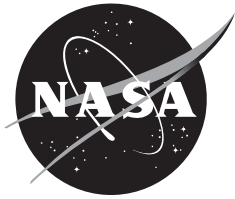# Management by Trajectory: Trajectory Management Study Report

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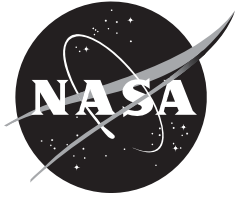- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

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Executive Summary

In order to realize the full potential of the Next Generation Air Transportation System (NextGen), improved management along planned trajectories between air navigation service providers (ANSPs) and system users (e.g., pilots and airline dispatchers) is needed. Future automation improvements and increased data communications between aircraft and ground automation would make the concept of Management by Trajectory (MBT) possible. Key components of an MBT concept include:

- The ability for air traffic controllers and managers to quickly generate, evaluate and implement changes to an aircraft's trajectory.

- Imposing constraints on flight operator-preferred trajectories only to the extent necessary to maintain safe and efficient traffic flows.

- A method for the exchange of trajectory information between ground automation systems and the aircraft that allows for trajectory synchronization and trajectory negotiation.

MBT addresses shortfalls that remain in the Trajectory Based Operations (TBO) solution set, despite years of research into various aspects of transitioning from the current airspace environment to TBO. This report is the result of a survey of this research, as well as enabling technologies. The report provides insights into previous related concepts and technologies, with a particular focus on lessons that can be applied to the MBT concept development and evaluation effort in order to improve the feasibility and ultimate adoption of MBT. Specifically, for each topic covered in the study, the report identifies roadblocks to adoption and/or enablers that should be considered in MBT concept development.

The objectives of this study are to describe previous attempts at developing and/or implementing MBT concepts and concept elements. The description of these efforts identify:

- Likely reasons why previous MBT concept elements have not been fully adopted.

- Portions of previous concepts that have been adopted and the likely enablers of these adoptions.

- Whether there is growing consensus, or lack thereof, about aspects of MBT concept elements.

Key findings determined from this study include the following:

1. During the original Controller-Pilot Data Link Communication (CPDLC) program, the Federal Aviation Administration (FAA) had identified airborne reroutes as a benefit mechanism, but did not have the modeling tools to assess the benefit. Had the FAA included the reroutes benefit mechanism, users may have seen a tangible benefit that would support a decision to invest in CPDLC equipment. Voice communication of complex reroutes is impractical for widespread use in the National Airspace System (NAS). The nine-year deferment of data link capabilities has slowed progress toward TBO in general, and MBT in particular. Future MBT cost/benefits assessment should: a) identify benefit mechanisms that are tangible to users; b) identify methods for determining hard-to-assess benefit mechanisms; and c) consider providing financial incentives for flight operators to equip with capabilities that are foundational to the MBT concept.

2. The Automatic Dependent Surveillance – Contract (ADS-C) Extended Projected Profile (EPP) report appears to be the only capability on the horizon with any

momentum that can be utilized for sharing complete (or near-complete) flight management system (FMS) trajectory intent with ANSP ground systems. However, there is no mandate to equip aircraft to provide the EPP report, which is expected to be very expensive. The MBT concept should include a concept variant that assumes the EPP report will not be available to provide intent for a high percentage of aircraft. However, for aircraft that cannot downlink the EPP report, managing aircraft trajectory prediction uncertainty will be more difficult, lessening the effectiveness of MBT. However, as noted below, there is a fast-growing industry and suite of technologies that may mitigate this impediment to full MBT implementation.

3. The wide range of FMS capabilities in the NAS that currently exists and will continue to exist for decades into the future results in a mixed capability environment. The MBT concept will have to consider the best approach for addressing the mixed capability environment on a concept element by concept element basis. It may be necessary to determine what "best equipped, best served" means for each MBT concept element.

4. High cost inhibits low-cost carriers from implementing in-flight connectivity (IFC) to the internet. Low-cost carriers may not be able to leverage electronic flight bag (EFB) applications and System Wide Information Management (SWIM) information. Thus, certain benefits of MBT (e.g., effective trajectory negotiation) that rely on dynamic information may not be attainable to them.

5. There are many letters of agreement (LOAs) and standard operating procedures (SOPs) that can change the aircraft trajectory but are unknown to the pilot and are not available in an FMS database. Furthermore, trajectory changes (e.g., altitude and speed restrictions) due to these procedures often put the aircraft on an open trajectory. LOAs and SOPs place constraints on aircraft trajectories that today are not published, and FMSs have limited database capacity to add the data associated with these SOPs and LOAs. MBT should account for these constraints and their effect on trajectories and trajectory negotiation.

6. Trajectory uncertainty causes controllers to use tactical clearances, which tend to be open trajectory clearances. Without the automation support for closed trajectories, controllers will continue to use open trajectory techniques. Open trajectory clearances exacerbate the trajectory uncertainty in the system. On the other hand, trajectory predictability enables controllers to use strategic, closed trajectory clearances, which then maintains a high level of trajectory predictability. Thus, the MBT concept needs to consider the set of technologies, procedures, and cultural changes that will be the *tipping point* that moves the NAS towards widespread use of closed trajectories and predictability to facilitate MBT.

7. The lack of interest among the air carrier industry in applications to leverage Collaborative Trajectory Options Program (CTOP), which provide similar types of benefits as trajectory negotiation, is a cautionary tale for trajectory negotiation participation. Trajectory negotiation is one of the MBT benefits that provides users direct, tangible benefits across the fleet or for individual flights. If users choose not to upgrade their capabilities to facilitate trajectory negotiation, it is an indicator that they may not upgrade for other aspects of MBT. It will be difficult to make realistic estimates of user participation for trajectory negotiation, which will have a direct bearing on benefits.

8. The lack of a single concept of operations for TBO has led to many different opinions about what TBO should be with little convergence by the air traffic management

(ATM) research community. The FAA needs to clearly define the TBO concept and the NAS Enterprise Architecture evolution associated with the transition to TBO. This provides an opportunity for NASA to provide leadership to help the FAA define the TBO concept elements, of which MBT is one.

9. Weather will continue to be a major contributor to residual trajectory uncertainty as well as traffic flow management (TFM) uncertainty. Yet it is well known in the ATM community that many decision support tools (DSTs) do not perform well in dynamic situations such as weather. This is not a coincidence – rather it is because they have not been designed to handle dynamic situations. Weather problems are often "assumed away" in the concept description or just completely ignored. The underlying justification, whether stated or not, is that most days in the NAS do not have major weather disruptions. Furthermore, the complexity of addressing dynamic weather situations during concept evaluations limits their assessment. Thus, while lateral and temporal trajectory constraints are seen as the interface between TFM and MBT, the validity of these constraints in addressing demand/capacity imbalances in the presence of weather will likely be degraded.

10. Controller complexity and traffic density in the eastern US will continue to prevent the use of user preferred routes (UPRs) in that region, yet no research has been performed to identify the traffic level threshold where UPR requests should be accepted or rejected.

Lastly, there is growing consensus that the introduction of SWIM, airborne access to SWIM (AAtS), IFC, and EFBs has significant potential to disrupt *business as usual* in the ATM environment, particularly for MBT concepts such as trajectory negotiation, which provides a tangible benefit to the user. And the FAA is making important strides to enable more effective airborne reroutes. These are all predicated on Data Comm equipage. There is also the realization that a mixed equipage environment will exist on many fronts for the foreseeable future for Data Comm, Automatic Dependent Surveillance-Broadcast (ADS-B) In, and ADS-C EPP. Each concept element will have to be evaluated to determine how best-equipped, best-served should be applied with an emphasis on identifying tangible benefit mechanisms.

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1.   Introduction

In the current operational environment, air traffic control (ATC) automation, such as arrival and departure schedulers in the Time Based Flow Management (TBFM) system, develops plans based on aircraft trajectory predictions using available information such as aircraft performance and winds/weather. However, once that plan is in place, controllers tactically manage the aircraft, using vectors, altitude, or speed clearances, to either conform to the schedule at control points or to address other issues that come up, such as maintaining separation, or changing weather conditions. Since these tactical actions are not directly communicated to the automation systems, the underlying trajectories may not be properly updated, which can lead to inefficiencies in the air traffic system. Although aircraft are equipped with many capabilities to predict and fly a trajectory, the controller's tactical instructions often prevent full use of these capabilities.

In order to realize the full potential of the Next Generation Air Transportation System (NextGen), there needs to be better coordination between air navigation service providers (ANSPs) and system users (e.g., pilots and airline dispatchers) in terms of better managing aircraft along planned trajectories. Future automation improvements and increased data communications between aircraft and ground automation would make this idea of Management by Trajectory (MBT) possible. Key components of an MBT concept include:

- The ability for air traffic controllers and managers to quickly generate, evaluate and implement changes to an aircraft's trajectory.

- Imposing constraints on flight operator-preferred trajectories only to the extent necessary to maintain safe and efficient traffic flows.

- A method for the exchange of trajectory information between ground automation systems and the aircraft that allows for trajectory synchronization and trajectory negotiation.

MBT addresses shortfalls that remain in the Trajectory Based Operations (TBO) solution set, despite years of research into various aspects of transitioning from the current airspace environment to TBO. This report is the result of a survey of this research, as well as enabling technologies. The report provides insights into previous related concepts and technologies, with a particular focus on lessons that can be applied to the MBT concept development and evaluation effort in order to improve the feasibility and ultimate adoption of MBT. Specifically, for each topic covered in the study, the report identifies roadblocks to adoption and/or enablers that should be considered in MBT concept development.

1.1   Objectives

The objectives of the trajectory management study are to describe previous attempts at developing and/or implementing MBT concepts and concept elements. The scope of the study includes available research and development efforts in government, industry, and universities as well as operational implementation examples in the US or elsewhere. The description of these efforts should identify:

- Likely reasons why previous MBT concept elements have not been fully adopted, including any faulty assumptions and technical, political, cultural, and other limitations.

- Portions of previous concepts that have been adopted and the likely enablers of these adoptions.

- Whether there is growing consensus, or lack thereof, about aspects of MBT concept elements.

1.2 Document organization

This document is organized as follows:

Section 2 describes the approach for scoping prior work for review to support the study objectives.

Section 3 discusses enabling technologies and automation systems that are considered important for realizing the potential of MBT.

Section 4 discusses previous research into topics considered to be elements of the MBT concept.

Section 5 discusses safety considerations for the MBT concept.

Section 6 summarizes the key findings.

1.2.1 A note on reference sources

In an effort to present timely information about recent developments, some of the references used in this document are web pages with uniform resource locaters (URLs) that may or may not be available in the future. If the reference source is a URL to a webpage, a footnote is utilized with the URL identified to provide the reader with convenient access to the information (usually just one click away). Note that some websites require a free user account and password to access. If the reference is an electronic document in a format such as Acrobat PDF, MS Word or PowerPoint, the document is given a full bibliography entry in the Bibliography section and an abbreviated reference in the appropriate location in the document text. The Chicago Manual of Style 16th Edition was chosen since its abbreviated format for references provides the reader with some context (author and date) about the reference without having to bounce back and forth between the main document and the bibliography (a shortcoming of the IEEE numbering format). No paper-only references were used, such as books, so the reader should be able to obtain all the references electronically if so inclined.

2. Approach for scoping prior work for review

A review of the vast amounts of NextGen literature produced since 2010 without a method for filtering with respect to MBT is untenable. Unfortunately, MBT itself is rarely used in the literature and TBO is a buzzword where its usage in paper titles and keywords often has little to do with TBO as a concept. To assist with scoping the literature review, the few existing TBO Concept of Operations (ConOps) documents were reviewed. The FAA produced a draft version in 2014 (FAA 2014d). It is unclear if a finalized version exists. The International Civil Aviation Organization (ICAO) produced a draft TBO ConOps in 2015 (ICAO-ATMRPP 2015). While not a ConOps per se, Radio Technical Commission for Aeronautics (RTCA) developed a set of mid-term NextGen TBO scenarios to support further concept exploration (RTCA 2011) with a brief description of the concept elements. Lastly, NASA recently published an integrated gate-to-gate ConOps of which MBT represents the airborne portion (Johnson and Barmore 2016). Collectively, these documents were reviewed with the intention of identifying the concept elements to be explored further with this study. In addition, the down-selected concept elements were used to structure the report document, becoming the names of the sections within Section 4 (e.g., user preferred routing, closed trajectories and closed trajectory clearances).

Once the concept elements within MBT were identified, search engines within American Institute of Aeronautics and Astronautics (AIAA), Institute of Electrical and Electronics Engineers (IEEE), and NASA publication libraries were utilized. In addition, Google searches of FAA, Air Traffic Management (ATM) Seminar, RTCA, Eurocontrol, and other websites were also performed. In both search approaches, different keyword combinations of the selected concept elements were employed to ensure relevant documents were not overlooked. In addition, aviation periodicals, such as *Aviation Week and Space Technology*, were searched to provide a more topical, industry perspective. A similar search process was utilized to discover relevant issues pertaining to the enabling technologies in Section 3.

3. Enabling technologies and automation systems

This section discusses the following key enabling technologies and automation systems for MBT including the planned timeline of needed capabilities (if available) for supporting MBT:

- Aircraft/ANSP data communication
    - Controller-pilot data link communication (CPDLC) – original program
    - Data communication (Data Comm) – current program
- Automatic dependent surveillance – contract (ADS-C)
- Automatic dependent surveillance – broadcast (ADS-B)
- Flight Management System (FMS)
- Electronic flight bag (EFB)
- En Route Automation Modernization (ERAM)
- Traffic Flow Management System (TFMS)
- Time-Based flow management (TBFM)
- System Wide Information Management (SWIM)
- In-flight connectivity (IFC)
- Airborne Access to SWIM (AAtS)

Where applicable, the sub-sections attempt to identify:

- Enablers
- Roadblocks to adopting the enabling technology/automation system
- Negative impacts of roadblock on MBT
- Specific implications for MBT

3.1 Aircraft/ANSP data communication

The FAA's first efforts with aircraft/ANSP data communication began with American Airlines strongly advocating for its implementation based on their internal analysis showing the National Airspace System (NAS) hitting capacity limitations, including those caused by voice frequency congestion. The FAA and American Airlines began CPDLC field tests in Miami Center in 2003

with a limited set of messages (initial contact, transfer of communication, altimeter settings, and free-text messages) using Very High Frequency (VHF) data link (VDL) Mode 2. The benefits case focused on reduced voice frequency congestion at the sector level, which would thereby allow more aircraft in a sector. Unfortunately, Miami Center had limited overflights so this particular benefit was understated in the field tests. Furthermore, other airlines were not willing to equip because of their financially weak state in the aftermath of 9/11. The Inspector General wrote:

> *For CPDLC benefits to exceed costs, FAA estimated that more than 200 equipped airplanes had to use CPDLC. Program documents note that FAA assumed at least 100 aircraft would be equipped by the time CPDLC became operational in Miami, and 200 to 400 would be equipped by the time the program was deployed nationwide. However, by mid-2003, only about 30 aircraft had been equipped. FAA was concerned about users' ability and willingness to equip given the airline industry's economic downturn in 2001. In 2001, network carriers began incurring substantial net losses, accumulating to a total of $23.4 billion by the end of the first quarter of 2004. The financial health of the industry influenced FAA's decision because FAA was relying on voluntary equipage (FAA 2004).*

Based on projections of air carrier equipage, the return on investment would not be reached until 2018. Given other FAA priorities, nationwide deployment of CPDLC was deferred despite broad agreement in the ATC community that data link *"is the key architectural enabler of almost any future envisioned air traffic management system."* [1]

With CPDLC deferred in the US, Eurocontrol moved forward with their version of CPDLC through the Link 2000+ Programme. The Eurocontrol benefits case also focused on increased sector capacity due to reduced voice frequency congestion, but some European airspace was much closer to saturation compared to the US. To encourage early adoption, the first 15 airlines to equip were provided a financial subsidy of 20,000 euros per aircraft – this applied to about half of the 350 *pioneer* aircraft under Link 2000+.[2] The pioneer aircraft provided early lessons learned across a broad range of flight operators. In addition, Eurocontrol imposed an equipage mandate on flight operators by 2015. However, due to an abnormal number of datalink disconnections, or *provider aborts*, the mandate has been delayed until 2020 to provide additional time to find solutions to the existing problems.[3]

It is important to note that the FAA identified airborne reroutes as a benefit of CPDLC, but in the 2003 timeframe this benefit was not well understood. What was well understood is that voice communication of complex reroutes (e.g., reroutes involving significant changes to the airways and/or waypoints in the flight plan) is impractical for widespread use in the NAS as it is workload-intensive, prone to error, and increases voice frequency congestion. While the need for airborne reroutes seemed intuitively paramount, the benefits case would require significant fast-time modeling development to assess the benefit along with assumptions about the conditions in which reroutes would be warranted. Furthermore, airborne reroutes are subject to several dependencies that would be years away from implementation including: 1) a capability to send reroutes generated by TFMS to the applicable controller's ERAM workstation; 2) a capability to generate reroutes in ERAM directly; 3) integration of ERAM and CPDLC to automatically compose reroute messages; and 4) integration of the FMS and CPDLC to enable auto-loading the reroutes into the FMS.

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[1] "A Tale of Two Data Links," Aviation Week and Space Technology, July 14, 2003.
http://archive.aviationweek.com/search?QueryTerm=A+Tale+of+Two+Data+Links&DocType=All&sort=
[2] http://www.aviationtoday.com/av/commercial/Europe-Moves-on-Datalink_10778.html
[3] http://www.ainonline.com/aviation-news/air-transport/2015-02-24/europe-postpones-controller-pilot-datalink-mandate

Thus, in the 2003 timeframe, it is fair to say a benefits assessment for reroutes would have been a complex and expensive undertaking and it is understandable why the FAA focused on the simpler benefit of reduced voice frequency congestion instead. In a similar context, the fast-time modeling analysis to support NASA's Distributed Air/Ground Traffic Management (DAG-TM) En Route Trajectory Negotiation concept element (conducted in 2002-2003) specifically did not address airborne rerouting around weather due to a lack of fast-time modeling capabilities in this area.[4] In hindsight though, the FAA's decision to defer nationwide deployment of CPDLC by almost a decade has been the key roadblock to operational MBT thus far.

In 2012, the FAA began the nationwide deployment of a CPDLC capability (now referred to as Data Comm) with an award to Harris Corporation. The award includes administering an avionics equipage initiative with $80 million in incentive funding to supply early equipping airlines.[5] Data Comm leverages Future Air Navigation System (FANS)-1/A and VDL-2 avionics, widely used in air transport and business aviation. The goal is to equip 1,900 airplanes by 2019. Eight air carriers committed through memorandums of agreement to equip their aircraft with Data Comm avionics under the incentive program. As of July 13, 2016, 867 aircraft have equipped under the incentive program. Another 820 are equipped outside of the incentive for a total of 1,687 equipped aircraft.[6]

As of the end of 2016, Data Comm was operational in all 56 ATC towers (20 months ahead of the schedule), enabling delivery of departure clearances (DCLs) (full route clearances and revisions) to aircraft on the ground.[7] A key benefit of DCL is that *"the controller is able to amend the clearance as volume or weather conditions change, thereby eliminating the voice bottleneck during these high workload conditions."*[8] In these voice bottleneck conditions, equipped aircraft avoid significant delay.

