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

Banavar Sridhar [*] and David Bell[†]
USRA@NASA Ames Research Center, Moffett Field, CA, USA

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.

I. Introduction

There is increased awareness of aviation-induced environmental impact affecting climate change [1]. Estimates show that aviation is responsible for 13% of transportation-related fossil fuel consumption and 2% of all anthropogenic CO_2 emissions[2]. Although emission contributions from aviation are small, a large portion of the emissions takes place at altitudes where the emissions remain longer in the atmosphere than if emitted at the surface. After a small decline over the last few years, air traffic has increased since 2011, and the Federal Aviation Administration (FAA) expects domestic air traffic to grow at an annual rate of 2.0 % over the next 20 years[3]. Global air traffic is expected to grow more rapidly than domestic air traffic at an annual rate of 4.8% from 2011 to 2030. The desire to accommodate growing air traffic needs while limiting the impact of aviation on the environment has led to research in green aviation with the goals of better scientific understanding, utilization of alternative fuels, introduction of new aircraft technology, and rapid operational changes. Aviation operations affect the climate in several ways. The climate impact of aviation is expressed in terms of "radiative forcing" (RF). RF is a perturbation to the balance between incoming solar radiation and outgoing infrared radiation at the top of the troposphere. The amount of outgoing infrared radiation depends on the concentration of atmospheric greenhouse gases (GHG). RF associated with each type of emission has an approximately linear relationship with global mean surface temperature change. CO_2, water vapor, and other gases are unavoidable by-products of the combustion of fossil fuel; of these CO_2 and water vapor are GHG resulting in a positive RF. Because of its abundance and long lifetime, CO_2 has a long-term effect on climate change; the non-CO_2 emissions have a short-term effect on climate change. The important non-CO_2 impacts associated with aviation are water vapor, oxides of nitrogen (NO_X), condensation trails (contrails) and cirrus clouds due to air traffic. Contrails[4] are clouds that are visible trails of water vapor made by the exhaust of aircraft engines. The latest estimates indicate that contrails caused by aircraft may be causing more climate warming today than all the residual CO_2 emitted by aircraft. Aircraft noise near major airports and the effect of small particles from engine combustion, referred to as non-volatile Particulate Matter

---

[*] Principal Scientist, USRA@NASA Ames Research Center, Moffett Field, CA 94035, USA , Fellow AIAA

[†] Director, USRA@NASA Ames Research Center, Moffett Field, CA 94035, USA

(nvPM), on local air quality needs to be addressed as part of the environmental impact of aviation. The CO$_2$ impact on climate is well understood while there is uncertainty about the impact of other emission sources and contrails. The International Civil Aviation Organization (ICAO) in its 37th assembly held in 2010 established global aspirational goals of (a) 2% annual fuel efficiency improvements through 2050 and (b) carbon neutral growth from 2020 onwards. The ICAO portfolio to reach these goals, as shown in Figure 1 consists of a three-fold approach of improvements in aircraft technology,improvements in operations and development and market-based approach to the use of alternative aviation fuels.

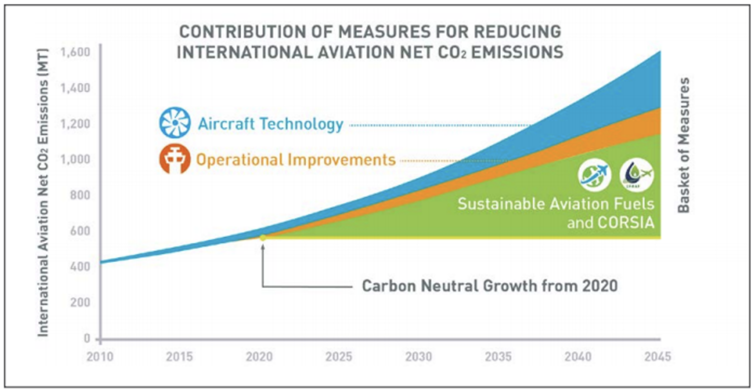

Fig. 1 ICAO global aspiration goals

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 global efforts to minimize the impact of aviation on climate and achieve Sustainable Aviation Operations in (SAO) is led by the ICAO. ICAO achieves these goals by coordinating and aligning the efforts of US, Europe, Japan, and other countries under the Aviation System Block Upgrade (ASBU) described in the Global Air Navigation Plan (GANP). ASBU harmonizes the implementation of new technologies, procedures, and operational concepts to provide interoperability of international aviation operations. The SAO during the period emphasized safety, fuel efficiency and maintaining robust operations by minimizing air traffic delays. The environmental benefits are due to the direct relationship between fuel savings and CO2 emissions. ICAO expects air traffic to grow 4.3% over the next 20 years and ASBU is designed to reduce the greenhouse gases per flight while maintaining safety and capacity. The ASBU operational concepts are divided into four areas namely airport operations, globally interoperable systems and data, optimum capacity and flexible flights, and efficient flight paths. ICAO expects these concepts to be introduced in a series of time frames or blocks, each starting with the year, Block 0 (2013), Block 1 (2019), Block 2 (2025), Block 3 (2031). Aircraft fuel efficiency is maximized by following optimum 4D trajectory during taxi, climb, cruise and descent. The IPCC in 1999 estimated aviation fuel burn could be reduced by between 8% and 18%, thus implying an average flight efficiency of 82% to 92%. In 2008, the Civil Air Navigation Services Organization (CANSO) estimated that the Global ATM system is between 92% and 94% fuel efficient. It should be and that 100% ATM fuel efficiency is not achievable while meeting constraints due to safety, capacity, weather, noise, and airspace structure The operational efficiency goals for US flights in 2026 is between 93-96% based on the 2006 level of efficiency between 92-93%. CANSO estimates 75% of fuel efficiency can recovered during cruise and the remaining 25% by improving efficiency of vertical flights. The horizontal flight efficiency levels for global traffic varied between 94-98% during 2017 with a value 96.5% for US traffic. The world-wide improvements in flight efficiency were made possible by the implementation of new technologies, concepts and procedures developed under the regional air traffic management (ATM) improvement programs such as NextGen (US), SESAR (Europe), and CARATS (Japan).

