PILOT IN COMMAND: A FEASIBILITY ASSESSMENT OF AUTONOMOUS FLIGHT MANAGEMENT OPERATIONS

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Abstract

Several years of NASA research have produced the air traffic management operational concept of 'Autonomous Flight Management' with high potential for operational feasibility, significant system and user benefits, and safety. Among the chief potential benefits are demand-adaptive or 'scalable' capacity, user flexibility and autonomy that may finally enable truly successful business strategies, and compatibility with current-day operations such that the implementation rate can be driven from within the user community.

A concept summary of Autonomous Flight Management is provided, including a description of how these operations would integrate in shared airspace with existing ground-controlled flight operations. The mechanisms enabling the primary benefits are discussed, and key findings of a feasibility assessment of airborne autonomous operations are summarized. Concept characteristics that impact safety are presented, and the potential for initially implementing Autonomous Flight Management is discussed.

1 General Introduction

NASA is conducting feasibility research and development on an advanced operational concept in air traffic management termed 'Autonomous Flight Management' (AFM). This concept is chiefly characterized by a revised distribution of responsibilities and authorities between air traffic service (ATS) providers and flight crews of specially equipped 'autonomous' aircraft. Proceeding along the conceptual path offered by the original 1995 RTCA concept of 'Free Flight' [1], these flight crews select their path and speed in real time while conforming to restrictions established for safety and flow management. AFM in the en-route and terminal-transition domains of flight are founded on a new category of flight operations: 'autonomous flight rules' (AFR). The term AFM refers to the process of exercising the authorities and responsibilities of an AFR flight. The operational concept of AFM is an outgrowth of NASA's research of the Distributed Air/Ground Traffic Management (DAG-TM) concept element 5, 'En Route Free Maneuvering' [2]. AFM is an airborne concept that would integrate into a complete gate-to-gate system containing many other components beyond those described in AFM.

According to the AFM concept, an AFR aircraft would generally operate in the same airspace as existing instrument flight rules (IFR) aircraft, but the AFR flight crew would exercise an expanded set of authorities and responsibilities. In summary, trained flight crews of AFR-equipped aircraft are given the authority to dynamically plan and execute user-preferred three-dimensional (3D) paths without coordinating with the ATS provider, thereby placing the pilot truly in full command of the flight. With this authority comes full responsibility for traffic separation and conformance to operational constraints; the ATS provider establishes these constraints in order to safeguard special-use airspace and manage traffic flows into high-demand terminal areas. An illustration of a typical AFR flight is shown in Fig. 1.

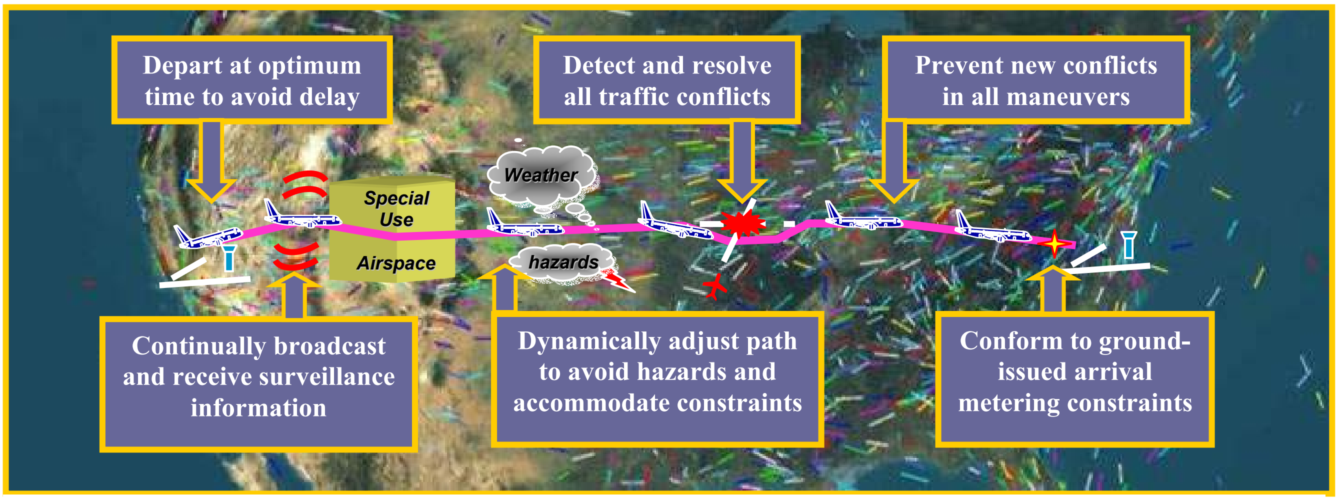

Fig. 1. Illustration of a typical AFR flight with associated flight crew tasks.

This paper summarizes the characteristics and current feasibility status of AFM. Section 2 of this paper will discuss the most significant potential benefits of AFM. Section 3 will describe the concept in greater detail, including roles and responsibilities, and how it integrates with the current IFR air traffic system. Section 4 will summarize findings of a recently completed AFM feasibility assessment [5]. Sections 5 and 6 will address safety and initial implementation potential.

2 Why Pursue AFM?

AFM is expected to substantially benefit both the airspace system and the airspace users. The primary anticipated benefit to airspace users is the substantial business flexibility enabled by AFM. Airspace users would have the flexibility to self-optimize their individual and fleet operations largely independent from ground-based air traffic control, while simultaneously contributing to the system-wide objectives of safety, security, airspace access, and expedited traffic flow. This flexibility is made possible in AFM because the traditional restrictions placed on IFR aircraft will not apply to AFR aircraft. These aircraft will be free to choose their lateral flight path, vertical and speed profiles, and even optimal departure time to meet their schedule arrival slot. Flexibility of fleet operations allows dispatchers to make real-time priority adjustments between flights with minimal ATS coordination. To the airspace user community, self-optimization within AFM means each operator can maximize efficiency according to their own business model, which may vary significantly between operators. This benefit offers the potential for most or all aircraft operators to fully achieve their unique business goals.

