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The Next Generation Air Transportation System of the United States: Vision, Accomplishments, and Future Directions

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1. Introduction

The US Federal Aviation Administration (FAA) manages the largest air traffic control system in the world. This system controls approximately 50 000 flights per day covering almost 7.61×10^7 km^2, equivalent to approximately 15 percent of the Earth's surface. Ensuring the safety of these flights, while maintaining a high degree of efficiency and low delays, is a constant challenge.

To address concerns regarding anticipated increases in air traffic, leverage the capabilities of new technologies to enhance services, and accommodate new classes of airspace users (such as commercial space and drone operators), the FAA and its partners have embarked on a modernization effort known as the Next Generation Air Transportation System (NextGen). NextGen encompasses a wide range of improvements to communications, navigation, surveillance, and air traffic management (ATM) automation systems. NextGen also includes many procedural improvements for leveraging new technologies and advances in ATM science.

2. NextGen vision and plans

In a response to heavy congestion and associated delays, the FAA outlined its vision for NextGen in 2004 [1]. NextGen was intended to increase airspace system capacity, improve flight efficiency, increase system predictability, increase access, and improve system resiliency, while simultaneously maintaining or improving the safety in air transportation. While there are many features in the program, its key aspects are satellite-based surveillance and navigation, digital communications, information exchange, ATM decision-support aides (such as time-based management tools), and new wake separation standards.

The FAA's NextGen plans are described in the enterprise architecture (EA) of the National Airspace System (NAS). Our architectural model is a modified version of the US Department of Defense Architecture Framework Version 1.5 [2]. According to the International Organization for Standardization, "Architecture descriptions are used by the parties that create, utilize and manage modern systems to improve communication and co-operation, enabling them to work in an integrated, coherent fashion" [3]. The NAS EA is a hierarchical representation of the services, operations, and systems that comprise the NAS, and is illustrated by a set of views describing the relationships between the various NAS elements. Our planning processes then describe how this architecture will evolve from its current state to a desired "to be" state, in this case, NextGen. The point of origin for these plans is the FAA services hierarchy, which describes the FAA's core services and their constituent capabilities. These services are time-invariant (although periodically, there can be changes as the FAA's mission evolves) and solution-independent. The strategy for developing the NAS from its current state to its future NextGen state is depicted by a series of service roadmaps. These service roadmaps describe the "operational improvements" that are captured in the NextGen vision, that is, the new capabilities in air traffic control that will benefit the industry and the flying public.

There currently are 65 operational improvements that describe NextGen. The NAS Segment Implementation Plan (summarized in the NextGen Implementation Plan) decomposes these operational improvements into discrete steps or increments needed to develop, integrate, and implement the desired new capabilities, and identifies their associated capital investments [4]. Finally, the EA infrastructure roadmaps illustrate the progressions of system deployments, investments, and key decision points for major acquisitions [5].

Many of the NextGen improvements are functionally independent. For example, a change to wake separation minima on final approach is functionally distinct from an automation tool that helps en route controllers. Therefore, many improvements can be engineered and implemented independently. However, while the functions may be independent, the resulting operational impacts may be coupled. For example, multiple capacity-related improvements will affect the system performance non-linearly, owing to the non-linear relationship between capacity and delay. For this reason, we use a system-wide model to analyze the impacts of simultaneous improvements, and to prioritize investments.

For functions that are not independent, such as different means for controlling traffic flow (or time-based management), models and human-in-the-loop (HITL) simulations are used to validate new concepts throughout the development lifecycle. For example, the FAA's William J. Hughes Technical Center can perform cross-domain HITL simulations of new concepts using actual automation system hardware and software. Ongoing experiments

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for evaluating terminal airspace metering can involve six en route and eight terminal controllers working simultaneously, along with two traffic managers and pilots.

3. Business case

We completed the first business case for NextGen in 2010 and updated it as recently as 2017 [6]. This business case captures the cash flows associated with the costs and benefits of the various NextGen investments that are properly discounted and in accordance with the standard government practice (as prescribed by the Office of Management and Budget). The costs include capital costs for major FAA infrastructure investments, operations costs to sustain these investments and for procedural modifications, and operator costs (e.g., equipping aircraft with new avionics). As the FAA must include all stakeholders in the cost/benefit calculus, the benefits include those accruing to the operators, passengers, government, and society at large. The specific benefit categories captured in the business case are as follows:

- Internal FAA cost savings
- Reducing passenger travel time
- Decrease in the aircraft operating costs
- Avoiding flight cancellations
- Increase in scheduled flights
- Reducing carbon dioxide emissions
- Reducing injuries, fatalities, and aircraft losses/damages from accidents.