III. Technology Implementation, Concepts and Procedures

In the US capacity improvements needed for meeting the needs of future air transportation, Next Generation Air Transportation System (NextGen), was led by the establishment of a public-private multi-agency Joint Planning and Development Office (JPDO) in 2003 by the United States Congress. This office included Department of Transportation, Department of Defense, Department of Commerce, Department of Homeland Security, FAA, National Aeronautics and Space Administration (NASA) and White House Office of Science and Technology. JPDO ended its mission in 2014. JPDO developed a comprehensive concept-of-operations [5] that advocates operations based on four-dimensional aircraft trajectories. NASA collaborated with the FAA and other industry partners to develop advanced automation tools to provide air traffic controllers, pilots and other airspace users accurate real-time information about traffic flow, weather, and routing. The greater precision of this information is a key enabler of NextGen. The FAA has also invested in providing real-time and near real-time system-wide air traffic data to the stakeholders via the System-Wide Information Management (SWIM) data feed starting with the completion of Segment 1 in 2015—to foster common understanding and to aid decision-making.

A. NextGen Implementation

The NextGen portfolio of projects seeks to plan and implement improvements to infrastructure, new innovative technologies, and procedures to modernize the air transportation system. This section describes some of the mature concepts and technologies that are being considered for implementation [3].

1. Automatic Dependent Surveillance-Broadcast (ADS-B)

ADS-B [6] is expected to transform air traffic control by providing surveillance information directly from the aircraft as opposed to indirectly from the current radar-based systems, providing surveillance information in oceanic airspace and in remote locations lacking radar coverage such as the Gulf of Mexico and parts of Alaska, providing traffic data for display on the onboard Cockpit Display of Traffic Information (CDTI) system for improving pilot situational awareness and by promoting better controller and pilot decisions with common situational awareness. ADS-B capable aircraft derive their position from the onboard systems such as the Global Positioning System (GPS) and broadcast their position along with state variables such as speed, heading and altitude, and short-term intent information—consisting of locations of the next several waypoints describing the planned route—using satellite communication. The broadcast information can be received by other ADS-B capable aircraft and ATC in real time. ADS-B consists of two different services: ADS–B Out and ADS–B In. ADS–B Out is the capability for periodically broadcasting information and ADS-B In is the capability for receiving traffic and weather information data from nearby-aircraft and ground-based systems. Vehicle position data provided by ADS-B, and displayed on cockpit and controller displays, has been found to reduce the risk of runway incursions and collisions especially during nighttime and low visibility conditions on the airport surface. ADS-B is also expected to help reduce separation between aircraft, which will lead to increasing airspace capacity.

The FAA has integrated ADS-B into automation platforms at all 24 en route air traffic control facilities and into most of the TRACON facilities, including the 30 busiest terminal areas in the U.S. They plan to integrate into the remaining terminal area automation platforms as the platforms are updated. The FAA has engaged with several airlines to obtain ADS-B data to validate the business case for early adoption. The FAA mandated aircraft need to be equipped with

ADS-B Out capability to operate in Class A, B, C and E airspace after January 1, 2020. Currently, there is no mandate for aircraft to be equipped with ADS-B In capability.

2. Performance-Based Navigation (PBN)

Area Navigation (RNAV) is a method of navigation that enables an aircraft to fly along a desired flight path within the coverage of the navigational aids, within the limits of the aircraft or a combination of both. RNAV capable aircraft can fly directly between points in the airspace rather than from navigation aid to navigation aid. Safety along an RNAV route is ensured by a combination of aircraft navigation accuracy, route separation, and ATC radar monitoring and communications. Required Navigation Performance (RNP) is a navigation accuracy requirement that RNAV capable aircraft—equipped with onboard avionics—can monitor and comply with during flight.The Performance Based Navigation (PBN) [7] concept assumes the navigation accuracy specification is met using a combination of ground-based, satellite-based, and aircraft-based hardware and software. RNP specifies the cross-track accuracy between the desired and actual trajectory of the aircraft.

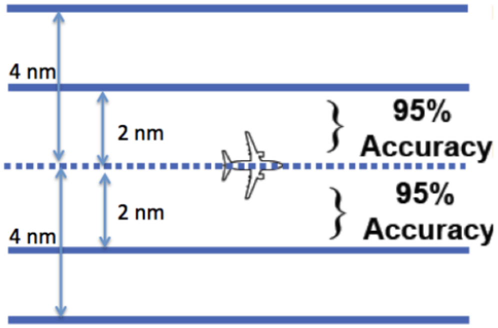

Fig. 2 Aircraft with RNAV capability of RNP2

As shown in Figure 2,an aircraft with RNAV capability of RNP 2 should be able to follow the desired trajectory with a cross-track accuracy of two nautical-miles 95% of the time and within a lateral containment region of four nautical-miles 99.999% of the time. RNP values ranging from 10 to 0.1 nautical miles are typically used. Lower values such as RNP 0.1 are specified for Authorization Required (AR) approaches for instrument landing. Table 1 shows some of the commonly used RNP during different phases of flight.

