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The Air Transportation System

Amy R. Pritchett*
Georgia Institute of Technology, Atlanta, Georgia 30332-0150

I. Introduction

When first formally established, the air transportation system made maximal use of technology that, to modern ears, is quite simple. Voice radio was used for communication, directional and non-directional ground-based radio beacons were used for aircraft navigation, and ground-based radar was used for surveillance. To best use these core communication, navigation, and surveillance (CNS) technologies, detailed operating concepts specified detailed procedures and airway structures for every operator in the system.

This original construction was a phenomenal achievement. In 1949, the Radio Technical Commission for Aeronautics (RTCA) received the Collier Trophy for "A guide plan for the development of a system of air navigation and traffic control for safe and unlimited aircraft operations under all weather conditions." This air transportation system has grown to be a vital part of everyday life. In the United States alone more than 5000 flights may be in the air at one time. At the same time, travel on modern airliners is the safest method of transportation, even as revenue passenger miles have grown by 200% since de-regulation in the 1970s to approximately 500 billion passenger miles per year. Air cargo has also become vital to the nation's economy: while only 0.3% of cargo by ton miles is shipped by air (30 billion ton miles in the year 2000), this corresponds to shipping 7.4% of cargo by value in the United States, making air transportation fundamental to just-in-time manufacturing and business practices.[1,2]

However, the current air transportation system has limits to its capacity. Of particular note are how many aircraft can fit in existing en route airway structures, and how many take-offs and arrivals can be handled by major airports. At an extreme, airlines are now restricted in the number of flights they may schedule into Chicago O'Hare airport, and must obtain 'slots' for operations out of New York La Guardia airport; in both cases, these represent situations where stated demand exceeds capacity. On a broader basis, many airports (and corresponding metropolitan areas) are predicted to have too little available capacity for expected future demand, already evinced by air traffic control delays and longer scheduled flight times.[2,3]

Many improvements are underway in the near-term to improve capacity of the current system. For example, in the United States, the Federal Aviation Administration (FAA) is implementing their Operational Evolution Plan (OEP), a rolling 10-year effort to increase capacity by a third.[4] Developments include new runways at the most capacity-limited airports, technologies and procedures to help increase departure/arrival capacity and reduce en route congestion, and methods for operating in a wide range of weather conditions. With the OEP developments currently being implemented and proposed, air traffic will still primarily follow the same general operational concept as current day, including positive control of aircraft at high altitude by air traffic controllers to ensure aircraft separation; flight plans determined before take off to which pilots may then request modifications from controllers in flight; and airports having one to six or seven (at the largest airports) runways, with aircraft arrivals and departures carefully spaced for wake vortex separation and collision avoidance. While the OEP is expected to increase capacity, some studies have found demand growing to a greater extent. For example, by the year 2020, without OEP developments, a recent FAA study estimates 41 major airports in the United States will be capacity-limited; with OEP developments, this number reduces to 18 major airports.[3]

In the longer-term, changes to the air transportation system will need to be revolutionary. Such fundamental changes will also require establishing new operational concepts, which may correspondingly require a new CNS architecture, operating procedures, automation for air traffic control and management, cockpit systems, and vehicle performance.

*Associate Editor, *Journal of Aerospace Computing, Information, and Communication*. Associate Professor, 270 Ferst Drive. Senior Member AIAA.

II. What is the Challenge?

Even conceiving of a fundamentally new air transportation system is a challenge. Engineers are trained to create designs that work within the physical constraints of the (physical) environment and available technology. In contrast, while technology will be vital to the next generation air transportation system, it is no longer the dominant constraint on the feasible design space. It is conceivable to use CNS technologies to locate and communicate with an aircraft anywhere on the globe, and to guide it precisely to reach a specific point at a specific time. However, this technological capability stated by itself does not specify how to and who will sequence and space aircraft for take off (assuming the use of at least airports, if not runways), how to and who will specify conflict-free routes for aircraft through congested airspace, how to and who will sequence and space aircraft for arrival (again, assuming the use of at least airports, if not runways), and how to and who will 'recover' from disruptions to predicted operations due to unforeseen events and events.

A number of operational concepts have been proposed with answers to these questions; many use very similar technology, and yet have very different ramifications for not only system performance in terms of safety, capacity and environmental impact, but also in terms of economic and regulatory considerations. Thus, from an engineer's point of view, the task must transition from designing technology alone to conceiving a technologically-feasible operational concept that meets a host of policy, regulatory, and economic concerns.

Another challenge in conceiving a future air transportation system is the increasing integration of all operators. Historically, individuals in the system have had comparatively distinct, contained roles, likely due in large part to their access to operating information: the controller as the sole recipient of traffic surveillance information was focused on separating traffic; the airline operational controllers, knowing their business concerns, were focused on keeping their operations on schedule; and pilots, knowing their immediate situation, were responsible for aircraft control, navigation, guidance, and systems management once in flight. Integrating their access to information has great potential for coordinating decision making towards meeting system-wide goals as well as individual objectives, as already evidenced by the Collaborative Decision Making project involving the FAA and major airlines in the United States.[5] However, it also precludes decomposition of the design problem into more manageable sub-elements, and, in some situations, has been shown to enable new functions by operators that were not anticipated (and, perhaps, not desired) by others.

Implementing a new operational concept is also a challenge for many reasons. Most obvious is the magnitude of the system, and the multitude of aspects to be designed, including not only technologies, but operating procedures, information-sharing protocols, and crew training. Ideally the system must also harmonize with other air transportation systems around the globe. Perhaps most daunting is the need to establish a transition plan to transform the system to the ultimate operational concept in a safe, controlled manner. The air transportation system cannot be shut down and then restarted in a new mode of operation. Instead, it needs to transition while it is in continuous operation, an effect sometimes compared to conducting brain surgery on a person driving down the highway in rush hour.

