# Towards Autonomous Aviation Operations: What can we learn from other areas of automation?

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**The introduction of automation has accelerated in many industries to perform dangerous tasks or to achieve high efficiencies. Space autonomy, Internet, robotic vehicles, intelligent systems, wireless networks and power systems provide successful examples of various levels of automation. Advances in computing, communications and control have enabled automation. The need for automation in aviation has been recognized for many years. However, aviation continues to be anchored in human-centered automation and the progress of automation in aviation has been more about modernizing equipment, introducing new sensor and surveillance technologies and procedures. Aviation operations are being challenged in unprecedented ways with the introduction of low-cost, low-weight Unmanned Aircraft Systems (UAS) operating at low altitudes. NASA is conducting research in autonomy and developing plans to increase the levels of automation in aviation operations. This paper provides an overview of the fundamentals of automation, levels of automation and automation advances in other areas that bear functional similarities to Air Traffic Management (ATM). It provides a comparison between the requirements for automation in ATM and other areas and points to lessons learned in the development of successful automation. A description of some of the planning tasks performed in Traffic Flow Management (TFM) is provided to understand how developments in automation technologies and methods can advance the level of automation in the generation of TFM advisories. The paper discusses some of the research challenges in introducing increased levels of automation in ATM systems.**

## I.   Introduction

Rapid advances in automation have disrupted and transformed several industries in the past 25 years. Automation has evolved from regulation and control of simple systems like controlling the temperature in a room to the autonomous control of complex systems involving a network of systems. The reason for automation varies from industry to industry depending on the complexity and benefits resulting from increased levels of automation. Automation may be needed to either reduce costs or deal with hazardous environment or make real-time decisions without the availability of humans. Space autonomy, Internet, robotic vehicles, intelligent systems, wireless networks and power systems provide successful examples of various levels of automation. The U.S. Air Force Report on Technology Horizons 2010-2030[1] identifies the benefits of autonomous systems and a roadmap for the development of the underlying science and technology needed to achieve successful autonomous systems. NASA is conducting research in autonomy[2] and developing plans to increase the levels of automation in aviation operations. Aviation operations are being challenged in unprecedented ways with the introduction of low-cost, low-weight Unmanned Aircraft Systems (UAS) operating at low altitudes. This paper provides a brief review of the efforts to introduce automation in Air Traffic Management (ATM) and the new computation, communication and control technologies and procedures planned for the next decade under the Federal Aviation Administration's (FAA) NextGen program. It describes the functions associated with Traffic Flow Management (TFM), the current level of automation in the various TFM tasks, developments in automation in other industries and how these methodologies can be applied to increase the level of automation in conventional TFM and in UAS Traffic Management (UTM).

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Section II describes the new technologies planned in Air Traffic Management to enable increased levels of automation in the next decade. Section III provides an overview of the fundamentals of automation, levels of automation and automation advances in two areas, Space Autonomy and Intelligent Transportation Systems, that bear functional similarities to ATM. Section IV provides a comparison between the requirements for automation in ATM and other areas and points to lessons learned in the development of successful automation. Section V provides a system description of the different functions performed under TFM. Section VI examines a specific task in TFM, Severe Weather Avoidance Plan (SWAP), and describes how developments in automation technologies and methods can advance the level of automation in the generation of SWAP advisories. Section VII describes some of the research challenges in introducing IA in ATM systems. Section VIII discusses the differences between the automation issues in TFM and UTM. Section IX provides remarks about the evolution of IA in future ATM systems.

## II.  Air Traffic Management

The need for automation in aviation has been recognized for many years. There have been several attempts to develop decision aids to improve controller productivity and enhance system safety. FAA Automated En Route Air Traffic[3] (AERA) program was started in 1984 and NASA started Air Traffic Control (ATC) automation research as far back as 1983[4]. Several decision support tools and advanced procedure have been implemented in NextGen[5]. There have been big advances in cockpit automation. However, aviation continues to be anchored in human-centered automation[6] and the progress of automation in aviation has been more about modernizing equipment, introducing new sensor and surveillance technologies and procedures.

### II. 1 NextGen Technologies

The NextGen consist of a combination of projects to improve infrastructure and introduce new technologies and procedures. This section describes some of the matured concepts considered for implementation in FAA's NextGen projects[5]. These enabling concepts and technologies are Automatic Dependent Surveillance-Broadcast, Performance-Based Navigation, Weather Integration and Data Communications.

### ADS–B

Automatic Dependent Surveillance-Broadcast ADS-B[7] is a technology to transform air traffic control from the current radar-based system to a satellite-based system. ADS-B brings the precision and reliability of satellite-based surveillance and provides common situation awareness between pilots and controllers. ADS-B is expected to reduce separation margins between aircraft, leading to increases in airspace capacity. ADS-B provides surveillance in remote areas currently without radar coverage, and enables aircraft to fly more direct and efficient routes.