The benefits of increased capacity and reduction in noise and emissions in the terminal area are accrued by using integrated Standard Terminal Arrival Route (STAR) and RNP approaches and optimized profiles and by decoupling flows between primary and satellite airports.

Table 1 PBN requirements during different phases of flight

Phase of flight	RNP
Oceanic	RNP10,RNP4
U.S. En route	RNP2
Terminal area	RNP2,RNP1
Approach under IMC	RNP0.3

3. Weather Integration

Severe weather has been identified as the cause of 67% of the traffic delays in the United States [8]. Weather factors such as wind, icing and visibility reduce the arrival and departure capacity at the airports. Convective weather and turbulence reduce the number of aircraft that can travel through a given airspace. Weather information is also important for imposing airspace and airport constraints [9] in advanced planning algorithms for TFM. The NextGen Network Enabled Weather (NNEW) will provide a single authoritative source of weather information to all the users of the NAS for enabling dynamic and collaborative planning especially during severe weather conditions by interfacing with the 4-Dimensional Weather Data Cube. The National Weather Service is primarily responsible for populating the Weather Data Cube. The Weather Data Cube will link FAA, National Oceanic and Atmospheric Administration (NOAA), Department of Defense (DOD) and commercial weather data provider databases. The system will provide the ability to convert the data between standard formats, units, and coordinate systems. Finally, it will provide interfaces for retrieval of large volumes of weather data such as in a region and along the planned flight trajectory.

4. Data Communications

Currently, voice is the primary communications method for exchanging critical ATM information between the pilots and ground-based controllers. Communication via voice while efficient is error prone. To guard against errors, ATC communication requires read-back from the receiver, which can be time consuming especially if the read-back is incorrect. Voice communications for supporting the expected future growth of air traffic with new entrants such as Urban Air Mobility (UAM) is also not scalable because of the radio-frequency spectrum limitations. Digital data communications are less prone to errors and systems can be built with error checking and correction mechanisms. Digital data communication has the potential of improving system safety by relieving both pilots and controllers from routine tasks and enabling them to focus on strategic tasks. Increased use of digital communication in dense traffic environment will relieve radio-frequency congestion, thus freeing up voice communication for critical communications. Data communications were first introduced in operations as a part of the Future Air Navigation System (FANS) program. FANS-1 and FANS-A developed by Boeing and Airbus, respectively, provide the ability to autonomously send some data from the aircraft to the air traffic control system using Automatic Dependent Surveillance–Contract (ADS-C) capability. The introduction of these capabilities in the oceanic airspace enabled separation distance between aircraft to be reduced from 100 to 50 nautical miles. A modified version of FANS—FANS-1/A+—that uses VHF Digital Link (VDL) mode-2 is designed for use in the higher traffic density domestic airspace. A new data communication standard harmonizing the global needs of civil aviation, Aeronautical Telecommunication Network (ATN) Baseline-2, is currently under development by ICAO [10].

5. FAA Nextgen Decision Support Systems

The FAA Nextgen Decision Support Systems (sometimes referred to as 3Ts) are the engines of NextGen and, along with SWIM, form the foundation for the future of air traffic management. Time-Based Flow Management (TBFM) supports metering based on time to optimize the flow of aircraft. Terminal Flight Data Management (TFDM) is a decision support system for airport surface management and ATC tower functions. Traffic Flow Management System (TFMS) is a decision support system for planning and mitigating demand-capacity imbalances in the NAS. System Wide Information Management (SWIM) is the digital data-sharing backbone of NextGen delivering the right information to the right people at the right time.

B. Operations

Some concepts and technologies for improving the efficiency in the descent, en route and surface phases of flight are discussed below.

1. Optimal Descent Trajectories (ODT)

ODT tools provide decision support data to air traffic controllers [44] for enabling continuous descents at near-idle thrust, ensuring conformance to arrival schedule constraints for maximizing throughput, avoiding traffic and airspace constraints along the arrival path, and providing clearance delivery—by voice or data link—guided by knowledge of flight deck capabilities for precision guidance and control available onboard the aircraft. Different implementations of the ODT tools, Efficient Descent Advisor (EDA) [45], Continuous Descent Approach [46, 47] and Optimal Profile Descent [48], have been tested in field-evaluations. These tests have demonstrated that ODT technology can save fuel and reduce emissions while avoiding conflicts with other aircraft in busy terminal areas [48]. The feasibility of use of three-dimensional trajectory clearances issued over data link for automated guidance and control using on-board flight management system was evaluated in Tailored Arrivals (TA) to San Francisco operational trials. Tests of this NASA developed technology were conducted by a partnership between FAA, Boeing, and United Airlines during 2006 and 2007. Boeing estimated use of the TA process could save between 400 to 800 pounds of fuel per arrival. In 2012, NASA transferred the results of the research for defining and validating the EDA concept to the FAA for further evaluation, development, and operational use as a part of NextGen technologies.

2. Wind-optimal and User-Preferred Routes

Airline's operations are focused on reducing the cost during cruise—considering cost of fuel and crew time—because most of the time is spent and fuel is consumed in the cruise phase. In the current system, aircraft cruise at a fixed altitude and airspeed along the planned horizontal route from origin to destination. The optimal route, cruise altitude and cruise speed are amended to comply with terminal area and en route restrictions due to airport and airspace capacity constraints and for circumventing regions of severe weather. Flying this non-optimal trajectory results in higher fuel consumption and greater emissions. A study using air traffic data covering flights to/from the top 34 airports in the continental United States during 2007 estimated the routes used by aircraft were 2.9% longer than the direct routes between the city-pairs. The corresponding distance for traffic between the top 34 city-pairs in Europe was 4% longer [47]. The extra distance travelled over great-circle routes is significantly greater over US-Europe oceanic airspace because of reliance on procedural separation due to the lack of radar surveillance and VHF radio communication coverage. This could change with more aircraft equipped with the ADS-B system. Flights from Europe to Asia need to fly longer routes due to large amount of restricted airspace, strict entry points and steep terrain. Several studies have determined the limitations of the current routing structure and estimated the benefits of using wind-optimal routes [49-51]. Even though wind optimal routes are longer compared to direct routes, the direct operating cost is reduced by taking advantage of the winds.