An additional significant benefit of AFM to the airspace user community is direct control over the implementation rate of AFM. Since AFR and IFR will both be available flight options in AFM, operators will only equip aircraft for AFR if and when it directly benefits the operator. Business strategies that thrive on the flexibility afforded by AFR operations may dictate a quick equipage of large portions of the operator's fleet and widespread flight crew training. Other operators may choose a more gradual implementation based on their unique economic situation, whereas others yet may decide that IFR fully meets their needs and therefore avoid AFR operations altogether. The growth rate of AFM is therefore somewhat unpredictable but certain to meet the expectations of the user community. This benefit would not likely exist if AFR operations were mandated or if ATS operations could not accommodate unrestricted growth of the AFR population.

The primary anticipated benefit of AFM operations to the airspace system is that en-route capacity dynamically 'scales' to significant variations in demand, thereby accommodating a substantial increase in traffic volume over that manageable by a ground-based IFR system. The FAA air traffic forecast for 2004 to 2015 [3] illustrates the need for this demand-adaptive system capacity attribute, otherwise termed 'scalability'.

During the 12-year forecast period, total passenger enplanements for air carrier, regional, and commuter aircraft are forecast to increase nearly 65 percent, and total air cargo revenue ton-miles are projected to increase about 70 percent, both signs of a healthy, growing economy. Forecasted aircraft fleet growth indicates a significant increase in the use of smaller, regional jets. Whereas large passenger jet and cargo jet fleets are expected to grow by about 40 percent, the regional jet fleet is predicted to grow by over 140 percent, increasing from 17 percent to 28 percent of the total non-general-aviation fleet. According to the FAA workload forecast, commercial aircraft handled at Air Route Traffic Control Centers are expected to increase 40 percent by 2015. However, since regional jets will cruise in the upper flight levels along with the large passenger jets, the result will likely be an extra burden on high altitude sector controllers.

These forecast data indicate substantial growth in air travel demand over the next 12 years. The slowdown caused by the terrorist attacks on September 11, 2001 has nearly passed, as the FAA predicts prior enplanement levels to return by 2005. Barring further unpredictable disastrous events, this growth in demand will likely continue in the years well beyond 2015, provided that system capacity can keep up.

Such substantial growth can only be accommodated by a demand-adaptive air traffic system. Such a system would grow and shrink automatically with demand, and therefore would not stifle national or global economies that depend heavily on viable air transportation as their lifeblood. An air traffic system that grows freely with demand might even invigorate economic growth like never before.

Other key characteristics would also define this demand-adaptive system. A demand-adaptive system grows only at a rate determined to be cost-effective by the system users that equip, and is therefore never behind or ahead of their current need. A demand-adaptive system is also cost-effective in the long term because it will not continually require redesign to prevent its capacity limit from being reached. Whether a truly demand-adaptive air traffic system can be achieved is a research subject of great interest and importance. After six years of NASA research and development, the AFM concept described in this paper is thought to have this quality.

The time may be right to consider an advanced operational concept such as AFM. In the U.S., a national consensus now exists that marginal improvements to the current system will be inadequate to meet the nation's growing needs for air transportation. A Next Generation Air Transportation System (NGATS) initiative involving seven departments and agencies has initiated planning and development of a national roadmap for the future air transportation system, and has established a requirement that nothing less than a complete transformation of the system is in order to meet national needs [4]. AFM is indeed a transformational concept, and it offers the potential for achieving many stated goals of the NGATS initiative, including safety, security, capacity, efficiency, and adaptability to changing market conditions. Although substantial work remains to validate this potential, research to date shows that AFM holds much promise.

3 Description of AFM

In order to lay the foundation for a discussion of AFM feasibility, further concept details are provided as follows: the proposed structure of air traffic operations, the roles and responsibilities of AFR flight crews and ATS providers, airborne technology requirements, and required changes to the communications, navigation, and surveillance (CNS) infrastructure.

3.1 Structure of Air Traffic Operations

The structure of AFM features a combination of centralized and decentralized control of air traffic. The ATS provider centrally controls IFR operations, while AFR operators participate in a distributed network of control, wherein each flight crew exercises control authority over their individual flight. System-level objectives (e.g., safety, expedited traffic flow) are achieved through distributed decision-making. Aircraft operating on a VFR flight plan are similarly part of a distributed control network.

Under the AFM concept, airspace users are free to select AFR, IFR or VFR operations as appropriate for their aircraft equipage, flight crew qualifications, airspace conditions, and flight objectives. VFR and IFR operations are essentially unchanged relative to present-day definitions. All AFR crews and aircraft are IFR-qualified. To operate as an AFR flight, however, the aircraft must be additionally equipped, and the flight crew must be additionally qualified to execute their new roles and responsibilities.

AFR and IFR operations coexist in the same en-route and terminal-transition airspace without mutual segregation. As will be discussed subsequently, several concept features exist to minimize the impact of AFR operations on IFR operations. However unlike IFR, AFR operations <u>do not</u> depend upon an air traffic control (ATC) clearance, and therefore, AFR cannot be "canceled" by ATS. AFR pilots may, of their own volition, transition to VFR (if permitted by airspace regulations and weather conditions), or to IFR (if cleared by ATS). Transition to IFR would normally be pre-planned, and an IFR clearance would be waiting at a pre-arranged pickup point. Pilots may also request a "pop-up" IFR clearance, which would be accommodated by ATS on a workload-permitting basis. A denial or delay of a pop-up IFR clearance by ATS does not absolve the flight crew of their AFR responsibilities.