Typically, an ADS-B capable aircraft derives its position from the Global Positioning System (GPS) of satellites, and may combine that position with any number of aircraft variables, such as speed, heading, altitude and flight number. This information can be shared with other ADS-B capable aircraft and air traffic control centers in real time. ADS–B consists of two different services: ADS–B Out and ADS–B In. ADS–B Out is the capability to periodically broadcast information about the own-ship, such as identification, current position, altitude, and velocity, through an on-board transmitter in order to display the aircraft's location to controllers on the ground or to pilots in the cockpits of aircraft equipped with ADS-B In. ADS-B In is the reception by aircraft of traffic and weather information data and other ADS-B data such as direct communication from nearby aircraft.

FAA has mandated the use of ADS-B Out capability in Class A, B, C airspace by January 1, 2020. Currently, there is no mandate for ADS-B In and airspace regularly used by general aviation is exempt from ADS-B in requirements.

### 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 or within the limits of the aircraft, or a combination of both. The safety along an RNAV route is ensured through a combination of aircraft navigation accuracy, route separation, and ATC radar monitoring and communications. Required Navigation  Performance (RNP) is RNAV operations with aircraft on-board equipment for performance monitoring and alerting. The Performance Based Navigation (PBN) concept assumes the navigation specification will be met through a combination of ground-based, satellite-based and aircraft-based hardware and software. RNAV and RNP equipped aircraft can fly direct trajectories between points in the airspace. RNAV and RNP specify the

cross-track accuracy between the desired and actual trajectory of the aircraft. For example, an aircraft with RNP 2 capability will be able to follow the desired trajectory with a cross-track accuracy of 2 nm 95% of the time and within a lateral containment region of 4 nm all (99.999%) the time. PBN varies from RNP 10 to the 0.1 nm precision and curved paths of RNP 0.1 Authorization Required (AR) approaches. The benefits of PBN in the terminal area include integrated Standard Terminal Arrival Route (STAR) and RNP approaches, optimized profiles, decoupling of flows between primary and satellite airports, increased capacity in the terminal area and reduction in noise and emissions. The realization of the benefits of PBN depends on aircraft equipage[8].

**Weather Integration**

Severe weather has been identified as the source of 70% of the air traffic delays in the United States. Currently, controllers in ATM and pilots and dispatchers in airlines use different weather data to make safe and efficient routing decisions. The NextGen Network Enabled Weather (NNEW) is the ability to provide a common weather picture to all the users in the NAS to enable dynamic and collaborative planning in the presence of severe weather. The National Weather Service is responsible for populating the 4-Dimensional Weather Data Cube. NNEW interfaces with the Cube and provides a single authoritative source of weather information for ATM planning. Weather may reduce the arrival and departure capacity at airports due to wind, icing, convection and visibility conditions. En route convective weather and turbulence may reduce the number of aircraft that can travel through a given airspace. The weather information is translated into airspace and airport constraints[9] for use in advanced planning algorithms.

**Data Communications**

Currently, voice is the primary source of communications to exchange critical information between the cockpit and ground-based controllers. The use of voice communication is labor intensive, time consuming, error prone and limits the ability of the NAS to meet future traffic demands. The availability of digital data communications improves system safety by relieving both pilots and controllers from routine tasks. Pilots and controllers are enabled to focus on strategic and critical tasks such as providing more preferred and direct routes and altitudes, saving fuel and time. In areas with dense traffic, fewer voice communications also will reduce radio-frequency congestion and spoken miscommunication.

Data communications were first introduced in operations as part of the Future Air Navigation System (FANS) program. FANS 1 and FANS A develop by Boeing and Airbus respectively, provide the ability to autonomously send some data from the aircraft to the air traffic control system through Automatic Dependent Surveillance–Contract (ADS-C). The introduction of these capabilities in the oceanic airspace enabled safe separation distance between aircraft to be reduced from 100 nm to 50 nm. In the continental US, FANS will be modified for greater traffic density and available surveillance as FANS 1/A+ using VHF Digital Link (VDL) mode 2. A new data communication standard harmonizing the global needs of civil aviation, Aeronautical Telecommunications Network (ATN) Baseline 2, is currently under development by International Civil Aviation Organization[10].

The NextGen technologies are providing ATM operations with the sensors, computing and information network systems needed to advance the levels of automation in the system.

## III.  Automation

The desire to build autonomous systems has its origins in the regulation/control of parameters such as temperature, air traffic density, and gross national product and interest rates, affecting the comfort, economy and safety of society. The change or control of any process requires the ability to model the process, understand the relationship between the inputs and the outputs of the process, ability to observe the states of the process, decision making about the changes to the inputs to achieve the desired outputs and actuation to change the desired inputs. This methodology applies to simple tasks like regulating the temperature in a room to complex tasks like controlling the aviation system operations. Figure 1 shows the components of a control system and the status of various boxes in the figure defines the level  of automation.

