29].

However, ILS, especially CAT III systems, do have their downsides. They are expensive to implement and maintain and they only serve a single runway end. As such, they are not installed at many airports (only 68 throughout the US [27]). Another class of systems already in use that can be considered for future airport accessibility of UAS are Ground Based Augmentation Landing Systems (GLS) [30]. GLS systems need only one installation per airport. Once installed, the Global Positioning System localizer works for all runways, making it a cheaper system to install, maintain, and upgrade than ILS [31]. Of course, aircraft must be equipped with the necessary on-board systems to utilize GLS. The categories (CAT I, II, and III) of GLS are the same as for ILS, though only CAT I and II are operational as of this writing.

Of the five different landing systems, ILS CAT I, II, and III and GLS CAT I and II, the final three are considered *UAS IAP* insofar as they provide a higher potential for utilization by UAS operations. ILS CAT III is included because it is the highest-level IAP currently in use. The GLS approaches are included because they can be upgraded to CAT III more easily than ILS, once CAT III systems become available [32]. According to a SESAR estimate, full GLS compliance may be achieved as early as 2036 [33]. Based on the availability of *UAS IAP*, this study further distinguishes between 1) *Potential UAS airports* providing *UAS IAP* and 2) *Potential UAS airports* without *UAS IAP*.

Potential UAS airports that provide *UAS IAP* have a higher potential to be initially utilized for UAS operations than *potential UAS airports* without *UAS IAP*. However, *potential UAS airports* without *UAS IAP* will still be considered for future UAS operations, as they could be retrofitted with required *UAS IAP* at any time. Additionally, there will likely be further technological advancements that could enable UAS accessibility at these *potential UAS airports*.

C. Data sources

The data on operational airports in Germany were accessed from the Aeronautical Information Publication Germany from DFS, which are publicly accessible since January 2023 [9]. In addition to general national regulations and requirements, specific information on airports and air navigation services can be retrieved. For this paper, information was collected about the name and operational type of airport, availability of IAP, such as ILS and GLS, aircraft permitted by MTOW at the airports, and hours of operation for all available German operating airports.

For the US, airport and runway data (e.g., landing systems available, runway weight restrictions) were gathered from the FAA's National Airspace System Resource [34]. Airport classification information was obtained from the FAA's National Plan of Integrated Airport Systems (NPIAS) [35]. IFR movement counts at towered airports were sourced from the FAA's Operations Network database [36].

The statistics on commercial flight movements by regional aircraft for Europe and Germany were retrieved from Eurostat [13]. Here, a commercial flight movement represents the sum of the arrival and departure of an aircraft at an airport. In this context, specific data of the year 2022 on all domestic (e.g., flight movements within Germany) and international (e.g., flight movements between Germany and another country) flight movements for passenger and cargo transports were analyzed. The data for the domestic European flight movements include data for 35 European countries, although complete data were not available for every country. Note here that domestic operations within a European country can also be referred to as "intra-state" flight movements. Such intra-state flight movements for the US indicate a flight within a single US state, whereas domestic US flight movements could move between any US state or territory.

Statistics for flight movements in the United States[9] were sourced from the Bureau of Transportation Statistics (BTS) T-100 Segment data [14]. BTS data combine segment data by aircraft type, origin, destination, and airline. The data denote the number of passengers, the amount of freight, and the amount of mail per segment. Flight movements with both origin and destination outside the US are excluded from the BTS data. Additionally, only airlines with annual operating revenues of $20 million USD or more are included in the data, so some smaller airlines are excluded due to lack of data.

IV. Analysis of UAS Accessibility Potential

This section focuses on the airspace system accessibility of flights eligible for UAS operations based on availability of *UAS IAP*. The potential to use UAS for regional aircraft at the identified *potential UAS airports* is discussed.

[8] To operate in true zero visibility conditions, surface operations, such as taxiing, also need to be automated.

[9] Unless otherwise specified, data for the United States includes Puerto Rico and other US territories. A flight from Miami, Florida to San Juan, Puerto Rico, for example, would be counted as domestic.