AFR operations are not envisioned in Terminal Radar Approach Control (TRACON) airspace surrounding capacity-limited airports. Thus, AFR operations between capacity-limited airports are nominally initiated at the departure TRACON boundary and terminated at the arrival fix at the destination TRACON boundary, from which point onwards the aircraft is managed on an IFR clearance. Terminal airspace at non-capacity-limited airports may include AFR departure and arrival procedures.

Predicted arrival saturation at a destination airport is managed via arrival-time assignments for AFR aircraft, and AFR aircraft determine their own strategies to meet the assigned arrival time. AFR aircraft are not subject to IFR departure ground delay programs and are free to determine their preferred departure time to meet the scheduled arrival time assignment. AFR traffic in the presence of en-route airspace constraints such as weather is self-organizing through distributed decision-making by AFR aircraft flight crews. Flow management techniques applied to IFR operations may remain unchanged from present-day, including the use of departure control for IFR aircraft to resolve predicted arrival saturation at destination airports, and the use of pre-departure and en-route re-routing to avoid airspace congestion or significant weather.

3.2 Roles and Responsibilities

AFM does not impact the responsibilities of the VFR and IFR pilots or flight crews. The role of the ATS provider is also largely unchanged from present-day, although traffic flow management takes on greater importance, given the higher traffic levels expected.

ATS Provider

As in present-day operations, the ATS provider continues to ensure separation between IFR aircraft. When maneuvering IFR traffic, however, they must prevent the creation of very-near-term conflicts with AFR traffic, just as they do with VFR traffic. ATS providers are not responsible for separating IFR traffic from AFR traffic, nor for monitoring separation of AFR aircraft pairs. They provide emergency services to AFR aircraft when required, and they support the transition from AFR to IFR status when requested and able. Apart from these considerations, their roles and responsibilities relative to AFR operations extend only to managing traffic flows and special-use airspace.

The ATS provider is responsible for ensuring that capacity-limited airports are not over-saturated by establishing and managing a TRACON arrival schedule. They generate metered arrival slots based on airspace, airfield, traffic density, and other constraints, and they provide these slots to all aircraft (IFR and AFR) on a first-come, first-served basis. They also re-integrate off-schedule AFR aircraft into the arrival sequence as traffic permits. The ATS provider is not responsible for monitoring AFR aircraft for flow conformance.

AFR Flight Crew

The crews of AFR aircraft are free to select, optimize and manage their own aircraft trajectories, bounded only by aircraft limits, ATS-provided airspace and arrival time constraints, and regulatory traffic separation requirements. In order to maintain separation from all surveilled traffic, AFR flight crews are required to act promptly to resolve separation conflicts when prompted by their onboard alerting system. In addition, AFR flight crews are required to not create near-term conflicts with any other aircraft when maneuvering or changing flight modes. To minimize the impact of AFR operations on ground-controlled IFR operations, AFR aircraft always yield right-of-way to IFR aircraft.

Flight crews of AFR aircraft are also responsible for adhering to all airspace and arrival-time restrictions. When arriving into a capacity-limited airport, they are required to remain outside the TRACON until they have been issued an IFR clearance for entry and have verified that they conform to that clearance within established tolerances. If unable to meet their arrival constraints, AFR flight crews are responsible for notifying ATS as soon as possible and in supporting ATS in determining an achievable amended IFR clearance.

AFR flight crews monitor Controller Pilot Data Link Communications (CPDLC) for ATS uplinks of airspace/traffic flow constraints, and promptly acknowledge communications from ATS. AFR flight crews may use radio telephony (R/T) for non-routine or time-critical message exchange with ATS. Air-to-air R/T has no defined function in AFR operations and is not used for coordinating conflict resolutions.

3.3 AFR Supporting Technology

As a participant in a distributed decision-making network, each AFR aircraft uses onboard technology to perform efficient, self-separated and time-constrained operations in shared airspace. To perform the self-separation, flow-conformance, and flight optimization tasks, all AFR-capable aircraft are equipped with a flight-deck decision-support system that supports flight crews in performing 'autonomous operations planning' (AOP). The AOP system supports the flight crew in all modes of aircraft control and navigation, including when in the presence of traffic flow management (TFM) constraints. Both Flight Management System (FMS) and non-FMS operations are accommodated. Fig. 2 presents an illustration of how an AOP system can integrate traffic conflict alerting and flight-path resolutions onto digital flight displays.

The AOP system is fully integrated with the avionics system of the aircraft so that the system has full access to aircraft state, configuration, guidance mode, navigation and performance capabilities, programmed (FMS) trajectories, constraints, and surveillance data.

Fig. 2. Illustration of conflict alerting and strategic resolution advisory from an integrated AOP system.

Flight crews are provided adequate situation awareness and access to the AOP toolset via suitable displays and automation interfaces.

AFR aircraft have the same Traffic Alerting and Collision Avoidance System (TCAS) equipage requirements as IFR aircraft. For safety and redundancy, the AOP system on AFR aircraft is independent from the onboard TCAS, but the two systems are both inter-operable and non-conflicting.

The primary mechanism currently proposed for surveillance information exchange is airborne broadcast data link, such as Automatic Dependence Surveillance Broadcast (ADS-B). Therefore, all AFR aircraft both transmit and receive surveillance information via ADS-B. Transmitted ADS-B messages are likely to include intent information, the extent of which depends upon flight situation, autoflight mode, and data link technology limits. Since not all non-AFR aircraft may be ADS-B equipped, AFR aircraft are also equipped with a Traffic Information Service Broadcast (TIS-B) receiver.