The focus of the Data Comm program is now shifting to en route services (see Figure 1). Figure 2 shows the most recent FAA Communications Roadmap (top) (FAA 2016b) and a roadmap from 2015 that identifies message types (bottom). Initial en route services will become available starting in 2019, thus making datalinked airborne reroutes possible.

SEGMENT 1 PHASE 2	
Data Comm Segment 1 Phase 2 Initial En Route Services FID	October 2014
Data Comm Segment 1 Phase 2 Full En Route Services FID	December 2016
Data Comm Segment 1 Phase 2 Development Test and Evaluation Complete	June 2018
Data Comm Segment 1 Phase 2 IOC at first site	July 2019
Data Comm Segment 1 Phase 2 ISD	March 2020
Data Comm Segment 1 Phase 2 IOC at last site	February 2021

Figure 1. Data Comm program milestones from the NextGen Implementation Plan (FAA 2016c)

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[4] Conversation between NASA Technical Monitor and the author, who worked on the benefits analysis of DAG-TM En Route Trajectory Negotiation concept element.

[5] http://www.ainonline.com/aviation-news/air-transport/2012-09-24/faa-taps-harris-build-nationwide-data-comm-network

[6] https://www.faa.gov/nextgen/update/progress_and_plans/data_comm/

[7] https://www.faa.gov/nextgen/snapshots/priorities/?area=dcom

[8] http://interactive.aviationtoday.com/nextgen-data-comm-facilitates-digital-dcl/
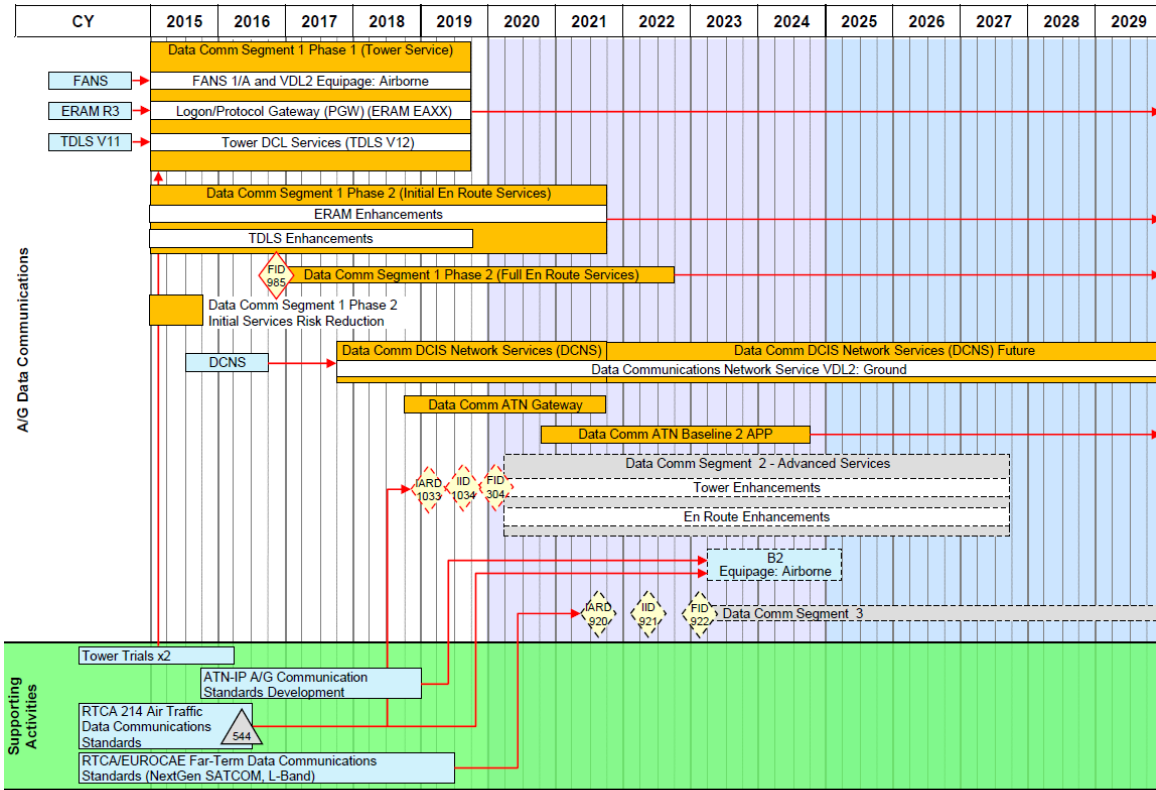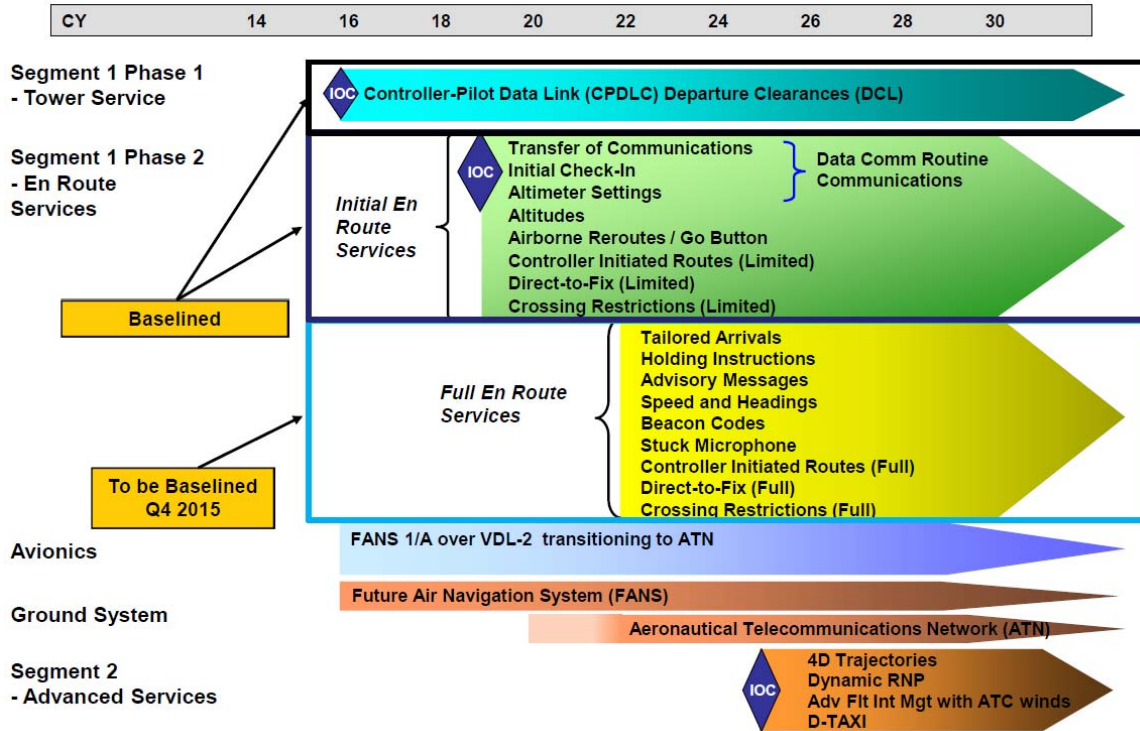
Figure 2. FAA Data Comm Roadmaps

To support more advanced data communications services, the FAA will support future use of Aeronautical Telecommunication Network (ATN) avionics. The ATN was developed through ICAO to provide a more universally capable and reliable data communication system. After en route services deployment in the NAS with FANS 1/A and VDL-2, the FAA will support the transition to ATN, referred to as Baseline 2. Capabilities to support TBO-related message types will be available starting in 2024. Data link message types are described in Annex B of DO-351A (RTCA SC-214 2016b).

3.1.1 Enablers

- Government provides financial incentives for flight operators to equip.

- Widely viewed as the key enabling technology for NextGen capabilities.

3.1.2 Roadblocks to adopting CPDLC/Data Comm

During the CPDLC program, the FAA had identified airborne reroutes as a benefit mechanism, but did not have the modeling tools to assess the benefit. Instead, the benefit assessment focused on the reduced voice frequency congestion benefit mechanism and associated increase in en route sector capacity. However, en route sector capacity is not a major bottleneck in the NAS and it is also not a tangible benefit to users. Had the FAA included the reroutes benefit mechanism, the users may have seen tangible benefits - particularly benefits to support equipping.

3.1.3 Negative impacts of roadblock on MBT

Without Data Comm, voice communication of complex reroutes is impractical for widespread use in the NAS. The nine-year deferment of data link capabilities has slowed MBT concept element progress.

3.1.4 Specific implications for MBT

History may repeat itself if the MBT cost/benefits assessment makes the same mistake as the original CPDLC cost/benefits assessment. To mitigate these concerns, MBT should:

- Identify benefit mechanisms that are tangible to users.

- Identify methods for determining hard-to-assess benefit mechanisms.

- Provide financial incentives for flight operators to equip (as was done with the 2012 Data Comm program and with the European Link 2000+ Programme).

3.2   ADS-C

ADS-C is a method of surveillance that is dependent on downlink reports from an aircraft's avionics that occur automatically in accordance with contracts established between the ATC ground system and the aircraft's avionics. Reports are sent according to a contract type: on demand, on a periodic basis, or when triggered by an event (e.g. change of waypoints and/or constraints, deviation of estimates more than defined thresholds, etc.). ADS-C is supported by FANS-equipped aircraft. Boeing developed FANS-1 and Airbus developed FANS-A; collectively they are referred to as FANS-1/A.

While the original purpose of FANS1/A ADS-C was to provide accurate surveillance reports in remote and oceanic areas, a lesser known aspect is that it also has the ability to provide basic trajectory intent down-link referred to as intermediate projected intent (IPI). Since a clear concept of use for IPI never existed, its content is limited (next 10 waypoints) and its format has many limitations (Bronsvoort et al. 2016). However, a new, more complete framework to provide

the trajectory intent of the FMS has been developed. This trajectory intent information will be contained in a new ADS-C report referred to as the Extended Projected Profile (EPP) report. The EPP report represents the FMS trajectory intent through a maximum of 128 waypoints or pseudo waypoints[9] with associated estimates and constraints. The EPP message, shown in Table 1, is defined in Annex B of DO-351A (RTCA SC-214 2016b):

Table 1. EPP Message Content*

Waypoint latitude and longitude	Flight level constraint
Flight level	Speed constraint
Fix name	Time constraint (e.g., Required Time of Arrival [RTA])
ETA	Gross mass
Estimated speed	Trajectory intent status: Booleans for each of the following: lateral flight managed, vertical flight managed, speed managed, and time managed.
Vertical type: top of climb (TOC), top of descent (TOD), start of climb, start of descent, start of level flight, start of speed change, end of speed change, speed limit, and cross over.	Lateral type: flyby, fixed radius transition, offset start, offset reached, return to parent path initiation, offset end, offset, overfly, and followed by discontinuity.

* Note that all fields are optional except for waypoint latitude and longitude.

3.2.1   Enablers

- Agreement between stakeholders on the requirements for Baseline 2, allowing avionics suppliers to bring it to market.

3.2.2   Roadblocks to adopting Baseline 2 ADS-C EPP

A potential roadblock to MBT is that there is no mandate for ADS-C EPP. Aircraft that are equipped with FANS 1/A, which supports basic ADS-C, will need to upgrade to what is referred to as a Baseline 2 for an EPP capability, which Boeing says *"is going to be prohibitively expensive."* The FAA has not committed to widespread ground deployment, and without that, Boeing does not believe there is a business case for B2 (Nguyen 2016).

3.2.3   Negative impacts of roadblocks on MBT

ADS-C EPP appears to be the only capability on the horizon with any momentum that can be utilized for sharing complete (or near-complete) FMS trajectory intent with ANSP ground systems. For aircraft without EPP, managing aircraft trajectory prediction uncertainty will be more difficult, lessening the effectiveness of MBT.

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[9] Pseudo waypoints are waypoints inserted into the flight plan by the FMS for flight management purposes. Pseudo waypoints include items such as top of climb, top of descent, and change of speed. They are updated dynamically by the FMS according to the actual profile being flown.

3.2.4 Specific implications for MBT

The MBT ConOps should consider developing a concept variant that assumes ADS-C EPP intent will not be available for high percentage of aircraft.

In addition, the same lessons learned in the Data Comm section apply here:

- Identify benefit mechanisms that are tangible to users.
- Identify methods for determining hard-to-assess benefit mechanisms.
- Provide financial incentives for flight operators to equip.

3.3 ADS-B

ADS–B is a surveillance technology in which an aircraft determines its position via Global Positioning System (GPS) and periodically broadcasts it, enabling it to be tracked by ground-based systems. The information can be received by air traffic control ground stations and by other aircraft to provide situational awareness and, in the future, allow for self-separation. ADS-B broadcasts the latitude, longitude, velocity (relative to the earth), geometric altitude (height of the vehicle above the earth ellipsoid), and pressure altitude every second.

ADS-B consists of ADS-B Out and ADS-B In. ADS-B Out refers to the broadcasting of information. ADS-B In refers to an aircraft receiving the broadcasts and also receiving messages from the ground network (see below). The FAA has mandated through 14 CFR 91.225 and 14 CFR 91.227 that aircraft operating in airspace that now requires a Mode C transponder must be equipped with ADS-B Out by January 1, 2020. ADS-B In is not mandated. The mandate requires aircraft operating in Class A airspace to broadcast data with a Mode S, 1090 Extended Squitter (1090 ES). Aircraft operating in designated airspace exclusively below 18,000 feet MSL can broadcast the required information with either 1090 ES or the Universal Access Transceiver (UAT) on 978 MHz. Aircraft equipped with UAT will also receive significant weather activity information, Notices to Airmen (NOTAM), and pilot reports via the Flight Information Services–Broadcast (FIS-B) service – a free service provided by the FAA.

Since aircraft can broadcast on one of two frequencies, Automatic Dependent Surveillance–Rebroadcast (ADS-R) is part of the ground infrastructure. ADS-R collects position information broadcast on each frequency and rebroadcasts it on the other frequency. Traffic Information Services–Broadcast (TIS-B) is another part of the ground infrastructure. Since it will be a few years before all aircraft are equipped with ADS-B Out, TIS-B broadcasts the position of non-ADS-B Out aircraft that ground surveillance radar detects. Combined, TIS-B and ADS-R provide ADS-B In-equipped aircraft with a more complete airspace and airport surface traffic picture. ADS-R delivers traffic data within a 15 nm radius, 5,000 feet above or below relative to the receiving aircraft's position. TIS-B provides traffic data within a 15 nm radius, 3,500 feet above or below.[10]

The combination of ADS-B Out, with higher update rate and improved position accuracy compared to ground surveillance radar, and ADS-B In with a cockpit display of traffic information (CDTI) enables NextGen concepts such as closely spaced parallel operations and advanced interval management. Another example is strategic conflict management where a controller provides a clearance consisting of a RTA, associated waypoint, and identification of the aircraft to avoid, which the pilot then can correlate to the correct target on the CDTI.

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[10] https://www.faa.gov/nextgen/update/operator_investments_and_airports/operator_investments/adsb/

Note that there is currently no plan for ADS-B to support broadcast of aircraft intent information that would facilitate MBT concepts. Originally, DO-260 (RTCA SC-186 2000) specified that 1090 ES would support reporting of aircraft intent for the aircraft's next two trajectory change points (TCPs) (where *change* refers to changes in altitude, heading, speed or any combination thereof). Note that having only two TCPs for aircraft intent has limited applications for MBT, but it could improve shorter time horizon concepts such as conflict probe performance. Regardless, the FAA had concerns about congestion on the 1090 MHz frequency in high density airspace and was trying to reduce the types of reports that ADS-B would have to support (ADS–B Aviation Rulemaking Committee 2008). Trajectory change reports were subsequently removed from DO-260A. While the current version, DO-260B (RTCA SC-186 2011), still contains an appendix describing trajectory change reports, there is currently no plan to resuscitate aircraft intent. Similarly, a Target State report is defined in DO-260B that would identify the current flight segment target states such as target altitude of climbing or descending aircraft or target heading for turning aircraft, but there is currently no implementation schedule for this capability.

Lastly, Aireon, a joint venture between Iridium Communications and several ANSPs, is developing a space-based ADS-B service by installing ADS-B receivers on Iridium NEXT satellites. The service is planned to be operational in 2018 and will consist of 66 operational low-earth-orbit satellites providing a *global aircraft surveillance capability*.[11] Initially, Nav Canada plans to use this service to manage North Atlantic oceanic airspace.[12]

3.3.1 Enablers

- The key enabler is the 2020 FAA mandate for ADS-B Out.

- Best-equipped, best-served operational practices can encourage upgrades to ADS-B In.

- NextGen Equipage Fund for GA aircraft ($550M) with 15-year contract agreements and federal loan guarantees to pay for equipment upgrades.[13]

3.3.2 Roadblocks to adopting ADS-B In

While ADS-B Out is mandated, ADS-B In is not so what will entice users to equip? The NextGen Equipage Paradox refers to the following:

Despite the potential for significant benefits from NextGen, airlines and other operators are not making the needed aircraft equipage investments. There are still uncertainties in NextGen requirements and benefits. This means that in the end, those operators who are last to equip with NextGen avionics will reap the most financial benefit, while those operators who are first will get the lowest returns at a far greater risk. [14]

3.3.3 Negative impacts of roadblocks on MBT

Any MBT concept elements that require self-spacing, self-merging, and/or self-separating will not be feasible for aircraft without ADS-B In.

3.3.4 Specific implications for MBT

Same lessons learned in the Data Comm section apply here:

- Identify benefit mechanisms that are tangible to users.

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[11] https://aireon.com/company/

[12] http://www.navcanada.ca/en/products-and-services/pages/on-board-operational-initiatives-ads-b.aspx

[13] http://www.avweb.com/avwebflash/news/Congress-Mandates-ADS-B-Loan-Program-225480-1.html

[14] http://www.rtca.org/Files/NAC%20Recommendations/NAC%20EquipAdHoc%20FinalApprvd.pdf

- Identify methods for determining hard-to-assess benefit mechanisms.

- Provide financial incentives for flight operators to equip.

3.4 FMS

The FMS is the avionic automation that enables an aircraft to follow a lateral and vertical profile with optional specified speeds for each segment of the profile. It has the capability to optimize the trajectory based on a cost index. The cost index enables the pilot to minimize time of flight or minimize fuel burn or the continuum between these two extremes along a pilot-specified profile. The FMS does not have a capability to generate wind-optimal routes – it can only optimize based on the specified lateral profile. There are many variations in capabilities between FMS models – for example, most FMS models support RTA, which is a key capability for NextGen time-based operations. This difference in capabilities creates a *mixed capability* situation (analogous to mixed equipage) where some aircraft will be able to support NextGen concepts and others will either require explicit controller instructions to replicate the behavior (e.g., an aircraft meeting an RTA or a controller giving an Efficient Descent Advisor (EDA) clearance to the aircraft).