As mentioned previously, the coupled, non-linear nature of NAS performance implies that the benefits must be calculated for the program as a whole, rather than as a sum of its components. To a possible extent, the FAA's business case for NextGen complies with this condition and takes an integrated approach towards modeling system-wide benefits. A system-wide mathematical model of the NAS is used to estimate the benefits of the entire program and to account for the interdependencies and non-linearities within the system. While the FAA's modeling capability has improved tremendously in recent years, significant modeling limitations still persist; for example, many operational improvements cannot be appropriately represented in the model. For this reason, the estimates of the benefits provided by the model are augmented with detailed, discrete studies performed by the FAA program offices, where required.

We have estimated the total costs of NextGen for the time period between 2007 and 2030 to be $35 billion USD: $22 billion USD for the FAA and $13 billion USD for the operators. The FAA has already spent $8.2 billion USD between 2007 and 2019.

We have estimated total benefits to be approximately $100 billion USD through 2030. To date, we have estimated that more than 20 capabilities have accrued $7.3 billion USD in the form of benefits to the industry and society, which are shown as follows:

- $1.2 billion USD in fuel savings
- $1.5 billion USD in other aircraft operating cost savings
- $4.2 billion USD in passenger travel time savings
- $0.4 billion USD in safety.

As is generally the case, costs are front-loaded, with most benefits accruing later in the lifecycle. Air traffic delays tend to increase geometrically with increasing traffic. Likewise, the delay savings from capacity improvements, and hence the NextGen-related benefits, increase geometrically with time.

4. Implementations to date

The following are examples of some of the NextGen capabilities that have been implemented to date.

Surveillance—The FAA has fully deployed a network of approximately 630 ground-based automatic dependent surveillance-broadcast (ADS-B) transceivers. These transceivers receive Global Position System (GPS)-derived positional broadcasts from aircraft (known as "ADS-B Out") providing air traffic controllers with more precise and timely information. They are also used to transmit weather, airspace, and traffic information to aircraft, for display in the cockpit. Pilots can see other aircraft in proximity on their displays (known as "ADS-B In"), thus significantly increasing safety, particularly for general aviation operations. Since January 1, 2020, the use of ADS-B transmitters has been made compulsory for aircraft operating in most controlled airspace in the United States.

Navigation—The use of GPS for navigation has improved flight operations, greatly enhancing safety, airport access, and flight efficiency. The FAA has published over 17 000 area navigation (RNAV) instrument approach procedure minima (one procedure can include several minima, each for a specific aircraft capability), approximately 4500 of which utilize a space-based augmentation system to provide instrument-landing-system-like performance. In addition, there are 685 required navigational performance (RNP) approach procedures. RNP incorporates monitoring and alerting capabilities in the cockpit and special flight crew training to ensure that the aircraft comply with extremely stringent precision requirements. The FAA has published approximately 1000 RNAV arrival/departure procedures and approximately 270 RNAV routes. Lastly, the FAA has completed eight "Metroplex" implementations, each incorporating redesigned procedures and airspace in a major metropolitan area affecting multiple airports.

Communications—The FAA is currently implementing controller pilot data link communications (CPDLC) using very high frequency data link (VDL) Mode 2. The system is now providing departure clearances at 62 airports. Recently, these capabilities also became operational at the Indianapolis, Kansas City, and Washington area control centers, with eight more centers to be completed in 2020. The en route services include frequency and altitude assignments, reroutes, and altimeter settings.

Information management—The FAA has implemented a digital data and information sharing system known as "System Wide Information Management" (SWIM). Through SWIM, users who are both inside and outside the FAA can subscribe to the data they need and consume information in standardized, well-documented formats. SWIM has reduced the cost of integrating information systems and has greatly increased access to information.