 The model/plant represents the ability to represent the real world in terms of static and dynamic equations. The uncertainties represent conditions in the real world that cannot be modeled either due to variations in the condition of the plant, lack of knowledge about external environment influencing the operations and inability to control the operating environment. The goal of the controller is to modify the inputs to the system via feedback/decisions to make the outputs of the system meet desired conditions. A modern complex system is made up of thousands of control systems interacting with each other and the

inputs, outputs and decision making associated with each subsystem could be automatic or subject to human control. The decision-making can be done by an individual or supervised in situ or remotely by an individual or done autonomously by the machine.
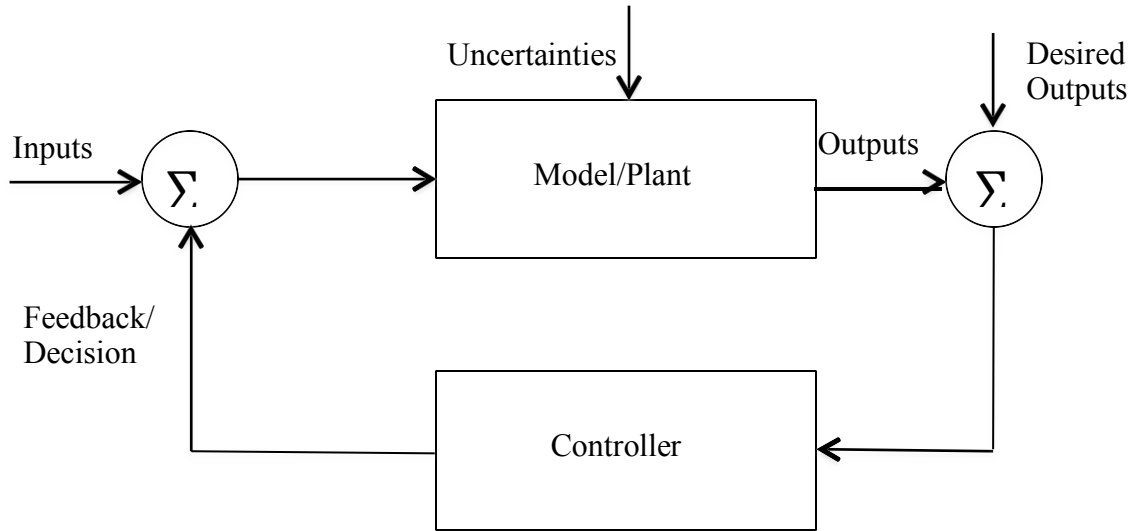


Figure 1. Components of a control system

Control system technology has evolved from the control of single input single output systems to multiple inputs multiple outputs systems while adapting and learning to adjust decisions to changing conditions[11]. Advances in information technology, the ability to collect, distribute and process information to perform various functions, has revolutionized decision-making. Cyber-Physical Systems[12] are systems where computing, communications and control technologies are tightly integrated to increase the level of automation in the system. The technology for a network of Cyber-Physical Systems is at its nascent stage and requires a combination of the numerical algorithmic methods from control to work with the decision-making developments in intelligent systems and machine learning.
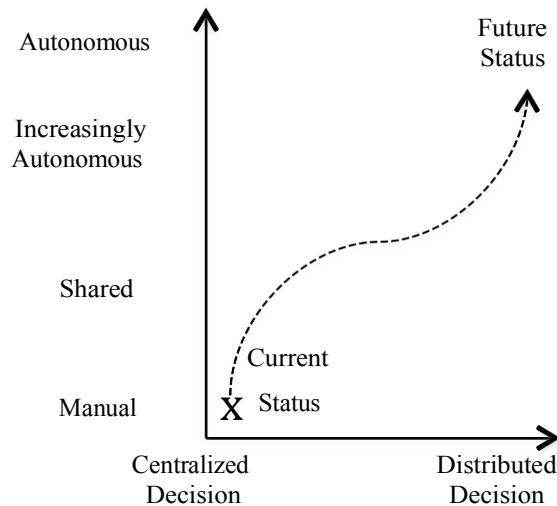


Figure 2. Levels of automation in networked systems

The level of automation depends on the complexity of decision-making and the replacement of a decision previously performed by a human operator to that performed by a machine. There are many classifications of the levels of automation dividing the spectrum from manual to autonomous systems. Next to manual, the task can be shared between man and machine. In this paper, Increasingly Autonomous[13] (IA) systems refer to the beneficial replacement of any task or decision-making previously performed by people. In an IA system, the task can be either (a) delegated to the machine, (b) or done by the machine if there is

no exception, (c) or done by the machine after consent from the operator. The completely autonomous level does not involve operator intervention once the task is assigned. Even in a specific task the level of automation may vary depending on the external conditions. Another dimension to automation arises in a network of systems. The decision-making can vary from a centralized structure to distributed decision making. Figure 2 illustrates the levels of automation in networked systems. The reasons for automation and the resulting benefits vary with each application. The next section provides two applications, which have pioneered automation concepts and autonomous systems, and compares them with the current status and automation needs of Air Traffic Management.