Looking to the future, integration of Data Comm, ADS-C EPP, context management, and advanced FMS to support NextGen capabilities is referred to as Baseline 2. This integration requires substantial changes to the FMS including new flight plan uplinks and loading rules and RTA changes. Baseline 2B would include additions for Dynamic Required Navigation Performance (RNP) and Advanced Interval Management (A-IM) procedures. Boeing states the following about the cost of Baseline 2B (Nguyen 2016):

Current iteration (B2B) is going to be prohibitively expensive:

- *Software development alone will exceed FANS-1 and ATN costs combined for each model*

- *Hardware changes probably necessary on some models too*

- *To allow backward compatibility, airline will have to purchase FANS-1 and FANS-2 features as well as pay for this*

- *Ancillary equipment costs (e.g. A-IM equipment) will be in addition*

Boeing believes Baseline 2B will only be available on aircraft produced in the mid-2020 timeframe, further exacerbating the mixed capability situation.

3.4.1 Roadblocks to adopting advanced FMS capabilities

For older aircraft with older avionics, FMS upgrades are not possible because of the inherent differences with newer technology. Looking to the future, Boeing says Baseline 2B *"is going to be prohibitively expensive."* Air carriers have had bad experiences in the past where their investment in avionics upgrade have not been utilized and thus not provided any benefit because the corresponding investments on the ANSP side did not materialize. The FAA has not committed to widespread ground deployment, and without that, Boeing does not believe there is a business case for Baseline 2 (Nguyen 2016).

3.4.2 Negative impacts of roadblocks on MBT

The wide range of FMS capabilities in the NAS that currently exists and will continue to exist for decades into the future results in a mixed capability environment. The MBT concept will have to consider the best approach for addressing the mixed capability environment on a concept

element by concept element basis. In other words, what does best equipped, best served mean for each MBT concept element?

3.5   EFB

EFB gets its name from the traditional pilot's flight bag of documents, including operating manuals and navigational charts, which pilots would carry to the cockpit. The EFB is the replacement of those documents in a digital format. The FAA defines an EFB as *an electronic display system intended primarily for flight deck or cabin crew member use that includes the hardware and software necessary to support an intended function* (FAA 2014a). EFBs can be portable or installed.[15] Portable EFBs such as iPads can only support Type A or Type B software applications (see Table 2) such that failure of the EFB will not directly affect the operation of the aircraft. Installed EFBs are fully certified as part of the aircraft avionics system and are integrated with aircraft systems such as the FMS. These advanced systems are also able to display an aircraft's position on navigational charts, depict real-time weather, and perform many complex flight-planning tasks. Installed EFBs support Type C software applications.

Table 2. Description of types of EFB software applications from FAA AC 120-76C.

Type A software applications are those paper replacement applications primarily intended for use during flight planning, on the ground, or during noncritical phases of flight having a failure condition classification considered to be a minor hazard or less.
Type B software applications are those paper replacement applications that provide the aeronautical information required to be accessible for each flight at the pilot station and are primarily intended for use during flight planning and all phases of flight. They may also include miscellaneous applications (e.g., aircraft cabin and exterior surveillance video displays, maintenance applications) having a failure condition classification considered to be a minor hazard or less.
Type C software applications are approved by the FAA using RTCA/DO-178 or another acceptable means. These are "non-EFB" software applications found in avionics and include intended functions for communications, navigation, and surveillance that require FAA design, production, and installation approval. Type C applications are approved software for surface and airborne functions with a failure condition classification considered to be a major hazard or higher.

There is significant potential for new Type B applications that leverage IFC and the Aircraft Interface Device (AID), which provide secure interfaces between portable EFBs and onboard avionics and aircraft systems. Applications that utilize real-time access to weather and other dynamic information can increase operational efficiencies including fuel and time savings and mitigations to impending turbulence.[16,17]

While more expensive than portable EFBs, installed EFBs with Type C applications are expected to continue to have a role in NextGen applications. For one, they may prove to be a less costly approach than integrated avionics in the forward field of view of the cockpit:

There is also a future-proofing aspect of the nascent ADS-B In application. While those new applications could be hosted in the forward panel, "then you'd have to pay fees to

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[15] This is based on the *draft* version of AC 120-76D. The previous Class 1, 2 and 3 categories of EFBs in AC 120-76C have been replaced by two new categories: portable and installed to try and clear up previous confusion
[16] http://www.aviationtoday.com/av/EFBs/Aircraft-Interface-Technology-Continues-to-Expand-With-Latest-737-Approval_88337.html
[17] http://interactive.aviationtoday.com/avionicsmagazine/october-november-2016/coming-off-the-production-line-is-your-aircrafts-gps-receiver-accurate-enough-for-ads-b/

the integrated avionics companies," says Dewar. Legacy EFB providers have a slight edge because their systems are not in the forward field of view of the pilot and hence can be less costly to update, even though the devices can be certified as an additional avionics display. That makes the EFB an ideal candidate to host NextGen applications, which are evolving and progressing as ADS-B Out surveillance comes into force via mandates globally and airlines, albeit slowly, begin purchasing ADS-B In equipment as well.[18]

In addition, installed EFBs may provide more flexibility than the forward display alone (from the same article):

New models for software security are also giving traditional EFBs more flexibility. The Astronautics Corp. of America's Nexis Flight-Intelligence System has software-only partitioning that allows operators to have certified and non-certified (consumer) applications running simultaneously in the same side display unit. The non-certified side can often be updated or loaded with no recertification, reducing costs and giving airlines the freedom to write their own applications. "On the forward display, no one is going to let you touch that code," says Cundiff. "If you want a change, you have to go back through the [original equipment manufacturer] and decide on a certification plan. The bill you get at the end is going to have a lot of zeros on the end of it."

3.5.1 Enablers

- IFC, AAtS

- May prove to be a more flexible and less costly means for getting NextGen capabilities into the cockpit compared to implementation through traditional avionics

3.6 ERAM

ERAM processes flight and surveillance data, enables efficient controller-pilot communications, and generates detailed display data to controllers. ERAM combines ICAO flight plan information and processing with surveillance data from ADS-B, wide area multilateration (WAM), and radar to automate a number of air traffic control functions such as tracking aircraft, providing conflict alerts and minimum safe altitude warnings, and recording air traffic events.

ERAM performs enhanced weather data processing, including weather grids containing wind, temperature, and pressure data for use by trajectory modeling and display at the controller positions. ERAM displays mosaic Next Generation Weather Radar (NEXRAD) and processes and distributes text-based meteorological information to the controller positions. ERAM provides conflict probe and alert notification with a 20 minute look-ahead for aircraft/aircraft and aircraft/airspace conflicts with a trial planning tool for what-if modeling of potential flight plan amendments (Ng 2011).

Each ERAM system can track 1,900 aircraft at a time, compared with 1,100 for the legacy HOST system. ERAM is now available in all 20 en route Centers in the contiguous US, with the last two, Jacksonville and Atlanta Centers, available since September 2014. In March 2015, the 20 ERAM sites achieved operational readiness, which signified the full commissioning of ERAM into the NAS and allowed the FAA to begin decommissioning the HOST system. ERAM serves as the platform upon which NextGen programs such as data sharing, Data Comm and TBO will reside.

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[18] http://aviationweek.com/aftermarket-solutions/next-generation-efbs-integral-nextgen-cockpit

Airborne Reroute (ABRR), a key enabler for MBT, became operationally available in December 2016. ABRR provides the ability to electronically send TFMS-generated airborne reroutes to ERAM enabling controllers to issue reroutes to pilots via voice. As mentioned in Section 3.1, the associated Data Comm functionality becomes available starting in 2019 (FAA 2016c).

The FAA's latest NAS Target Top Level Systems Requirement Document (FAA 2014c) identifies the following ERAM capabilities that would be relevant to MBT:

- Initial Conflict Resolution Advisories (2019)

- Traffic Management Initiatives with Flight-Specific Trajectories (2017)

- Support for TBFM's Point-in-Space Metering (2018)

3.7   TFMS

In today's NAS, there is not one encompassing tool that supports the needs of traffic management. The primary system designated to support traffic management is TFMS. It consists of centralized trajectory modeling capabilities, logic, and data as part of the TFMS core, and a decision support tool (DST) called the Traffic Situation Display (TSD). The TSD is used by traffic managers across the NAS and provides a NAS-wide view of current and future traffic demand, along with some system constraints. Reroutes, flow evaluation areas (FEAs), flow constrained areas (FCAs), and Collaborative Trajectory Options Program (CTOP) initiatives are all modeled and issued via the TSD.

The TSD allows the traffic manager to graphically display the current position of all instrument flight rule (IFR) flights. The TSD also uses a system of layers to display the current status of alerts and weather, as well as map overlays such as sectors, fixes, navigational aids (NAVAIDs), and airports. TSD allows communicating potential reroutes and constrained areas of airspace with other facilities and remote users of TSD (CSC 2012). In addition, TSD is used to create and examine FEAs and FCAs for demand/capacity imbalances. FEAs can be used for determining miles-in-trail (MIT) restrictions. FEAs can also be used as a precursor to actually constraining traffic through the FCA. An FCA is needed to support airspace flow program (AFP) or CTOP traffic management initiative (TMI) functions. The Monitor Alert function of the TSD is used to determine sector imbalances based on projected traffic counts and the sector's monitor alert parameter (MAP) (see Figure 3). Sector traffic counts that exceed their MAP values may result in a TMI response.

Flight Schedule Monitor (FSM) is a separate client/server application used to model and issue other types of TMIs, to include AFPs, ground delay programs (GDPs), and ground stops (GSs), along with additional tools for modifying those events to include compressions and blankets. FSM is considered part of TFMS from a program perspective, but technically, it is a different application and communicates with the TFMS core via custom interfaces. It is expected that the FSM capabilities will eventually be absorbed within the TSD.

FSM monitors scheduled flight arrivals and departures from an airport, or flights entering and departing from defined volumes of airspace (i.e., FEA and FCA) to identify demand/capacity imbalances (Metron Aviation, Inc. No date provided). When an imbalance exists, traffic management specialists at the Air Traffic Control System Command Center (ATCSCC) are able to model different TMIs that would be able to alleviate the imbalance, including analyze combinations of GSs, GDPs, and AFPs to determine the best approach to address the imbalance. FSM updates demand in the flight schedule display approximately every five

minutes to keep the picture current. FSM users can also examine historical data to replay a day's events and analyze the effects of all traffic management programs.
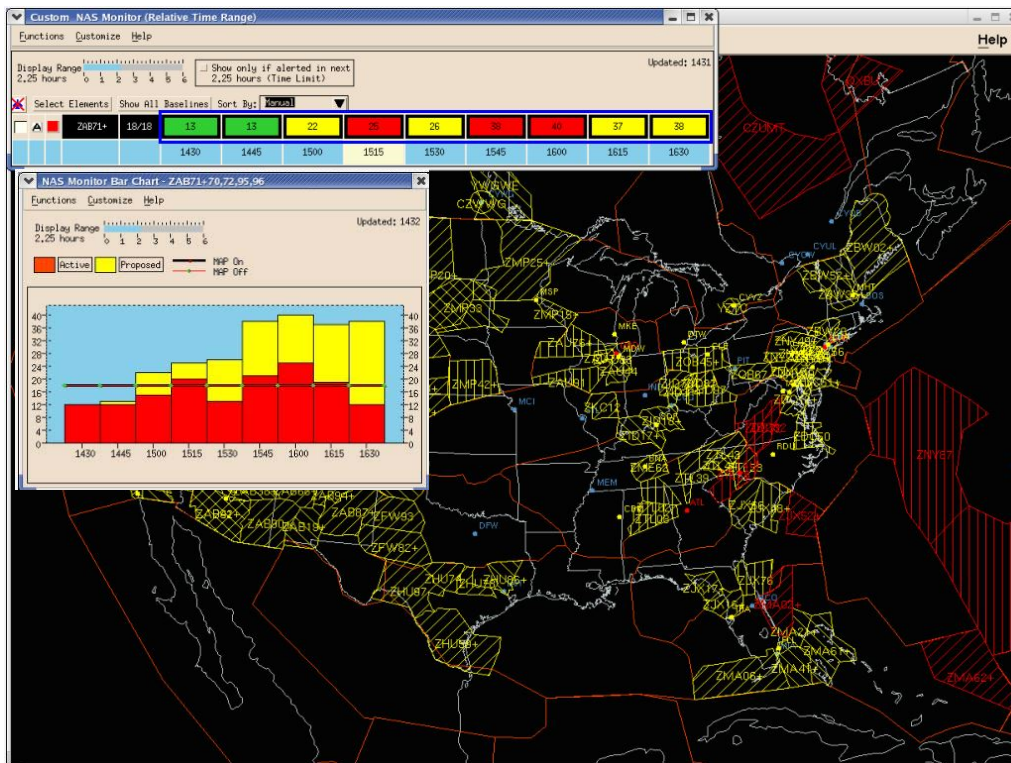
Figure 3. TSD with Monitor Alert function displaying green, yellow and red sectors

Both the TSD and FSM have reduced functionality versions called *thin clients* available to flight operations centers (FOCs) that are part of the FAA's collaborative decision making (CDM) partnership. The thin clients facilitate a common situational awareness among the ATCSCC and users in the NAS. For example, FOCs can model the effects of the TMI and decide whether to alter their own operations by cancelling, delaying, or rerouting flights.

The last component of TFMS is the National Traffic Management Log (NTML), which is both an application and an archive. Traffic managers use NTML to coordinate TMIs between facilities and then log the TMIs, which are captured in the archive. The NTML archive includes TMIs issued by the TSD, FSM, TBFM, and the Departure Spacing Program (DSP) (Shisler, Leiden, et al. 2014).

The FAA's latest NAS Target Top Level Systems Requirement Document (FAA 2014c) identifies the following planned TFMS capabilities:

- Integrate TMI Modeling
- Airport Acceptance Rate Decision Support
- Improve Demand Predictions
- Arrival Route Availability Planning
- Integrated Departure Route Planning
- Improve Special Activity Airspace (SAA)-Based Flow Predictions

3.8   TBFM

TBFM uses time instead of distance to help controllers sequence air traffic. Compared to the traditional miles-in-trail process, TBFM provides a more efficient traffic flow that reduces fuel burn and increases traffic capacity.

Departure Scheduling – TBFM enables traffic managers to control arrival times more efficiently at destination airports by adjusting departure times at originating airports.

En Route Departure Capability – Traffic managers also adjust departure times for more efficient integration of flights into the en route stream.

Airborne Metering – TBFM generates a scheduled time over an arrival point. Controllers will use vectoring, holding, or speed directives to deliver aircraft at the scheduled time.

Arrival Management/Situational Awareness – TBFM shares runway demand projections, route assignments, and arrival progress. With this enhanced situational awareness, traffic managers adjust routes and spacing to manage air traffic flows more effectively.

TBFM also calculates speed advisories for the ERAM displays so controllers can efficiently manage flow, and place each aircraft at the correct place and time to initiate an optimized profile descent (OPD) more than 100 miles from arrival airports.

Future work is moving TBFM into en route operations to replace MIT restrictions, such as pre-defined meter points along National Playbook routes for use during weather events (FAA 2013c).

3.9   SWIM

In the past, the state of the art for connecting two systems required a fixed network connection and custom, point-to-point, application-level data interfaces. SWIM reduces the high degree of interdependence among systems and unique, point-to-point application interfaces. SWIM's approach allows software applications in the NAS to interact with one another through information services that can be accessed without knowledge of an application's underlying platform implementation. This simplifies interface requirements to existing NAS systems and ensures new systems can be built with minimum technology (hardware, software, and data definition) constraints. SWIM producers and the types of information they provide are shown in Table 3. It is relatively straightforward for external consumers such as FOCs or research institutions to get access to SWIM.[19] Note that most if not all of this information would be highly valued by FOCs and pilots for planning, monitoring real-time activity, and shared situational awareness with the ANSP.

Table 3. SWIM producers and the information provided.[20]

Producer	Description of information
AIM FNS	Aeronautical Information Management (AIM) Federal NOTAM System (FNS) provides NOTAMs
AIM SAA	Provides Airport reference and configuration data, including: definitions and schedule information for SAA, Temporary Flight Restriction (TFR), procedure (Area Navigation [RNAV]/ RNP) data, and obstacles.

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[19] https://www.faa.gov/nextgen/programs/swim/products/getConnected/
[20] https://www.faa.gov/nextgen/programs/swim/products/

Producer	Description of information
AIM Modernization (AIMM) Segment 2	AIMM Segment 2 (S2) will modernize the ingestion, integration, management, and distribution of aeronautical information by establishing the Aeronautical Common Services (ACS) and a one-stop-shop (OSS) customer portal. ACS and OSS will streamline dissemination and updates to Airport reference and configuration data, SAA, FNS, and other types of aeronautical information.
CSS-Wx	Common Support Services-Weather (CSS-Wx) will modernize, centralize and streamline distribution of weather within the NAS. CSS-Wx will replace existing data feeds from the Integrated Terminal Weather System (ITWS), Corridor Integrated Weather System (CIWS), Enhanced Weather Information Network Server (WINS) Dissemination (EWD), Weather Message Switching Center Replacement (WMSCR) System, and Weather and Radar Processor (WARP).
ITWS	ITWS provides a variety of weather information in graphic and textual forms, such as wind shear and microburst predictions, storm cell and lightning information, and terminal area winds aloft.
NCR	The NAS Common Reference (NCR) Service will integrate, aggregate, correlate, and filter a variety of NAS data to form spatial and temporal relationships.
SFDPS	SWIM Flight Data Publication Service (SFDPS) provides a variety of En Route flight data, such as flight plans, beacon codes, and handoff status. SFDPS also disseminates data regarding airspaces, such as Sector configuration data, route status, SAA status, and altimeter settings, and General data including ERAM status information.
STDDS	SWIM Terminal Data Distribution System (STDDS) provides surface movement data, approach surveillance radar data from Standard Terminal Automation Replacement System (STARS) systems, Runway Visual Range (RVR), and a variety of departure event data.
TBFM	TBFM provides a variety of aircraft metering information, airport configuration and adaptation data.
TFDM	Terminal Flight Data Manager (TFDM) will provide a variety of Airport information, Surface and flight data, and flow information.
TFMS	Through Traffic Flow Management Data (TFMData), TFMS provides the equivalent of the legacy Aircraft Situation Display to Industry (ASDI) data (retired in 2016), which includes aircraft scheduling, routing, and positional information. In addition, TFMData provides AFP, ATCSCC Advisories, CTOP, FCA FEA, GDP, GS, Reroutes, airport runway configuration and rates, airport deicing status, restrictions, and Route Availability Planning Tool (RAPT) timeline data.
WARP/EWD	WARP provides NEXRAD data via the NAS Enterprise Messaging Service (NEMS)
WMSCR	WMSCR collects, processes, stores, and disseminates textual aviation weather products such as Pilot Reports (PIREPs) and Altimeter data.

3.9.1   Enablers

- Individual SWIM producers becoming compliant with SWIM standards.

3.9.2   Roadblocks to adopting SWIM

The following roadblock was identified in Wilber (2014):

Global harmonization across SWIM's and ANSP's has not yet begun.… US definition of SWIM… differs significantly from Euro-SWIM.

3.9.3   Negative impacts of roadblock on MBT

Dual standards for SWIM may limit international air carrier effectiveness with respect to certain MBT concept elements such as trajectory negotiations because of incomplete information.

