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Review

Sustainable Aviation Operations and the Role of Information Technology and Data Science: Background, Current Status and Future Directions

Banavar Sridhar[*]; **David Bell**[†]

USRA@NASA Ames Research Center, Moffett Field, CA, USA

[*]*Corresponding author*
Banavar Sridhar
USRA@NASA Ames Research Center, Moffett Field, CA, USA

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ABSTRACT

This paper reviews the achievements of the international community towards environmentally friendly aviation operations, also referred to as Sustainable Aviation Operations in the last 25 years and the aspirations and goals to limit the impact of aviation and climate in the future. The framework for achieving global progress is provided by the International Civil Aviation Organization. NASA and FAA supported research and development to advance ATM concepts, and implemented the technology, concepts, and procedures that were responsible for creating fuel efficient flights. Historically aviation operations have been analyzed using physics-based models and provide information for making operational decisions. The introduction of new class of vehicles in aviation operations require new concepts, procedure, modeling, and analysis techniques. Greater automation and decentralization will be key aspects of future aviation systems. There is an increasing interest in applying methods based on Machine Learning Techniques to problems in Air Traffic Management. Aviation operations involving many decision makers, multiple objectives, poor or unavailable physics-based models and the availability of a rich historical database provide opportunities to exploit the richness of data-driven methods. Although verifying and validating an AI system may not be different from introducing other complex systems, there are challenges in testing and certifying AI systems. Many of the emerging technologies in aviation need investment in infrastructure like vertiports and electric vehicle charging stations to meet the projected demand. They have to demonstrate value and earn community acceptance in order for the political system to invest in the infrastructure.

INTRODUCTION

The environmental impacts of aviation, which contribute to climate change, are becoming more widely recognized [1]. The aviation industry is estimated to be 2% of the total anthropogenic CO_2 emissions and 13% of the fossil fuel usage in the transportation sector [2]. Even while aircraft only contribute a minor amount to overall emissions, a significant amount of those emissions occur at high altitudes, where they stay in the atmosphere for far longer than they would at ground level. The Federal Aviation Administration (FAA) projects that domestic aviation traffic would rise at a pace of 2.0% over the next 20 years, after a little dip in recent years. The increase in traffic began in 2011. From 2011 to 2030, international aviation traffic is projected to increase at a faster pace of 4.8% per year than domestic air traffic. Research in green aviation aims to improve scientific understanding, use alternative fuels, introduce new aircraft technology, and implement rapid operational changes in order to accommodate growing air traffic needs while limiting the impact of aviation on the environment. There are several ways in which aviation activities impact the environment. Air travel's effect on the environment is quantified by the term "radiative forcing" (RF). Radiofrequency (RF) radiation disrupts the equilibrium between solar energy entering the troposphere and departing infrared radiation. The quantity of greenhouse gases (GHG) in the atmosphere determines the amount of outgoing infrared radiation. The connection between the change in global mean surface temperature and the RF associated with each kind of emission is almost linear. Combustion of fossil fuels always releases gases into the atmosphere, including carbon dioxide (CO2) and water vapor, both of which are greenhouse gases with a positive radiative forcing (RF). The impact of CO2 on climate change is long-lasting due to its abundance and longevity, in contrast to the short-term effects of emissions that do not include CO2. Water vapour, nitrogen oxides (NOx), condensation trails (contrails), and cirrus clouds are the most notable non-CO_2 consequences linked to aircraft. As a result of the water vapor trails produced by aircraft engine exhaust, a cloud known as a contrail[4] forms. Contrails created by airplanes may be more responsible for global warming than all the leftover CO_2 generated by planes, according to recent estimations. Airport noise and the impact of non-volatile particulate matter (PM) from engine combustion Minimal Involvement

The negative effects of aircraft on local air quality (nvPM) must be included when assessing the industry's environmental impact. Although the effects of CO2 on the climate are known, those of other emissions and contrails remain unclear. At its 37th session in 2010, the International Civil Aviation Organization (ICAO) set two ambitious worldwide objectives: (a) a 2% increase in fuel economy per year until 2050 and (b) a transition to carbon neutral growth starting in 2020. As seen in Figure 1, the ICAO's portfolio for achieving these objectives is composed of a three-pronged strategy: enhancing aircraft technology, enhancing operations and development, and implementing a market-based approach to the use of alternative aviation fuels.

Fig. 1 ICAO global aspiration goals

ICAO promotes international collaboration in three main areas (1) climate change and aviation emissions, (2) aircraft noise and (3) local air quality. The progress in advancing sustainable aviation is achieved by developing standards for noise, emissions, and fuel burn.

This paper reviews the achievements of the international community towards SAO in the last 25 years, the technology, concepts, and procedures that were responsible for creating fuel efficient flights, FAA and NASA's research and development to advance ATM concepts, new revolutionary trends affecting current aviation, equitable operations between commercial aviation and new types of aircraft and the opportunities and challenges for data science to support SAO in the future.

Section II provides an overview of the global efforts to improve the air transportation system operations based on providing airport and airspace capacity to meet demand safely while reducing traffic delays and maximizing fuel efficiency. The environmental benefit of reduced emissions are a byproduct of the fuel efficiency efforts. Section III provides background about the current air traffic system and discusses new airspace technologies and efforts to introduce them to modernize the system to meet new challenges facing the air traffic system and describes the implementation of the advanced concepts in NextGen. Section IV provides a description of NASA ATM technologies and the benefits resulting from the implementation of these techniques in the NAS. Section V on Newly Emerging Technologies describes new types of vehicles such as very light jets, unmanned aircraft systems(UAS) and commercial space launch vehicles and changes to the ATM system to accommodate new operations with current operations. Section VI on Green Aviation Challenges is limited to how changes in aviation operations can reduce the environmental impact of aviation. Section VII describes the role data science, artificial intelligence and machine learning techniques can perform to improve decision making in ATM systems and the challenges of explaining, justifying and developing trust in AI systems. Section VIII provides a discussion on Sustainable Aviation Operations and the Role of Information Technology and Data Science.