AFR aircraft typically use optimized en-route Area Navigation (RNAV) capability from departure to the TRACON arrival fix, and are capable of precisely meeting an assigned Required Time of Arrival (RTA) when TRACON metering procedures are exercised by ATS. In-flight re-planning of RNAV routes is performed for flight optimization in a dynamic weather environment. AFR aircraft compute actual navigation performance (ANP) in real-time and broadcast ANP over ADS-B. ANP must exceed the minimum acceptable Required Navigation Performance (RNP) for AFR operations. The minimum acceptable RNP for AFR operations may be situation dependent, and must be determined through research. ANP may be used for determining situation-specific separation criteria, possibly releasing AFR aircraft from 'one size fits all' standards.

3.4 ATS Supporting Technology

In regulating the flow of AFR and IFR aircraft into capacity-limited TRACON airspace, ATS providers are supported by an arrival-scheduling tool. The tool permits schedule adjustments for flow-disrupting events, changes in airport acceptance rate, and rescheduling individual aircraft. To maximize capacity, 15-second or better arrival metering accuracy may be required, and the ATS provider may benefit from the ability to uplink four-dimensional (4D) trajectories to IFR aircraft for increasing their arrival accuracy.

To minimize AFR impacts on ATS provider tasking, all inter- and intra-facility AFR communications transfer (R/T and CPDLC) is accomplished through automated handoff, and AFR aircraft schedule assignments are sent through CPDLC, with R/T as a backup.

While ATS providers may require no changes to their traditional separation techniques, their displays will require modifications to allow differentiation of AFR aircraft from IFR aircraft. ATS providers may also require decision-support systems to avoid maneuvering IFR aircraft into near-term conflicts with AFR aircraft.

4 Is AFM Fundamentally Feasible?

The feasibility of AFM has been undergoing scrutiny for several years in NASA's DAG-TM activity. AFM is closely related to DAG-TM Concept Element 5 [2], and is essentially equivalent to the free-maneuvering airborne operations in this concept element. Research and development efforts have focused on first maturing airborne AFR operations prior to studying the integration of AFR aircraft with ground-based IFR operations, and therefore this paper focuses primarily on the airborne side. In order to study feasibility of AFM, a simulation laboratory designed for multi-aircraft AFR operations research in the future airspace infrastructure was developed at the Langley Research Center [6], as were prototype flight deck decision-support tools for autonomous operations planning [7]. Piloted simulations combined with reviews of existing procedures and related research form the basis of the AFM feasibility assessment.

4.1 Feasibility Assessments Have Limits

It is important to recognize that feasibility of a concept should be interpreted not in absolute terms, but rather in terms of its known limits based on research to date. At this point in the research, NASA has not explored all of the issues critical to AFM feasibility, nor has it studied operations under all conditions necessary to categorically conclude the concept is feasible. Naturally, time, resources, and the shear complexity of the concept and real-world environment constrain such accomplishments.

To date, AFM has been explored in medium fidelity laboratory simulations, including both batch (i.e. fully automated) and human-in-the-loop part-task simulations. In the latter case, subject-pilots generally controlled single-pilot desktop flight simulators of commercial transport aircraft equipped with AOP decision-support capability of varying maturity. Fig 3. shows an airline pilot at a desktop aircraft simulator in the Langley Air Traffic Operations Lab. This decision-support capability used by the pilots had generally medium-level functionality and reliability due to the parallel efforts of designing and developing these tools while testing feasibility issues of AFM. Scenarios typically lasted 15 to 90 minutes in order to collect as much data as possible using professional pilots and controllers. AFR operations were investigated primarily in en-route cruise conditions since descent capability of the flight-deck automation tools was in parallel development during this period. The CNS infrastructure was represented

Fig. 3. Airline pilot participating in a laboratory simulation at Langley Research Center.

at low-to-medium fidelity, with some limited modeling of real-world systems performance. Recognizing the criticality of these performance limits to operational feasibility, efforts are continuing to improve modeling fidelity for higher Technology Readiness Level (TRL) research. Human-subject training was a continual challenge, as limited time was available to train to the level of would-be certified AFR and ATS operators.

The general approach to research was to explore and mature the airborne (AFR) and ground (ATS) components of AFM individually before joining these together in integrated air-ground simulations. This was done in recognition that an immature component (AFR or ATS) could cause the integrated system to fail, resulting in possibly improper findings of concept infeasibility. The experiments on AFR operations were therefore often conducted with scripted ATS behavior, and interaction issues have so far only been brushed upon. A joint simulation of air-ground integration by Langley and Ames research teams was recently conducted, and data analysis is shedding more light on interaction issues.

In contrast to these 'restraining' limits on the AFM feasibility assessment, several factors significantly expanded the limits of exploration. One example is traffic density, where AFR pilots easily accommodated a tripling of recent average traffic levels [8]. Additionally, some of the scenarios went significantly farther than previous airborne separation research, both in terms of operational constraints in place (e.g. RTAs, SUAs) and the nature of traffic conflicts (e.g., blunders, suddenly lost separation, over-constrained conflicts) [9]. The research approach was to attempt to stress the concept to a potential limit and then observe whether the limit was in fact reached.

An additional expansion of the 'feasibility space' was in the level of AFR decision-support capability provided to the simulation pilots. Previous investigations employed pure strategic (i.e. flight plan based) systems or pure tactical systems for conflict management. Development at NASA Langley produced an integrated capability that better supported both normal tactical and strategic modes of flight path control. This research-prototype 'Autonomous Operations Planning' system greatly expands the capabilities over those available for previous airborne separation research [7]. The research AOP system accomplishes this by integrating state and intent surveillance data for conflict detection, tactical and strategic capabilities for conflict resolutions, and intuitive tools for conflict prevention, into a logical, usable toolset for the AFR pilot, accompanied by carefully defined procedures to match [9]. Furthermore, TFM and local optimization capabilities were included in the toolset to more fully meet the anticipated operations of an AFR aircraft [10]. It is within these limits of exploration that the feasibility assessments should be interpreted.