A. *Availability of IAP at airports*

Table IV shows the count of all airports (public and non-public) and *potential UAS airports*, sorted by towered and non-towered, in Germany, Texas, and California that are equipped with different categories of ILS/GLS procedures. Airports that provide multiple ILS/GLS procedures are counted in all applicable categories.

TABLE IV. AVAILABILITY OF ILS/GLS PROCEDURES AT AIRPORTS

ILS/GLS availability	Count of airports (towered / non-towered)		
	Germany	**Texas**	**California**
Total at all airports	**35 / 6**	**38 / 5**	**37 / 8**
ILS CAT I	27 / 6	38 / 5	37 / 8
ILS CAT II	3 / 0	7 / 0	9 / 0
ILS CAT III *(UAS IAP)*	20 / 0	5 / 0	6 / 0
GLS CAT I *(UAS IAP)*	2 / 0	1 / 0	1 / 0
GLS CAT II *(UAS IAP)*	1 / 0	0 / 0	0 / 0
Total at potential UAS airports	**20 / 4**	**31 / 5**	**26 / 8**
ILS CAT I	17 / 4	31 / 5	26 / 8
ILS CAT II	2 / 0	1 / 0	3 / 0
ILS CAT III *(UAS IAP)*	9 / 0	1 / 0	1 / 0
GLS CAT I *(UAS IAP)*	1 / 0	0 / 0	0 / 0
GLS CAT II *(UAS IAP)*	0 / 0	0 / 0	0 / 0

In Germany, a total of 41 airports have ILS/GLS approach procedures. An ILS CAT III approach is available at 20 airports. In addition to ILS CAT III, two German airports, Bremen Airport (EDDW) and Frankfurt Airport (EDDF), provide GLS CAT I procedures. Additionally, Frankfurt Airport is the only German airport with GLS CAT II [31]. The only airports in California and Texas that have GLS procedures (CAT I at both) are George Bush Intercontinental (KIAH) in Houston, Texas and San Francisco International (KSFO) in San Francisco, California.

Texas and California have about the same number of airports with ILS availability as Germany (see Table IV). The two US states have more *potential UAS airports* with ILS/GLS availability than Germany (36 in Texas and 34 in California versus 24 in Germany). However, Germany has more *potential UAS airports* providing *UAS IAP* (one in Texas and one in California versus nine in Germany).

B. *UAS accessibility potential for regional aircraft at potential UAS airport*

In the previous analysis on the potential of regional air cargo operations for UAS [19], regional aircraft with turboprop engines were the focus of the investigation. In the US, the Cessna 208 Caravan aircraft was the dominant cargo-only aircraft with more than 83% of domestic US cargo flight movements in 2021. In Europe, the ATR 42, ATR 72, and Embraer EMB 120 aircraft account for more than 94% of domestic European cargo flight movements by regional aircraft in 2021. Discussions with industry experts indicated that, in addition to regional turboprop aircraft, larger regional jet-powered aircraft may also be considered for UAS operations. Previous research by the German Aerospace Center (DLR) investigated the development and validation of a concept for the operation of unmanned cargo as part of the "Unmanned Freight Operations" (UFO) project between 2014 to 2017 [37]. In that work, a Boeing 777F long-range wide body aircraft was analyzed covering three use cases: express freight, company internal transport, and disaster relief flights. However, as discussed in Section II.B, current efforts focus on using fixed-wing aircraft in the RAM realm at relatively small and under-utilized airports that typically do not service widebody aircraft. Hence this study was limited to regional aircraft, as defined in Section II.B.

1) *Types of regional aircraft eligible for UAS:*

It was assumed that domestic flights have the highest potential for initial UAS operations because different countries are likely to have different regulations regarding UAS operations. Table V provides an overview of aircraft types used for domestic flight movements at *potential UAS airports* [13, 14]. Note here that data are at the domestic level to give a more general picture of what type of regional aircraft are operating within different European countries versus the US. Significant differences in the total number of flights within European countries and the US are due, in part, to not counting flights between European countries.