II. Status of Environmentally Friendly (Fuel Efficient) Airspace Operations

The International Civil Aviation Organization (ICAO) spearheads international initiatives to achieve Sustainable Aviation Operations (SAO) and reduce aviation's carbon footprint. The International Civil Aviation Organization (ICAO) accomplishes these aims by bringing together the aviation systems of many nations to implement the Aviation System Block Upgrade (ASBU) outlined in the Global Air Navigation Plan (GANP). For the benefit of all parties involved in international aviation operations, ASBU coordinates the adoption of new technology, processes, and operational ideas. Air traffic delays were minimized as part of the SAO's period-long focus on safety, fuel economy, and strong operations. The correlation between reduced fuel use and lower carbon dioxide emissions is the root cause of the positive environmental impact. With ASBU's goal of reducing emissions per flight without sacrificing safety or capacity, the International Civil Aviation Organization (ICAO) projects a 4.3% increase in air traffic over the next two decades. This is the ASBU

Optimal capacity and flexible flights, efficient flight pathways, internationally compatible systems and data, and airport operations are the four main categories into which operational ideas are split. Block 0 (2013), Block 1 (2019), Block 2 (2025), and Block 3 (2031) are the anticipated introduction dates of these ideas according to ICAO. Optimal 4D trajectories during taxi, climb, cruise, and descent allow aircraft to optimize fuel economy. In 1999, the IPCC predicted that aircraft fuel consumption could be cut by 8–18%, which would mean an average efficiency of 82% to 92% in flight. In 2008, the Global ATM system was assessed by the Civil Air Navigation Services Organization (CANSO) to be 92% to 94% fuel efficient. Considering the limitations imposed by safety, capacity, weather, noise, and the structure of the airspace, it is not feasible to achieve 100% fuel efficiency with ATMs. Operating efficiency targets for US flights in 2026 range from 93% to 96%, up from 92% to 93% in 2006. According to CANSO, you may recoup 75% of your fuel savings when cruising and the remaining 25% by making your vertical flights more efficient. In 2017, the horizontal flight efficiency levels for traffic throughout the world ranged from 94% to 98%, with the United States seeing the highest number at 96.5%. Regional air traffic management (ATM) development initiatives like NextGen in the US, SESAR in Europe, and CARATS in Japan introduced new technology, ideas, and processes that allowed for the worldwide gains in flight efficiency.

III: Methods, Ideas, and Technology

The NextGen Air Transportation System, which aims to increase US aviation capacity to meet future demands, was spearheaded by the Joint Planning and Development Office (JPDO), a public-private multi-agency organization, which was established in 2003 by US Congress. Each of these departments—Transportation, Defense, Commerce, Homeland Security, FAA, NASA, and the White House Office of Science and Technology—served under this umbrella. In 2014, JPDO's mission came to an end. JPDO promotes operations based on four-dimensional aircraft trajectories in their complete concept-of-operations [5]. Accurate real-time information on traffic flow, weather, and routing was developed by NASA in collaboration with the FAA and other industry partners. These tools will be used by air traffic controllers, pilots, and others who utilize the airspace. One of the main components of NextGen is the improved accuracy of this data. In order to promote consensus and facilitate decision-making, the FAA has also made an investment in the System-Wide Information Management (SWIM) data stream, which will provide stakeholders with system-wide air traffic data in near real-time or real-time as of the completion of Segment 1 in 2015.

A. Implementing NextGen

The air transportation system is set to be modernized via the NextGen portfolio of projects, which aims to develop and execute changes to infrastructure, new innovative technology, and processes. Some of the more developed ideas and technology that are being examined for implementation are detailed here [3].

First, ADS-B, or Automatic Dependent Surveillance-Broadcast The Advanced Direction-Sensing and Broadcasting (ADS-B) system is set to revolutionize air traffic control. It will transmit surveillance data directly from the aircraft, rather than relying on existing radar-based systems. With ADS-B, air traffic controllers and pilots will have better situational awareness, which will lead to better decisions. The system will also provide surveillance data in oceanic airspace and in remote areas without radar coverage, like the Gulf of Mexico and portions of Alaska. With ADS-B capability, aircraft use onboard systems like GPS to determine their position. They then use satellite communication to broadcast this position along with state variables like speed, heading, and altitude. Additionally, they broadcast short-term intent information, which includes the locations of the next several waypoints along the planned route. Air traffic controllers and other planes equipped with ADS-B may receive the broadcast data instantly. Two distinct services make up ADS-B: ADS-B Out and ADS-B In. With ADS-B Out, you may broadcast information at regular intervals, and with ADS-B In, you can receive data on traffic and weather from neighboring aircraft and ground-based systems. Using ADS-B-provided vehicle location data shown on controller and cockpit screens has been shown to lessen the likelihood of runway incursions and crashes, particularly at night and in poor visibility airport situations. Another anticipated benefit of ADS-B is that it would assist decrease aircraft separation, which in turn will increase airspace capacity.

The Federal Aviation Administration has included ADS-B into automation systems at the 30 busiest U.S. terminal regions, the majority of TRACON sites, and all 24 en route air traffic control facilities. With each platform upgrade, they want to include into the other terminal area automation systems. The FAA has reached out to many airlines in order to collect ADS-B data in order to support the early adoption business case. All aircraft that are required by the FAA must have An ADS-B After January 1, 2020, we will be able to fly in Class A, B, C, and E airspace. At this time, ADS-B In capability is not required for airplanes.

Airports are unable to process as many arrivals and departures due to factors such as wind, ice, and visibility. The number of aircraft allowed to fly through a certain area is reduced during convective weather and turbulence. When it comes to advanced planning algorithms for TFM, weather data is crucial for imposing airport and airspace limits [9]. Through its integration with the 4-Dimensional Weather Data Cube, the NextGen Network Enabled Weather (NNEW) will provide a centralized and reliable source of weather data to all NAS users, facilitating collaborative and dynamic planning, particularly in the event of severe weather. The majority of the data that is stored in the Weather Data Cube comes from the National Weather Service. Connecting databases from the Federal Aviation Administration (FAA), the National Oceanic and Atmospheric Administration (NOAA), the Department of Defense (DOD), and private meteorological data providers is the goal of the meteorological Data Cube. Data may be easily converted between common formats, units, and coordinate systems with the help of this system. Lastly, it will provide interfaces for retrieving massive amounts of weather data, including that which is expected in a specific area or along the flight path.