Given page length limitations of this paper, a tradeoff decision was needed on whether to discuss only a few feasibility issues in depth or to present the breadth of AFM feasibility findings with minimal supporting discussion. As this paper was intended to cover several years of diverse research and development, a summary of feasibility findings across the research spectrum will be presented with limited discussion. The more detailed analyses and discussions that support these findings are contained in the full report submitted to the NASA Advanced Air Transportation Technologies Project Office [5], planned for future publication as a NASA technical report.

4.2 Feasibility of AFM Operational Structure

AFM is to be introduced into NAS operations by establishing AFR, a third set of operating flight rules. Today's system of integrated VFR-IFR operations provides some precedence for the feasibility of also integrating AFR operations. Issues regarding shared airspace and distributed responsibility have already been dealt with in the current integrated system, and they can provide valuable guidance in addressing AFR integration issues. The analogy between VFR and AFR operations is certainly not perfect, but provides enough similarity to satisfy fundamental feasibility concerns.

The strength of AFM is the distributed nature of the critical components: aircraft surveillance, decision-support technology, and human responsibility. This distribution provides safety protection against system-level degradations caused by critical component failures. The effect of critical component failures has been analyzed for AFM, and none present a system-level feasibility concern except for TIS-B and its dependent components. TIS-B has many centralized qualities, and yet AFR aircraft must rely on it in detecting conflicts with IFR aircraft. A failure of radar, the ATS Host system, or a TIS-B broadcast station would put integrated operations in jeopardy, and yet tasking ATS with the backup task of AFR-IFR separation in the event of a widespread TIS-B failure is likely infeasible. Recovery strategies may involve switching to procedural separation (e.g. AFR and IFR segregated by altitude), and this plus other ideas should be studied. Mandated ADS-B equipage for all aircraft operating in AFR-permitted airspace may be the most robust and safe solution, as well as an attractive improvement to IFR radar surveillance for the ATS.

AFM distributes authority of decision-making among the AFR flight crews. This distributed authority does not, however, impose significant new training requirements in 'distributed decision-making', as the decisions regarding whether to accept or reject an offered maneuver, either from a controller today or AOP system in the future, are the same. Only the source of the maneuver is changed. Stability must still be investigated in the interactions between self-optimizing automation systems that recommend trajectories to the flight crews. Implicit coordination techniques, such as right-of-way rules and inter-compatible conflict resolution algorithms, can be applied to minimize adverse interactions and have been successfully tried in simulation.

Economic realities and safety protocols prevent gaming from being a feasibility issue for conflict resolution maneuvers in the en-route environment. Gaming only becomes a consideration when there is some total inefficiency that must be distributed to one or more aircraft, and each tries to minimize its share. Gaming activities should not damage system safety nor reduce system optimization at the TRACON boundary, but may cause a challenge for the assignment of meter-fix RTAs. At worst, they may cause an inequitable distribution of delay among participants.

Strategic TFM initiatives are still compatible with AFM, although AFR flights are handled differently and are afforded more flexibility than IFR flights. AFR flexibility in departure time and en-route maneuvering do not present feasibility issues for AFM. AFR flights are not limited in their capability of responding to changes in the airport acceptance rate, even while airborne. These flights possess the same capability as IFR flights in this regard. AFR self-routing through en-route weather hazards should not interfere with IFR pre-departure re-routes assigned by the ATS, as there will be little interaction between AFR and IFR aircraft in these regions.

Growth in AFR operations, including variations in the AFR-to-IFR population ratio, presents no feasibility issues for either AFR or IFR pilots. The ATS may find AFR population growth placing increasing restrictions on their ability to maneuver IFR aircraft, depending on how much time protection the ATS is required provide for conflict prevention, and so this feasibility issue must be further explored. Piloted simulations of pop-up conflicts provide encouraging evidence that the ATS maneuver restriction could be quite minimal.

Further study is needed to determine the feasibility of integrated operations in areas of dynamic weather. It may be necessary to determine if these situations warrant limited segregation of IFR and AFR traffic when necessary. This segregation may be on a short-term basis and by altitude rather than by geographic area. AFR operations are expected to better handle some weather conditions than IFR operations as a result of distributed self-optimization, but little data exists in this area and much further investigation of this issue is needed. Interference between AFR flights in thunderstorm-impacted areas should be mitigated by 'reduced vertical separation minimums' and free routing, but this scenario is dynamic and requires further study.

4.3 Feasibility for AFR Flight Crews

Provided that automation tools are available to give reliable and trust-worthy guidance in conflict management, there should be no feasibility issue with AFR flight crews providing traffic separation with no reliance on ATS as a backup. Significant progress has been made in developing prototype tools and procedures that make the separation task fit smoothly into normal flight deck operations, as opposed to having the appearance of an 'airborne air traffic control' task. Additional design issues remain regarding the automation interface and two-person crew procedures, but no fundamental human-factor feasibility issues have been identified within the domains studied to which plausible solutions have not been envisioned. The importance of the flight crew being able to rely on automation guidance in conflict situations cannot be over-stressed. Many flight conditions demand full attention to normal flying tasks by the crew, such as departures, arrivals, and unexpected emergencies. In these situations the crew would have no time for sorting through conflict resolution options or building the resolution themselves. However, taking time to implement a recommended single maneuver or flight-plan change during these task loaded situations should be feasible. AFR flight crew operations in significantly increased en-route average traffic levels, for example triple current levels, appear feasible based on simulations conducted.