Automation – Several automation and decision support systems are being enhanced as a part of NextGen. Notably, several enhancements have been made to the timebased flow management (TBFM) system, used to meter the traffic arriving into busy airports. The "En Route Departure Capability" functionality is used to schedule departures from outlying airports into the en route arrival stream for a hub airport. The "integrated departure/arrival capability" allows tower controllers to electronically request release times for departures from these outlying airports.

Airport capacity—The FAA has been pursuing several efforts to increase effective airport capacity using both procedural and technological means. We worked with the National Aeronautics and Space Administration (NASA), International Civil Aviation Organization, and others to develop novel same-runway wake separation standards, yielding increases in throughput at many airports. The FAA has also been able to modify separation standards for closely-spaced parallel runways. Finally, the FAA has been able to reduce ceiling and visibility minima through a combination of procedural modifications, increased runway visibility sensors, enhanced flight vision systems, and heads-up displays.

A transition to satellite-based technologies is taking several years. The US fleet consists of over 200 000 aircraft, including approximately 4400 aircraft operated by scheduled carriers [7]. The FAA published a regulation in 2008 requiring aircraft operating in most of the controlled airspace to be equipped with ADS-B avionics by January 1, 2020, giving manufacturers and operators sufficient time to develop and install equipment. All FAA automation systems can now use ADS-B data as the primary source for surveillance, with radar continuing to be used as a secondary source. Almost all air carrier aircraft are now equipped with RNAV systems; the number of general aviation aircraft that can use GPS is unknown.

5. Challenges

As one would expect, there have been a number of challenges for the implementation of the new and improved capabilities envisioned under NextGen. Undoubtedly, the greatest challenge has been the acceptance of the new RNAV arrival, approach, and departure procedures in the community. The FAA is now extremely limited in its ability to publish new procedures owing to community noise concerns (either real or perceived). In fact, in some cases, the FAA has had to abandon newly implemented procedures following court rulings in favor of communities. New procedures can move flight paths over different neighborhoods, and while this may not increase noise exposure, "new noise" can be perceived as worse than "old noise." There is also a concern that RNAV procedures can concentrate noise more than legacy procedures using terrestrial navigational aids. Improvements in aircraft technology will continue to make efforts in noise reduction; we have seen a 94% reduction in the number of people exposed to significant noise (i.e., within the 65 dB day–night level contour) over the past 43 years. These improvements take a long time to enter the fleet, however. According to Boeing's Commercial Market Outlook, roughly three percent of the fleet is retired each year, and the average age at retirement is over 20 years [8]. Recently, the FAA has instituted new community engagement strategies that will hopefully lead to more mutual understandings and beneficial outcomes for all the stakeholders.

The level of operator adoption of the new NextGen-related avionics continues to be a concern. The ADS-B equipment mandate took effect on January 1, 2020. Several years ago, it was not assured that the operators would comply with this rule. The airlines responded in a positive manner and have met the deadline, but many others (in particular, military and public service aircraft) are yet to comply. The inabilities of aircraft and crew to conduct RNP procedures remain problematic, as does the inconsistent manner in which the flight management systems handle turns, vertical navigation, and the required time of arrival (RTA) functionality. Aircraft avionics suites' inability to handle CPDLC messages has recently become a significant issue. The mixed equipment and inconsistent avionics performance have led to instances where air traffic control facilities have been unable to adopt new capabilities.

To address the equipment issues, the "NextGen Advisory Committee" (NAC), an industry group chartered to advise the FAA on air traffic control (ATC) modernization, has proposed a minimum capability list (MCL) for aircraft avionics. The core list includes:

- ADS-B Out
- CPDLC using VDL Mode 2, with push to load
- RNP 0.3 with radius-to-fix and coupled vertical navigation capabilities
- An inertial reference unit for resilient operations.

There is also a supplemental list with 12 more items. The FAA has asked the NAC to discuss these lists with other stakeholder groups (including aircraft and equipment manufacturers and regional airlines) and to make recommendations for encouraging MCL adoption.

Finally, while automation improvements have been a key element of NextGen, several capabilities have seen limited use because of a lack of automation support. For example, one of the reasons of the RNP approach procedures not being used more is owing to a lack of terminal automation to help controllers manage mixed fleets. Moreover, a reason why TBFM has not seen increased use is that the tools that help controllers maneuver their aircraft to comply with its metering schedules are yet to be deployed.