1. Communication of Data

At this time, pilots and controllers on the ground mostly communicate via voice for the exchange of important ATM information. While voice communication is efficient, it is also quite error-prone. Because ATC communication relies on receiver read-back to prevent mistakes, this process may be tedious and error-prone. The radio-frequency spectrum constraints also make voice communications impractical for facilitating the anticipated future expansion of air traffic with new entrants like Urban Air Mobility (UAM). Electronic records systems may be designed with error checking and repair methods, and communications are made less mistake-prone. The use of digital data transmission has the ability to enhance system safety by freeing up pilots and controllers to concentrate on strategic duties rather than mundane ones. By shifting to digital communication, we can alleviate radio-frequency congestion in high-traffic areas and save voice communication for mission-critical conversations. Operational data connections were first implemented as part of the FANS initiative. Airbus's FANS-A and Boeing's FANS-1 both have the capacity to transmit data from the aircraft to the air traffic control system independently via the Automatic Dependent Surveillance-Contract (ADS-C) system. Aircraft separation distances were lowered from 100 to 50 nautical miles when these capabilities were implemented in maritime airspace. For usage in domestic airspace, which experiences greater traffic densities, there is a modified version of FANS called FANS-1/A+ that utilizes VHF Digital Link (VDL) mode-2. The International Civil Aviation Organization (ICAO) is now working on Aeronautical Telecommunication Network (ATN) Baseline-2, a new data communication standard that would harmonise the worldwide requirements of civil aviation [10].

2. Systems for Next-Generation FAA Decision Support

Future air traffic management will be built on SWIM and the FAA NextGen Decision Support Systems, which are often called the 3Ts. NextGen is powered by these systems. The goal of Time-Based Flow Management (TBFM) is to maximize aircraft throughput by enabling time-based pricing. One decision-support system for airport surface management and ATC tower tasks is Terminal Flight Data Management (TFDM). One decision-support tool for NAS planning and mitigation of demand-capacity mismatches is the Traffic Flow Management System (TFMS). For NextGen to function properly, it relies on System Wide Information Management (SWIM) to centralize and share digital data in a timely manner.

B. Business Processes

Below, we will go over a few ideas and technology that may help you fly more efficiently throughout the descent, en route, and surface phases. first, ODTs, or optimal descent trajectories ODT tools give air traffic controllers decision-support data [44] for things like allowing continuous descents at near-idle thrust, making sure the plane stays on track to maximize throughput, avoiding airspace and traffic on the way to the airport, and giving the green light via voice or data link based on what the flight deck can do for precise guidance and control. Optimal Profile Descent [48], Continuous Descent Approach [46, 47], and Efficient Descent Advisor (EDA) [45] are some of the ODT tools that have been evaluated in the field. at addition to reducing pollution and fuel consumption, these experiments have shown that ODT technology can keep planes out of each other's way at crowded terminals [48]. Tailored Arrivals (TA) to San Francisco operational trials assessed the practicability of employing three-dimensional trajectory clearances provided via data link for automated guidance and control using the on-board flight management system. In 2006 and 2007, the FAA, Boeing, and United Airlines worked together to test this technology that was created by NASA. The TA procedure has the potential to save 400 to 800 pounds of fuel every arrival, according to Boeing's estimates. As part of NextGen technologies, the FAA received the findings from NASA's 2012 study that defined and validated the EDA concept. The FAA will now assess, develop, and put the idea into practical usage.

2. The Best Routes for Wind and Users

Since the majority of time and fuel are used during the cruise phase, the primary objective of airline operations is to minimize these costs. Under the existing setup, planes fly from point A to point B at a constant speed and altitude following a predetermined horizontal course. Due to airport and airspace capacity limits, as well as to avoid places with severe weather, the ideal route, cruise altitude, and cruise speed are adjusted to meet with terminal area and en route restrictions. This less-than-ideal flight path increases both fuel consumption and pollutants. A research that analyzed 2007 air traffic data from the top 34 U.S. airports found that planes took 2.9% longer paths than direct routes between city pairs. When looking at the top 34 city-pairs in Europe, the comparable distance for traffic was 4% longer [47]. Because of the dependence on procedural separation and the absence of radar surveillance and VHF radio communication coverage, the additional distance traversed via great-circle routes is much larger across US-European oceanic airspace. More planes fitted with the ADS-B system may make this different. Transport flights between Europe and Asia must travel more circuitous routes because to the number of airspace restrictions, the number of entrance locations, and the steepness of the terrain. The present routing system has its limits, and the advantages of employing wind-optimal routes have been evaluated in many studies [49–51]. Taking use of the winds reduces the direct operating cost, even if wind optimum routes are longer than direct ones.

2. Finish

Position data is provided by Airport Surface Detection Equipment-Model X (ASDE-X), which is installed at 35 major airports in the United States, in order to monitor the movement of vehicles and airplanes on the airport surface. Using radar, multilateration, and ADS-B, ASDE-X gathers data. Systems utilized by ramp operators, air traffic controllers, traffic managers, flight operators, and aviation system managers utilize the collected data for surfaces traffic management, including gate departure scheduling, conflict prediction and runway entry times, runway incursion prevention, conflict resolution, taxi route and schedule compliance determination, and airport performance evaluation using delay and throughput metrics and causal factors. To improve safety and traffic flow on ramps, taxiways, and runways, data sharing encourages shared situational awareness and group decision-making. Investigations into incidents and accidents at airports also rely on these data. Additionally, the FAA intends to deploy the multilateration and ADS-B based Airport Surface Surveillance Capability (ASSC) at nine more busy airports: Andrews Field (ADW), San Francisco International (SFO), Portland International (PIT), Ted Stevens Anchorage International (ANC), Kansas City International (MCI), Louis Armstrong New Orleans International (MSY), San Francisco International (SFO), Cincinnati/Northern Kentucky International (CVG), Cleveland Hopkins International (CLE), and San Francisco International (SFO). Aircraft passing within five nautical miles (nm) of airports, as well as surface vehicles equipped with ADS-B and transponders, are monitored by ASSC. Additionally, the SWIM feed provides the various stakeholders with surface data obtained by these devices. The digital data-sharing backbone of the NextGen is SWIM. As a result of processing the raw surface and terminal surveillance data, the SWIM Terminal Data Distribution System (STDDS) relays surface information from airport towers to the relevant TRACON facility via the NAS Enterprise Messaging Service (NEMS) for both internal and external NAS users [43].