## IV.  Automation Applications and Air Traffic Management

Space missions operated manually from the ground until mid-1980s. The need for autonomy and autonomic properties in space missions arises due to many reasons. Human involvement in monitoring and controlling spacecraft is both expensive and may not be feasible due to communication delays. Humans may not be able to go or deal with the harsh environments encountered by spacecraft. The range of current capabilities of spacecraft depends on the mission and consists of intelligent sensing for obstacle detection, planning and execution of trajectories to avoid obstacles, detecting and predicting system behavior using sensors, maintaining health of the system and coordinating the work of several distributed systems. Space automation has evolved from simple attitude control of spacecraft to the retrieval and analysis of soil samples on Mars, global path planning and visual tracking while avoiding large rocks[14-16]. A major challenge for Space Autonomy will be software verification and validation requirements for autonomous systems[15]. Also, current autonomous systems have few vehicles. Research is required to address how the requirements and complexity scale up when 1000 spacecraft are in a mission like NASA Autonomous Nano-Technology Swarm[17] (ANTS).

DARPA, an agency of the Department of Defense, pioneered research in the development of autonomous and intelligent vehicles. Many companies and organizations (Google, Volvo, Toyota) are experimenting in the ability to drive and navigate an automobile without direct human control. Several automobiles are available in the market with the functionalities of cruise control, lane departure warning systems and collision avoidance systems. Several States, e.g., California, Florida and Nevada, are considering legislation governing driverless cars. There are dynamic mobility applications based on communication between cars, trucks, buses and smartphones to share information about safety, mobility and local conditions[19]. The resulting state information and distributed control can be used to achieve Queue Warning, dynamic speed harmonization and cooperative cruise control to increase network capacity.

It is necessary to understand the similarities and the disparities between aviation system operations and other autonomous applications to benefit from the progress in automation in other areas. Table 1 provides a high-level comparison amongst the three systems.

Autonomous Systems require people willing to try it during its early stages, e.g., space autonomy and military autonomous vehicles where the customer is willing to take the risks and accept the costs. The systems and cultural impact of automation can be minimized by bringing together all the people, whose functions will be affected by automation, early in the development of IA with clear communication of the new concept of operations using common terminology[20]. A major impact of automation is to change the ATM from an open-loop control system to a closed loop control system. This requires a more robust understanding and model development of both the nominal and the off-nominal situations and the failure modes of the system. The introduction of automation may result in unexpected behavior as experienced by autonomous cars where precise algorithmic decisions about lane changes and stopping conditions have to deal with human drivers with different driving habits and understanding of the motor vehicle rules[21]. Increased automation creates more software, which results in more testing, verification and validation requirements.

Autonomous systems have been successful when it is the only way a function can be accomplished (e.g., Mars Rover) or when they provide significant cost benefits (e.g., wireless networks). Autonomous systems are successful where the cost can be spread over millions of systems. The public acceptance of the systems, as can be seen from the reception to autonomous cars, require long lead times for settling all the legal, financial, safety and cultural issues.

**Table 1: Comparison of ATM with other areas of automation**

| Property | Space Autonomy | Intelligent Transportation Systems | Air Traffic Management |
|---|---|---|---|
| Reasons for automation | Only solution for some missions due to hazard or delay | Cost Reduction, Increase in safety, capacity and efficiency | Cost Reduction, Increase in safety, capacity and efficiency |
| Stakeholders | One/few | Multiple | Multiple |
| Goals | Clearly stated goals and requirements | Serves personal, commercial and global community transportation needs | Serves transportation needs of national and global community |
| Sensor and communication requirement and availability | Extensive | Growing rapidly, highly dependent on perception sensors | Low network capability |
| Level of automation | Demonstrated autonomous systems | Demonstrated autonomous systems with limited number of vehicles in the network | Human-centered automation, Decision support tools |
| Assets | Ground-based systems, Spacecraft, Extraterrestrial systems | Ground-based systems, Vehicle, Space-based navigation | Ground-based systems, Aircraft, Space-based navigation and weather |
| Number of Vehicles | One of a kind | Millions | Thousands |
| Primary Tasks | Task allocation, Motion Planning, Coordination, Collision Prediction, Control | Similar with different emphasis levels | Similar with different emphasis levels |

IA systems are introduced with limited controllability for safety reasons and this may limit the systems ability to handle critical situations. Even in a relatively simple environment, such as autonomous cars on freeways, the number of possible scenarios is large, and it is a challenge to reach a level of intelligence in the automated driving system that parallels the human's ability to drive and react to situations [22]. Another important lesson from autonomous car research is that the first exposure to new technology must work well, feel safe and comfortable and can be trusted.

## V. Traffic Flow Management

The next steps in achieving IA in ATM requires an examination of the various tasks and a detailed examination of the system benefits accruing from increasing levels of automation in each task. This section provides a more detailed examination of some of these issues affecting automation in ATM by focusing on the TFM problem[23].