3. Surface

Airport Surface Detection Equipment–Model X (ASDE-X) deployed at 35 major U.S. airports provides position information for tracking the movement of aircraft and vehicles on the airport surface. ASDE-X acquires data using radar, multilateration and ADS-B. The acquired data are provided to systems used by ramp operators, air traffic controllers, traffic managers, flight operators and aviation system managers for managing surface traffic movement—scheduling gate departure, predicting conflicts and runway entry times, preventing runway incursions, resolving conflicts, determining taxi route and schedule compliance—and evaluating airport performance—delay and throughput metrics and causal factors. Data sharing promotes common situational awareness and collaborative decision-making for enhancing safety and traffic flow on runways, taxiways and in ramp areas. These data are also important for airport incident and accident investigations. In addition to ASDE-X at 35 airports, the FAA plans call for deployment of Airport Surface Surveillance Capability (ASSC), a multilateration and ADS-B based system, at additional nine busy airports—Portland International (PDX), Ted Stevens Anchorage International (ANC), Kansas City International (MCI), Louis Armstrong New Orleans International (MSY), Pittsburgh International (PIT), San Francisco International (SFO), Cincinnati/Northern Kentucky International (CVG), Cleveland Hopkins International (CLE) and Andrews Field (ADW). ASSC tracks transponder-equipped aircraft and ADS-B-equipped ground vehicles on the surface and aircraft flying within five nautical miles (nm) of airports. Surface data acquired by these systems are also provided in the SWIM feed to the different stakeholders. SWIM is the NextGen's digital data-sharing backbone. SWIM Terminal Data Distribution System (STDDS) processes the raw surface and terminal surveillance data and sends surface information from airport towers to the corresponding TRACON facility through NAS Enterprise Messaging Service (NEMS) for internal and external NAS users [43].

4. Global Harmonization

The FAA works with other international Air Navigation Service Providers (ANSP) to ensure the interoperability of technologies developed in the U.S. and in other countries under the auspices of the ICAO to enable equipped aircraft to operate globally. Collaboration with the Single European Sky Air Traffic Management Research (SESAR) continues to play an important role in coordinating research and technology development in the U.S. and Europe. The Asia and Pacific Initiative to Reduce Emissions (ASPIRE) [53] is a collaboration between the FAA and ANSPs in Australia, New Zealand, Singapore, Japan, and Thailand. ASPIRE conducted a series of flights in 2008-2011 to successfully demonstrate the potential for fuel and emissions savings in the region. These flights employed modified gate-to-gate operations, including reduced separation, more efficient flight profiles and tailored arrivals. The best practices from these tests can be applied to flights—with properly equipped aircraft—between some cities in the United States and in the Asia Pacific region. During 2011, the FAA, the European Commission, several European ANSPs and 40 European airlines participated in the demonstration of NextGen and SESAR capabilities on transatlantic flights. As a participant of the Atlantic Interoperability Initiative to Reduce Emissions (AIRE) [54, 55], Air France flew several flights between John F. Kennedy International (JFK) and Paris Charles De Gaulle (CDG) as well as between Paris Orly (ORY) and Guadeloupe's Pointe-a-Pitre Airport (PTP) during 2010-2011. The flights procedures were designed to reduce environmental impact without special equipage. Various improvements to taxiing, real-time lateral and vertical optimization and fuel saving RNAV approaches produced fuel savings ranging from 200 to 300 gallons per flight. Global harmonization must allow for the evolution of aviation systems around the world in a way that allows ANSPs and Airspace Users to invest in advanced capabilities. The harmonization work should identify key components that will guide prototype testing, functionality, and prioritizing implementation efforts to solve the roadblocks to global interoperability. ICAO has defined standards for global interoperability. Aviation System Block Upgrade capabilities [57] facilitate strategic planning and investment decisions with a goal of global aviation system interoperability. Initiatives around the world, like NextGen and SESAR, are addressing their own local or regional issues with initiatives to work together.

IV. NASA ATM Technology

NASA and FAA are collaborating to develop and demonstrate an integrated set of NextGen technologies [52] that provide an efficient arrival solution for managing aircraft beginning from just prior to the top-of-descent and continuing down to the runway. These technologies are ADS-B, RNAV arrival routes, Optimized Profile Descent(OPD) Procedures, Terminal Metering, Flight Deck Interval Management (FIM) and Controller Managed Spacing (CMS) tools. NASA and the FAA have demonstrated the feasibility of sustained high throughput of fuel-efficient arrival operations using precision time-based scheduling which provides runway arrival times and fix crossing times for arriving aircraft. Aircraft are delivered to meter fixes according to schedule, but with small spacing errors that need to be reduced to maximize throughput and avoid spacing violations. Most flight crews use FMS to fly OPDs along RNAV/RNP routes – largely without controller intervention. Terminal controllers correct residual spacing errors and cope with disturbances and off-nominal events using tools and display enhancements based on 4-D trajectories. The integration of these technologies and the associated tools will enable aircraft to fly closer together on more fuel-efficient routes, thereby providing even greater benefits in terms of increased capacity and reduced delay, fuel burn, noise, and greenhouse gas emissions.