In Table V, domestic cargo-only flight movements, as well as flight movements with passengers and/or cargo on board (all operations), are compared. The regional aircraft in the table have turboprop engines, unless labeled *(piston)* or *(jet)*.

TABLE V. DOMESTIC FLIGHT MOVEMENTS BY REGIONAL AIRCRAFT TYPES IN EUROPE AND THE US IN 2022

Domestic flight movements by regional aircraft		Europe[a]	US
All operations[b]	**Total flights[c]**	**246,796**	**1,313,204**
	ATR 42	6.9%	0.7%
	ATR 72	16.9%	0.6%
	Bombardier CL-600 (jet)	15.0%	0.2%
	Bombardier Dash 8-100	52.6%	1.0%
	Embraer EMB 120	1.4%	-[e]
	Embraer ERJ 145 (jet)	1.8%	19.5%
	Cessna 208/208B	-	23.5%
	Cessna 402 (piston)	-	5.8%
	Beech 18[d]	-	0.9%
	Canadair RJ200 (jet)	-	22.9%
Cargo-only	**Total flights[c]**	**10,529**	**155,266**
	ATR 42	23.6%	1.6%
	ATR 72	43.4%	3.3%
	Bombardier CL-600 (jet)	8.7%	<0.1%
	Bombardier Dash 8-100	<0.1%	-
	Embraer EMB 120	21.9%	-[e]
	Embraer ERJ 145 (jet)	-	-
	Cessna 208/208B	-	56.0%
	Cessna 402 (piston)	-	1.3%
	Beech 18[d]	-	11.4%
	Canadair RJ200 (jet)	-	0.6%

a. Domestic in Europe refers to flight movements within each European country, summed over all European countries.

b. Refers to commercial flight movements with passengers and/or cargo on board.

c. Refers to flight movements within the US and within individual European countries.

d. FedEx Express has a waiver to report all of its small aircraft as Beechcraft Beech 18 C-185 (Beech 18) to the BTS, without regard to the actual aircraft type. Therefore, it will be excluded from further investigation throughout the study.

e. Ameriflight, a regional air cargo carrier, operates fourteen Embraer EMB 120 aircraft but is not included in the BTS database.

For domestic cargo-only flight movements in Europe, three turboprop aircraft types (ATR 42, ATR 72, and Embraer EMB 120) are again as dominant as in the previous 2021 analysis, with a combined total of just under 90% of the operations. In fact, the only jet aircraft type with a notable number of domestic cargo-only flight movements is the Bombardier CL-600 (Bombardier Challenger 600) aircraft that accounts for 8.7% of the operations in Europe (with 15%

of all domestic operations in Europe). Cargo-only regional jet aircraft usage is even more rare in the US. Only 0.6% of cargo-only flights are operated by a single type of regional jet (Canadair RJ200). Conversely, the common aircraft in the US, the Cessna 208/208B and 402 or Beech 18 aircraft (see footnote d. in Table V), are not used in Europe. Nonetheless, these regional aircraft types combined account for a significant share (68.7%) of cargo-only operations in the US.

Looking at the engine type of regional aircraft, Table VI shows significant differences by the type of operation between regional jet aircraft and regional turboprop/piston aircraft (termed *prop* in Table VI) [13, 14].

TABLE VI. FLIGHT MOVEMENTS BY REGIONAL AIRCRAFT IN 2022

Flight movements by regional aircraft		Germany	Texas	California
All operations[a] total[b]	prop	18,521	17,112	21,911
	jet	45,565	111,108	60,459
Cargo-only total[b]	prop	9,225	11,544	13,546
	jet	55	229	8
All operations[a] intra-state[c]	prop	2,980	7,092	19,583
	jet	18,117	39,313	25,721
Cargo-only intra-state[c]	prop	112	7,058	13,540
	jet	2	25	0

a. Refers to commercial flight movements with passengers and/or cargo on board.

b. Refers to flight movements within the US and to intra- and extra-European flights.

c. Intra-state refers to flight movements within a US state and within a European country.