3.9.4   Specific implications for MBT

SWIM has vast potential for improving information sharing across stakeholders that has been impossible until recently. Existing concept elements should be reexamined to determine if newly available information can be leveraged to improve the concept element.

3.10   IFC

IFC is the term used by providers of airborne internet services. IFC can be provided by either ground-based (a network of transmission towers pointed upwards) or satellite-based systems. While primarily intended for passenger internet, the cockpit is now able to leverage IFC through EFBs. Internet speeds are expected to increase dramatically in the near-term. For example, domestic industry leader GoGo, originally a ground-based service, recently launched a 2Ku satellite-based service. The network reaches about 70 Mbps per aircraft and will possibly be as fast as 100 Mbps in the near future. Currently, each IFC provider installs proprietary equipment on the aircraft with signed long-term contracts, locking in the flight operator and making it difficult to switch to another IFC provider due to the aircraft down-time required.[21] A new IFC provider, SmartSky, is developing a ground-based system and advertising 4G speeds without the latency associated with high-bandwidth satellite systems.[22]

3.10.1   Roadblocks to adopting IFC

High cost inhibits low-cost carriers from implementing IFC.

3.10.2   Negative impacts of roadblock on MBT

Low-cost carriers may not be able to leverage EFB applications and SWIM information. Thus, certain benefits of MBT (e.g., effective trajectory negotiation) that rely on dynamic information may not be attainable to them.

3.11   AAtS

AAtS leverages information from SWIM producers to support operational strategies and decisions that are not considered safety critical. Below is a brief description of the AAtS concept:

> *AAtS is an air-ground solution that will leverage the SWIM infrastructure to give flight crews access to relevant, NAS data. The data delivered to flight crews via AAtS will come from a common infrastructure – SWIM. However, not all SWIM data will be available through AAtS in order to protect proprietary information and security. The information that will be available will increase common Situational Awareness (SA) between flight crews and ground operations, while promoting strategic planning and more informed decision making. AAtS will also be the mechanism that will afford airspace users the ability to provide near real-time input, such as atmospheric conditions, to ground operations and systems. Together, this timely, bi-directional communication link will help create a shared NAS picture and is expected to contribute*

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[21] https://www.bloomberg.com/features/2015-gogo-airplane-wireless-internet/
[22] http://smartskynetworks.com/

to increased predictability, flexibility, and efficiency within the NAS (Booz, Allen, Hamilton 2013).

The FOC may receive advisory information through AAtS via the vendor-managed AAtS data management service (DMS). The DMS accesses raw SWIM data that will manage, filter, validate and distribute relevant information in a usable format to customers. The FOC may also access SWIM data directly via the NAS boundary protection services (security gateway). In this case, the FOC acts as its own DMS.

Since ADS-B does not provide intent information, AAtS may prove to be the technology that facilitates aircraft receiving intent information about other aircraft via the flight plans published by TFMData.

3.11.1 Enablers

- IFC, SWIM, vendor DMS providers.

3.11.2 Roadblocks to adopting AAtS

The following roadblocks were identified in Wilber (2014):

- *Potential over regulation of currently unregulated information to facilitate government business goals may increase investment costs and reduce or kill business cases of many aircraft operators and potential DMS providers.*

- *Slow adoption of AAtS approach may result in many interim sub-optimal, often competing stove piped solutions that impede the rate of AAtS implementation and take up.*

3.11.3 Negative impacts of roadblock on MBT

Certain benefits of MBT such as effective trajectory negotiation will not be fully realized if the adoption rate of AAtS is slow.

4. Concept elements to support MBT

Review of existing TBO ConOps (see Section 2) documentation identified an initial list of concept elements expected to be relevant to MBT; in particular, the ICAO ConOps (ICAO-ATMRPP 2015) provided sufficient details. These concept elements are described in more detail in the following subsections:

- Information needs and sharing among stakeholders

- Closed trajectories and closed trajectory clearances

- Trajectory negotiation

- Managing residual trajectory uncertainty

- Improved climb and descent profiles

- User preferred routing and user preferred trajectories

4.1 Stakeholders' information needs and sharing

Much of the inefficiency in today's air transportation system can be attributed to a lack of timely and accurate exchange of information across relevant actors. This subsection identifies the information available to one actor that is needed by one or more other actors that is currently unavailable or outdated under today's operations.

The actors (and their associated automation in parenthesis) with the most relevance to MBT are the pilot (FMS, EFB), controller (ERAM, TBFM), FOC dispatchers and ATC coordinators (flight planning and fleet management), Air Route Traffic Control Center (ARTCC) Traffic Management Unit (TMU) personnel (TFMS/TSD, TBFM), and ATCSCC personnel (TFMS/TSD and TFMS/FSM). Due to the potentially vast scope of this topic, the description of information needs and sharing is limited in scope to MBT research areas. The sharing of information between actors in a MBT environment is depicted in Figure 4 (FAA 2014d).
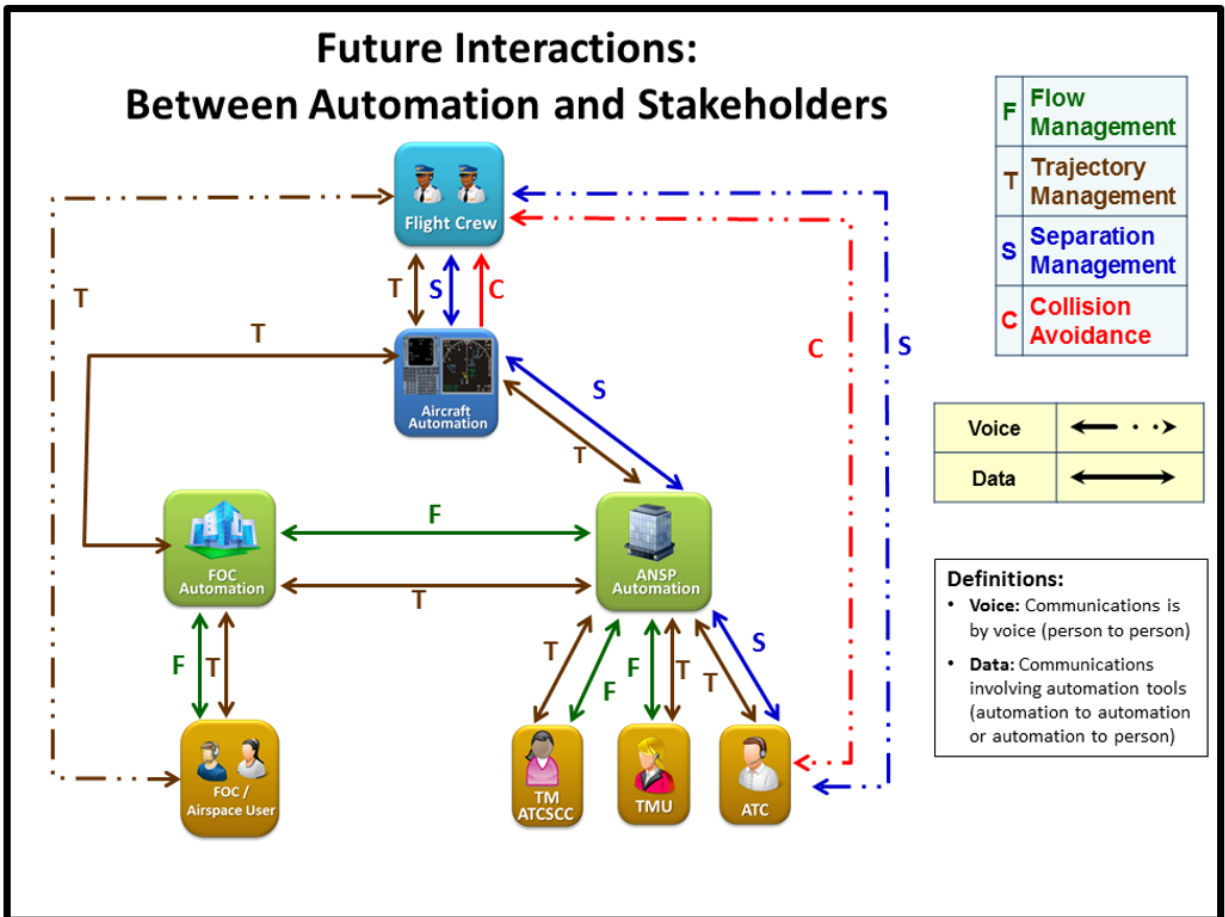
Figure 4. Information Flow in Support of MBT (FAA 2014d).

4.1.1 Pilot

Today's pilots perform extensive pre-flight planning prior to filing their IFR flight plan. However, once onboard the aircraft they are cut off from a great deal of information about what is occurring in the NAS. Pilots receive local area information from listening to local area VHF broadcasts and from onboard sensors such as weather radar, collision avoidance, and ADS-B. Pilots may receive updated information from their FOC about downstream conditions impacting their flight, but otherwise they have little insight into strategic impacts. Thus, as unplanned events unfold (e.g., weather, outages, early release of SAA), inefficiencies arise. In these situations, lack of dynamic information hinders the pilot's ability to improve flight efficiency (Wilber 2014).

NASA's Traffic Aware Strategic Aircrew Request (TASAR) ConOps (Henderson 2013) addresses the above shortcomings. The TASAR ConOps identifies the following types of information that can be gathered automatically to calculate a more efficient trajectory:

- Surveillance through ADS-B In – receives traffic information sent via ADS-B Out, ADS-R, and TIS-B.

- Surveillance through AAtS – while the TASAR ConOps called out ASDI, ASDI is no longer supported as of April, 2016, and has been recently replaced by TFMData (see Section 3.9). This includes flight plan, flight plan amendments, and current aircraft position for all aircraft in the NAS.

- Convective weather information – through onboard weather radar, AAtS, satellite weather, and FIS-B. Onboard weather radar is capable of detecting significant convection and lightning strikes at 200 nm or more from the aircraft to provide an indication of the current weather in the forward direction of the aircraft. Satellite weather and FIS-B provide both provide NEXRAD reflectivity, which provides an indication of current weather conditions, and convective Significant Meteorological Information reports (SIGMETs), which provide forecasted convection.

- Wind velocity and temperature – satellite weather, IFC, AAtS, and/or FIS-B. Updated wind field information in particular is key to effective trajectory optimization.

- SAA status – available through FIS-B, AAtS, and/or IFC. Early release of SAA provides an opportunity for more direct routing. Although not called out in the TASAR ConOps, airspace-related NOTAMs (e.g., facility/equipment outages and volcanic ash) would also be available through the above-mentioned services.

- Turbulence data – while identified in the TASAR ConOps, availability and quality of turbulence data needs to be improved before it can be used operationally for trajectory change requests.

- ATC procedures – departure, arrival, and approach procedures defined on charts and available in the FMS navigation database.

- Other ATC information such as sector boundaries – database of sector structure, letters of agreement (LOA) between ATC facilities, and standard operating procedures (SOPs) within a facility. Data rarely changes so updates are not required during flight. Consideration of these types of information in the proposed trajectory can improve ATC acceptability. Not currently available to pilots.

- TMIs – the TASAR ConOps only identified a small subset of TMIs, but since TMIs are now part of TFMData, the full list of TMI-related information should be included (see Section 3.9). The relationship between TMIs and trajectory constraints varies – some TMIs translate directly into constraints (e.g., a weather reroute trajectory) others are fuzzy as to the eventual impact on a trajectory (e.g., MIT restrictions). ICAO (ICAO-ATMRPP 2015) suggest minimizing TMI *"trajectory constraints to the extent possible and to the tolerance level commensurate with the ATM function it serves, to avoid limiting airborne operations more than is strictly required. One could for example adhere to a target time within a defined tolerance level of ± 2 minutes for arrival at a metering fix, and simultaneously allow for fluctuations (within limits) in speed to keep the flight optimized in a varying atmosphere, or add lateral or vertical trajectory constraints triggered by the need for conflict resolution."*

- Updated ATC Information – the FOC (primarily through the ATC Coordinator position) receives updated Traffic Flow Management (TFM) information through direct communication with an Air Route Traffic Control Center (ARTCC) or Terminal Radar Control (TRACON) TMU that could influence trajectory change requests (e.g., reroute to a different arrival corner post, avoid certain sectors or airways).

- Fleet optimization information from the FOC – fleet optimization may override individual trajectory optimization. For example: 1) the FOC directs own-fleet sequencing of flights at the arrival fix to facilitate passenger connectivity; 2) the FOC informs the pilot about lack of gate availability at the destination airport to inhibit trajectory change requests for reduced flight time, particularly for airports with congested ramp areas. In proposing new trajectory change requests, these examples may cause the pilot to change the optimization objective and/or manually impose new constraints.

4.1.1.1 Success stories

4.1.1.1.1 <u>Traffic Aware Planner</u>

The Traffic Aware Planner (TAP) is a cockpit decision support tool developed under TASAR. A modified version of NASA's Autonomous Operations Planner (AOP) is installed on a portable EFB. A flight-test aircraft was modified to host the EFB, the TAP application, an ADS-B processor, and a satellite broadband datalink. Nine evaluation pilots conducted 26 hours of TAP assessments using four route profiles in the complex eastern and north-eastern US airspace. Twelve TAP-generated trajectory optimization requests were submitted to ATC, of which nine were approved, and all of which resulted in fuel and/or time savings.

Of the information sources identified in the TASAR ConOps above, the trajectory change requests incorporated traffic information via ADS-B, SAA boundaries, and wind-field data derived from live broadband connectivity to the National Oceanographic and Atmospheric Administration (NOAA) Rapid Refresh system. Weather avoidance was not evaluated in the flight trials, and SAA boundaries were hard-coded into a database available to TAP and treated as "permanently hot" airspace.

All program objectives were met, and the next phase of TAP development and evaluations with Alaska Airlines and Virgin American Airlines is underway (Maris et al. 2014). Recently, a TASAR roadmap was developed for evolutionary implementation of TASAR concept elements leveraging advances in NextGen (such as Data Comm) while minimizing repetitive investments by users in hardware and certification. Each roadmap step is supportable on its own merits, enabling the choice by each operator on how far to proceed on the roadmap. (Cotton et al. 2016).

4.1.1.2 Roadblocks to adopting pilot/FMS information needs

- FMS database capacity (Herndon 2012):
  - Today's navigation databases (depending on vendor) range from 6 MB to 8.2 MB. There are several existing FMS models that store 2 MB or less.
  - Another FMS capacity issue is the number of waypoints available for processing. One widely used FMS model with ample navigation database capacity may store a maximum of 255 terminal waypoints for an individual airport. Some airports now exceed 300 waypoints.
  - One FMS model has a limit of 99 total procedures and a limit of 8 waypoints per procedure.
  - With the advent of Performance Based Navigation (PBN) procedures, the demand for increased navigation database memory capacity will continue.
  - Today, memory limitations require that some operators carefully customize their databases based on the individual needs of their operation. One example given is removing all holding patterns except those on missed approaches.

- While Section 4.1.1 identified ATC procedures as a type of information needed by the pilot/FMS, there are many ATC LOAs and SOPs that can change the FMS trajectory that are unknown to the pilot and are not available in an FMS database. Furthermore, trajectory changes due to these procedures often put the aircraft on an open trajectory (e.g., temporary altitudes – see Section 4.2).

4.1.2 Flight Operations Center

The FOC provides a wide range of capabilities for the air carrier: fleet management, dispatch, flight planning, ATC coordination, load planning, flight following, weather, maintenance, crew tracking, crew scheduling, passenger connectivity at hub stations, and understanding airport operations (IATA 2014). Most of the information needed for these capabilities is internal to the FOC. This section focuses on the information needed by the FOC from both the ANSP and the pilot to effectively manage their operations.

Section 4.1.1 identified the needs of the pilot. All of the information needed by the pilot is also needed by the FOC so it is not repeated here, but the granularity or time horizon of the information may be different. For example, the FOC, usually through the ATC coordinator position, needs additional information about TMIs as it may impact fleet management strategies as noted in Mafera and Smith (2000):

Need for causal information

The ATC coordinator must be able to understand why changes in NAS constraints have occurred. Often it is a challenge for the airlines to interpret an action taken by ATC. When asked how he dealt with MIT restrictions, a dispatcher replied, "When I see a miles-in-trail restriction, it's like a red flag … the first step is to figure out what is causing it." ATC coordinators and dispatchers need to know the context in which ATC has undertaken a particular system-wide action. In other words, restrictions implemented by ATC must be clearly associated with an event. The explicit linking of traffic-flow restrictions with their associated event provides causal information (i.e., the underlying reason) about the restriction. The presence of causal information, created by clearly identifying and defining events, provides critical route planning information. Different types of events usually require airlines to apply different strategies for minimizing their impact. For example, weather-related events are dealt with differently than events that involve high traffic volume. Knowledge of the nature of the event allows the airlines to react more effectively to the changing constraints and make the appropriate adjustments for future flights.

Currently, causal information is provided inconsistently. The FAA's TMI Standardization Project is working to ensure the same causal information is consistent and available across all TFM tools (TSD, FSM, and NTML) (Shisler, Cunningham, et al. 2014). This project is also working to identify coupled TMIs. For example, linking a passback MIT restriction to the original TMI (e.g., another MIT restriction or TBFM metering).

Mafera and Smith (2000) also notes that historical information about previous TMIs is useful:

Need for historical information

In order for ATC coordinators to infer ATC actions, there needs to be information available that will allow for the anticipation of constraint changes on the NAS. Access to a database of previous ATC actions would make it easier for ATC coordinators to anticipate constraint changes on the NAS. If this information were available, the ATC coordinator would be able to formulate a more comprehensive system outlook; the outlook may also include impending constraint changes on the NAS. This will enable

airlines to take the appropriate steps to minimize disruptions to service in advance of actual constraint changes.

Note that only CDM FOCs have access to historical information currently through the TFMS thin client applications (see Section 3.7).

4.1.2.1 Roadblocks to adopting the FOC's role in NextGen

In the Joint Planning and Development Office's (JPDO's) FOC report (JPDO 2012), the following shortcomings were identified regarding the FOC's limited role in NextGen:

Finding 4: The rules and content for data sharing are not clearly defined. While NextGen stresses the importance of "distributed decision making," increased user focus, and provisioning information to users, the current NGIP [NextGen Implementation Plan] does not address the data availability, rules, and related processes that will be required to bring this to fruition.

Finding 5: There is a lack of appreciation for and incorporation of the role of the FOC to ensure the success of the FAA Data Communications (DataComm) program.

4.1.3 Controller

The information needs of the pilot also apply to the controller to the extent that it supports the controller's view of the world (around the sector vs. along the flight plan for the pilot). In addition, an ICAO flight plan filed by the pilot or dispatcher provides the following information to the controller:

- Aircraft identification (Note: Aircraft identification means the radio call sign!)

- Flight rules and type of flight

- Number of aircraft, type(s) of aircraft and wake turbulence category

- Equipment on board

- Departure aerodrome ICAO code and planned time of departure

- First cruising speed and first cruising level or altitude

- Lateral route to be followed

- Destination aerodrome ICAO code and total estimated elapsed time (EET)

- Alternate aerodrome(s)

- Remarks and other equipment (emergency and survival)

- Fuel endurance and total number of persons on board

Equipment codes describe the communication, navigation, approach aids and surveillance transponder equipment on board an aircraft. Equipment is a key piece of information because it determines aircraft capabilities and the procedures the controller must use to accommodate those capabilities. In the mixed equipage environment of Data Comm and ADS-B, it will become even more important.