Harmonization on a global scale

In order for airplanes that have been outfitted with technologies developed in the United States and other nations to fly internationally, the FAA collaborates with other international Air Navigation Service Providers (ANSP) to guarantee that these technologies are interoperable. In order to coordinate the development of research and technology in the United States and Europe, collaboration with the Single European Sky Air Traffic Management Research (SESAR) is crucial. The FAA and ANSPs in Thailand, Australia, New Zealand, Singapore, and Japan work together as part of the Asia and Pacific Initiative to Reduce Emissions (ASPIRE) [53]. The potential for fuel and carbon reductions in the area was effectively shown by ASPIRE during a series of flights that took place between 2008 and 2011. Reduced separation, more efficient flight profiles, and customized arrivals were some of the changed gate-to-gate procedures used by these aircraft. With the right equipment, flights between certain U.S. cities and others in the Asia-Pacific area may benefit from the best practices established by these testing. Transatlantic flight demonstrations of NextGen and SESAR capabilities were place in 2011 with the help of the FAA, the European Commission, several European ANSPs, and forty European carriers. In 2010 and 2011, Air France operated multiple flights between JFK and Paris Charles de Gaulle (CDG) and Paris Orly (ORY) and Guadeloupe's Pointe-a-Pitre Airport (PTP) as part of the Atlantic Interoperability Initiative to Reduce Emissions (AIRE) [54, 55]. To lessen the planes' influence on the environment, they developed flight plans that don't need any specialized gear. Numerous taxiing enhancements, real-time optimization of lateral and vertical paths, and fuel savings From 200 to 300 liters of gasoline were saved every flight using RNAV approaches. The development of aviation systems worldwide necessitates global harmonization so that airspace users and ANSPs can finance cutting-edge capabilities. Finding critical components to lead prototype testing, functionality, and prioritizing implementation efforts to remove the obstacles to worldwide interoperability should be a primary goal of the harmonization process. ICAO has established guidelines for worldwide compatibility. With the capacity to upgrade aviation system blocks, investors and planners may more easily work toward the common objective of making aviation systems across the world compatible with one another. Globally, programs like NextGen and SESAR are tackling regional or local problems via collaborative efforts.

III. NASA ATM Technology

In order to manage aircraft more efficiently from the time they are shortly before top-of-descent and continuing onwards, NASA and the FAA are working together to create and showcase an integrated set of NextGen technologies [52]. onwards to the runway. Technology like as ADS-B, RNAV arrival routes, Terminal Metering, Flight Deck Interval Management (FIM), and Controller Managed Spacing (CMS) are all part of this technology. The FAA and NASA have shown that fuel-efficient arrival operations can maintain a high throughput using precision time-based scheduling, which gives planes their arrival timings at the runway and their fix crossing durations. Aircraft are being delivered to meter repairs on time, however there are some minor spacing problems that need to be minimized in order to prevent violating schedules and increase throughput. Using FMS, the majority of flight crews can fly OPDs along RNAV/RNP routes with little to no input from the controller. Terminal controllers use tools and display upgrades based on 4-D trajectories to rectify residual spacing errors and deal with disruptions and off-nominal occurrences. The combination of these technologies and the tools that go along with them will make it possible for planes to fly closer together on routes that consume less fuel. This will lead to even more advantages, such more capacity and less delay, fuel consumption, noise, and emissions of greenhouse gases.

The following ATM technologies, known as ATD-1: Terminal Sequencing and Spacing / Flight Deck Interval Management, were developed and given to the FAA by NASA from FY15 to FY17. ATD-1 increases arrival throughput and enhances the efficiency of terminal arrival operations. In order to increase arrival throughput and improve the efficiency of arrival operations, ATD-1 created and provided ground-based and aircraft-based automation technologies to the FAA Surveillance Based Systems Program Office, flight operators, the FAA NextGen and Air Traffic Organizations, and others. The use of ADS-B Infrastructure Area Navigation (RNAV), Arrivals Required Navigation Performance (RNP), and Optimized Profile Descents (OPD) in conjunction with NASA technology allowed for this to happen. There will be a 400-800 pound fuel savings each trip and a 10% improvement in throughput (to be confirmed).