Despite these challenges, a recent National Research Council committee stated: "Developing meaningful and useful operational concepts stemming from a broadly defined vision of the air transportation system 25 to 50 years hence is a critically important task in the process of improving the performance of the system."[6] The vision of such an operational concept includes its iterative generation such that all agencies and stakeholders can provide input as it becomes progressively more detailed. Ideally, the operational concept would ultimately have sufficient detail to generate and test requirements for the technology it requires.

III. What Are Some Potential Operating Concepts?

The National Research Council report previously mentioned also stated: "Today there is no single national vision for the air transportation system 25 to 50 years from now."[6] Many operational concepts can be envisioned to define this vision (and have been proposed). They may be distinguished by several interrelated factors: the role of the airline operational controllers, air traffic controllers, and pilots; corresponding changes in CNS technologies; reliance on new air vehicles or changes in vehicle performance; and changes in operating procedures and airway structures.

At one extreme, some operational concepts rely on a centralized structure in which all aircraft are given detailed specifications on their routes. With such a central authority, aircraft routes can be optimized for their individual objectives (e.g., fuel burn, time of flight) and system-wide goals (e.g., fairness, airspace capacity and utilization, reductions in emissions and community noise exposure). Such a centralized structure generally mandates strong observability and controllability criterions for the many aspects of the system, and would need to demonstrate robustness to these criterion being violated through machine failure, human error, or unexpected environmental conditions.

Conversely, other concepts tend towards a decentralized structure in which all aircraft determine their own courses of action, subject to general 'rules of the road'. Resolution of conflicts may be between pilots with the aid of traffic displays and cockpit design tools, or between automatic on board systems, or may be, in effect, negotiated for aircraft by air traffic controllers of airways. Such decentralized systems are generally hypothesized to be more adaptive and therefore robust to disturbances. However, their performance may need to be considered an emergent phenomenon that is difficult to predict and control. Between these extremes, many other concepts seek to distribute control in a beneficial manner between operators in a manner that is neither wholly centralized nor decentralized.

IV. Engineering Developments Needed

While technology may not single-handedly determine the operational concept for the future air transportation system, it will be a fundamental enabler of any revolutionary change. Some have traditionally been studied in the context of a next generation air transportation system, especially CNS technologies and systems allowing reduced separation standards between aircraft.

Other technological developments will also probably be required for the next generation air transportation system. First, the future air transportation system will likely involve a significant amount of automation and decision support. For example, "some functions may be fully automated (e.g. aircraft guidance); others may be supported via automated decision aids (e.g. controller decision aids; and automated monitoring and alerting systems); and still other functions may rely on human decision making while using information systems for communication, visualization and situation assessment, and prediction of future conditions."[6] Development of this automation faces several hurdles, including the design of intelligent systems robust to the full range of conditions in which they will need to operate.

Second, the human contribution to air transportation should be clarified and supported. Human limitations (e.g. error) are frequently posited by some as constraints on the air transportation system. Conversely, human capabilities are often described by others as the basis of our current system's performance. As such, the next generation air transportation system should not only be robust to error, but should also be designed to take advantage of human performance. To this end, human factors research has highlighted the need to guard against situations where the level of automation is driven by technological capability instead of functional need, and where the human operators are left as monitors to 'second guess' automated systems. These issues suggest the need to develop technology from the start for effective interaction with human operators.

Third, creating a next generation air transportation system will pose a systems engineering design challenge of vast proportions. Thus, systems engineering models are needed that are suitable for guiding their design, analysis and implementation. These models must be able to account not only for the physical technology, but also for safety-critical software, system-wide behavior in a wide-range of operating conditions, and human behavior.

Finally, the need to assure that a new operational concept is safe, technologically feasible and economically desirable requires an expanded process for modeling and simulation of air transportation.[6] Creating this process requires two advances. One is an increased range of phenomena that we, as a community, can model. For example, models for phenomena such as aircraft trajectories and airport capacity/delay have been rigorously established and widely used; conversely, phenomena such as airline responses to airport capacity/delay, and human behavior in non-nominal situations, have not. The second advance will be the ability to easily apply a wide range of simulations in a cost- and time-effective manner. This includes the need to easily develop simulations; often they build on legacy code that has a fixed level of detail and scope, and thus are not easily reconfigured or extended to analyze radically new operational concepts. Likewise, this requires the ability to easily translate between simulations; different simulations often have their particular data formats and run-time protocols, requiring mundane but extensive translations for one simulation to interact with, or serve as input to, another.

V. Looking Forward

Changes to the air transportation system must consider multiple dimensions: technology, operating procedures, human factors, policy, and economics. Looking forward to longer-term profound changes to the air transportation system, while the technology needs are great, they cannot be considered in isolation: they must work within a broader operational context which itself must be designed. Likewise, no one agency or stakeholder can single-handedly change the air transportation system: safety oversight, security, airport operations, air traffic operations, and airline/air cargo operations must all work together.

To this end, recent legislation in the United States has created "a joint planning and development office to manage work related to the Next Generation Air Transportation System," titled the Joint Planning and Development Office (JPDO).[7,8] At the time of writing of this paper, their first annual integrated plan for a future air transportation system has just been released. Given the magnitude of the air transportation system, this office's tasking includes coordinating between the multiple researchers, developers, operators and stakeholders in air transportation. Transforming the air transportation system may be seen as the biggest challenge facing the civil aeronautics community, requiring our collective, integrated effort.

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