TFM is the planning of air traffic to avoid exceeding airport and airspace capacity while making effective use of available capacity. At the top level, the Command Center uses predictions of traffic to form a strategic TFM plan. Under forecasted severe weather conditions, the Command Center may delay some aircraft at airports and/or reroute others. Regional adjustments to these plans are developed by the different Centers. Dispatchers and air traffic coordinators at airlines respond to these changes to the traffic flow by rerouting, rescheduling and canceling flights, thus changing flow patterns. Schedules and route preferences from airlines and other users of the system are factored in the development of the TFM strategy through the Collaborative Decision Making process[24]. TFM operations as practiced today can be viewed as a distributed, hierarchical process with decision-makers making hundreds of independent decisions at the

local and national levels asynchronously. Figure 3 provides a systems overview of the various tasks performed during TFM operations.
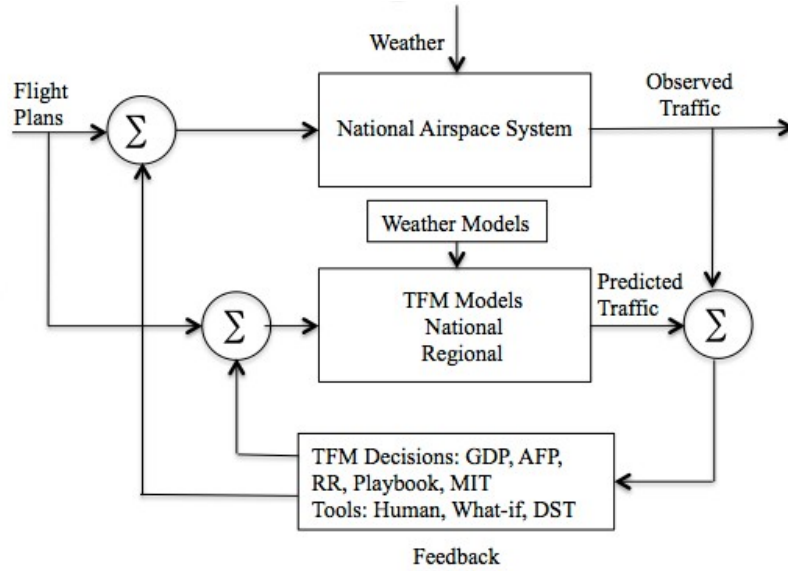


Figure 3. Tasks performed during TFM operations

## V. 1. National Traffic Flow Management

The goal of national traffic flow management is to accommodate user-preferred gate-to-gate trajectory preferences by managing and allocating NAS resources in situations where demand approaches or exceeds supply. The demand and supply situation is made worse during severe weather conditions that may reduce both airspace and airport capacity. The Command Center uses predictions of traffic to form a strategic plan over a 1-hour to 6-hour time horizon. Based on the expected weather conditions and demand in the different regions of the airspace and airports, the Command Center may delay some aircraft at airports and/or reroute others. The tools available to manage traffic in the presence of excess demand are Airspace Flow Program (AFP), Ground Stop (GS), Ground Delay Program (GDP), Playbook, Re-routing and Miles-In-Trail (MIT). Airspace Flow Program identifies flights scheduled to travel through capacity limited regions of airspace, such as a region impacted by severe weather. The impacted flights are delayed at airports, or the airspace users are provided with the option to route around the constrained regions of airspace. While AFPs are used to manage traffic flows due to en route constraints, GDPs and GSs are used for constraints impacting an airport. Ground Stops hold all flights at their departure points that are destined to an affected destination airport for the duration of the Ground Stop initiative. Like the Ground Stop, the Ground Delay Program controls the flow of traffic to an airport where the forecasted demand is expected to exceed the airport's predicted acceptance rate.

In addition to imposing departure controls on flights for regulating the flow of traffic into capacity constrained regions of the NAS, routing around these system constraints is a complementary control strategy. Under current operations, the FAA relies on the National Playbook[25]. It is a compendium of standardized alternative routes intended to avoid specific regions of airspace that are commonly impacted by severe weather during certain times of the year, based on historically validated data. Figure 4 shows a planning template, known as "Green Bay," provided in the Playbook for rerouting eastbound traffic through the Minneapolis Center when a large portion of airspace in the Midwest is affected by weather. The large rectangular pink region in the southern portion of the Minneapolis Center (ZMP) represents a predicted severe weather region. The routes represented with a solid line in this figure represent alternative routes for aircraft originating on the West Coast and traveling to select East Coast destinations, such as Boston (BOS), La Guardia (LGA) and Dulles (IAD).
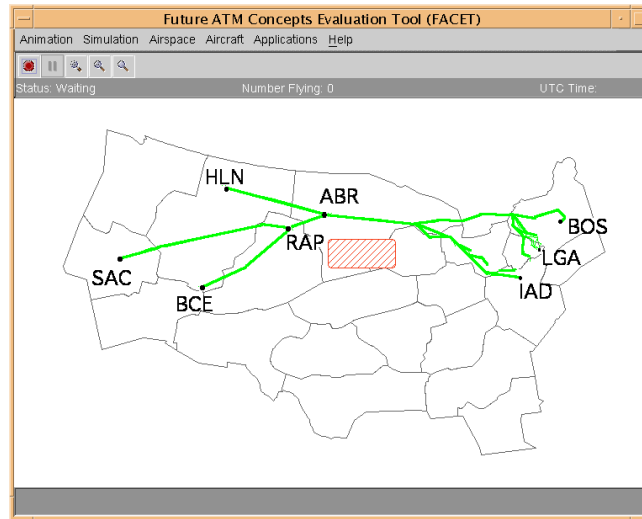
Figure 4. Graphical representation of the Green Bay National Playbook route with a conceptual region of severe weather depicted by the shaded polygon.