Domains not yet adequately studied for feasibility include situations with high perceived or actual workload and/or complexity, such as en-route transition (climb and descent) and flight in the vicinity of convective weather systems. Also recommended for further study are bottleneck situations, such as aircraft vying for the same altitude for smooth air. Significant feasibility issues still remain in these areas and are the next logical step for investigation. A recent joint simulation of AFM by Langley and Ames research labs, containing both subject-pilots and subject-controllers, studied high traffic densities, conflicts in descent, flow-constrained arrivals, and integrated AFR-IFR operations. Analysis is underway, and results are anticipated to increase the understanding of AFM feasibility.

It is feasible to incorporate complex right-of-way ('priority') rules into conflict resolutions without the AFR flight crew needing to remember or comprehend the rule set (as is needed today for VFR). Even in very challenging scenarios, the use of right-of-way rules was found not to be necessary for safety, but did provide benefits of predictability that may support better TFM procedures.

AFM research has purposefully avoided the use of explicit coordination in airborne separation assurance, including air-to-air voice communication or data link coordination of resolutions. Implicit coordination in the form of right-of-way rules and/or inter-compatible conflict resolution algorithms appears to meet the requirements for providing separation, even in scenarios with extraordinary constraints, such as two aircraft assigned the same waypoint crossing time and altitude. Explicit coordination may actually reduce AFM feasibility, given the extra complexity, frequency congestion, time required for coordination, and opportunity for miscommunications and errors.

4.4 Feasibility of AFR Technology

Feasibility of designing an AOP system to meet the requirements of AFR operations is evidenced by the existence of a working software prototype of a research AOP toolset. A representative screenshot of this toolset showing conflict management information and flight crew advisories is shown in Fig 4. Feasibility of integrating this system into current-day avionics architectures is evidenced by a prototype data-bus integration of the research AOP system. Through human-in-the-loop experimentation, the prototype toolset has verified the feasibility of supporting AFR operations in the presence of traffic, airspace hazards and TFM constraints, under different flight modes, and in certain nominal and off-nominal en-route traffic scenarios. Tool interfaces and capabilities continue to be refined to incorporate lessons learned from past and continuing studies, and so the full functionality for AFR operations has not yet been determined. A comprehensive determination of the feasibility of an AOP system cannot be made until research on the toolset functionality is furthered, and its operational utility verified through suitable testing.

The utility and applicability of the toolset under real-world constraints in different phases of flight, CNS infrastructure limitations, and environmental uncertainties must be investigated through further analysis and experimentation. Topics especially relevant to this feasibility assessment are the performance of the toolset under known surveillance system limitations such as broadcast range and update frequency, and toolset ability to handle wind and weather prediction uncertainties. Whereas feasibility of retrofitting AOP systems into currently flying aircraft has been established as primarily a cost issue, further research efforts must also examine the integration of the toolset into a variety of flight deck architectures with varying equipage types and technology levels.

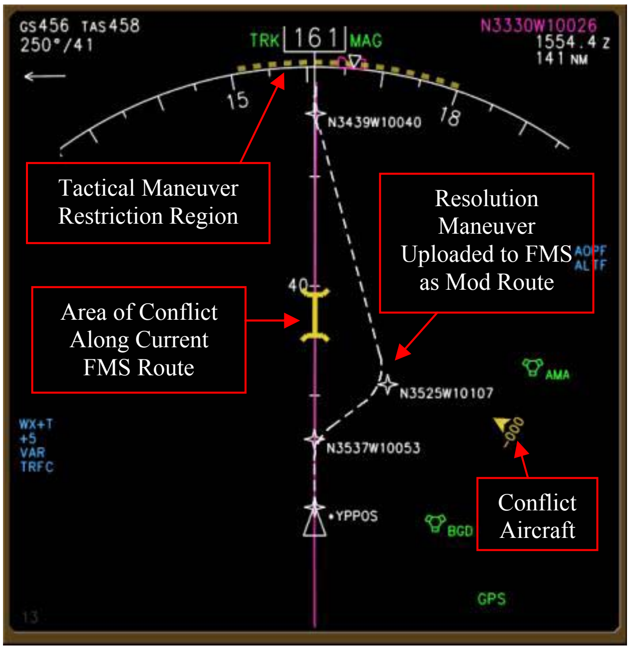

Fig 4. Replication of Boeing 777 navigation display with prototype AOP conflict management symbology.

Integration with airborne collision avoidance systems (such as TCAS II) is another topic that should be investigated for its impacts on AOP system design. Although a start has been made in this direction by the adoption of RTCA recommendations for collision avoidance zones [11], provision of consistent resolution strategies in time proximity to TCAS alerting time is an issue requiring dedicated research and analysis.

Several other issues impact the feasibility of implementing an AOP toolset. First among these may be the challenge of certifying a complex, multi-function ACM decision support toolset for use in commercial aircraft operations. This issue may impact the algorithms used within the toolset as well as the performance requirements to be met by the toolset. Formal verification of conflict detection and resolution algorithms may be an enabling step towards AOP system certification. The feasibility of constructing and fielding AOP systems is also dependant on the availability of ground infrastructure that supports toolset requirements for wind data, numerically defined boundaries of severe weather, and the state and intent of IFR traffic not equipped with ADS-B.

The currently envisioned performance of ADS-B surveillance using the 1090 Mhz Extended Squitter (1090ES) link only partially supports AFR operations, provided that full surveillance capability is actually needed in worst case scenarios. According to a simple approximation, the maximum theoretical range in non-interference environments should provide at least 6.4 minutes of alerting before separation loss, plenty of time for safe resolution maneuvers by the flight crew.