It is apparent that relatively few regional jet aircraft are used for cargo-only operations within Germany, Texas, or California, and that few are also used for cargo-only operations into and out of these areas. Rather, turboprop aircraft are predominant. However, jet aircraft are more common overall for all operations (commercial flight movements with passengers and/or cargo on board). Although flight movements with passengers on board are currently considered ineligible for conversion to UAS, the data show that intra-state flights, with regional flight distances of approximately <1,000 kilometers, with regional jets are common. Therefore, for this study, it was assumed that in the future, regional jet aircraft could be used for cargo-only UAS flights to serve under-utilized airports.

2) IAP availability at potential UAS airports:

Table IV shows that all *potential UAS airports* that provide *UAS IAP* are towered across Germany, Texas, and California. Yet, non-towered airports are far more numerous than towered airports (see Section III.A). To assess the availability of ILS CAT I and II and *UAS IAP* (ILS CAT III, GLS CAT I and II), Table VII breaks down the IAP by class of airspace and presence of air traffic control tower (towered) at *potential UAS airports*.

Table VII shows that Germany has a significant number of regional airports in uncontrolled Class G airspace. However, of these 151 *potential UAS airports*, only four provide ILS procedures, and none have *UAS IAP*. In controlled airspace, however, there exist 22 towered *potential UAS airports*, 20 of which enable ILS or GLS (nine with *UAS IAP*).

TABLE VII. POTENTIAL UAS AIRPORTS BY AIRSPACE CLASS AND IAP

Airspace classes	Count of potential UAS airports: Germany		Texas		California	
All	173		376		227	
	24 ILS /GLS	9 UAS IAP	36 ILS /GLS	1 UAS IAP	11 ILS /GLS	1 UAS IAP
C	-		6 towered		3 towered	
			6 ILS	0 UAS IAP	3 ILS	1 UAS IAP
D	22 towered		34 towered		40 towered	
	20 ILS /GLS	9 UAS IAP	25 ILS	1 UAS IAP	23 ILS	0 UAS IAP
E[a]/G	151 non-towered		336 non-towered		187 non-towered	
	4 ILS	0 UAS IAP	5 ILS	0 UAS IAP	8 ILS	0 UAS IAP

a. Germany does not operate airspace Class E (see Table I).

In the two US states analyzed, California has 39.6% more *potential UAS airports* than Texas. Moreover, California has 54.0% more *potential UAS airports* than Germany. Looking at the share of non-towered airports, the results are again similar. California has 44.4% more potential UAS non-towered airports than Texas and 55.1% more than Germany. Neither US state has more than one *potential UAS airport* with *UAS IAP* (Fort Worth Alliance, KAFW, in Texas and Fresno Yosemite International, KFAT, in California).

The visualization of all public airports, with *potential UAS airports* assigned a circle, including IAP configurations are shown in the following Figs. 1-3[10]. For each public airport, the highest possible IAP category is indicated with GLS being higher than ILS.

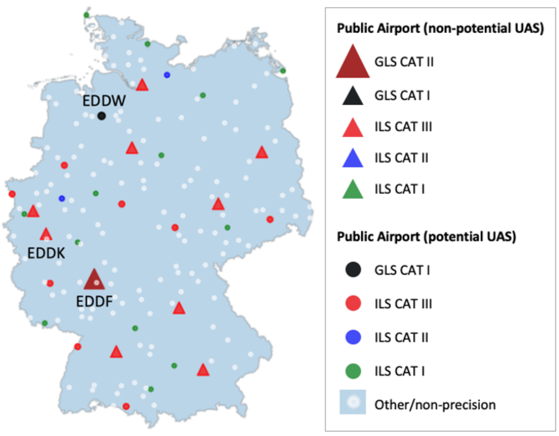

Fig. 1. Visualization of public airports in Germany with IAP availability

[10] Figs. 1-3 are not to scale with one another.