Controller and pilot views of the weather can be different. The controller can trust the pilot to maneuver as necessary, but this puts the aircraft on an open trajectory.

While the flight plan accurately portrays the lateral profile of the flight, the vertical profile is ambiguous to the controller so large buffers are used for separation. If FMS trajectory prediction for TOC and TOD were able to be provided to the controller, this would address some of the

ambiguity. The remainder of the ambiguity is a result of the differences in trajectory prediction between the FMS and ERAM, which is discussed in Section 4.3.5.

4.1.4 Traffic managers

The pilot and controller information needs also apply to traffic managers so it is not repeated here. However, the time horizon of traffic managers (and TFMS) is much larger than that of controllers and pilots. Filing flight plans as early as possible (preferably the day before) provides the ANSP with an accurate picture of expected demand and can help lessen delays that arise as a result of constraints in the NAS.

Flight planning services that are CDM participants have a direct connection to TFMS – flight plans filed through them go immediately into TFMS as *early intent* messages. This ensures that a flight will be considered *known demand* if any TMIs are issued. Then, usually a few hours before the flight, the actual flight plan is filed, detailing the route and other specifics.

When the ATCSCC implements a TMI, it models the initiative based on the available traffic information present in TFMS. When a flight plan is in TFMS during the planning process for the TMI, the flight is considered known demand and is accounted for in TFMS planning.

If a flight plan is not in TFMS due to late filing, any modeled TMIs will be based on incomplete information and will not accurately and efficiently address the imbalance that TFMS is trying to solve. The most restrictive TMIs tend to occur when TFMS suddenly has too much demand for a given area or airport within the NAS, without adequate time to proactively plan for it. Late filers will likely receive additional delay as a result. These additional delays can be significant, many times resulting in the maximum delay for the TMI, which can be hundreds of minutes.

4.2 Closed trajectories and closed trajectory clearances

A closed trajectory refers to ANSP automation, FMS, and FOC automation all having a common, shared view of the aircraft's intended trajectory. Closed trajectories enable accurate evaluation of the paths of multiple aircraft at points ahead of the respective aircraft for the purpose of conflict detection and flow management (JPDO 2011a), thereby reducing the need for downstream controller intervention. A closed trajectory clearance is any controller-issued clearance that ensures the updated trajectory is closed (e.g., an OPD or a route amendment). One of the objectives of MBT is to utilize closed trajectory clearances in the lateral, vertical, and temporal dimensions as much as possible to improve trajectory predictability and overall NAS predictability.

In contrast, an open trajectory refers to aircraft no longer flying a shared view between the aircraft and ground automation. If the aircraft is flying based on selected heading, speed, or altitude in the mode control panel, then this typically represents an open trajectory because it is overriding the FMS trajectory.

An open trajectory can be identified in ERAM in two ways:

1) The controller enters the temporary trajectory change information into ERAM at the same time as the controller gives the instruction to the pilot – for example, heading (lateral dimension), temporary altitude (vertical dimension), temporary speed (temporal dimension), and hold with expected time duration (temporal dimension) can all be entered into ERAM quickly. The ERAM display indicates these are temporary changes in the flight data block, which serves as a reminder to the controller and facilitates handoff coordination with the next sector.

2) If the controller does not enter information per #1, then ERAM will eventually identify that the aircraft is out of the conformance bounds of the predicted trajectory.

In either case, identification of an open trajectory in ERAM triggers logic to rebuild the trajectory, which is dependent on the dimension. For example, in the lateral dimension, it does this by returning the aircraft to some waypoint in the planned route of flight (where the waypoint selected is based on assumptions about controller's intent – e.g., the controller would not send an aircraft back to a waypoint it has already passed). In the vertical dimension, ERAM continues to use the intended altitude. The main issue with temporary trajectory changes is not knowing when the aircraft will return to the intended trajectory – it could be 30 seconds, or it could be several minutes. Open trajectories are known issues for ERAM, particularly with regards to conflict probe performance (Mondoloni et al. 2016).

Unlike ERAM, TFMS does not have access to controller entries for temporary trajectory changes so conformance monitoring is the only way to identify an open trajectory. Like ERAM, there is logic to rebuild a trajectory when out of conformance. In addition, TFMS has special consideration for the temporal dimension since it must also perform trajectory prediction for pre-departure aircraft. If an aircraft has not departed within 5 minutes of the departure time, the departure time used in the trajectory prediction is set to the current time and the time counter gets reset. This logic assumes the aircraft will eventually depart, which ensures that the trajectory is accounted for in demand predictions. If the flight still has not departed after 90 minutes and there is no explicit action to update the departure time, the flight is cancelled from the perspective of TFMS trajectory predictions.

When MIT restrictions are in effect in the NAS, currently TFMS does not account for those restriction in any of its logic. It does not try to estimate a delay for individual flights or the flights in aggregate, meaning that estimated demand on downstream sectors or airports will be inaccurate until each affected aircraft has met the MIT restriction and is back on its intended trajectory.

Another situation that causes temporally open trajectories in TFMS (but much less frequently than MIT) is when a flight is awaiting departure, but the flight is constrained by a call for release (e.g., no space in the overhead stream) (note: this applies to situations where TBFM is not managing internal departures). If the traffic management coordinator (TMC) knows a particular flight will be on the ground for, say, at least an extra 15 minutes, the TMC generally does not update the departure time. Some temporal uncertainty would be removed if they did update the departure time instead of relying on the 5 min reset logic. This is in contrast to TMIs such as GDPs and AFPs, where required departure delays are captured through the Expect Departure Clearance Time (EDCT) parameter and are incorporated into the TFMS trajectory predictions.

4.2.1 Closed trajectory clearances issued by voice communication

The near-term MBT concept must handle a mixed equipage environment where some aircraft will not have Data Comm, but would expect to receive some level of MBT services. This section identifies the types of closed trajectory clearances that can be issued by voice that could be available to support near-term MBT. In the en route cruise environment, the most common closed trajectory clearance issued by voice is the direct-to clearance where one or more waypoints in the flight plan are skipped and the aircraft flies direct to the waypoint stated in the clearance.

Other commonly used closed trajectory clearances are standard terminal arrival routes (STARs), standard instrument departure (SIDs), and instrument approach procedures (IAPs). Collectively, these procedures identify both the lateral and vertical profile, which can be stored

in the FMS navigation database. When a controller clears a pilot to fly any of these types of procedures, it is understood that the aircraft follows both the lateral and vertical path without any additional instruction. For example, "*Descend via [STAR name]."* If the controller wants only a portion of the procedure to be followed an exception is used. For example, "*Descend via [STAR name] except maintain [altitude]"* requires the pilot to level off at the specified altitude unless additional instruction is provided later.

While TBFM includes the vertical window constraints associated with these procedures in its trajectory prediction, ERAM currently does not. However, there are plans to include them when ERAM incorporates Kinetic Vertical Modeling in the trajectory prediction (Young, Faith, and Schnitzer 2016).

4.2.1.1 Success stories

4.2.1.1.1 Efficient Descent Advisor (Coppenbarger et al. 2010)

NASA's EDA is a trajectory-based tool for en route air traffic controllers that computes OPD solutions designed to minimize aircraft fuel consumption and associated carbon dioxide emissions while maximizing airspace throughput. EDA advisories are designed to facilitate clearance delivery by voice using standard FAA phraseology and procedures. If the EDA advisory is airspeed only, there are two airspeed components – one for the cruise segment through the TOD and another for the descent segment. For advisories that include path stretching, the controller first issues EDA airspeed clearances to the flight deck followed by saying "advised routing when ready to copy," which prepares pilots for receiving the subsequent path stretch clearance.

The path stretch maneuver, if needed, uses auxiliary waypoints defined with the fix/radial/distance FRD naming convention: NAMEDFIXxxxyyy where xxx = 3-digit radial (deg) and yyy = 3 digit distance (nm) (note: these are also called degree distance fixes). For example, AMWAY125051 means an auxiliary waypoint relative to named waypoint AMWAY on a radial of 125 degrees and 51 nm distance as depicted in Figure 5. Once received on the flight deck, pilots enter the EDA clearances directly into their FMS (Coppenbarger et al. 2010).

Example EDA Advisory:

* M70/250K

* @LBF..AMWAY125@051..AMWAY TELLR1 PROFILE

Corresponding ATC voice clearance:

* "United 123, EDA clearance, maintain Mach point seven slant 250 knots, revised routing when ready to copy"

* "United 123, at North Platte, proceed direct to the AMWAY one two five at zero five one, then direct AMWAY, descend via the TELLR1 profile" (where LBF is the North Platte VORTAC)"
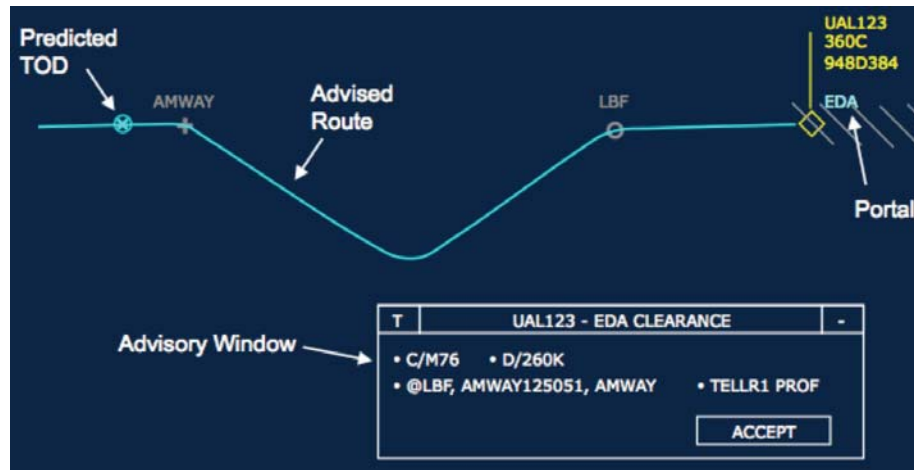
Figure 5. Example EDA path stretch advisory (Coppenbarger et al. 2010)

Maneuver execution delay is the period of time between the issuing of a trajectory clearance by a controller and the actual execution of that clearance by the aircraft (McNally et al. 2010). Maneuver execution delay for voice clearances that involve only a change in mode control panel (MCP) settings are small, but it can be larger if the voice clearance requires changing the route in the FMS. The EDA voice clearance described above *ensures the maneuver execution delay is zero with regards to the path stretch maneuver.* The aircraft receives the clearance well before it reaches North Platte (LBF), which is the start of the path stretch as indicated by *"United 123, at North Platte, proceed direct to …"* This formulation of the clearance provides sufficient time for the pilot to make the change in the FMS prior to the start of the path stretch ensuring that the trajectory prediction and actual trajectory are in close agreement.

4.2.1.2 Other types of closed trajectory voice clearances

4.2.1.2.1 Parallel-offset routes

A parallel-offset route is a parallel track to the left or right of the designated airway or route (see Figure 6). Such routes are normally associated with RNAV operations and entered into the FMS with just a few button pushes. Parallel-offset routes are a method for creating ad hoc routes that can be easily communicated by voice from controller to pilot and have been used for over a decade by controllers. The parallel offset can be used as a resolution to conflicts (e.g., overtaking slower aircraft or climbing through a stream of traffic to reach a higher flight level). When supported by ANSP automation,[23] offset routes are closed trajectories that are theoretically easy to specify to a pilot via voice communication, as only a turn-out angle, an offset distance, and a return waypoint are required (Lauderdale, Santiago, and Pankok 2010). Offsets are not currently modeled in ERAM.

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[23] In ERAM, creation of a parallel offset maneuver is currently not supported, but a controller could quickly develop a parallel-offset route (or path stretch for that matter) by "route clicking" to insert waypoints that approximate the path of the parallel-offset and then send this as a route amendment to ERAM, thus maintaining the closed trajectory.
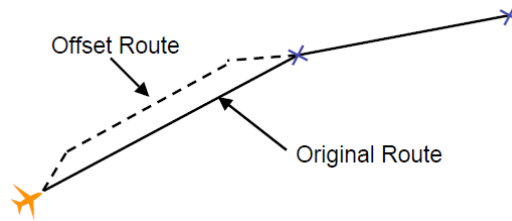
Figure 6. Parallel offset route from (Lauderdale, Santiago, and Pankok 2010)

4.2.1.2.2 New approach for full-route clearances by voice: Coded Airborne Reroutes?

This section discusses a concept that has not been pursued by the FAA to date. It is included here as a potential method for allowing aircraft not equipped with Data Comm to receive MBT services via voice communication. As background, pre-coordinated/published Coded Departure Routes (CDRs) allow controllers to instantaneously issue a reroute (containing a long route string) to a pilot prior to departure using an abbreviated clearance. The computer entry is abbreviated so that the controller does not have to type in a long sequence of route components and the pilot can have these routes pre-stored in their FMS. This procedure significantly improved ground movement at many airports during thunderstorm events by expediting the flows and allowing controllers to issue the best available route right up until "cleared for takeoff".

CDRs are based on airport-pairs, but it could be extended to airborne flights by leveraging other existing categories of routes such as:

- Navigation Reference System (NRS) Wind Routes are pre-coordinated and published ATCSCC advisories, but are ***not*** available to issue in an abbreviated form.

- National Playbook Routes are pre-coordinated and published ATCSCC advisories, but are ***not*** available to issue in an abbreviated form.

- National Q-Routes are pre-coordinated and published ***and are*** available to issue in an abbreviated form (typically have 5-10 on-ramp/off-ramp points).

Coded Airborne Reroutes (CARs) would allow controllers to use abbreviated clearances to expeditiously reroute airborne aircraft, leveraging the technology, procedural, and flexibility advantages that already exist with pre-coordinated/published CDRs, Playbooks, NRS Wind Routes, and Q-Routes (Kaler 2011).

4.2.2 Closed trajectory clearances using automation and Data Comm

Data Comm enables complex, closed trajectory clearances and is viewed as one of the key enablers for MBT going forward from today's capabilities.

4.2.2.1 Success stories

A comprehensive simulation study in 2010 utilized NASA's suite of strategic and tactical tools for conflict resolution and efficient descents (via EDA) integrated with simulated Data Comm capabilities. These tools offered five types of closed resolution trajectories (path stretch, direct-to, offset, altitude, speed) for each aircraft in a detected conflict pair. The simulation utilized 102 hours of actual Fort Worth Center traffic recordings from 32 separate 3-hour and 4-hour samples from busy weekday periods on 30 different days in 2010. In total, the analysis is based on 37,631 individual flights.

Results clearly demonstrate under a wide variety of traffic conditions that 4D trajectory automation can provide minimum-delay solutions to traffic conflicts, identify time/fuel-efficient flight trajectories, and substantially reduce the number of clearances compared to today's operations. Figure 7 shows the comparison between the flight plan amendments implemented in the simulation (top) vs. the actual flight plan amendments issued on May 13, 2010 (bottom). The very high number of temporary altitude clearances by the ZFW controllers in the field indicates a conservative strategy when dealing with the uncertainty in transition airspace. Nonetheless, the results support the hypothesis that closed trajectories improve predictability and reduce the need for controller intervention (McNally et al. 2010).
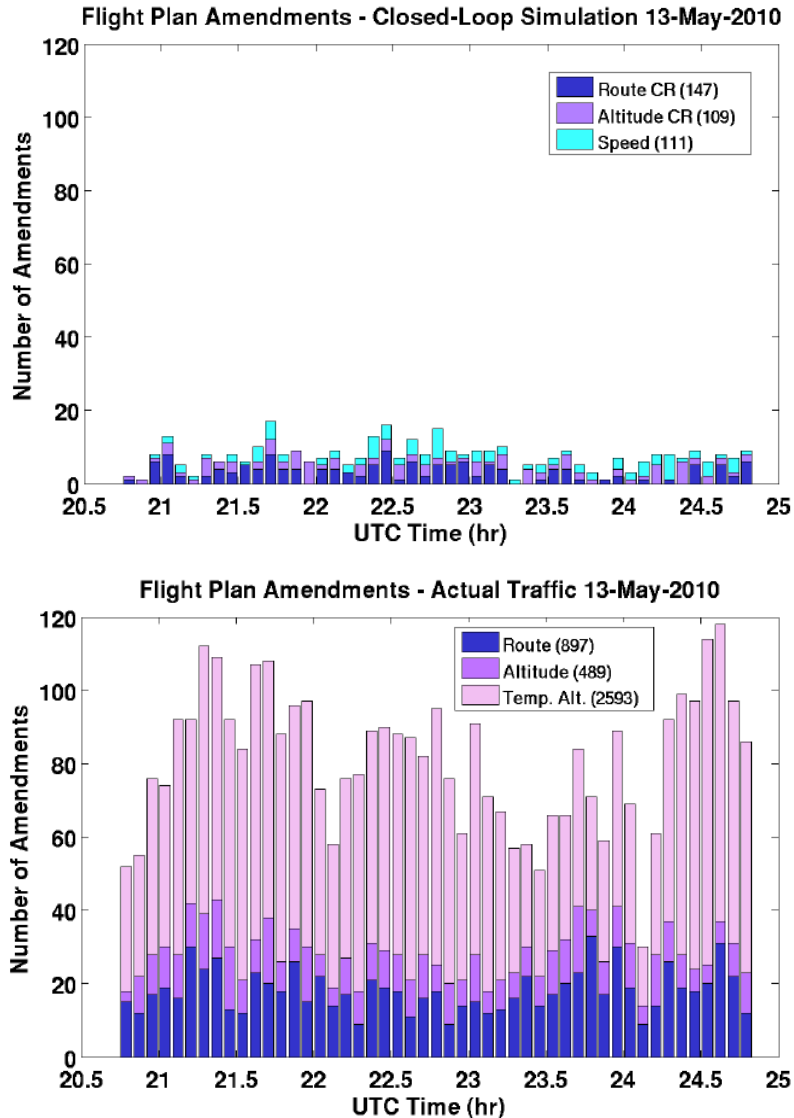
Figure 7. Comparison of actual Host with simulation flight plan amendments for common traffic sample (McNally et al. 2010).

In 2012, NASA's Airspace Operations Lab conducted a human in the loop study (HITL) to investigate the effects of varying levels of controller automation and Data Comm equipage (which enables complex, closed trajectory clearances) on controller acceptability and workload. Scenarios for four equipage levels were developed. The fourth level is omitted below because it

was a fully autonomous scenario and out of scope for MBT. The first three stages are described below:

The first stage, "Current Day", was designed to provide data approximating current day operations with the addition of ADS-B out surveillance data. The traffic levels were selected to be representative of current day peak traffic levels with a Monitor Alert Parameter (MAP) value of 18 aircraft per sector.

The second stage, labeled "Minimum NextGen", introduced limited data communication between the groundside and 25% of the simulated aircraft. This data communication enabled an automatic transfer of communication of aircraft from one sector to the next. This eased the controller workload in handling those aircraft. … This stage also introduced more decision support capabilities for the controllers, none of which were integrated with data comm. So, all control instructions still had to be communicated via voice. It was hoped that the new technologies could enable a capacity increase of 20%, and the MAP value was set to 22 aircraft per sector for the "Minimum NextGen".