A. Airspace Technology Demonstration-2 (ATD-2): Comprehensive Operations

Management of Arrival, Departure, and Surface Traffic in a Metroplex Problems in sharing information contribute to the current system's inefficiency, which makes it difficult to manage traffic in high-traffic terminal areas. An integrated approach with information sharing across airlines, air traffic service providers, airport authorities, and technology vendors has been sought after by NASA's ATD-2 initiative to enhance the predictability of aircraft movement times on the airport surface and in the airspace, with the goal of reducing fuel burn and emissions. This initiative builds upon previous efforts to improve arrival, departure, and airport surface traffic operations. Timely push back from the gate and uncertainty in predicting taxi, takeoff, and climb periods are among the inefficiencies that ATD-2 aims to address. There will be delays due to taxiway congestion and extended runway lineups caused by uncoordinated push back from the gate. When taxi, takeoff, and ascent times can't be predicted with any degree of certainty, the predicted arrival times at metered places are wrong, and the traffic demand at resource-constrained locations is also off. The end effect is usually traffic flow control programs that are too cautious. With ATD-2, metroplex traffic management is improved by incorporating arrival, departure, and surface (IADS) principles [26]. While maintaining or increasing throughput, the technologies will make the air traffic system more predictable and boost operational efficiency. In IADS, several ideas and technologies come together, including three operational decision support tools from the FAA (TFMS, TBFM, and TFDM) and two technologies from the NASA (SARDA and PDRC) that help with runway and spot departures. PDRC combined TBFM's tactical departure scheduling capabilities with a trajectory-based decision support functionality, leading to more accurate scheduling of surface departures into constrained overhead flows, while SARDA was developed to enhance airport surface operations through time-based aircraft metering and improved stakeholder situational awareness. The Surface Trajectory-Based Operations (STBO) tool, which combines SARDA and PDRC, communicates with a tool for airline operators called a Ramp Traffic Console (RTC) to arrange pushback timings for departures based on the readiness times of aircraft at the gate. The TBFM system coordinates the outbound scheduling of departures to another airport, usually internal departures, as part of its scheduling process. Developed between FY18 and FY21, ATD-2 provided the FAA NextGen, Air Traffic Organizations, flight operators, and airport operators with an integrated metroplex traffic manager that uses NASA, FAA, and industry technology to improve the efficiency and predictability of arrivals, departures, and surface operations all at once. At Charlotte, North Carolina (CLT) airport, ATD-2 saved 48-59 kg fuel/flight and decreased CO2 emissions by 4.6 million kg per year.

B. ATFD-3: Applied Traffic Flow

In order to "reduce weather-induced delays through integration of weather information to better manage aircraft, traffic flow, airspace and schedule constraints by delivering air-ground procedures and user-tool technologies," NASA's ATD-3 subproject [27] attempted to address this technological difficulty. Dynamic Routes for Arrival in Weather (DRAW), Multi-Flight Common Route (MFCR), and Traffic Aware Strategic Aircrew Requests (TASAR) were the main technologies that helped accomplish the technological hurdles of ATD-3. Automatically seeking out effective weather avoidance is the focus of MFCR. paths (in terms of time and fuel) and superfluous weather-evasion routes mandated by previous traffic-management projects that are now superfluous because of weather-related changes. Reducing time is possible by avoiding needless reroutes. The primary goal of TASAR is to minimize fuel consumption and flight time during the airborne phase by automatically searching for efficient reroutes that avoid restricted airspace, traffic, and bad weather. This search is conducted from the flight deck. Meeting meter-fix capacity restrictions is the goal of DRAW as it relates to arriving aircraft weather avoidance routing. Flights that are expected to be in conflict with weather are given routes to avoid it by the DRAW algorithm, which then sends them to the scheduler. The scheduler's timeline displays the redirected flights' projected arrival timings with respect to other flights' and available slots'. Iteratively constructing routes and assessing the schedule effect is what trial planning is all about. This process continues until traffic flow managers find the chosen route and timetable acceptable. Matching the demand with the arrival meter-fixes is one way DRAW is put into practice. For a departure-to-arrival route solution, the ATD-3 Integrated Concept employs MFCR, TASAR, and DRAW. In order to better manage aircraft, traffic flow, airspace, and scheduling limitations, ATD-3 was developed between FY17-FY19 and offered air/ground technologies and procedures to the FAA and flight operators. This allowed for a reduction in weather-induced delays. With ATD-3, we were able to cut emissions by 5.6 million kg of CO2 per year and save 13 kg of fuel every trip.

IV. Cutting-Edge Technological Advancements

Very light planes, unmanned aircraft systems (UAS), and commercial space launch vehicles are examples of new vehicle types that will need to be accounted for by the future ATM system. A great deal of low-altitude air traffic will enter the NAS as a result of advancements in Urban Air Mobility (UAM), which entails on-demand flights with two to six passenger aircraft, and Unmanned Aircraft System (UAS), which involves package delivery drones. In order to integrate the operations of these new types of vehicles safely and efficiently, the FAA and NASA have been working on operational principles. A model for establishing UAM air traffic services is the architecture that was created under NASA's UAS Traffic Management (UTM) project with the help of several organizations' air traffic services. As of late, the FAA has made public the UAM flight operations concept-of-operations (ConOps1.0) [23]. New electric vertical takeoff and landing aircraft will soon be a part of the future air transportation system that will serve metropolitan areas, intraregions, and local, regional, and regional locations. UAM is a part of the Advanced Air Mobility (AAM) project, which is a joint effort between the FAA, NASA, and industry. Autonomy is crucial to the desired final outcome of UAM activities. As the number of UAM operations grows, new vehicles authorized under the existing regulatory frameworks will acquire operating experience. These frameworks are likely to change over time. At some point, new legislation, infrastructure, autonomous cars, operational controls, and traffic management systems are likely to be introduced via ordinary operations. As the need for commercial high-altitude traffic continues to expand, we will continue to develop our systems to accommodate new vehicle types while also making them safer and more efficient. By improving data sharing and decision-making across various systems used for air traffic control, airport surface, terminal, and en route airspace traffic flow management, we can potentially eliminate unnecessary restrictions and make more coordinated decisions. This will lead to less fuel consumption, fewer delays, and better utilization of airport and airspace resources that are limited in capacity. This section provides an overview of a few of these developing technologies that are now undergoing different phases of development and review.

A: UTM (Unmanned Air System)

Transportation of products, monitoring of infrastructure, agricultural monitoring, search and rescue, and other useful civilian uses of Unmanned Air System (UAS) vehicles under 20 kg have been suggested. No current system is in place to support or oversee the broad use of unmanned aerial system (UAS) activities in low-altitude airspace, and this is true across all UAS types. If a UTM system wants to save operating expenses, it needs to automate more. It is unrealistic to expect human operators to keep a constant eye on every single vehicle. Human managers might use the data provided by the system to decide how to start, keep going, or stop airspace activities according on weather and wind conditions.