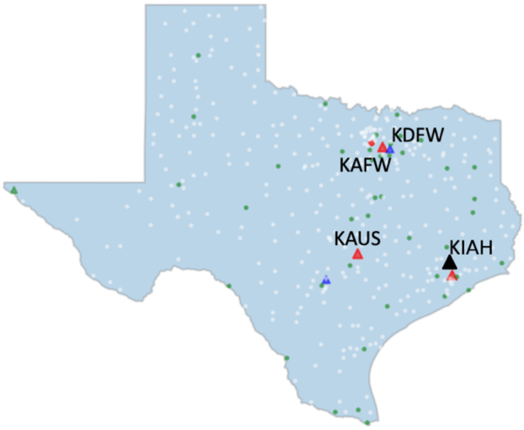

Fig. 2. Visualization of public airports in Texas with IAP availability

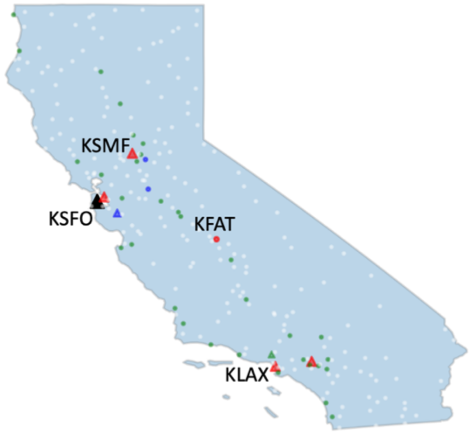

Fig. 3. Visualization of public airports in California with IAP availability

Figs. 1-3 clearly show that many of the smaller airports are located closer to the areas with larger airports providing ILS CAT III and/or GLS close to the relatively larger cities. In Germany, there is a relatively high density of *potential UAS airports* in the densely populated Ruhr region in the west of Germany (Cologne/Bonn Airport, EDDK) and around Frankfurt (Frankfurt Airport, EDDF). In Texas, airport density around the metropolitan areas of Dallas (Dallas/Fort Worth International Airport, KDFW), Austin (Austin-Bergstrom International Airport, KAUS), and Houston (George Bush Intercontinental Airport Houston, KIAH) is significantly increased. A similar picture can be drawn for California, where the density of smaller *potential UAS airports* increases around the metropolitan areas of Los Angeles (Los Angeles International Airport, KLAX), San Francisco (San Francisco International Airport, KSFO), and Sacramento (Sacramento International Airport, KSMF).

C. Discussion of UAS accessibility potential for regional operations

After identifying regional aircraft types eligible for UAS operations and *potential UAS airports* in Germany, Texas, and California in the previous section, the next step is to analyze and discuss the accessibility potential of these regional aircraft at these *potential UAS airports*. For this analysis, regional aircraft are classified based on their operational empty weight (OEW[11]) and MTOW in tonnes. As regional aircraft have a wide variety of payload tonnage, the range between OEW and MTOW was considered for the UAS accessibility assessment to give a feasible range. Evidence from a regional cargo industry expert also indicates that regional aircraft are often volumetrically filled before the aircraft's MTOW is exceeded. Therefore, if the OEW and MTOW of an aircraft is less than or equal to the rated gross weight capacity of the airport runway for the aircraft's wheel configuration, it was included in the accessibility assessment of the respective airport. UAS accessibility of regional aircraft is differentiated between total number of *potential UAS airports* as well as between towered (twrd) and non-towered (ntwrd) *potential UAS airports*.

Table VIII provides an overview of the most widely used regional aircraft types in Europe and the US (see Table V) that are likely to be eligible for UAS operations and their accessibility potential at *potential UAS airports*.