### V.2 Regional Traffic Flow Management

Regional traffic flow management, which operates on a forecasted time horizon of roughly 20 minutes to two hours, provides a tactical control loop to adjust the control strategies generated by national flow management based on improved aircraft demand, airspace capacity, and weather intent information. These adjustments are done through local re-routing or by spacing aircraft in a stream, referred to as miles-in-trail (MIT). The number of aircraft entering a region is inversely proportional to MIT. MITs are used in increments of 5 miles, and a value ranging from 10 to 30 miles is routinely used to reduce congestion. The current TFM has a hierarchical and distributed control structure. Dispatchers and air traffic coordinators at airlines respond to these flow control actions by rescheduling and canceling flights, thus changing flow patterns. Schedules and route preferences from airlines and other users of the system are factored in the development of the TFM strategy through the Collaborative Decision Making process.

Traffic management initiatives such as Playbook routes, Ground Stops, Ground Delays, AFPs and MIT restrictions are based on attempts at solving particular problems. For example, Playbook routes are used for circumventing severe weather, Ground Stops and Ground Delays are used for controlling demand at the airports, and MITs are employed for controlling workload in the sectors. The various TFM actions are imposed independently based on experience, and the interaction between different actions may not always be accounted for while making the decisions.

## VI.  Severe Weather Avoidance Plan (SWAP)

SWAP[26] is a FAA plan to mitigate disruption to air traffic due to severe weather on a specific day in the United States. The planning and execution of the plan is the joint responsibility of the Command Center (CC) and the Centers affected by the severe weather. The Centers affected by the severe weather generate a plan using a combination of Traffic Flow Management Initiatives (TMI) such as Playbook, Airspace Flow Program, GDP, Rerouting and MIT. The Centers plan, coordinate and implement a SWAP plan that makes the best use of available airspace and minimize the impact on aircraft routes affected by severe weather. The Strategic Planning Team (SPT) under the CC discusses the plan and the SWAP advisories are distributed to the users and Centers. The Centers are responsible for monitoring the plan, evaluating it and modifying it due to reaction to the plan from users resulting in cancellations, delayed  departures  or rerouting of flights affected by severe weather. This may result in rerouting major flows and changing the number of aircraft in each flow. The Centers are also responsible for maintaining National Traffic Management Log (NTML), a database of TMIs resulting from the SWAP. The Centers  communicate aircraft cancellations or delay in departure/arrival times to the CC.

The SPT is responsible for reviewing the weather data and evaluating its impact with the affected Centers. The SPT is also responsible for holding a telephone conference with representatives from major airlines, General Aviation and the Centers.

The generation of SWAP advisories can be described as shared distributed decision-making. The development of playbook routes is experience-based and deals only with a finite number of frequently occurring severe weather scenarios. The playbook provides a feedback law to modify the flows in a general way and leaves the specific rerouting plans to lower level decisions. The decoupling of decisions may result in two TMIs affecting the routing of a particular aircraft in an adverse manner[27].

The functions involved in the generation of SWAP advisories have similarities to the major functions performed by Autonomous Transport Vehicles (ATV) such as path planning, rerouting to avoid obstacles and vehicles, efficiency of operations and a network of vehicles, computers and communication. Task allocation function in ATV may include places to visit, objects to be picked and the order it will be done. It may use a centralized task allocation system and the output of the task allocator is a set of start position and times for all vehicles. The correct sequence of tasks is ensured by temporal limits and by constraint-based trajectory envelope representation. Motion planning in ATV involves the development of spatial envelope for a fleet of vehicles compute starting from an initial set of information, either known or computed dynamically. The centralized motion planner minimizes a cost function using a combination of algorithms and heuristics. The task allocation and motion planning in ATV is equivalent to the planning of aircraft trajectories in TFM using aircraft dynamics, departure times, city-pairs, and airspace and weather constraints while optimizing a cost function. The temporal and spatial overlap in ATV planning is resolved by coordination between conflicting vehicles. Some of the algorithms used for planning are computationally significant as the problem is NP-hard. Heuristic algorithms are used to simplify the problem. The extension from ATV planning requires the scaling of the methods from tens of vehicles to thousands of vehicles. Collision prediction in ATV depends on perception sensors. Generally probability of intersections is computed using sequential Monte Carlo techniques and vehicle trajectories are revised if the probability of collision increases above a threshold at a certain time. Aircraft to aircraft conflicts are well understood and many efforts are underway to achieve IA in conflict detection and resolution. Obstacle detection at low altitudes is similar to collision prediction in ATV planning. The control actions in ATV planning is computed in milliseconds and executed with minimum delay. Here is a major difference between ATV planning and Playbook advisories. The reaction times in the NAS are long with decisions depending on multiple sources and a main goal of automation should be to reduce the reaction times while maintaining safety.