A set of ever-more-complicated flight tests has been carried out by NASA, the FAA, industry, and academic partners to establish specifications for a system. Field testing of rural UAS operations for agricultural, firefighting, and infrastructure monitoring was the primary emphasis of the first test, which took place in August 2015. It gave pilots of unmanned aerial systems (UAS) the ability to submit flight plans that reserved airspace for their missions and offered real-time information on competing missions in the region. The second trial, which took place in October 2016, proved that in sparsely inhabited locations, apps may function even when the operator is not directly in front of them. It was a test of systems that could handle contingencies and dynamically change airspace availability. Cooperative and uncooperative UAS tracking capabilities were part of the third test that took place in May 2018.

to guarantee the overall security of activities over regions with a modest population, whether they are manned or unmanned. Unmanned Aerial System (UAS) activities in densely populated metropolitan areas for jobs like news gathering and package delivery were the subject of the fourth and last test, which took place in May–August 2019. Technologies that may be used to handle large-scale eventualities were also put to the test during these operations. During 2013 and 2015, the FAA released regulations for the use of small drones. New regulations mandate the remote identification of drones registered after September 2023. Recreational drones accounted for 68% of the 860,000 drones registered with the FAA by March 2022, while commercial drones accounted for 32%.

A. Urban Air Mobility (UAM)

Road transportation was the mode of transportation for short distances, as seen in Figure 3, during the 20th century and air transportation flourished for distances greater than 500 miles [11].

Fig. 3 Choice of mode of transportation with distance

The development of Short/Vertical Take-Off and Landing (S/VTOL) vehicles in the 1970s did not spread widely due to noise problems and ride comfort.[Ref]. Helicopters remained special purpose vehicles used for emergency operations, fire-fighting and other applications where terrain was a factor. This model is changing with advances in cloud computing, data science, open source software, satellite based surveillance and battery technology. The new technologies have enabled the building of small vehicles with electric propulsion(eVTOL) and creating unprecedented growth based on the diversity of applications in package delivery, inspections, surveillance and expectations as a solution to decrease the congestion in urban and inter-city traffic and improve urban mobility.

The actual growth will depend in addition to the economics of operations and on the public perception of the noise and visual characteristics of hundreds low flying objects in densely populated areas. A recent market study for NASA

[12] considered the demand and barriers for Airport Shuttle, Air Taxi, and Air Ambulance. The study concluded that Air Ambulance is currently not viable using eVTOL. It valued the Air Taxi, and Air Ambulance market at $250 billion and reduced the available market size to $2.5 billion based on overcoming legal/regulatory, certification, public perception and weather constraint challenges.

The UTM and UAM systems have to be provided with all the services (separation between aircraft , resolution of conflicts and efficient path planning) enjoyed by traditional air traffic at a fraction of the cost. The ability to model and predict winds at low altitudes presents a challenge to the safe and efficient operations of electric-propelled vehicles. These systems have to be effectively integrated in the airspace with minimal disruption to the current commercial and general aviation operations.

B. Commercial Space Transportation (CST)

Commercial Space Transportation (CST) has become a reality with the successful launch of rockets and space planes by several organizations. The commercial operators are planning for new and emerging vehicle concepts as well as new mission types in the next few years. Such concepts include: 1) space travel for recreational, leisure, or busines purposes, 2) orbital space tourism for visiting the International Space Station (ISS) or other private on-orbit facilities,

3) Sub-orbital space tourism to provide one to five minutes of weightlessness to people on board, and 4) lunar space tourism for traveling to the Moon and orbit the Moon one time before returning to the Earth via free return trajectory. There is a new mission type like point-to-point (PTP), providing transport between any two locations around the world in less than an hour. Also, a rapid growing market for microsatellites is projected. The FAA permitted 409 licensed launches during the period March 1989 to June 2021. Several States in the US, Alaska, Colorado, Florida, New Mexico, Oklahoma, Texas, and Virginia, have one or more space ports inside them. The FAA Aerospace Forecast Fiscal Years 2021-2041 estimates the number of operations during FY25 to range between 45 to 65. However, the industry forecasts the number to be 266 for the same period. In the past, the FAA forecast estimate has been closer to the actual number of launches. Today, space launch/reentry operations are managed by taking an airspace segregation approach, which is characterized by relatively large volume of airspace and large time window. This approach is taken because of the inability to perform real-time monitoring, execute standardized planning process, and archive the integrated operation data for post-launch and reentry analysis.

However, such airspace segregation approach for managing space launch/reentry operations will not be able to accommodate the anticipated growth in the demand efficiently and safely. Also, the fair access to the airspace by the NAS users is expected to be impacted. Hence, the FAA, NASA and the industry are currently developing new technologies and capabilities to improve the current launch/reentry operations, ensuring safety, efficiency, and predictability for all NAS users. The roles and responsibilities of space port operators, space launch companies and the interaction with the current NAS traffic is described in the FAA Commercial Space Integration into the NAS (CSINAS) concept of operations.

The current NAS system only extends up to 60,000 feet (FL600). However, in addition to CST, a significant increase in operations in other types of vehicles such as high altitude balloon, supersonic transport, and airship above FL600 is expected soon. Now, such operations above FL600 needs to be considered during the space launch/reentry operations for safety and efficient use of airspace. Hence, The FAA and the industry need the simulation, modelling, and analysis capability to develop: 1) efficient and safe streamlined and standardized planning process among the airspace users (e.g., data exchange protocols), 2) capabilities to proactively monitor both normal and emergency operations space launch/reentry, and 3) tools to evaluate the impact of the commercial space launch and reentry operations in the NAS, including the operators above FL600. Simulation and modeling tools were developed at NASA [13] to support display and analysis useful in developing training, analysis and development of CST concept and policies for use by FAA and commercial operators. Figure 2 shows some of the analysis and display capabilities of the tool.

Fig. 4 CST Launch, traffic and and Debri Display

The interaction between the ETM vehicles and CST is an area that has not been looked at previously due to missing infrastructure and concepts of operations in the upper Class E airspace. The analysis and display capabilities of [13] can be leveraged to simulate and investigate the interaction between CST and the ETM vehicles. The simulation will be a valuable tool for the optimal design of airspace, a national resource, for the benefit of both commercial and national needs.