TABLE VIII. POTENTIAL UAS AIRPORT ACCESSIBILITY BY AIRCRAFT TYPES ELIGIBLE FOR UAS

Aircraft types MTOW (OEW)	**Count of accessible potential UAS airports** MTOW (OEW)		
	Germany	**Texas**	**California**
ATR 42 18.60 t (11.75 t)	**40 (61) total** 20 (21) twrd 20 (40) ntwrd	**73 (75) total** 36 (36) twrd 37 (39) ntwrd	**77 (187) total** 36 (44) twrd 41 (143) ntwrd
ATR 72 23.00 t (11.80 t)	**36 (61) total** 20 (21) twrd 16 (40) ntwrd	**73 (75) total** 36 (36) twrd 37 (39) ntwrd	**77 (187) total** 36 (44) twrd 41 (143) ntwrd
CL-600 21.86 t) (12.32 t)	**36 (59) total** 20 (21) twrd 16 (38) ntwrd	**73 (75) total** 36 (36) twrd 37 (39) ntwrd	**77 (151) total** 36 (43) twrd 41 (108) ntwrd
Dash 8-100 16.47 t (10.48 t)	**40 (72) total** 20 (22) twrd 20 (50) ntwrd	**74 (75) total** 36 (36) twrd 38 (39) ntwrd	**77 (187) total** 36 (44) twrd 41 (143) ntwrd
EMB 120 11.50 t (7.07 t)	**61 (76) total** 21 (22) twrd 40 (54) ntwrd	**75 (75) total** 36 (36) twrd 39 (39) ntwrd	**77 (195) total** 36 (44) twrd 41 (151) ntwrd
ERJ 145 20.99 t (11.95 t)	**36 (61) total** 20 (21) twrd 16 (40) ntwrd	**73 (75) total** 36 (36) twrd 37 (39) ntwrd	**77 (187) total** 36 (44) twrd 41 (143) ntwrd
C 208 3.63 t (2.21 t)	**148 (158) total** 22 (22) twrd 126 (136) ntwrd	**293 (294) total** 38 (38) twrd 255 (256) ntwrd	**206 (206) total** 44 (44) twrd 162 (162) ntwrd
C 208B 4.00 t (2.41 t)	**146 (158) total** 22 (22) twrd 124 (136) ntwrd	**293 (294) total** 38 (38) twrd 255 (256) ntwrd	**206 (206) total** 44 (44) twrd 162 (162) ntwrd
CRJ200 23.13 t (13.84 t)	**36 (59) total** 20 (21) twrd 16 (38) ntwrd	**73 (74) total** 36 (36) twrd 37 (38) ntwrd	**77 (120) total** 36 (38) twrd 41 (82) ntwrd

The OEW and MTOW in tonnes (t) of each aircraft are listed in the column "Aircraft types" after the regional aircraft types. The metrics were used for the following regional aircraft type variants: ATR 42-600 (ATR 42) [38], ATR 72-600F (ATR 72) [39], Bombardier Challenger 650 (CL-600) [40], Bombardier DHC-8 Q200(-100) (Dash 8-100) [41], Embraer EMB 120 Brasilia (EMB 120) [42], Embraer ERJ 145 EP (ERJ 145) [43], Cessna 208 Caravan with cargo pod (C 208) [44], Cessna 208 Grand Caravan with cargo pod (C 208B) [45], and Canadair RJ200 ER (CRJ200) [46].

Taking the ATR 72 with an OEW of 11.80 tonnes and an MTOW of 23.00 tonnes as an example, this regional aircraft

[11] The OEW is the empty weight of an aircraft plus operational items including supplies necessary for full operations such as airline equipment and engine oil. Usable fuel that is needed to power the aircraft engines and the actual aircraft payload are excluded from the OEW.

type can serve a total of 36 to 61 German[12] *potential UAS airports*, depending on how much usable fuel and payload is carried. Based on the rated gross weight capacity of the runways, 61 *potential UAS airports* allow an aircraft MTOW of >10.50 tonnes (with the next higher airport MTOW being 12.00 tonnes) and 36 *potential UAS airports* an aircraft MTOW of >20.00 tonnes (with the next higher airport MTOW being 25.00 tonnes) at which the ATR 72 would be allowed to operate in Germany. For each regional aircraft type analyzed in Table VIII, accessible German *potential UAS airports* (173 in total) include all 20 potential UAS towered airports with ILS/GLS, with nine of these *potential UAS airports* having a *UAS IAP*.

For the comparatively smaller regional aircraft types that are only used in the US for air cargo operations (e.g., Cessna 208), the Table VIII also indicates the number of German *potential UAS airports* that are eligible for fixed-wing UAS operations. However, it is not clear at present whether such aircraft would be utilized for cargo operations in Germany or Europe in the future.