It is feasible to conduct AFR operations using the 1090ES in low interference environments, where sufficient bandwidth exists for state vector and intent messages. High interference environments such as overflight or arrival into terminal areas present a feasibility concern regarding 1090ES performance and message bandwidth. Upgrading to monopulse secondary surveillance radar and mode S transponder technology can be effective in reducing interference significantly, which would reduce the geographic areas of concern. A change in procedures such as reduced speeds or lower RNP may also reduce the adverse effect of signal interference.

It is feasible to have AFR aircraft with different ADS-B links other than 1090ES operating in proximity through the crosslink application of TIS-B. The interoperability of ADS-B and TIS-B surveillance needs further study before feasibility concerns are satisfied. Additional functional and performance requirements beyond those currently envisioned may be necessary to enable integrated AFR-IFR operations.

AFR operations based on varying levels of ANP rather than RNP present technical challenges but are unlikely a feasibility concern. Benefits could include significantly reduced separation standards and therefore even greater airspace capacity. Waypoint designation in a navigation environment supporting free-maneuvering flexibility is a human factor issue with a number of potentially suitable solutions and is not a feasibility limitation.

Graphical modification of strategic trajectories is not a feasibility concern based on simulation prototypes. The importance of graphical strategic flight-path management has yet to be determined under different nominal and off-nominal conditions. If it proves to be an important stabilizing influence for AFR operations, then further studies will be necessary to determine a suitable avionics solution for in-flight graphical route modification.

Direct communications between controllers and AFR pilots are expected to be infrequent in AFM. The most commonly expected messages (transfer of communications, RTA assignment, and TRACON IFR initial route clearance), lend themselves well to automation. Much of the technology to provide this communication already exists or is in advanced stages of development. Therefore the communication between the en-route controller and AFR flight crews should add minimally to the workload of the controller, if at all, and does not appear to be a feasibility issue.

Mixed communication modality issues are not expected to present a feasibility concern for AFR flight crews, given the rare expected use of voice communications in AFM. Loss of "party line" information source, if in fact this happens, is also not expected to be a feasibility issue.

In summary, many issues key to concept feasibility have been considered. In most respects, AFM does appear feasible within the limits studied. However, several areas of concern have been raised, and many aspects of flight operations have yet to be considered.

5 Can AFM be Safe?

Among the prominent questions that are frequently asked regarding airborne separation concepts are the questions of feasibility, benefits, and safety. The current ATC system is often described as one of the safest in the world. Can AFM also be safely executed within this system? True investigation of whether AFM *is safe* will require an exhaustive analysis, but insight into whether it *can be safe* may be gained by making some elementary comparisons to current operations.

Surveillance comparison: In today's system, controllers maintain traffic situation awareness using radar position data, updated Host flight plans, and personal memory of assigned vectors, altitudes, and speeds. In AFM, AFR pilots and their automation systems will have more accurate and complete traffic data broadcast directly from the traffic aircraft, including ANP position, state vector reports, and commanded intent. They also have full knowledge of their own aircraft state, intent, and autoflight configuration. In addition, widespread failure of a distributed surveillance system may not be possible.

Workload comparison: Currently, air traffic controllers divide attention among all aircraft in their sector. To mitigate unmanageable workload and situation complexity, the traffic flow is typically organized into structured routes and normalized flight levels which are often non-optimal for the aircraft. In AFM, pilots and their automation will focus only on traffic in proximity or convergent to their own trajectory. With more people (i.e. pilots in all AFR aircraft) each looking at fewer aircraft, more total human attention is applied to every possible conflict pair and the human workload bottleneck is released. Conforming to organized routes and altitudes will no longer be necessary, given the reduced monitoring task and the automation assistance. This greater use of the airspace will reduce conflict occurrences. In fact, freeing AFR aircraft from having to fly at normalized flight levels will better distribute the aircraft vertically and reduce likelihood of collisions, while also benefiting fuel economy.

Conflict management comparison: Today, controllers use experience-based judgment and heuristic guidelines on aircraft performance and trajectories to detect and resolve conflicts. In AFM, pilots will be alerted to conflicts by decision-support computer automation with trajectory prediction algorithms that use highly accurate surveillance data (discussed earlier), aircraft performance models, measured and forecast winds, and own-aircraft autoflight mode status. These factors should combine to provide an airborne capability for highly accurate conflict management.

'Sidewalk' scenario: Many safety concerns in distributed management of traffic separation are captured in the generic scenario depicted in Fig. 5. wherein two conflicting aircraft execute uncoordinated resolution maneuvers, possibly resulting in an unresolved or potentially more hazardous conflict situation. This scenario is analogous to two people approaching each other on a sidewalk, and both stepping to the same side and then back again in uncoordinated unison in a distributed effort to avoid colliding. Several factors can help preserve safety in such distributed decision-making situations:

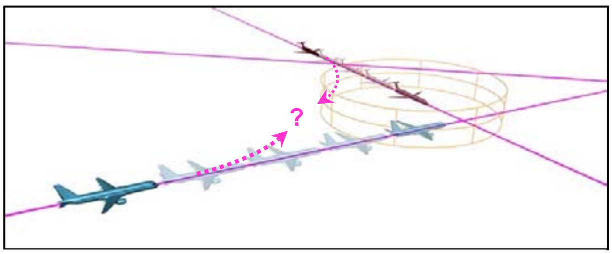

Fig. 5. AFM analog to a sidewalk scenario.

- Conflict detection look-ahead horizons of 5 to 10 minutes have been commonly used in simulations (much longer than the sidewalk time horizon), providing early detection and ample time for pilots to consider and execute options, and even replan new maneuvers if the conflict reappears.
- Resolution maneuvers are broadcast immediately upon execution, which when received and used by the conflicting aircraft system would preempt further unnecessary or non-complementary maneuvers.
- Right-of-way rules can be used to stagger the conflict alerting of the two flight crews, thereby reducing the likelihood of simultaneous resolutions. Piloted simulations have shown how such rules can be helpful in improving predictability and yet may not be a necessity for preserving safety.
- Conflict prevention software tools can be used by pilots in choosing conflict-free maneuvers. Piloted simulations have shown the benefits of these tools.
- For the residual short-term conflicts, research simulations have explored the use of 'implicitly coordinated' conflict resolution algorithms, those designed to give compatible tactical maneuvers to both flight crews.
- State and intent trajectory projections, when used together, permit additional alerting for blunder protection.
- TCAS, the backup to today's ATC system, will still be used.