The effort to achieve IA in SWAP planning requires two types of development. The first consists of applying existing methodology to increase the level of automation. The automation of certain tasks in generating SWAP advisories are well understood and some of them are currently under consideration in the NextGen ATM. Some of the basic automation enhancements may involve (a) automation of the need to reroute several aircraft by a Center or schedule the departure of a number of aircraft by a dispatcher while maintaining the ability to intervene manually in rerouting/scheduling aircraft, (b) better sensing for the location of aircraft and other vehicles by increasing the role of ADS-B, See and avoid (role of perception), and external markers to aid in location and (d) reduction of the uncertainty in trajectory generation by reduced departure time uncertainties and shared aircraft intent information for all users. Automation should recognize the dynamic nature of the environment. Automation of planning, rerouting and monitoring the aircraft while retaining the ability of the human to intervene will result in IA during SWAP.

However, automation can play a bigger role in generating SWAP advisories, using the second kind of development, going beyond the traditional methods, by adapting methodologies from other areas. The current SWAP planning is deterministic and has a few heuristics for optimization. There is a technology gap in automated planning capability. TFM should move towards a more adaptive, stochastic, and contingency plan methodology. There are many topics needing further exploration[28-29]. Aggregate flow models[30] of traffic under normal conditions and stochastic models of weather can be used to design changes to nominal flows using Model Predictive Control[31] (MPC) and Adaptive Control. MPC has been used for the development of safe collision-free autonomous ground transportation systems. MPC enables a vehicle to generate a user-preferred trajectory locally while taking into account the states of other vehicles and obstacles in its neighborhood based on some optimization methodology. However, the safety and "liveness", the ability of all vehicles to perform their objectives, are system-wide network properties. Intelligent Transportation Systems research provides examples of two vehicle-to-vehicle (V2V) coordination rules combining local and global properties. The challenge for automation in generating SWAP advisories will be the extension of these V2V methods involving a large number of flows/aircraft with several distributed optimizations.

The development of IA for SWAP planning brings together the discrete and powerful algorithms from computer science and learning systems to monitor and control the continuous spatio-temporal dynamics of a networked system of aircraft and facilities at the FAA and airlines. The precise nature of certain parts of the system has to interact with disturbances, varying reactions to similar events and failures of components at the cyber and physical level. Hybrid Systems[32] provide the tools to model, monitor and develop control techniques for complex systems with continuous and discrete elements. They provide a way to abstract the continuous dynamics of aircraft flows with the discrete state and dynamics of the controller in situations where the control may switch the IA levels in either direction.

Data mining and neural networks have been used extensively to learn decision-making in many different industries. Data mining approaches can be applied to the generation of playbook routes by analyzing historical data of past traffic plans, weather forecast, TMIs and performance metrics of the systems like fuel efficiency and delays to identify plays and TMIs which may have been used in the past under similar traffic and weather conditions. The data analysis may provide a good starting point to select and improve TMIs for the current conditions. However, there are many issues to be addressed in applying this methodology. As the past data was collected for other purposes, it may not have some critical information such as the performance criteria used in making the decisions. Also, there may not be sufficient data to train and validate the learning algorithms. Nevertheless, this is a rich source of information to increase the level of automation. Some recent efforts to data mining to ATM applications are reported in references[33-38].

## VII.    Research Challenges

The IA trajectory in ATM will be different for different tasks in ATM. The changes to the trajectory will be dictated by the benefits resulting from IA in a particular task while maintaining current levels of safety. Some areas of ATM are better suited for IA than others due to acceptance and our ability to achieve IA in a reliable manner with low risk. All planning functions can be taken to levels where decisions are automated with humans providing the performance criterion. Separation assurance may move towards IA initially in high altitude, low-density operations, and as it gains acceptability from this experience may move towards terminal area operations. There are many questions of a fundamental nature that requires resolution before autonomous decision-making is applied in separating traffic in ATM.

There are many research challenges to the introduction of IA systems into ATM[13]. Some challenges like security, verification and validation share commonality with other systems and are not addressed here. Currently, airspace capacity is limited by the workload capacity of a controller. The capacity of a sector is expressed in terms of Monitor Alert Parameter (MAP), the number of aircraft that can be safely handled by a sector controller. Although attempts have been made to replace MAP by a better representation of controller workload, MAP remains the current measure for sector capacity. A clear understanding how airport and airspace capacity change with IA is needed both to increase the trust in IA and to design an ATM system with shared responsibilities. There is a need to understand and learn what aspects of a controllers approach to separating traffic can be relaxed using IA while maintaining the ability to deal with non-normal situations.