Overall, the analysis of current IFR flight movements in Section III.A shows that most of the flights are not operated at *potential UAS airports* today. The ten German towered airports that are not considered as *potential UAS airports* (*Hub* and IAA1) account for 87.7% of all annual IFR flight movements [25]. Similarly, a significant share of all IFR flight movements is operated at airports not considered as *potential UAS airports* in Texas (72.4%) and in California (78.5%) [36]. IFR flights are heavily concentrated at a few, large airports, lending support to the assumption that there exist many under-utilized airports, many of which can be considered for initial UAS operations. Looking at the regional aircraft analyzed, there are numerous different *potential UAS airports* in the investigated areas where an initial integration of fixed-wing UAS into the airspace system could be realized. Depending on the actual operating weight of the investigated regional aircraft based on its individual mission, a maximum of 158 *potential UAS airports*, mainly accessible by smaller turboprop aircraft (e.g., Cessna 208), and a minimum of 36 *potential UAS airports* would be accessible for fixed-wing UAS operations in Germany. In the US, a maximum of 294 and 206 *potential UAS airports* in Texas and California, respectively, would be accessible, again, mainly by smaller turboprop aircraft (e.g., Cessna 208/208B). On the other hand, a minimum of 73 and 77 *potential UAS airports* in Texas and California, respectively, would be accessible by regional aircraft. In this context, the share of *potential UAS airports* located in controlled and uncontrolled airspace varies. All three areas investigated have more *potential UAS airports* in uncontrolled airspace (non-towered airports) that are eligible for initial UAS operations.

V. Conclusion and Future Work

Regional aircraft and their accessibility potential at *potential UAS airports* were analyzed using 2022 data to assess the integration potential of regional fixed-wing cargo UAS into the airspace system. This study builds on previous research that identified Germany, Texas, and California as suitable areas for an initial integration of regional cargo UAS due to their relatively high number of smaller airports and current air cargo traffic. This paper investigates operations of regional piston, turboprop, and jet aircraft to identify airports suitable to serve regional aircraft eligible for UAS. All airports in Germany, Texas, and California were analyzed according to their current IAP, with those procedures best suited to initial fixed-wing UAS operations (e.g., ILS CAT III or GLS), termed *UAS IAP*, given special attention. Emphasis was also given to the investigation of less busy *potential UAS airports* as it is anticipated that cargo UAS will initially start operating from under-utilized airports.

To establish a baseline for the comparative analysis of different areas, airports were defined as *potential UAS airports* if they provide public air transport services and have <2.2% IFR flight movements of all towered airports in the country/state. Additionally, all non-towered airports were classified as *potential UAS airports*. The total number of *potential UAS airports* with public air transport services was identified, with 173 in Germany, 376 in Texas, and 227 in California. However, currently, only nine *potential UAS airports* in Germany, one in Texas, and one in California provide *UAS IAP* availability. In the future, it is likely that *potential UAS airports* will be equipped with GLS rather than ILS CAT III for UAS operations, since only one GLS installation per airport is required, as opposed to one installation per runway end, like ILS CAT III. However, this analysis shows that there is currently a dearth of *potential UAS airports* equipped with *UAS IAP*. Either more *UAS IAP* need to be installed, or other landing technologies, such as vision-based technologies, will need to be developed to enable UAS accessibility at many under-utilized airports. Should other landing technologies be developed, however, the results of this study indicate that future fixed-wing UAS, regardless of powerplant, could access a high number of *potential UAS airports*.

Although this study focused on UAS accessibility based on the availability of *UAS IAP* at airports, other challenges also limit UAS operations. Future work will attempt to quantify these limitations, including the availability of reliable command and control (C2) link performance, interactions with other IFR and VFR traffic, availability of contingency airports, and plans to mitigate the loss of the C2 link. The analysis presented in this paper will also provide inputs to fast-time simulation studies, whereby different percentages of current regional air cargo operations may be replaced with UAS operations and extended to additional routes operated by UAS.

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