In the third stage, entitled "Moderate NextGen", the controller planning tools and the flight management systems on-board the aircraft were integrated with data comm., and 50% of the aircraft were assumed data comm equipped. Controllers were able to issue trajectory change instructions to equipped aircraft via data comm. Based upon earlier research, it was hypothesized that this environment could enable a capacity increase of 50% over the Baseline and therefore the MAP value was set to 27 for this stage. (Prevot et al. 2014)

Results indicated that although the aircraft count increased by 20% and 50%, respectively, for the Minimum and Moderate NextGen conditions (with respect to Current Day), controller workload stayed constant across all three conditions. Controller acceptability improved slightly under the Minimum condition compared to Current Day, but dropped significantly under the Moderate NextGen condition because two participants rated the operations as "unsafe" due to not being alerted to conflicts (Wing et al. 2013). This indicates that simply adding automated functions for conflict resolution advisories without changing the operational paradigm may be problematic (Prevot et al. 2014).

4.2.3   Roadblocks to adopting closed trajectories

Appendix 1 of the En Route traffic Soft Management Ultimate System (ERASMUS) Concept of Operations (European Commission 2007) states:

Risk is linked to uncertainty which in turn causes the controller to doubt. Managing doubt is a very resource intensive activity – it consumes cognitive resources and represents one of the main draws on the mental economy. Because of the uncertainty inherent in the system, the controller's expert judgment is not always able to immediately categorize traffic situations as "conflict" or "no conflict". Some doubts can remain with regard to any particular perceived conflict. In this case, the controller can let the situation develop in order to refine their assessment and defer making a decision to intervene only when they are certain it is justified.

In other words, trajectory uncertainty causes controllers to use tactical clearances, which tend to be open trajectory clearances. Consider that automated conflict resolution advisories have been discussed for over two decades and still have not been implemented in ERAM.[24] Without the automation support for closed trajectories, controllers will continue to use open trajectory techniques.

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[24] https://www.caasd.org/library/papers/uret/

The following examples result in open trajectories because the ANSP and FMS automation do not have intent information about when aircraft will return to their intended trajectories.

- Conflict resolution strategies such as leveling aircraft off during climb or descent, vectoring, altitude changes, or speed changes.

- Vectoring and/or speed changes to meet MIT restrictions.

- Vectoring or altitude changes to bypass or climb above weather.

- SOPs and LOAs not accounted for in navigation databases (and thus not in the FMS) that specify crossing restrictions that require aircraft to level off and/or change speed.

Lastly, historical procedures remain entrenched in aviation culture and automation:

As a consequence, remaining at the cleared en-route altitude was seen as essential for safety and aircraft were not allowed to alter their altitude without explicit clearance. This explicit requirement for clearance to change altitude from the late 1920s is hard coded into ATM systems and Flight Management Computers to this day …(Wilson and Sipe 2016)

While aircraft can implicitly change direction when transitioning between lateral waypoints, aircraft cannot change altitude when encountering a vertical waypoint without an explicit clearance (except when allowed by specific departure, arrival, and approach procedures). This inhibits *implicit* altitude changes in the FMS that may be desired by the pilot and FOC such as efficient step-climbs as fuel is burned, improved flight efficiency due to altitude-related wind gradients, or avoiding turbulence by including planned altitude changes.

4.2.4   Negative impacts of roadblock

Open trajectory clearances exacerbate the trajectory uncertainty in the system. On the other hand, trajectory predictability enables controllers to use strategic, closed trajectory clearances, which then maintains a high level of trajectory predictability. Thus, one negative impact is not knowing what set of technologies, procedures, and cultural changes will be the *tipping point* that moves the NAS towards wide-spread use of closed trajectories and predictability to facilitate MBT. There is clearly cultural resistance to automated conflict resolution advisories.

4.3   Trajectory negotiation

The current system is not very conducive to trajectory negotiation. There are two main reasons for this: 1) voice communication of complex reroutes is impractical for widespread use in the NAS; and 2) the pilot or FOC negotiating the trajectory does not have complete visibility into static (e.g., SOPs and LOAs) and real-time ANSP constraints. Some users have gone to great length to incorporate unpublished ANSP constraints into their flight planning automation:

… an informal interview was conducted with a dispatch operator from the United Parcel Service (UPS). UPS uses a dispatch support tool called Lido Flight Planning Services, which considers all valid aeronautical restrictions (e.g. NOTAMs or "Notice to Airmen", restricted airspaces, weather minima, etc.) in creating flight plans that are optimized for various factors such as winds …

*… UPS decided to stop using these more direct routes, and worked closely with the ATC facilities to understand what procedures, **both official and unofficial,** could be expected and planned. UPS found that for their operations, it was most efficient to file their flights in line with what the ATCs were least likely to cancel. This knowledge base is very valuable to UPS since it is now also a part of their Lido system. For example, any*

procedure, e.g., "always expect 'FL290' as early as ZOB when going to any airport in ZNY" and "we typically prefer arrival procedure 'XYZ' during our morning rush" was documented and integrated into the Lido system as "fixed route" objects. With all this information integrated into the Lido system, UPS dispatch operators can create a flight plan by checking for any fixed-routes for a given city-pair, and can file the most optimal routing. If no fixed route constraints exist, then flight plans are optimized for winds. Due to the nature of traffic patterns in the NAS, flights in the Northeast corridor mainly use flight plans based on fixed-route constraints, whereas flights in the western part of the country typically use more wind-optimal routing (Lee et al. 2008). [Note: bold text added for emphasis]

One-off approaches like the one UPS has undertaken, while industrious, should not be the norm for users in the NAS.

Trajectory negotiation is used in oceanic operations through the Dynamic Airborne Reroute Procedure (DARP), but it is coordination-intensive and time-consuming:

Inadequate inter-FIR [flight information region] coordination also is a significant barrier to trajectory modification. Oceanic reroutes often traverse multiple FIRs. En route trajectory amendments in oceanic airspace are governed by the Dynamic Airborne Reroute Procedure (DARP). While DARP allows en route trajectory amendments, the procedure is time-consuming, requiring the dispatcher to coordinate with the FIR where the aircraft is currently operating and all downstream FIRs, possibly by e-mail, before the flight crew can request the route amendment. New York and Oakland Oceanic have developed procedures for coordinating with their international counterparts for some common routes and continue to work to improve the implementation of the procedure, but the significant amount of coordination required makes the procedure time consuming. (Fernandes, Rebollo, and Koch 2016)

The authors of this report were authors of the NextGen Trajectory Negotiation (NTN) ConOps (Hatton 2014). Some key points from NTN ConOps are listed below:

Problem Statement: *The route amendment process in today's system includes a number of manual steps that can be slow, cumbersome, and require involvement of actors that may not have access to the best information to determine the most appropriate amendment. As a result, it can be difficult for the NAS to respond to events in a dynamic and timely fashion. There are missed opportunities when flight operators that desire a different trajectory are not able to negotiate it. Today's system is not agile enough to consistently orchestrate user-preferred trajectories for all flights.*

Concept Overview: *NTN is a process by which the ANSP and flight operator negotiate trajectories that meet NAS constraints and flight operator objectives. Trajectory information is exchanged digitally among ATC, TMU, FOC (for aircraft supported by an FOC), and equipped aircraft (by voice for non-equipped aircraft) to ensure accurate and complete information is shared, resulting in more efficient negotiations.*

The specific actors required to participate in a negotiation may vary by situation. Actors' level of participation, procedures, and capabilities needed for trajectory negotiation depend on:

- *Aircraft phase of flight during the negotiation*
- *Time/distance until the aircraft reaches the expected Trajectory Change Point (TCP)*
- *Actor initiating the negotiation (controller, flight crew, traffic manager, or FOC)*
- *Reason for the negotiation*

- *The number of aircraft and flight category (e.g., same destination airport, within same fleet, shared route, and shared downstream sector) needing negotiated trajectories and consideration of any resulting demand/capacity imbalances*
- *Whether the aircraft is supported by an FOC, flight planning service, or has no ground support*
- *Aircraft equipment (e.g., digital data exchange, trajectory planning and evaluation capabilities)*

Some other key concept elements of NTN are:

1. The TMC can implement a negotiated trajectory directly without involving the controller currently responsible for the aircraft, assuming the first trajectory change point is sufficiently downstream of the controller's time horizon. This would be useful in situations where the current controller is too busy with events such as weather and/or the TMC is acting on behalf of many flights simultaneously that must all avoid a downstream constraint where a coordinated reroute plan is required.

2. While negotiating a specific trajectory is still an option, this lacks flexibility since the exact time duration of the negotiation process is uncertain. For example, the aircraft may pass the first trajectory change point before the trajectory is accepted by the ANSP, thereby invalidating the trajectory. Or the negotiation occurs very quickly but the aircraft must now wait 5 minutes for the first trajectory point, decreasing efficiency. To provide flexibility in the presence of negotiation duration uncertainty, the NTN ConOps proposed the notion of negotiating based on goals and constraints as depicted in Figure 8. In this example, the goal is to turn north as soon as possible via multiple options depending on the negotiation duration. The constraint is to reconnect with the route as it skirts the weather.
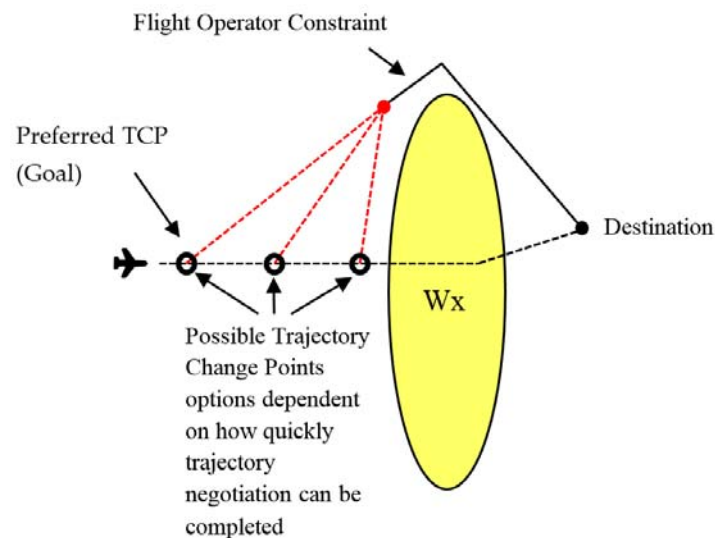

Figure 8. Trajectory negotiation by goal and constraint (Hatton 2014).

One question not explored by the NTN ConOps is how to equitably negotiate trajectories when multiple flights from multiple air carriers are involved. Park and Menon (2017) propose applying Bargaining Theory where the trajectory negotiation mechanism is formulated as an n-player, finite strategy game.

The objective of each aircraft in the game is to minimize its cost of deviating from its desired trajectory, while the objective of the controller is provide clearances that ensure fairness while preventing conflicts. In order to avoid the need to share competition sensitive business logic employed by individual aircraft, the utility function is formulated in terms of the percentage cast deviation for each aircraft…The feasibility and the performance of the proposed game-theoretic trajectory-negotiation mechanism are demonstrated in a merging arrival traffic situation.

4.3.1 Success stories

- The TASAR/TAP capability described in Section 4.1.1.1.1.

4.3.2 Enablers

- Data Comm is the key enabler. Others include AID, EFB, AAtS, IFC, and ADS-B In.

- The NTN concept for the TMC uplinking the negotiated trajectory, bypassing the controller, would require a TMC/pilot datalink capability.

4.3.3 Roadblocks to adopting trajectory negotiation

FMS capabilities do not support proposing a new trajectory, only to propose a flight-optimal way to achieve the given flight plan. EFB applications to support trajectory negotiation do not currently exist. While these applications will likely get developed when sufficient enablers are in place, the air carrier industry lack of interest in applications to leverage CTOP (which provide similar types of benefits as trajectory negotiation) is a cautionary tale for trajectory negotiation participation.

4.3.4 Negative impacts of roadblock

Trajectory negotiation is one of the MBT benefits that allows users to see direct, tangible benefits across the fleet or for individual flights. If users choose not to upgrade their capabilities to facilitate trajectory negotiation, it is an indicator that they would not likely upgrade for other aspects of MBT.

4.3.5 Specific implications for MBT

It will be difficult to make realistic estimates of user participation for trajectory negotiation, which will have a direct bearing on benefits.

4.4 Managing residual trajectory uncertainty

"*A 'predicted trajectory' represents the path that an aircraft is expected to follow from its current position onwards.*" (ICAO-ATMRPP 2015)

Traditionally, ATM systems have attempted to predict an aircraft's trajectory independent of the control system that is planning that trajectory and issuing control instructions. In automatic control theory, this is an open-loop system with an external observer. For example, a controller wants to merge two aircraft that will land on a runway. The controller notionally constructs a planned trajectory in his/her head, and then issues speed and heading commands to the aircraft. As the aircraft proceed, the controller's envisioned trajectory may change, and the controller will issue new commands reflecting the current state of the aircraft. Separately, an automation system is trying to predict the aircrafts' trajectories without knowing the planned trajectory (which only exists in the controller's head and may contain very little detail) or the commands issued to the aircraft. In this type of traditional ATM system, the trajectory prediction problem became one of making intelligent guesses based on generic knowledge about typical controller procedures and aircraft characteristics. Although the automation may be fine-tuned to

produce prediction errors that have a zero average error over many flights, for any specific flight, the trajectory prediction errors may be very large.

TBO introduces a closed-loop control model in which a detailed (rather than approximate) trajectory is planned (and captured in an electronic form, rather than residing only in a controller's head) and then the controller, pilot, and aircraft collectively attempt to control the aircraft to follow that planned trajectory, with a goal of minimizing error relative to the planned trajectory. The predicted trajectory is the planned trajectory, and the prediction becomes a self-fulfilling prophecy. Furthermore, the TBO concept generally involves aircraft being flown via FMS which is more accurate at following a target trajectory than a pilot manually flying the aircraft or a pilot manipulating autopilot inputs via the mode control panel.

Trajectory prediction uncertainty behaves considerably differently in a closed-loop system than it does in an open-loop system. In an open-loop system, the uncertainty increases monotonically with increasing prediction horizon since the future is unbounded. In a closed-loop system, the uncertainty depends on the constraints that are part of the 4D trajectory.

TBO concepts also include methods for trajectory synchronization (Torres, Martin, Klooster, and Ren 2011), which includes communicating trajectory assignments and constraints to all interested parties, sharing information such as wind data so that trajectory predictions can be based on common information (Mondoloni et al. 2016), and sharing the aircraft's FMS-calculated trajectory prediction with other systems via various datalink protocols (Konyak et al. 2008). Trajectory synchronization helps reduce trajectory prediction errors by enabling each prediction to utilize the best information possible.

While describing TBO, the ICAO TBO Concept (ICAO-ATMRPP 2015) describes *residual uncertainty* or *residual unpredictability* as follows:

> *With improved data communications for synchronizing information and its updates amongst the various operational actors and systems, and with the introduction of improved performance based navigation, the level of uncertainty is reduced substantially. However, the ATM network will never become fully deterministic; some level of inherent unpredictability will remain.*

Residual uncertainty is the trajectory prediction uncertainty that will continue to exist after implementing TBO. Furthermore, because of the residual uncertainty the planned trajectories will need to be continuously refined during both pre-departure and flight execution time frames to incorporate the latest data to achieve system objectives:

> "*Increasing performance of the overall system [through TBO] is therefore not simply a matter of freezing a plan and ensuring that all aircraft follow that plan. It requires planned trajectories to be continuously refined and revised during the execution phase, based on latest data, observations and predictions…*" (ICAO-ATMRPP 2015)

This section discusses the causes and impacts of residual uncertainty.

4.4.1   Sources of Trajectory Uncertainty

4.4.1.1 Predictable vs. Unpredictable Uncertainty

Trajectory uncertainty describes the possible error between the predicted trajectory and the trajectory that will actually be flown. One way to decompose trajectory uncertainty is by considering the "expected error" and the "unexpected error." The expected error is error that you know will exist and can describe in some mathematical sense. For example, you can write a model for how much the aircraft will deviate from the assigned trajectory due to flight navigation error. The unexpected error is the error from unpredictable events - events that may occur (and may even been expected to occur) but for which there is insufficient knowledge to describe their

occurrence in any useful way. For example, an aircraft may have an emergency and need to descend rapidly. Before this happens, the aircraft has an assigned trajectory and a predicted trajectory. There exists some uncertainty in the predicted trajectory that, at any moment, the aircraft might deviate dramatically from the predicted trajectory. However, there is no utility in trying to model this very low probability of the aircraft doing one of a very large number of possible deviations. Therefore, while the uncertainty exists, it is not included in models of the trajectory uncertainty.

Unpredictable events do not have to have a low probability of occurring. Another example of an unpredictable event that creates trajectory uncertainty is the need to re-plan the assigned trajectory. It is known that the assigned trajectory likely will be adjusted, either significantly to avoid a region of weather or congestion, or simply to add an RTA at a point along the assigned path. However, it is not known in advance when or how the trajectory will be adjusted. Therefore, there is trajectory uncertainty resulting from the possibility of future assigned trajectory changes, and the probability of this happening is not low, but we may not be able to model the uncertainty in a useful way. Sometimes an event could fall into either category depending on how much information is available about the event.

4.4.1.2 Trajectory Prediction Errors

Trajectory prediction errors contribute to residual uncertainty. Whether the trajectory is predicted by the FMS or ground-based automation systems, the models of future aircraft motion depend on wind data; the actual winds may differ from the forecast winds. Wind errors result in along-track trajectory prediction errors. Similarly, other data that affect the aircraft's trajectory (e.g., aircraft weight) may not be known accurately (Mondoloni et al. 2016). Weight is not known when the trajectory is initially planned prior to departure. Casado, Vilaplana, and Goodchild (2013) discusses how trajectory prediction accuracy is affected by errors in aircraft performance data. Wickramasinghe et al. (2016) compares actual flight data with modeled data to understand the characteristics of modeling data errors, concluding that actual aircraft mass values vary substantially and have a large effect on trajectory prediction accuracy.

4.4.1.3 Weather Forecast Errors

Because of wind and temperature forecast errors, or unpredictable weather events such as gusts, ground and airborne [trajectory] predictions are subject to deviations… Particularly for medium and long haul flights the longer time-horizon requires updates of meteorological information during flight execution to reduce the difference between weather forecast and reality. (ICAO-ATMRPP 2015)

Most TBO concepts include that weather forecasts will be shared as part of trajectory synchronization. However, weather forecast errors will remain a source of trajectory uncertainty. The trajectory actually flown is sensitive to wind and air temperature. If the trajectory is predicted using wind and temperature data different from what is actually experienced, the trajectory prediction will include errors.

Weather forecasts also affect regions of airspace that are avoided due to expected hazardous conditions. Errors in weather forecasts will result in trajectory changes either to avoid or use airspace for which the forecast was wrong. Anything that causes trajectories to change represents a source of residual uncertainty – the initial trajectory prediction did not turn out to be correct.

Turbulence is not currently forecast well, such that pilots often request altitude changes and even route changes to avoid regions of poor ride quality. This source of trajectory changes will persist in TBO concepts.