NASA developed the above ATM technologies, referred to as, ATD-1: Terminal Sequencing and Spacing / Flight Deck Interval Management during FY 15-FY17 and transferred it to the FAA. ATD-1 improves terminal arrival operations efficiency while increasing arrival throughput. ATD-1 developed and delivered integrated aircraft-based and ground-based automation technologies to the FAA NextGen and Air Traffic Organizations, the FAA Surveillance Based Systems Program Office, and flight operators, to enable improved arrival operations efficiency while increasing arrival throughput. This was made possible using NASA technologies together with ADS-B Infrastructure Area Navigation (RNAV), Arrivals Required Navigation Performance (RNP) and Optimized Profile Descents (OPD). ATD-1 10% increase in throughput and fuel savings 400-800 lbs fuel/flight (to be verified).

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

Integrated Arrival/Departure/Surface Metroplex Traffic Management Some of the inefficiency in today's system stems from impediments in information sharing for effectively managing traffic in busy terminal areas. While technologies for improving the arrival, departure and airport surface traffic operations have been under development for quite some time, NASA's recent ATD-2 initiative seeks an integrated approach with information sharing across airlines, air traffic service providers, airport authorities and technology vendors to improve predictability of aircraft movement times on the airport surface and in the airspace to reduce fuel burn and emissions. Several of the inefficiencies targeted by ATD-2 include untimely push back from the gate and uncertainties in prediction of taxi, takeoff and climb times. Uncoordinated push back from the gate can cause congestion on the taxiways and long runway queues resulting in delays. Inability to predict taxi, takeoff and climb times reasonably accurately leads to inaccurate prediction of time of arrival at metered locations, and therefore, to inaccurate traffic demand at constrained resources. This often results in overly conservative traffic flow management initiatives. ATD-2 integrates arrival, departure, and surface (IADS) concepts for traffic management in a metroplex environment [26]. The technologies will increase predictability of the air traffic system and enhance operational efficiency, while maintaining or improving throughput. IADS combines multiple concepts and technologies, including the FAA's three operational decision support tools (TFMS, TBFM, and Terminal Flight Data Management (TFDM)), as well as the NASA's Spot and Runway Departure Advisor (SARDA) and Precision Departure Release Capability (PDRC) technologies. SARDA was developed to improve the efficiency of airport surface operations through time-based metering of aircraft and improved situational awareness amongst stakeholders, while PDRC coupled a trajectory-based decision support functionality with the tactical departure scheduling capabilities of TBFM, resulting in more precise scheduling of surface departures into constrained overhead flows. Based on ready times of aircraft at the gate, the Surface Trajectory-Based Operations (STBO) tool, which incorporates both SARDA and PDRC, schedules pushback times for departures for communication to a tool for the airline operators in the form of a Ramp Traffic Console (RTC). Outbound scheduling of departures under TBFM scheduling to another airport (typically internal departures) is coordinated with the TBFM system scheduling those departures. ATD-2 was developed during FY18-FY21 and delivered an integrated metroplex traffic manager to the FAA NextGen and Air Traffic Organizations, flight operators, and airport operators, that leverages NASA, FAA and industry technologies to enable simultaneous improvement of the predictability and efficiency of arrival, departure and surface operations. ATD-2 saved 48-59 kg fuel/flight at Charlotte, North Carolina (CLT) airport and reduced CO_2 emissions 4.6 Million kg per year.

B. Applied Traffic Flow Management (ATD-3)

The technical challenge for NASA's ATD-3 subproject [27] was 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." The key technologies for achieving the ATD-3 technical challenges were: Multi-Flight Common Route (MFCR), Traffic Aware Strategic Aircrew Requests (TASAR) and Dynamic Routes for Arrival in Weather (DRAW). MFCR is concerned with automatically searching for efficient weather avoidance routes (in terms of fuel and time) and unnecessary weather avoidance routes imposed by earlier traffic management initiatives that are no longer needed due to changes in weather conditions. Avoiding unnecessary reroutes reduces delay. TASAR's focus is flight-deck-based automated continuous search for efficient reroutes in the airborne phase for reduced fuel consumption and flight time while avoiding traffic, weather, and restricted airspace. DRAW seeks to find efficient en route weather avoidance routes for arrival flights while complying with meter-fix capacity constraints. The DRAW algorithm computes weather avoidance routes for flights that are predicted to conflict with weather and provides these routes to a scheduler. The timeline generated by the scheduler shows the estimated arrival times of the rerouted flights in relation to the other flights and the available slots. The trial planning process consists of iteratively creating routes and determining the schedule impact until the desired route and schedule are found to be acceptable to traffic flow managers. An application of DRAW is balancing the demand between the arrival meter-fixes. The ATD-3 Integrated Concept utilizes MFCR, TASAR and DRAW to create a departure to arrival route solution. ATD-3 developed during FY17-FY19 delivered air/ground technologies and procedures to the FAA and flight operators that enable reduced weather-induced delays through the integration of weather information to better manage aircraft, traffic flow, airspace and schedule constraints. ATD-3 has resulted in savings of 13kg of fuel per flight and an annual emission savings of 5.6 Million kg of CO_2.