The next important research question revolves around how to improve trust in an automated ATM world? Automation increases the productivity of ANSPs, AOCs and pilots. ANSPs may be able to increase capacity of airspace resulting in reduced delays incurred by aircraft during adverse weather. AOCs will be able to get more user preferred routes. However, users need to trust the system and retain their decision-making skills in the event of failure of one or more components of the automated system. This emphasizes even more how to deal with non-normal situations resulting from the failure of automated systems. The transition from one mode of control to another or a graceful switching of systems under various levels of control is essential for IA.

Weather has a major impact on the performance of ATM systems. Pilots, AOC and ANSP from different viewpoints, do the translation of weather impact on traffic at various levels, from a single aircraft to major flows. Research is needed for the correct interpretation of the impact of forecasted weather in reducing airspace capacity under IA. Another issue will be how do we move from deterministic weather models to probabilistic weather models and train people to trust probabilistic decision-making.

The extension of current network approaches to a large number of aircraft and other vehicles with a large number of decision makers with different objectives and different levels of IA requires research in Cyber-Physical Systems.

## VIII.  UAS Traffic Management (UTM)

UAS is a topic of wide interest today. Several organizations and companies are devoted to the promotion and introduction of various UAS services to the society[39]. Many of the automation issues involved in the design and development of UAS are similar to the development of other robotic and intelligent systems. The introduction of UAS provides both challenges and opportunities for IA in ATM. UAS introduces disruptive forces e.g., large number of vehicles, lowering of the cost barrier, limited training needed to operate and the ability to introduce new services, into aviation. A recent conference  was devoted to safely enable UTM in low-altitude civilian airspace[40]. UAS provides an early opportunity to introduce IA concepts into ATM. The NASA Strategic Implementation Plan Thrust 6, Innovative technologies to the problem of enabling autonomous aviation operations, identifies integration of UAS capabilities into the NAS, as well as exploitation of autonomous systems technologies within the aviation infrastructure during 2015-2025.

The impact of UAS on ATM can be separated into two categories depending on the size of the vehicle. The first class consists of large UAS operated by public entities in support of military and border security operations. FAA[41] has established the RTCA Special Committee 203 (SC-203) to  develop recommendations for the safe, efficient, and compatible operation of UAS with other aircraft operating in the National Airspace System. This class of UAS requires appropriate equipage, airworthiness certification and will be operated by certified UAS pilots.

The practices and procedures developed for the safe and efficient management of large and expensive aircraft and UAVs need to be reassessed in several different areas. The technology, cost and number of small UAVs make human-centered conflict detection and resolution less appealing and unlikely. Conflict detection and resolution standards have to be modified to deal with vehicles moving at low speeds and highly agile. Many of the UAVs may be built using low cost manufacturing techniques and limited testing. Both safety and risk require new procedures commensurate with the cost, weight and services provided by the vehicles. The UAVs will bring more distributed decision-making into UTM. UTM has to deal with uncertain, aperiodic demand and unconventional flight plans due to new types of applications. In addition to other vehicles and obstacles at low altitudes, heavy winds, ground effects and large temperature variations will influence the behavior of small UAVs. UTM operations in both in urban and rural areas will need better wind prediction at low altitudes. The last 50 feet poses significant challenges to UAVs performing delivery services. It will rely on well-calibrated recent maps, vehicles publishing their positions and augmented by on-board obstacle detection sensors.

## IX.  Concluding Remarks

Automation of ATM tasks should be examined considering several factors and challenges in the development of IA. Some of them are opportunities for early adaptation of the technology based on risk, e.g., it may be possible to automate long-term planning before decision-making  involving  separating aircraft and areas where it is relatively easy to overcome social and cultural barriers. Improving automation and decision aids where currently decisions are made based on limited or old information seems like a natural starting point. This can be followed by a move towards a more agile system with re-planning capabilities to deal with weather uncertainties and multiple plans to meet contingencies. Increased automation should generate and take advantage of a data-rich world with communication between all the decision-makers and aircraft to get a better understanding of the human decision-making  process  in aviation operations and to enable better designing of human/machine interfaces. The development should emphasize realistic simulations to demonstrate the benefits and cost savings of increased automation. On a fundamental level, IA in aviation operations should address the scalability of methods developed for autonomous vehicle systems and Cyber-Physical Systems to aviation system involving thousands of aircraft.

Technology adaptation in new areas, whether it involves Smartphones or Uber, requires customer acceptance and depends on users who are willing to take some risk. Some changes require the systems to recognize the cultural impact of the changes. Laboratory demonstrations and higher fidelity simulations may not always capture the success of the acceptance of a new technology. Although lessons can be learned from the automation successes in other areas, achieving IA in ATM will follow its own path.

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