4.4.1.4 Capacity Forecast Errors

Often due to weather forecast errors, capacity of constrained resources will also remain uncertain under TBO concepts; the actual capacity may be either larger or smaller than what was forecast. Trajectories may change as the actual capacity for a period of time becomes more certain as that period of time gets closer to the present time.

Furthermore, TBO will not (at least initially) change how TFM is performed. While demand uncertainty will be reduced, remaining uncertainty in demand and uncertainty in capacity motivate TFM strategies that "hedge" by applying some of the delay that is expected to be required but waiting to apply all of the expected-to-be-required delay, in case it is not required. The assigned trajectories should be designed to apply some pressure to the capacity-constrained resource so that if the actual capacity is larger than the forecast, capacity is not wasted and delays are minimized. However, if the actual capacity is as forecast, or less than forecast, then assigned trajectories will need to be modified. This TFM process of absorbing some of the necessary forecast delay at longer time horizons while leaving some necessary forecast delay until later, in case it is not required, must continue to operate in MBT. Therefore, residual uncertainty exists because the assigned trajectories are expected to be modified for TFM reasons for many flights.

If TBFM continues to operate in the current method of allowing a flight's STA to vary based on the varying ETAs of all of the flights being scheduled, until the flight crosses a freeze horizon, then this varying STA is a source of trajectory uncertainty while the flight is outside of the freeze horizon.

4.4.1.5 Trajectory Flexibility

Trajectory flexibility can be a source of residual uncertainty. Currently, when an aircraft is flying through a region with sparse convective weather, the pilot often uses some flexibility to avoid convective cells, using the aircraft's weather radar. In this situation, planning a precise trajectory could be problematic, even over a shorter time horizon. Instead, the assigned trajectory needs to provide flexibility to allow piloting without violation of the assigned trajectory. However, in this case, the FMS is not flying the aircraft and does not know the pilot's intentions; the intent information from the FMS will not be overly helpful. Residual uncertainty could be elevated in such situations, as even if the lateral and vertical path is within a defined distance of the assigned path, the timing of the aircraft along that path, or the timing of the aircraft at the exit point from that airspace region, will not be known accurately.

Another source for assigned trajectory changes is the flight operator whose business considerations may change and who may initiate a trajectory negotiation to modify the assigned trajectory.

Pilots are accustomed to negotiating altitude changes "just in time". Implementing a 4DT that includes pre-cleared altitude changes will be a major culture shift since pilots do not always know what altitude they actually want ahead of time (Fernandes, Rebollo, and Koch 2016).

4.4.1.6 Departure Delay

Prior to takeoff, one of the largest sources of uncertainty is the time at which the flight will actually take off. Takeoff time can be planned and controlled to, especially once the aircraft is taxiing. However, unpredictable events frequently occur both before leaving the parking gate and after. The aircraft may be ready to depart early or late relative to a planned or scheduled time. Until flight operators are able to better manage the boarding and preflight period, a trajectory that is planned in advance will likely need to be updated to reflect the actual gate departure time.

The turn-around process involves many actors, systems and planning functions which work towards a shared common departure time. Elements of disturbance impacting the flight till take-off stem from irregularities with security, passengers, fueling, aircraft technical maintenance, baggage handling, etc. (ICAO-ATMRPP 2015)

Currently, aircraft taxiing in the airport movement area are handled first-come, first-served with the exception of controllers attempting to comply with departure release traffic management initiatives such as EDCTs. These TMIs often have a wide compliance window and are not always satisfied. Trajectories planned prior to takeoff will likely need to be updated based on the actual takeoff time. The runway assigned and terminal area flight pattern may not be known when planning the trajectory and, therefore, may result in required revisions to the assigned trajectory.

Even if the TBO concept is applied to the surface such that the aircraft is following an assigned trajectory during taxi operations, the FMS is not able to control the aircraft and the navigational errors of the pilot manually taxiing the aircraft will be larger in the time dimension. (ICAO-ATMRPP 2015)

4.4.1.7 Oceanic Airspace

Prior work determined that in the oceanic domain, key contributors to residual trajectory uncertainty include: takeoff weight, push back timing, en route winds/turbulence, airport configuration (runway assignment and terminal area routing), airport congestion (e.g., arrival delays) and controller flexibility. Takeoff weight is not known until right before pushback. Oceanic wind forecasts are out of date by the time they are published. Furthermore, flight operators can only file routes that comply with constraints but controllers can provide clearances that utilize all of the airspace. For example, in oceanic airspace controllers will give them "wrong-way" altitudes since traffic is highly directional with time of day, but the flight operator cannot file a wrong-way altitude as the preferred trajectory (Fernandes, Rebollo, and Koch 2016).

4.4.1.8 NAS Changes

If other flights change their trajectories or there are un-forecast NAS configuration changes (e.g., SAA opening or closing), a flight may be forced to change its trajectory. Therefore, these unpredictable events are sources of residual uncertainty.

Air traffic behaves as a complex system, not just as a consequence of non-deterministic external factors influencing execution (e.g. weather or passengers) as previously explained, but also because of the high degree of interaction between many parallel operations: Individual flights interact with each other as they share the same resources like airspace and runways (separation shall be assured) and air traffic control (overload of sectors shall be avoided, complexity shall not exceed certain levels). A change in one flight may affect many others. (ICAO-ATMRPP 2015)

4.4.1.9 Lack of Synchronization

At times, the assigned trajectory may not be synchronized across all stakeholders and systems. For example, if one function, such as conflict detection, must adjust the aircraft's trajectory quickly, there may be a period of time before the new trajectory is communicated to all of the other stakeholders, resulting in uncertainty for some of the system's functions (Mondoloni 2016). Furthermore, limitations in communication bandwidth (or the ability of the flight operator's automation to process information) may cause some systems to not receive every update to the information about a flight.

A continuous synchronization of information between all stakeholders is not technically feasible due to bandwidth and communication cost limitations. An event driven update

mechanism is required to trigger actors and systems about updates when surpassing a predefined threshold level, based on accuracy requirements for a specific ATM function. This includes for example the air-ground synchronization of the FMS trajectory prediction. (ICAO-ATMRPP 2015)

4.4.1.10   Navigational Errors

While generally small, some residual trajectory uncertainty exists due to errors in the aircraft following the trajectory. This error will be larger for aircraft not equipped with an FMS. Uncertainty in the altitude dimension includes navigation error (following the assigned altitude in the presence of dynamic air) as well as the potential for non-FMS aircraft to fail to level off at the assigned altitude.

TBO concepts call for the controller to use closed or "elastic" (ICAO-ATMRPP 2015) vectors commands when there is a tactical need for an aircraft to deviate from its assigned trajectory. These commands may be initially issued by voice, since datalink can take more time for the aircraft to receive and respond to the command. Until the controller enters the command into the automation, or the aircraft returns to its previously assigned trajectory, the automation systems predicting the trajectory, including the aircraft's FMS, will be out of sync with the controller and flight crew. Even if the controller's automation helps define a closed trajectory update, until that is synchronized with the aircraft, the pilots will be manually flying the verbally issued command and there is uncertainty with how aircraft will comply with instructions (e.g., delayed turn or slower turn). The ground automation may need to temporarily not use the aircraft's intent data since the aircraft does not have the complete assigned trajectory.

4.4.1.11   Communication

Mondoloni (2012) investigates how ambiguities in CPDLC messages detract from trajectory prediction accuracy.

4.4.2   Impacts of Residual Trajectory Uncertainty

The effect of trajectory uncertainty in current NAS operations has been studied extensively. Archer and Landry (2014) is an example that studies how different uncertainties affect NAS-level operations. Torres and Nagle (2016) investigates the effect of prediction uncertainty on arrival metering and interval management. Thipphavong and Schultz (2012) and Thipphavong (2013) study how errors in climb rate, due to aircraft weight and engine performance modeling errors, affect the performance of an adaptive algorithm designed to improve trajectory prediction of departing aircraft. Reynolds et al. (2013) addresses the problem of making ATM decisions when you know there is uncertainty and have a stochastic model of the uncertainty, using convective weather as the problem context. Kirkman, Gaydos, and Weitz (2014) describes an alternative time-based metering scheduling algorithm that is robust to trajectory prediction uncertainty. Mercer et al. (2013) describes a HITL simulation in which controllers use a time-based metering tool to manage arrival flights under varying levels of trajectory uncertainty; the results showed that the human controllers were able to compensate for high levels of trajectory uncertainty. Garcia-Chico, Vivona, and Cate (2008) introduces a method for estimating the trajectory uncertainty, so that knowledge of the uncertainty can be used in ATM decision making.

TBO will reduce but not eliminate trajectory uncertainty.

Trajectory based operations need to be resilient to these changing circumstances and shall be able to deal with this residual unpredictability ("fine-tuning" the trajectory). (ICAO-ATMRPP 2015)

The ICAO TBO Concept identifies three cases: major deviations that require coordinating a new trajectory, minor deviations that do not require the trajectory to be changed, and deviations that although minor, due to circumstances such as proximate traffic, do require a new trajectory to be coordinated.

Major deviations from a coordinated trajectory prediction occur and the earlier agreed TBO plan needs to be adjusted. Major deviations can be caused by significant unpredicted weather changes, unplanned runway closure, engine failure. Pre-departure deviations can be caused by irregularities with security, passengers, fueling, aircraft technical maintenance, baggage handling, etc. In those cases, trajectories may need to be re-planned and trajectory constraints need to be re-considered.

Minor deviations from a coordinated trajectory prediction (e.g. due to deviation from a weather prediction) occur in reality, but the ATM network does not experience any problem because the tolerance levels of the trajectory and/or generic constraints ("sensitivity threshold") are wide enough to allow this variation. The updated trajectory prediction will be synchronized, but there is no impact on the trajectory constraints.

Minor deviations from a coordinated trajectory prediction (e.g. due to deviation from a weather prediction) occur in reality and the aircraft needs to re-adjust through a loop of continuous corrections to ensure it meets the trajectory and generic constraints that has a too small tolerance to accept the variation. (ICAO-ATMRPP 2015)

4.4.2.1 Robustness to Uncertainty

TBO requires the management of residual trajectory prediction uncertainty through reduction of the residual uncertainty, decision-making that is robust to the uncertainty, and a feasible revision process that is able to recover when the uncertainty does disturb the plan. Mondoloni (2016) focuses on robust decision-making by applying a margin and deferring uncertain decisions.

Advanced Technologies & Oceanic Procedures (ATOP), controller automation for oceanic airspace, currently runs into problems when requiring each pre-cleared oceanic trajectory to be conflict free from departure to destination (Fernandes, Rebollo, and Koch 2016). The machine does not understand things that people understand. For example, two trajectories that require 10 minutes of separation might be in conflict because they have only 9:59 separation. The automation will reject the flight plan during the negotiation stage, when the controller would easily be able to maintain separation and the residual uncertainty makes the separation prediction of 9:59 inaccurate.

4.4.2.2 Tradeoff between Constraints and Uncertainty

Trajectory constraint(s) may be used to reduce residual unpredictability, allowing separation provision within an enlarged conflict horizon without the need for additional separation buffers. (ICAO-ATMRPP 2015)

Adding constraints to an aircraft's assigned trajectory can have multiple purposes. Some constraints, to manage NAS resources and avoid unsafe airspace, are operationally necessary. Another purpose of trajectory constraints is to manage the trajectory uncertainty, which may be desirable to enable better TFM performance. Such constraints may benefit the MBT concept without being operationally necessary, but they reduce flexibility for the aircraft operator, creating a tradeoff. How many constraints, what type, and in what situations, should MBT use to manage uncertainty? High trajectory uncertainty reduces the performance of conflict detection technology and TFM initiatives, and may reduce the capacity of some airspace resources. In the extreme case, low uncertainty can be achieved by placing RTA constraints frequently along a tightly defined corridor. However, there is likely diminishing benefit as the trajectory uncertainty

is reduced further, and many types of unpredictable uncertainty cannot be reduced through constraints.

4.4.2.3 Predictability and Flexibility Tradeoff

From an airline perspective, some level of flexibility is required in this trajectory management loop for continuous optimization in an environment that contains residual unpredictability. From an ATM perspective, a certain level of predictability of flight behavior is needed to ensure the required performance of the ATM functions in support of these flights. There is, therefore, a need for a balance between the actual need of the ATM system and the needs of individual airspace users. (ICAO-ATMRPP 2015)

High predictability implies low residual trajectory prediction uncertainty. High flight operator flexibility implies the flight is subject to few constraints, allowing the flight operator to change their desired trajectory at any time. If the flight operator was given high flexibility initially but was then required to not make any subsequent changes, that initial flexibility would not reduce future predictability. However, if the flight operator is allowed to alter its predicted trajectory at any time, then there is a direct tradeoff between predictability and flexibility. The larger the magnitude of the allowed trajectory flexibility, the larger the resulting trajectory uncertainty. For example, if the assigned trajectory provides a 10 nm lateral envelope, then there is at least that much trajectory uncertainty in the lateral position of the aircraft. Similar flexibility in the vertical and longitudinal dimensions results in uncertainty in the vertical position and the time at which the aircraft will reach specific points along its route.

The trajectory uncertainty resulting from flexibility also depends on how likely the flight operator is to utilize the available flexibility. In the example that the flight operator is allowed to navigate laterally within a 10 nm corridor, in good weather the flight operator may have no reason to not follow the centerline of the corridor and the lateral uncertainty (i.e., the prediction error or predictability) may be much smaller than 10 nm. However, in scattered convective weather, the aircraft may weave between weather cells unpredictably and the lateral trajectory uncertainty may be based on the full 10 nm width of the corridor.

Predictability and flexibility also each have different "dimensions". For example, lateral, vertical, and longitudinal flexibility relate, respectively, to lateral positional, vertical positional, and temporal predictability. Other dimensions, such as near-term and longer-term, could also be postulated. The value of high trajectory predictability (i.e., low residual uncertainty) depends on the application and may only be needed in some dimensions. A TFM automation system responsible for metering arrivals into the destination airport only cares about when the flight will arrive at a particular point in the airspace; it does not care about how the aircraft got there. The aircraft could fly a constant speed or could fly very fast for a period of time and then very slow for the remainder of the time. The aircraft could fly the shortest path to the particular point or could fly a very circuitous route. None of these variations matter to the TFM automation system.

In contrast, a conflict detection and resolution (CD&R) automation system responsible for ensuring separation between aircraft does care about the route the aircraft will follow and the aircraft speed profile along that route. The CD&R system cares about where the aircraft will be (and possibly its energy state) at every point in time, but for a shorter time into the future. Flexibility in changing the trajectory outside the time horizon of CD&R would have no effect on the predictability that is important to CD&R.

The tradeoff between predictability and flexibility is complex because neither flexibility nor predictability is scalar in nature. In the design of the MBT concept, each dimension of flexibility will need to be examined for its impacts on predictability in the context of how that predictability is used within the concept.

4.4.2.4 Negotiation versus Centralized Command and Control

The ICAO TBO Concept (ICAO-ATMRPP 2015) states "While ATM's primary function is to enable the safe and expeditious handling of air traffic, a secondary objective is to do so while optimizing the airspace user's trajectories to the extent possible." "Optimize trajectories" means allow the users to select trajectories that best meet their business metrics.

One aspect of flexibility is the ability to negotiate both the initial trajectory assignment and trajectory assignment changes. The ability to request a trajectory change at any time, which could be an alternate route or could be a change in an assigned arrival slot which would require shuffling many other flights to accommodate, creates significant trajectory uncertainty that cannot easily be modeled. Eliminating trajectory negotiation from a TBO concept, therefore, improves trajectory predictability, especially in situations such as adverse weather or limited capacity in which flight operators are more likely to initiate trajectory changes.

The argument against authoritarian control by the ANSP in determining the assigned trajectories in TBO concepts is that the ANSP cannot know the flight operator's business objectives and, therefore, the traffic management solution (i.e., the set of all assigned trajectories) may be optimally efficient in terms of airspace resource usage but will not be optimal with respect to flight operator business interests. Many papers on trajectory negotiation make this point; Torres, Martin, Klooster, Hochwarth, et al. (2011) is an exception that argues sharing cost information could allow the ANSP to sufficiently consider the flight operator's objectives. TBO without trajectory negotiation is similar to today's NAS - the flight operators file a flight plan and the FAA tells the flight where to fly, which could be a different route than the operator filed. The pilot's only recourse is to refuse the clearance. Negotiation has the potential to provide additional benefits but likely requires substantial more complexity and, therefore, cost to TBO concepts. This complexity and cost occurs on both the ANSP side of the concept as well as the flight operator's side to be able to take part in the negotiation, which flight operators have historically been reluctant to invest claiming the benefits are uncertain. Whether the additional benefit justifies the additional cost is a question that warrants research that has not been performed.

In the extreme case, flexibility to negotiate takes the form of self-organization.

The concept is an application of the principles of self-organization (swarm theory) where safety and traffic flow management goals are achieved by broadcasting all the operational constraints on a 4D-Grid and populating the grid with the 4D-trajectories of all other flights. As new flights get added to the system the remaining capacity is in full view to prospective operators who will be able to plan flights using available capacity. The paper shows how self-organized air traffic leads to optimality… (Torres and Delpome 2012)

Under some assumptions, self-organization can lead to maximum efficiency in some sense with maximum flexibility. However, the required assumptions are highly academic and not consistent with the NAS and the metric of optimality is likely not acceptable since the last flight to plan its trajectory is limited to whatever airspace resources have not already been claimed by other users.

4.4.2.5 Variations between Residual Uncertainty

The ATM functions differ significantly in the nature of the trajectory information they need, in particular their time horizon. (ICAO-ATMRPP 2015)

Different predictions of the trajectory or different descriptions of the predicted trajectory, depending on how the MBT concept handles this situation, will have different trajectory uncertainty. The aircraft's FMS predicts the aircraft's trajectory, but only provides sparse

information about that predicted trajectory to other systems (e.g., estimated times at specific points along the trajectory). A ground-based conflict detection system needs a trajectory prediction that is spatially and temporally dense, so that no interpolation between points is required, but only over a relatively short time horizon. In contrast, a TFM automation system may require a less dense description of the predicted trajectory but over the full remaining trajectory of the aircraft (Mondoloni et al. 2016). A consequence of there being distinct trajectory predictions is that each may have different residual uncertainty (Cate 2013).

The ICAO TBO concept (ICAO-ATMRPP 2015) lists a TBO specific requirement: "The quality of service of the synchronization of the expected remainder of the trajectory… shall be commensurate with the required accuracy and reliability of the various ATM components…" In this concept, there is only one predicted trajectory because there is no assigned trajectory, but the concept accepts that different stakeholders should have different descriptions of it based on their needs.

The process of sampling and encoding the trajectory prediction itself can contribute to lost information and, therefore, residual uncertainty.

The effectiveness of TBO is limited by trajectory accuracy, which depends on prediction errors due to assumptions and limitations in the construction process (wind errors, unknown aircraft intent, etc.) and in losses introduced in the sampling and representation of the trajectory. Trajectory sampling is the process of selecting the points included in the trajectory that is exported to clients. Trajectory representation is the set of attributes, such as location, speeds, etc., associated with each trajectory point. Emerging trajectory exchange standards need to take into account the effects of sampling and representation because the loss of accuracy in trajectory representation has a direct and significant impact on the ability to support TBO (Torres 2013).