IV. Green Aviation Challenges (GAC)

This section is limited to the discussion of how changes in aviation operations can reduce the impact of aviation on climate in the future. The roles played by vehicle design, alternate fuels, research in carbon capture and other efforts are discussed in [14].

Earlier research has focused on reducing fuel usage in the terminal area and ground movements of the aircraft. This research needs to be extended to reducing emissions beyond arrivals and departures to the entire flight (Fuel consumption during a flight is about 85% cruise, 10% taxi, take-off and climb and 5% descent). Aircraft trajectories are the result of a trade-off between the need to maintain safety, capacity, flight efficiency and reduce environmental impact. Aircraft in the U.S operated with a fuel efficiency in the range 92-94% during 2008 and the goal is to reach 93-96% by 2026. 75% and 25% additional fuel efficiency gains are expected to be recovered by improvements in the horizontal and vertical phases of flight respectively.

Aircraft experience a necessary delay, the smallest amount of delay forced on aircraft to maintain safety and maximize throughput to deal with en route weather and arrival uncertainties in the ATM system. It is suggested that delays in the terminal area can be redistributed and delay and fuel burn can be absorbed more efficiently during cruise. The concept of changing cruise speed by a small amount to absorb delays has been investigated for many years [15]. Recent FAA study[16] indicate 11% of the flights in US could benefit from delay distribution with fuel savings of 40-250 kg per flight and 12-75 Million kg of CO2 per year. The Ability to redistribute delay is higher for long-haul flights than short-haul flights.

In the past, aviation has addressed GAC as equivalent to fuel efficient aircraft operations. These efforts, while addressing the effect of □□2 emissions, do not account for the significant contribution of contrails to climate change. Efforts to limit the impact of contrails require more operational experience regarding the ability to predict contrails with greater certainty and a trade-off between contrail avoidance and resulting extra fuel usage [17].The effect of various emissions like □□2,□□ □ and Methane depend on time horizon. In the short-term, 10-20 years, reducing contrails offers significant environmental benefits. The mitigation efforts require a better understanding of the metrics, like Aggregate Global Change Potential (AGTP), associated with climate change for different policy horizons. Earlier research at NASA [17–19] developed capabilities and tools to (a) model U.S. air Traffic integrated with aircraft emissions □□2,□□ □ and other emissions and Contrails, (b) design of optimal aircraft trajectories to reduce the impact of □□2,□□ □ and Contrails, (c) integrate Air Traffic Models with linear climate models, (d) extension of the U.S. integrated air traffic

, emissions and contrails models to global traffic and (e) an environmental tool box. It was observed that contrails reduction strategies can be summarized as: (a) Changing altitude is an efficient way of achieving contrail reduction, (b) Contrail reduction is more efficient on high-contrail days , (c) Short flights (less than 500 miles), although half the number of flights in the National Air Space, contribute a small amount of contrails (about 7%) due to their altitude profile, (d) Contrail reduction beyond a certain amount may not be environmentally friendly due to the use of extra fuel and the emission of additional amount of CO2 , (e) Effect of contrails becomes less important as the decision-making horizon is increased, (f) Effect of NOX negligible except for a small impact around 25 years and (g) the findings true even in the presence of uncertainty relating to contrails.

The development of a Contrails Data and Analytics Platform will bring current research on contrails models and avoidance more useful for aircraft operations by integrating the contrail models and avoidance concepts with air traffic analytical tools and air traffic databases. They can be used for (a) rerouting trade-offs between extra fuel usage due to contrail avoidance and the environmental benefit of reduced contrails, (b) relationship between environmentally optimal route and uncertainty in PCF regions, (c) analyze historical PCF regions using machine learning techniques, (d) develop core PCF regions with low uncertainty, (e) analyze the benefits and risks of contrail avoidance based on the prediction interval of PCF and visualize benefits and risks, (f) examine whether the ability to make onboard predictions of contrails using Relative Humidity (RH) sensors improves long-term contrail prediction.

Many of the emerging Advanced Air Mobility (AAM) and regional transportation concepts use vehicles powered by non-fossil sources like electric or hydrogen power. These vehicles produce zero emissions. However, the generation of electricity and hydrogen needed to power these vehicles will result in various types of emission. Also, the eVTOLs have to compete for their share of electric power from electric powered autonomous cars, electric trucks and increasing demand from other users of electricity.

V. ML in aviation operations

There is an increasing interest in applying methods based on Machine Learning Techniques (MLT) to problems in Air Traffic Management(ATM). The current interest is based on developments in Cloud Computing, the availability of open software and the success of MLT in automation, consumer behavior and finance involving large databases. Historically aviation operations have been analyzed using physics-based models and provide information for making operational decisions. Aviation operations involving many decision makers, multiple objectives, poor or unavailable physics-based models and a rich historical database are prime candidates for analysis using data-driven methods. MLTs have been applied to several different problems in Air Traffic management such as air traffic performance estimation, conflict detection and resolution, anomaly detection, weather categorization, grouping of routes and re-routes, controller workload and others Reference [20]. The promises and challenges in applying MLT to ATM is traced through three examples each separated by a decade, in [21], to show the influence of data and feature selection in the successful application of MLT to ATM. Table 2 summarizes some of the similarities and differences between physics-based and data-driven approach to modeling complex systems.MLT provides a new set of tools to model the complex problems in aviation operations. As always, the best approach depends on the task, the physical understanding of the problem and the quality and quantity of the available data.