V. Newly Emerging Technologies

The future ATM system will need to accommodate operations with new types of vehicles such as very light jets, unmanned aircraft systems(UAS) and commercial space launch vehicles. The developments in Urban Air Mobility (UAM)—on demand flights with two to six passenger aircraft—and Unmanned Aircraft System (UAS)—package delivery drones—will introduce a large amount of low altitude air traffic into the NAS. NASA and the FAA have been developing operational concepts for the safe and efficient integration of the operations of these new classes of vehicles. The architecture developed under NASA's UAS Traffic Management (UTM) project with air traffic services provided by multiple organizations is considered a model for developing UAM air traffic services. The FAA has recently released the concept-of-operations for UAM flight operations (ConOps 1.0) [23]. UAM is a subset of the Advanced Air Mobility (AAM) initiative of NASA, FAA, and industry for developing the future air transportation system for serving local, regional, intraregional, and urban areas with new electric vertical takeoff and landing aircraft. The envisioned end state of UAM operations depends heavily on autonomy. Initial operational experience will be gained with new vehicles certified under the current regulatory frameworks, which are expected to evolve as UAM operations increase. Eventually, routine operations are expected to introduce new rules and regulations, infrastructure and automated vehicles, operational control, and traffic management systems. In addition to enabling operations with new types of vehicles, enhancements will continue for improving safety and efficiency with growing demand for commercial high-altitude traffic in the future. Better sharing of data and decisions across different systems employed for airport surface, terminal and en route airspace traffic flow management and air traffic control offer the potential for eliminating unnecessary restrictions and uncoordinated decisions, thereby, reducing delays and fuel consumption and increasing utilization of capacity constrained airport and airspace resources. Several of these newly emerging technologies in various stages of development and evaluation are outlined in this section.

A. Unmanned Air System Traffic Management (UTM)

Many beneficial civilian applications of the Unmanned Air System (UAS) with vehicles weighing less than 20 kg have been proposed, from goods delivery and infrastructure surveillance, to search and rescue, and agricultural monitoring. Currently, there is no established infrastructure to enable and safely manage the widespread use of low-altitude airspace and UAS operations, regardless of the type of UAS. A UTM system has to use higher levels of automation to reduce operational costs. It cannot rely on human operators to monitor every vehicle continuously. The system could provide to human managers information to make strategic decisions related to initiation, continuation, and termination of airspace operations depending on wind and weather conditions.

NASA in collaboration with the FAA, industry and academic partners has conducted a series of increasingly complex flight tests to develop requirements for a system. The first test conducted in August 2015 focused on field testing rural UAS operations for agriculture, firefighting and infrastructure monitoring. It enabled UAS operators to file flight plans reserving airspace for their operations and provide situational awareness about other operations planned in the area. The second test in October 2016 demonstrated applications that operate beyond visual line of sight of the operator in sparsely populated areas. It tested technologies that allowed dynamic adjustments to availability of airspace and contingency management. The third test in May 2018 included cooperative and uncooperative UAS tracking capabilities to ensure collective safety of manned and unmanned operations over moderately populated areas. The final fourth test in May-August, 2019 focused on UAS operations in higher-density urban areas for tasks such as news gathering and package delivery. These activities also tested technologies that could be used to manage large-scale contingencies. The FAA published the rules for operation of small drones during 2013-2015 and the recent revised rulings require remote identification of drones registered after September 2023. By March 2022, FAA has registered about 860,000 drones with commercial drones and recreational drones contributing 32% and 68% respectively.

B. 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].

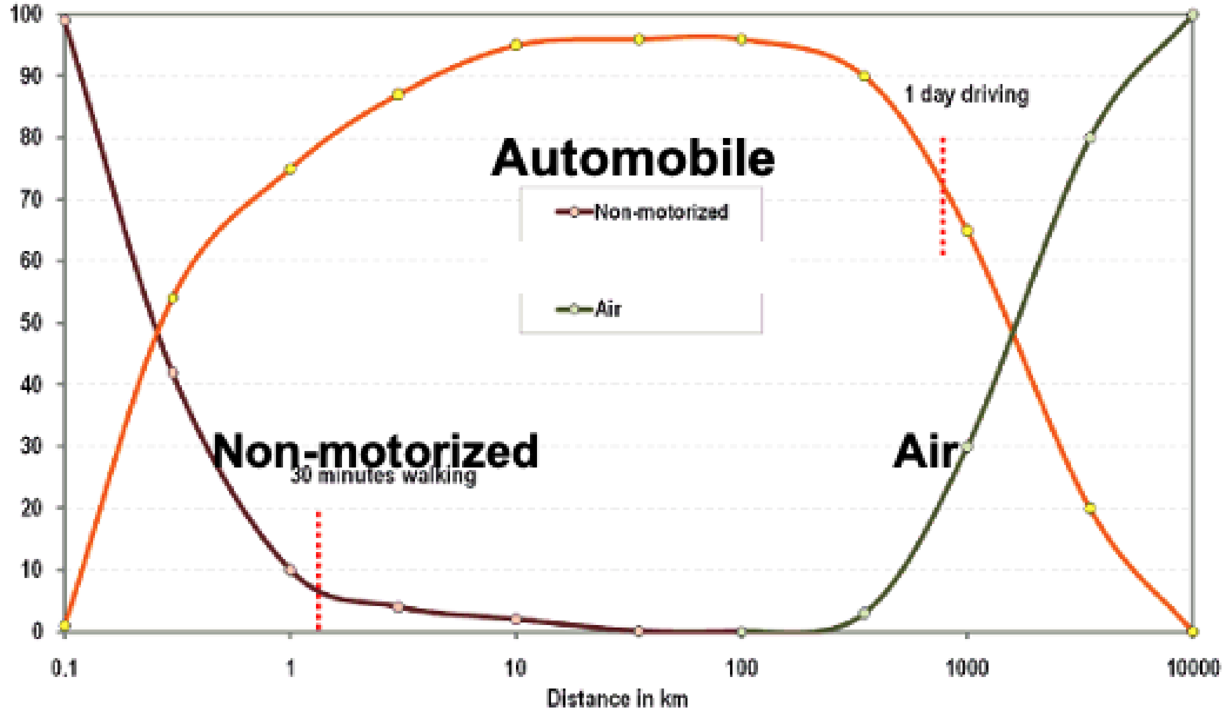

Fig. 3 Choice of mode of transportation with distance

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.