6. Future directions

The FAA has several unimplemented NextGen capabilities which are to be fully developed and deployed, some of which will address the challenges above. The FAA works with industry via the NAC to prioritize near-term efforts. These priorities, published annually in a joint implementation plan [9] are currently organized into five portfolios: multiple-runway operations (MROs), data communications, surface and data sharing, performance-based navigation (PBN), and northeast corridor improvements.

Any improvements that can directly increase airport throughput tend to have the highest payoff, as runway infrastructure at congested airports tends to be the most binding constraint on overall system performance. There is little opportunity for increasing capacity by constructing new runways at these airports; thus, changes to procedures and improved controller tools are imperative. MRO efforts focus on consolidated wake turbulence (CWT) separation standards, which harmonize the new same-runway standards for all airports. CWT standards have been implemented at five locations to date. Over the next two years, the FAA expects to implement these standards at an additional 12 airports.

The data communications program has implemented CPDLC at 62 airports and three en route centers. Completion of CPDLC implementation at the remaining 17 en route centers is a high priority.

In 2020, the FAA will begin to deploy a new tower (i.e., surface) automation platform, the "terminal flight data manager" (TFDM). TFDM will implement electronic flight strips in our air traffic control towers, fully integrate surface operations with TBFM, and provide a departure queue management capability for limiting surface congestion.

FAA's PBN efforts focus on the completion of the Metroplex projects and on airspace redesign efforts. The Denver, Las Vegas, and Florida Metroplex projects will be completed over the next two years. Additionally, the FAA is implementing the established-on-RNP (EoR) concept. EoR allows for a reduction of the radar separation minima in terminal airspace for aircraft on an RNP approach procedure. This can lead to shorter downwind traffic pattern segments, fuel and time savings, and reduced noise exposure.

The northeastern United States is home to the nation's most congested airports and airspace, including the New York metropolitan area. A wide variety of improvements are planned for this region, including initial trajectory-based operations (TBOs). A key NextGen concept, TBO is an ATM method for strategically planning, managing, and optimizing flights by using time-based management, information exchanges between air and ground systems, and the aircrafts' ability to travel precise paths in time and space. The FAA hopes to fully implement TBO over the next decade through a series of upgrades to the TBFM system and the en route and terminal automation platforms. The first phase of TBO, known as initial TBO, is being developed in the northeast. In the near term, the FAA will implement the following improvements [9]:

- Improving and evaluating airborne metering for arrivals to Philadelphia International Airport (PHL) by refining the metering parameters and expanding the scope to encompass more area control centers;
- Implementing pre-departure scheduling for PHL arrivals from eight area control centers;

- Enhancing pre-departure reroute/airborne reroute capabilities to enable aircraft-specific reroutes.

Based on the experience gained from these TBO efforts, the following significant aspects are revealed:

- Controllers must have a thorough understanding of the objectives of TBO for it to be successful, because TBO affects the workloads and the functions performed by the controllers;
- For multi-runway airports (such as PHL), the algorithms must address all major airport configurations;
- Automation algorithms must work in off-nominal conditions, such as during convective weather; and
- Demand uncertainty, and in particular, close-in departures (for which meter fix arrival times are difficult to estimate), must be considered.

In addition to the near-term NAC priorities, the FAA continues to explore ADS-B in applications such as flight interval management (FIM). FIM provides another means for ensuring precise compliance with the TBFM schedule times. The FAA will also be enhancing en route CPDLC capabilities after the system is fully deployed, for example, by adding new messages for a better control of aircraft trajectories.

NextGen was conceived nearly 20 years ago, before the recent breakthroughs in artificial intelligence (AI) and machine learning (ML). Thus, NextGen does not incorporate any aspects of AI/ML. Nevertheless, NextGen and the related FAA initiatives for data sharing (i.e., SWIM), enterprise information management, and big data analytics have laid the foundation for AI/ML applications in ATM. The FAA and NASA have been researching AI/ML applications for traffic flow management for several years. Recently, there has been a significant interest in using AI/ML to integrate unmanned aerial systems and urban air mobility into the airspace. The FAA is also researching AI/ML for use in cybersecurity. These technologies hold great promise for further improving the safety, efficiency, environmental impact, and cost effectiveness of ATM.

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