These mitigating factors indicate that distributed traffic management need not be considered inherently unsafe. Nevertheless, many issues affecting AFM safety remain that require scrutiny. Some examples include: reliability of automated conflict detection in unpredictable wind environments; airborne conflict management in high-workload flight phases; interaction of distributed strategic resolution algorithms; protected zone sizing and the corresponding role of ANP; interoperability of ACM systems with TCAS; ADS-B broadcast limitations (e.g. effective range, intent message rate and content, message dropouts in high interference environments); various technology and procedural failure modes, unplanned transfer from AFR to IFR; and interaction of weather hazard avoidance with airborne conflict management.

6 Can AFM be Gradually Implemented?

To start a realistic transition to AFM operations, it must be feasible for the very first AFR flight to occur without disrupting the existing ATC system. AFR has been designed to be compatible with IFR and VFR operations in the same airspace, and therefore initially segregated AFR operations should not be a necessary step in the transition. This provides advantages of not shutting down a working, safe system and yet giving more options to aircraft operators, thereby improving business flexibility. The key factor that permits integrated operations through the non-interfering introduction of AFR is the priority given to IFR operations in all separation situations. Although priority might be given to the AFR flight in their position in the arrival schedule, once the schedule is set, the AFR flight must remain clear of IFR flights. In this way, the first aircraft to fly AFR gains immediate benefits (3D en-route trajectory and preferred arrival schedule) and yet does not impact the IFR ATC system.

In order for the first AFR flight to occur, the aircraft will need surveillance on all proximate traffic. A TIS-B system would be required until such time that all aircraft are broadcasting through ADS-B or some equivalent mechanism (should that time ever be reached). These early AFR flights can be carefully monitored for safety until sufficient experience is gained such that independent ground monitoring is no longer deemed necessary. Security concerns may perpetuate ground monitoring to ensure flights continue to proceed on schedule to their filed destination. Indeed, continual ground awareness of real-time aircraft state and autoflight-commanded intent, and comparison to filed destination and arrival schedule information, can directly support an aviation security monitoring function.

The AFR aircraft will need a flight-certified decision-support automation system with AOP functions similar to the research prototype, but probably less capable because this system was designed to explore the full range of capabilities that might be needed and may therefore be overdesigned. Although FMS integration is not believed to be essential to feasibility or safety, it may provide operational benefits. Certification of an AOP system would be a non-trivial expense. However, much of the research-prototype AOP system's functionality relates more to efficiency than to safety, and therefore methods to streamline certification of a fielded system may be possible.

As stated earlier, once AFR flights are operating in the system, the aircraft operator community itself will determine how quickly to equip more aircraft for AFR flight based on each company's own cost-benefits assessment. The choice to operate IFR or AFR allows AFM to grow at the pace dictated by the economic demand and the ability of aviation businesses to respond. It also allows operators to employ individual business strategies tuned to their own model for highly efficient operations.

7 Conclusions

Several years of NASA research have produced the air traffic management operational concept of Autonomous Flight Management with high potential for operational feasibility, significant system and user benefits, and safety. Among the chief potential benefits are demand-adaptive or 'scalable' capacity, user flexibility and autonomy that may finally enable truly successful business strategies, and compatibility with current-day operations such that the implementation rate can be driven from within the user community. Two mechanisms are considered fundamental factors toward achieving these benefits: distributing key components of the air traffic management system; and providing airspace users the alternative of not participating in AFM (i.e. continue IFR operations) until and unless it makes business sense to do so.

Feasibility of AFM has been explored through prototype flight-deck tool development, simulation exploration, and comparative analysis with current operations. Conditions tested in piloted simulations include significant increases in average traffic density over current levels, a wide variety of conflict situations and alerting times, and a range of operational constraints applied to simulate traffic flow management and airspace availability. Different levels of surveillance data availability were explored, and realistic limits on surveillance range were applied.

Based on the issues explored to date, AFM is considered feasible in the domestic en-route domain, and the likelihood of achieving the expected benefits appears to be good. Feasibility in the more challenging transitional domains of significant climbs and descents has not yet been fully established, although indications from preparatory work are promising. Conditions yet to be explored for feasibility are many and include AFR operations in areas of adverse convective weather and system failure modes. Integration of AFR and IFR operations in shared airspace is expected to be feasible, although more information is being learned through analysis of a recent AFR/IFR human-in-the-loop simulation.

The safety potential of AFM has been illustrated through a discussion of hazard-mitigating factors in relation to current operations. Although a rigorous safety assessment must yet be performed to determine the true level of safety, this discussion demonstrated the tremendous safety advantages that AFM may provide.

Widespread implementation of AFM has a realistic growth path, because the very first and subsequent AFR flights should be possible without disrupting the existing IFR system, and each new AFR flight will produce immediate benefits for the operator.

The time may be right to consider an advanced operational concept such as AFM. In the U.S., a national consensus now exists that marginal improvements to the current system will be inadequate to meet the nation's growing needs for air transportation and that nothing less than a complete transformation of the system is in order. AFM is indeed a transformational concept, and it offers the potential for achieving fundamental aviation goals including safety, security, capacity, efficiency, and adaptability to changing market conditions. Although substantial work remains to validate this potential, research to date shows that AFM holds much promise.

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