C. 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.

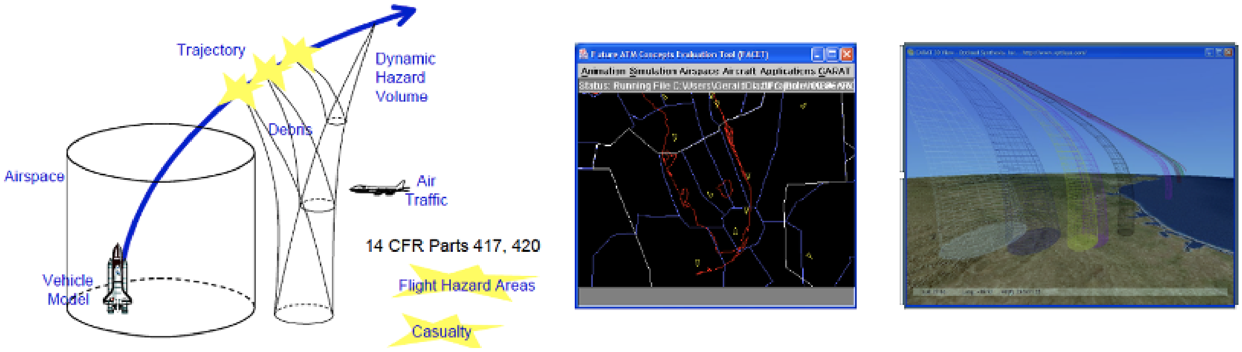

Fig. 4 CST Launch, traffic and and Debri Display

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.

VI. 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 CO_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 CO_2,NO_x 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 CO_2,NO_x and other emissions and Contrails, (b) design of optimal aircraft trajectories to reduce the impact of CO_2,NO_x 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 on-board 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.

VII. 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

AI is used in all walks of life influencing decisions varying from which product to buy, identifying a person accused of committing a crime and controlling an autonomous car. Some errors in systems using AI software as in the case of Uber self-driving car could be fatal. The vehicle's sensors detected the person crossing the road but failed to activate the brakes to stop the car. As AI plays a bigger role in making critical decisions users need to trust the judgement of AI systems. Currently, the decisions of AI systems are opaque and does not provide adequate reasoning for the decision. Several organizations at the government and industrial levels have been examining what it means to be "Trustworthy AI" and how to increase Trust in AI. Trustworthy AI is defined by each organization using slightly different set of principles and properties.

The European Union provided guidance outlining seven essential features of trustworthy AI [22]. Trustworthy AI while respecting all laws and regulations, should (1) provide equity to all members of the society, (2) be secure, robust, and reliable in the presence of uncertainties and variations in real life, (3) provide control to citizens on privacy and data, (4) provide transparency, (5) provide diversity, non-discrimination, fairness, and equal access, (6) provide environmental and societal well-being and (7) provide accountability. European AI strategy is based on trust as a prerequisite to ensure human-centric approach to AI.

An industrial view of trusted AI is provided by IBM [23]. The four pillars of trusted AI, according to IBM, are (1) explainability , (2) fairness, (3) robustness and (4) lineage. The solutions provided by AI/machine learning algorithms is a trade-off between simplicity and complexity. Simple algorithms like linear regression with few features representing physical variables are easy to explain but may have low levels of accuracy. Complex algorithms like Deep Neural Networks can fit complicated decision surfaces with thousands of features with high levels of accuracy but may not provide good understandable physical explanation. The explanations necessary varies with the sophistication of the user and the application. Fairness of ML algorithms depend on the data used for training. Bias can come from the absence or sparsity of certain types of data. This makes the ML algorithms perform poorly in practice. AI algorithms should be secure and robust to tampering of the data by malicious actors. Lineage keeps track of various changes to the databases, algorithms, training, validation of the AI software to help traceability and better explanation.

The interaction between human users and AI presents difficult issues about bias (in both directions-human perception of AI systems and biased decision making on the part of AI systems), verification certification and acceptability of AI systems. Human bias is a big concern and may require intense training to overcome habits built controlling systems manually. Recently, there has been many papers discussing both the many advantages of AI and its shortcomings in the real-world. Reference [24] argues that part of the mistrust in AI is confusion about what AI means to people. AI is not a replacement for human intelligence it is an engineering discipline to augment human intelligence by thorough analysis of large datasets. The role of AI is to add value to human decisions without creating inequality.

When considering how to build trust in AI systems the task and the role played by AI in decision-making makes a big difference in the emphasis placed on the evaluation of the system based on factors like decision impact and authority, data and methods used to train the model, model interpretability, and model accuracy. AI models used to assist human decision makers in areas like prison terms, college admissions, and hiring need different emphasis on these factors compared to an ATM system providing controllers support on aircraft separation. These types of critical decisions pose a challenge to AI systems and a way to build trust may involve a lower level of automation maintaining human supervision.

ML algorithms used in ATM applications use factors like accuracy, precision, recall, and F measures to estimate the goodness of training and validation of algorithms. It may be necessary to augment these quantitative measures by qualitative measures discussed earlier to increase "Trustworthiness of an AI based ATM system [25]."