Table 2 Comparison of Physics-based and Data-driven Models

Property	Physics-based Models	Data-driven Models
Model	Linear, Non-Linear, Dynamic, Static, Queueing	Black-Box
Interpretation	Easy to explain results in terms of physical quantities	Hard to interpret and gain trust in the system
Model-Building	Expensive and requires lot of application expertise	Availability of quantity and quality of data
Suitability	Availability of well-defined physical models	Ideal for building causal relationship between inputs and outputs when good physics-based models are non-existent or expensive to build
Feature Selection	Defined by the model and various methods to reduce dimensions (Aggregation, time and space separation)	Major issue to reduce the dimension in complex problems
Size	Various methods to determine minimal order unbiased minimal variance models	Efforts to balance over-fitting and under-fitting by cross-validation,

regularization and other methods

A. Applications and Opportunities

AI and MLT provide valuable new tools in many different ATM applications. The desire to reduce the impact of aviation on the environment and the emerging UAM operations require merging of large diverse databases from local, regional,national and global organizations and industry. AI can play an important role in using historical data both for learning and training systems and people. AAM and UAM need higher levels of automation and AI can help with decision making under uncertainty.Many critical tasks are performed today by people without the ability to articulate their decision making process.AI can play a role in learning from the experts and use the learning to train other people and systems.AI is fragile in certain tasks involving vision and cognition. Similarly, people are not good at performing certain tasks.AI has an important role to play in an environment with increasing collaboration between automation and people while complementing the strengths of the two entities.

B. Challenges for AI

Artificial intelligence (AI) is pervasive, impacting choices in every industry and every aspect of life, from autonomous vehicle control to the identification of criminal suspects. Systems using AI software, like the Uber self-driving vehicle, are susceptible to mistakes that might have catastrophic consequences. The pedestrian was identified by the vehicle's sensors, but the

to bring the vehicle to a halt. Users must have faith in the judgments made by AI systems as it becomes more involved in making important decisions. At the present time, AI system judgments lack sufficient justification and are murky. Many groups, both public and private, have been trying to define "Trustworthy AI" and find ways to make people more confident in AI. Every group has its own somewhat distinct set of criteria for what constitutes trustworthy AI.

In its recommendations, the European Union outlined seven characteristics that must be included in reliable AI systems [22]. Respecting all rules and regulations, trustworthy AI should do the following: (1) ensure that all members of society are treated fairly; (2) be secure, resilient, and dependable even when faced with uncertainties and variances in real life; (3) provide individuals control over their data and privacy.

offer environmental and social well-being; (5) provide diversity, non-discrimination, equity, and equal access; (7) ensure accountability. In order to guarantee a human-centric approach to AI, the European Union's AI policy is built on trust.

An industrial vision of trustworthy AI is presented by IBM [23]. Explainability, fairness, robustness, and lineage are the four cornerstones of trustworthy AI, as stated by IBM. There is a trade-off between complexity and simplicity in the answers supplied by AI/ machine learning algorithms. Linear regression and other simple algorithms with few features that describe physical factors are easy to explain but may not be very accurate. Though they may not provide a strong physically explicable explanation, complex algorithms such as Deep Neural Networks may accurately match intricate decision surfaces with hundreds of features. Depending on the user's level of expertise and the program, different explanations may be required. The data utilized to train ML algorithms determines how fair they are. A lack of complete or sparse data might introduce bias. The ML algorithms' performance suffers as a result. Artificial intelligence algorithms need to be safe and resistant to data manipulation by bad guys. With the use of lineage, AI software may be better explained and traced by keeping track of changes to databases, algorithms, training, and validation.

Challenges with bias (in both directions, in how humans perceive AI systems and in how AI systems make decisions), verification, certification, and AI systems' acceptability arise in interactions between humans and AI. Overcoming human bias in manually controlled systems may need extensive training. A plethora of recent articles have covered the pros and cons of AI in the real world. According to reference [24], people don't fully understand what AI is and it contributes to their skepticism of it. Instead of aiming to replace human intellect, artificial intelligence (AI) is an engineering field that aims to supplement it via the meticulous examination of massive datasets. Artificial intelligence should complement human decision-making without causing inequity.

The focus on evaluating the system based on criteria like decision authority and impact, data and methods used to train the model, model interpretability, and model accuracy changes depending on the task and the role of AI in decision-making when thinking about how to establish trust in AI systems. A system that aids air traffic controllers in maintaining aircraft separation requires a different set of considerations than an AI model designed to aid human decision makers in areas such as jail sentences, college admissions, and employment. Making such important judgments without human oversight is difficult for AI systems, and one solution might be to use less automation while yet allowing for human oversight.

When estimating the quality of training and validation, ML algorithms used in ATM applications take into account aspects such as recall, accuracy, precision, and F measures. To improve the "Trustworthiness of an AI based ATM system [25]." it could be required to add qualitative metrics to existing quantitative ones.

Multiple rounds of testing and validation are standard procedure for any complicated systems. Testing and certifying AI systems isn't easy, even if it may not be that different from adding other complicated systems. How do you record the details of AI systems? This is a crucial topic to answer. Any AI system worth its salt will be forthright about the following: the datasets used to train and validate the model, the limits of those datasets, and whether or not the Neural Network or another MLT produces limited outputs in response to limited inputs. Although this method may not be ideal in every situation, it might be enough for certain applications. It is important to use caution when extrapolating the procedure to other contexts since its generalizability is not certain. It is important to provide a solid foundation around the modeling process so that AI systems may make judgments that are near to what humans would anticipate. The capacity to audit and trace back is essential for AI systems. Incorporated robustness, predictability, and consistent operations are key to AI systems' success. The potential for failure of the AI system and methods to lessen that risk via design integration with other systems are additional critical factors to think about.

VI. Conclusions

In order to attain sustainable aviation operations, this report included an outline of the research that is now underway as well as the technological and infrastructure enhancements that are currently being implemented. There has been significant progress in the effort to decrease

the consequences of carbon dioxide emissions. Reducing the environmental effect of emissions other than CO2 and contrails will need a higher priority moving forward. Depending on the method of power production, the new aircraft vehicles that are coming into operation will produce emissions that are different from those of older vehicles fueled by fossil fuels. In the aviation industry of the future, decentralization and increased automation will play crucial roles. In an increasingly automated world, a major obstacle will be figuring out how human decision-makers like pilots and air traffic controllers should work together. In a world where humans and machines are working together more closely, AI may play a significant role by enhancing each other's capabilities. Testing and certifying AI systems isn't easy, even if it may not be that different from adding other complicated systems. To accommodate anticipated demand, several new aviation technologies need investments in charging stations for electric vehicles and vertiports. For the political system to fund the infrastructure, they must prove their worth and gain community support.

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