All complex systems go through several layers of testing and validation. 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. It is important to address questions like how do you capture the specification of AI systems? AI systems require transparency about whether the Neural Network or another MLT responds with bounded outputs with bounded inputs, how it performs under various datasets and limitations of the datasets used for training and validation of the MLT. This approach may be sufficient for certain application and may not work always. The applicability of the method to more generalized situations is not guaranteed and extrapolations to other applications need to be done carefully. A robust framework should be built around the modeling process and the decisions proposed by the AI systems should be close to human expectation. AI systems need the ability to audit and track back. The success of AI systems will come from built in resilience, predictability and consistent operations. Another important consideration is the risk of failure associated with the AI system and how the to mitigate the risk by design integration with other systems.

VIII. Conclusions

This paper provided an overview of the research under development, and technology and infrastructure upgrades currently being deployed to achieve sustainable aviation operations. Significant progress has been made to reduce the impact of CO_2 emissions. In the future, greater emphasis is required in reducing the environmental impact of non-CO_2 emissions and contrails. The emerging vehicles in aviation are powered by non-fossil sources like electricity and Hydrogen and contribute emissions depending on the source of power generation. Greater automation and decentralization will be key aspects of future aviation systems. A fundamental challenge will be to develop the functional relationship between pilots, air traffic controllers and other human decision-makers in the presence of greater automation. 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. 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.

References

[1] Penner, J., Lister, D., Griggs, D., Dokken, D., and McFarland, M., "Aviation and the global atmosphere: Summary for policymakers, IPCC Special Report," , 1999.

[2] Brasseur, G. P., and Gupta, M., "Impact of aviation on climate: Research priorities," *Bulletin of the American Meteorological Society*, Vol. 91, No. 4, 2010, pp. 461–464.

[3] Forecast, F. A., "Fiscal Years 2020-2040," *Federal Aviation Administration*, 2020.

[4] Duda, D., Minnis, P., Costulis, P., and Palikonda, R., "CONUS contrail frequency estimated from RUC and flight track data," *European Conference on Aviation, Atmosphere, and Climate*, 2003.

[5] Baxley, B. T., Johnson, W. C., Scardina, J., and Shay, R. F., "Air Traffic Management Technology Demonstration-1 Concept of Operations (ATD-1 ConOps), Version 3.0," 2016.

[6] Administration, F. A., "Automatic Dependent Surveillance-Broadcast," 2013.

[7] Devlin, C. J., Herndon, A. A., McCourt, S. F., and Williams, S. S., "Performance-based navigation fleet equipage evolution," *2009 IEEE/AIAA 28th Digital Avionics Systems Conference*, IEEE, 2009, pp. 1–D.

[8] Administration, F. A., "The economic impact of civil aviation on the US economy," 2011.

[9] Krozel, J., Kicinger, R., and Andrews, M., "Classification of weather translation models for NextGen," Tech. rep., American Meteorological Society, 2011.

[10] Jackson, M. R., "RTCA Special Committee 214-Standards for Air Traffic Data Communication Services," 2007.

[11] Schafer, A., "Regularities in travel demand: an international perspective," 2000.

[12] Goyal, R., Reiche, C., Fernando, C., Serrao, J., Kimmel, S., Cohen, A., and Shaheen, S., "Urban air mobility (UAM) market study," Tech. rep., 2018.

[13] Cheng, V., Diaz, G., and Sridhar, B., "Flight safety analysis tool for space vehicle operations in the national airspace," *AIAA's 3rd Annual Aviation Technology, Integration, and Operations (ATIO) Forum*, 2003, p. 6793.

[14] Nelson, E. S., and Reddy, D. R., *Green aviation: reduction of environmental impact through aircraft technology and alternative fuels*, CRC Press, 2018.

[15] Delgado, L., Prats, X., and Sridhar, B., "Cruise speed reduction for ground delay programs: A case study for San Francisco International Airport arrivals," *Transportation research part C: Emerging technologies*, Vol. 36, 2013, pp. 83–96.

[16] Ramadani, A., Durbin, M., Kravitz, B., and Knorr, D., "Redistribution of Necessary Delay in the US National Airspace System: Benefits from Trajectory-based Operations," ????

[17] Sridhar, B., Chen, N. Y., and Ng, H. K., "Energy efficient contrail mitigation strategies for reducing the environmental impact of aviation," *Tenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2013)*, 2013.

[18] Sridhar, B., Chen, N. Y., Ng, H. K., and Morando, A., "Modeling and simulation of the impact of air traffic operations on the environment," *Air Traffic Control Quarterly*, Vol. 20, No. 4, 2012, pp. 285–310.

[19] Sridhar, B., Sheth, K., Ng, H. K., Morando, A. R., and Li, J., "Global simulation of aviation operations," *AIAA Modeling and Simulation Technologies Conference*, 2016, p. 0422.

[20] Sridhar, B., "Applications of machine learning techniques to aviation operations: Promises and challenges," *2020 International Conference on Artificial Intelligence and Data Analytics for Air Transportation (AIDA-AT)*, IEEE, 2020, pp. 1–12.

[21] Sridhar, B., Chatterji, G. B., and Evans, A. D., "Lessons Learned in the Application of Machine Learning Techniques to Air Traffic Management," *AIAA AVIATION 2020 FORUM*, 2020, p. 2882.

[22] Smuha, N. A., "The EU approach to ethics guidelines for trustworthy artificial intelligence," *Computer Law Review International*, Vol. 20, No. 4, 2019, pp. 97–106.

[23] Banavar, G., "Learning to trust artificial intelligence systems," *Report, IBM, Armonk, NY*, 2016.

[24] Jordan, M. I., "Artificial intelligence—the revolution hasn't happened yet," 2019.

[25] Wickramasinghe, C. S., Marino, D. L., Grandio, J., and Manic, M., "Trustworthy AI development guidelines for human system interaction," *2020 13th International Conference on Human System Interaction (HSI)*, IEEE, 2020, pp. 130–136.