4.4.2.6 Scope of Assigned/Predicted Trajectory

A predicted trajectory that extends to the aircraft's destination is essential for enabling the benefits of TBO with respect to improved TFM performance. The extent of the assigned trajectory is a topic of some debate in the literature. The ICAO TBO Concept preserves the concept of clearances that limit the flight's authority to proceed toward its destination:

Due to the residual unpredictability, it cannot be assured that the predicted trajectory will remain free of conflicts, even in the theoretical case that it would have been initially de-conflicted from all other trajectories during flight preparation. (ICAO-ATMRPP 2015)

One fundamental question regarding MBT, and TBO in general, is whether the trajectory must be, or should be, planned in detail all the way to the destination, or whether portions of the trajectory farther into the future can or should be planned in less detail. For example, before a flight leaves LAX going to JFK, should the trajectory include RTAs associated with arrival metering into JFK?

The answer to this question has a profound impact on the required automation systems. Currently, TFM systems such as TBFM do not operate on such a long time horizon and would require enhancements and procedural changes to support assigning meter times 6 or more hours in advance. For example, TBFM currently includes a concept of freeze horizons in which meter times are calculated but can be changed each time the algorithm runs until the meter times need to be published to a controller for implementation. This allows the system to control to upstream meter times while downstream meter times continue to "float" based on actual events. One of the motivations for the concept of freeze horizons was to handle the increasing trajectory uncertainty at longer time horizons and the need for metering sequences to be

acceptable to controllers. Would MBT, or TBO in general, reduce the uncertainty and then alter the controller's role such that freeze horizons could be removed?

If the MBT concept is to assign RTAs many hours in advance, is the concept that these times would not change except in exceptional cases, or is the concept that these RTAs would be expected to change as the flight approaches that point along its trajectory?

If the concept is that the RTAs would not change except in infrequent cases, is the trajectory uncertainty small enough or would trajectory uncertainty require larger buffers between flights which would result in inefficient use of airspace resources? One way to keep the uncertainty smaller is to require RTAs at some interval along the entire trajectory. This approach would impose constraints that are not necessarily required except by the concept design; would this reduced flexibility be unacceptable or reduce overall concept benefits?

When unpredictability grows to the order of magnitude of the applicable separation criteria there is no point in further de-conflicting individual trajectories. However, it is possible to extend the conflict horizon, by adding one or multiple trajectory constraint(s) for separation purposes, reducing residual unpredictability. (ICAO-ATMRPP 2015)

There have been many studies on compliance with RTAs under various situations and with various technology. All of the studies of which the authors are aware consider relatively short time horizons (i.e., not on a traffic management time horizon). In the absence of any "exceptional" events occurring, the compliance accuracy may not be dependent on the time horizon; this would have to be proven. However, what is the frequency of "exceptional" events that would disrupt the aircraft's ability to achieve accurate compliance? How does the system perform in these situations; are the benefits greatly reduced? Would other flights experiencing an exceptional event cause a disruption that would affect the ability of other flights to comply with their RTAs or require those RTAs to be changed?

Conflict detection and resolution is typically applied only a short time into the future, due to trajectory uncertainty. How long will this conflict detection horizon be in MBT? The answer likely depends on various factors that affect how the trajectory prediction uncertainty varies with time. If an RTA is assigned at a meter point hours into the future, conceivably conflict detection could be applied at that time horizon and the RTA would be calculated to be free of conflicts with other aircraft. Is there a benefit to TFM systems at long time horizons assuming specific flights at specific times, or would TFM systems work better if each flight were predicted as a probability distribution for when it would be demand on that resource and the TFM system would operate on the expected demand and its probability distribution?

If the concept is that the RTAs at the meter points would change as the aircraft approached, then what is the value in assigning the RTAs many hours in advance? Does assigning the RTAs early, even if they will change, reduce the trajectory prediction uncertainty, which benefits TFM performance, or does it reduce flexibility for the aircraft? This likely depends on what other constraints exist along the trajectory. What is the best tradeoff between flexibility and reduced trajectory uncertainty?

In either approach, there is still a predicted trajectory to the destination airport. If the RTA at the arrival meter point is not initially assigned, but will be assigned as the aircraft nears the destination airport, the trajectory uncertainty may seem to be larger until the RTA is assigned. However, if the RTA is assigned prior to departure but allowed to change (equivalent to saying there is a larger compliance bound around it that shrinks as the aircraft approaches the airport), then that initial RTA is not actually reducing trajectory uncertainty. If the RTA is assigned prior to departure and not allowed to change except in exceptional situations, then that RTA may be more constraining than necessary or desirable, but providing some improved predictability.

4.4.3   Enablers

Reduced trajectory prediction uncertainty will be an outcome of TBO that will enable various benefit mechanisms. Reducing trajectory prediction uncertainty can also be viewed as something that will enable TBO.

Considerable literature discusses how various aspects of TBO will result in improved predictability (i.e., less trajectory prediction uncertainty). Data from the aircraft can improve ground-based trajectory prediction (Mondoloni et al. 2016). Closed trajectories improve trajectory prediction accuracy. Trajectory synchronization ensures all stakeholders have access to improved trajectory predictions (López Leonés et al. 2013).

4.4.4   Roadblocks to adopting the management of residual trajectory uncertainty

Residual uncertainty is not a primary reason why TBO adoption has been slow. Modern TBO concepts recognize the existence of residual uncertainty and include concept elements to accommodate it. These concept elements, while adding some complexity beyond the original "perfect world" concept that trajectories would be planned once and then followed precisely with no disturbances, are no more difficult to develop than other aspects of TBO concepts. Understanding how much residual uncertainty will exist, how to minimize it, and how to tradeoff between accommodating uncertainty and expending additional effort to reduce it, may have occupied some research effort that could have otherwise gone toward adopting TBO concepts operationally. In this way, residual uncertainty has contributed to "concept paralysis" in which not knowing which TBO concept should be pursued has prevented quicker adoption of TBO. For example, questions such as what types of trajectory synchronization should be included in the concept and are multiple trajectory predictions permitted or must there be only one trajectory prediction has allowed academics to write numerous papers without a consensus that encourages moving forward with concept validation.

4.4.5   Negative impacts of roadblock on MBT

The lack of a single concept of operation for TBO has led to many different opinions about what TBO should be with little convergence by the ATM research community. The FAA needs to clearly define the TBO concept and the NAS Enterprise Architecture evolution associated with the transition to TBO. This provides an opportunity for NASA to provide leadership to help the FAA define the TBO concept elements, of which MBT is one.

4.4.6   Specific implications for MBT

Weather will continue to be a major contributor to residual trajectory uncertainty as well as TFM uncertainty. Yet it is well known in the ATM community that many DSTs do not perform well in dynamic situations such as weather (Gong and Mcnally 2015). This is not a coincidence – rather it is because they have not been designed to handle dynamic situations. Weather problems are often "assumed away" in the concept description or just completely ignored. The underlying justification, whether stated or not, is that most days in the NAS do not have major weather disruptions. Furthermore, the complexity of addressing the dynamic weather situations during concept evaluations limits their assessment. Thus, while lateral and temporal trajectory constraints are seen as the interface between TFM and MBT, the validity of these constraints in addressing demand/capacity imbalances in the presence of weather will likely be degraded. If these constraints create inefficiencies, MBT can provide flexibility and agility when the constraints are updated to mitigate to some extent the initial inefficiencies.

4.5   Improved vertical profiles

EDA has been previously discussed in Section 4.2.1.1.1.

4D FMS RTA flight trials are discussed in Section 5.2.2.1.

Regarding the sharing of aircraft parameters to improve trajectory prediction, the ongoing FAA Advanced Trajectory Modeling project has shown that using aircraft mass, thrust, and drag is a straightforward approach because some ground automation trajectory predictors can use that data directly. However, the project has developed a method using TOD and iterative adjustment of thrust to adjust the predicted trajectory.

4.6   User preferred routes and user preferred trajectories

Eurocontrol defines a user preferred route (UPR) and user preferred trajectory (UPT) as follows:

UPR – A route defined during the planning phase by Airspace Users, the UPR describes the entire airborne phase of a flight as an expression of their Business / Mission intentions.

Note: Airspace Users are free to define UPRs taking into account the network constraints already defined and shared …[25]

UPT - The trajectory initially provided by the Airspace User.

Note: During planning phase, it may be amended by the AU to integrate ATM constraints … in execution phase, it may be revised to integrate new ATM constraints …[26]

UPT includes the temporal element, which at a minimum would be departure time and ETA. A formal definition for UPR and UPT from the FAA perspective could not be found. Furthermore, it appears that there is disagreement among stakeholders whether UPR/UPT are intended to incorporate ATM constraints:

For example, "User Preferred Trajectory" for some this means that the aircraft user can fly the aircraft anywhere they want with conflict resolution from a 'separation manager'. To others it means that the user can choose any fixed adapted route or in some views choose a set of adapted routes with a controller choosing which of the 'user preferred' adapted routes will be flown (cf. Collaborative Trajectory Options Program). Despite these being widely differing concepts, the proponents of both will, at formal meetings, agree that they support 'User Preferred Trajectories' and come to full agreement. (Wilson and Sipe 2016)

4.6.1   Non-restrictive routing

In domestic US operations, UPRs are limited to non-restrictive routing (NRR) airspace at and above FL 350:

Special high altitude routes allow pilots routing options for flight within the initial high altitude routing (HAR) Phase I expansion airspace. Pilots are able to fly user-preferred routes, referred to as non-restrictive routing (NRR), between specific fixes described by pitch (entry into) and catch (exit out of) fixes in the HAR airspace. Pitch points indicate an end of departure procedures, preferred IFR routings, or other established routing programs where a flight can begin a segment of NRR. The catch point indicates where a flight ends a segment of NRR and joins published arrival procedures, preferred IFR routing, or other established routing programs.

The HAR Phase I expansion airspace is defined as that airspace at and above FL 350 in fourteen of the western and southern ARTCCs. The airspace includes Minneapolis (ZMP), Chicago (ZAU), Kansas City (ZKC), Denver (ZDV), Salt Lake City (ZLC), Oakland (ZOA),

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[25] https://ext.eurocontrol.int/lexicon/index.php/User_Preferred_Route
[26] https://ext.eurocontrol.int/lexicon/index.php/User_Preferred_Trajectory

Seattle Centers (ZSE), Los Angeles (ZLA), Albuquerque (ZAB), Fort Worth (ZFW), Memphis (ZME), and Houston (ZHU). Jacksonville (ZJX) (FAA 2013b).

NRR is an enhanced version of the North American Route Program (NRP) that began in the mid-90s. The primary difference is that NRP is constrained to NAVAID routes/fixes whereas NRR leverages RNAV waypoints (named waypoints or part of the NRS grid). A key drawback to NRP was identified in Lee et al. (2008):

NRP had limited success in spite of its inherent route flexibility because aircraft were often ("90% of the time") taken off of NRP routes for one reason or another, so airlines stopped requesting them. Currently, the number of aircraft that fly NRP is lower than during the earlier years of its implementation. One problem contributing to its lack of use was a lack of suitable routes through congested terminal areas, creating problems for ATCs – i.e. many of the NRP-filed aircraft were taken off their routes due to incompatible entry and exit points near the SIDs and STARs. NRR addressed this by using pitch and catch points (described in the previous section) to facilitate exit from / entry into congested terminal areas.

Surprisingly, NRR appears to be suffering the same fate as NRP:

When the HAR elements were first introduced, UPS also started filing flights with pitch and catch points, but was not able to gain any benefit from them, as it was very common for the ATC to cancel the flight plan and reroute the aircraft …UPS found that for their operations, it was most efficient to file their flights in line with what the ATCs were least likely to cancel (Lee et al. 2008).

Another reason for lack of acceptability of NRR by controllers, TMCs, and pilots is the underlying NRS grid of waypoints which is described below:

NRS waypoint names are composed of two letters followed by two numbers, followed by a single letter … The first and second characters of NRS waypoints are the FIR identifier for the United States ("K") and the FIR subdivision, or ARTCC center in which the waypoint is located (e.g. "D" for Denver ARTCC). The third and fourth characters are a number group representing the latitude of the waypoint. These numbers begin at the equator with 00 and advances north and south from 01 to 90 and correspond to every 10 minutes of latitude and repeating every 15°. The final character in the NRS waypoint is a letter representing the line of longitude for which the waypoint is located. This identifier starts at the prime meridian moving west to east and uses the letters A to Z while repeating every 26° (Pruchnicki, Christopher, and Burian 2011).

Despite training efforts, Lee et al. (2008) and Pruchnicki, Christopher, and Burian (2011) identified several human factors and other issues with NRS waypoints:

- Controller, TMC, and pilot unfamiliarity with waypoints outside of their normal airspace environment
- Both alphabetic and numeric characters must be typed on the keyboard, which is more time-consuming (and likely more prone to data-entry errors)
- Similarity of waypoint names in a route could cause confusion and lead to data entry errors (e.g., KG78K-KP90G-KP09A).
- Five or six syllables to pronounce instead of one to three syllables for conventionally named waypoints
- NRS has not gained traction beyond the US so the FIR identifier "K" is unnecessary

- FMS database storage limitations

- Lack of ability to overlay the NRS grid structure over their respective radar and navigation displays greatly reduced the usability of NRS waypoints in their daily operations.

- If NRS is used as an adjunct tool in addition to the current system, its use is likely to drop in preference to the original non-NRS system as the workload and/or the traffic complexity increases

Anecdotally, it is known that controllers accept UPRs when traffic levels are very low and cancel them when traffic levels are high because of the complexity caused by ad hoc intersecting flows. What is not known is the threshold between acceptance and cancellation. A significant amount of dynamic airspace configuration research was conducted by NASA in the 2007-2012 timeframe of which the authors of this report were involved. A large focus of this research was investigating when to adjust sector boundaries to mitigate unacceptable levels of complexity, which is often used as a proxy for controller workload. To the authors' knowledge, no research has been performed to identify the traffic level threshold where UPR requests should be accepted or rejected. This could be an MBT concept element or a concept on its own.

Although not specifically related to UPR, one way to manage route unavailability uncertainty is to employ a design paradigm that focuses on providing actionable information to operational personnel without explicitly telling them what decision to make. This design paradigm was utilized in the development of RAPT.

RAPT improves departure rates by determining the specific routes and times that will be affected by operationally significant thunderstorm activity before a storm moves into a specific region. RAPT helps decrease weather-related departure delays and ground holding by providing air traffic managers with automated, objective guidance for:

- *Visualizing the impact of approaching weather systems*

- *Determining when to close and reopen departure routes*

- *Determining optimum departure routing on the basis of forecasts of convective weather*

- *Determining when to allow limited route usage during thunderstorms (LL/MIT 2012)*

The RAPT counterpart for arrivals, Arrival Route Status and Impact (ARSI), is part of TFMS Work Package 4 (FAA 2013a).

4.6.2 Success stories

4.6.2.1 ASPIRE partnership

The ASPIRE (Asia Pacific Initiative to Reduce Emissions) partnership was formed in 2008; a partnership between Airways New Zealand, the FAA, and Airservices Australia. Membership has since extended to include the Civil Aviation Authority of Singapore and the Japan Civial Aviation Bureau. Flights meeting the minimum equipage requirements are able to file UPRs to support their business objectives. These flights are also able to take advantage of DARP (described in Section 4.3) and 30/30 (30 nm lateral and 30 nm longitudinal) reduced oceanic separation.[27]

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[27] http://www.aspire-green.com/dailyroutes/default.asp

4.6.2.1.1   Enablers

ATOP provides a fully modernized oceanic ATC automation system. ATOP significantly reduced the intensive manual processes of the old system that limited the ability of controllers to safely handle airline requests for more efficient tracks or altitudes over long oceanic routes. ATOP fully integrates flight and radar data processing, provides satellite data link communication and surveillance capabilities, and detects conflicts between aircraft. Collectively, these capabilities enabled aircraft separation standards to be reduced, thereby dramatically increasing capacity and efficiency.[28]

4.6.2.2 Optimized Profile Descent procedures

OPD procedures have been developed to provide UPTs in the vertical dimension during arrival. The OPD procedure is designed to provide flexibility to pilots to begin the descent based on the FMS determinations of the optimal TOD location. Figure 9 depicts the RIIVR2 arrival. Anywhere along the top of the yellow region is allowable for the TOD.
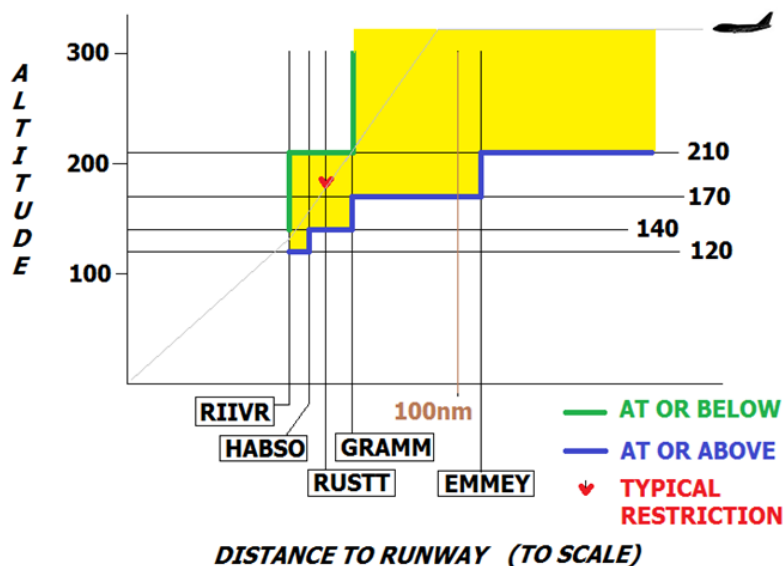
Figure 9. RIIVR2 arrival vertical profile restrictions[29]

4.6.3   Roadblocks to adopting UPR/UPT

- Controller complexity and traffic density in the eastern US will continue to prevent the use of UPRs in that region.

- No research has been performed to identify the traffic level threshold where UPR requests should be accepted or rejected.

- FMS database capacity limitations impact UPR flight planning capabilities and potential airborne rerouting.

- Human factors issues associated with the NRS grid can tip the scale towards denying UPRs.

- Misunderstanding among stakeholders about whether UPTs include constraints can delay progress.

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[28] https://www.faa.gov/air_traffic/technology/atop/
[29] Courtesy of: http://www.ifatca.org/

- Many SOPs/LOAs contain trajectory constraints that are unknown to the navigation databases used by the FMS and FOC flight planning applications, which can result in flight plans getting amended to support ANSP needs.

4.6.4 Negative impacts of roadblock

Trajectory negotiation is one of the MBT benefits that allows users to see direct, tangible benefits across the fleet or for individual flights. If these roadblocks cannot be addressed, then it will limit user participation and the loss of a key benefit.

5. Safety considerations for MBT

5.1 Safety Objectives

There are two common methods for establishing safety objectives, and either method could be applied in support of an MBT concept. The first method, and most common in regulatory applications, is through the establishment of a Target Level of Safety (TLS). Within the FAA, the TLS is established through application of risk matrices that provide the acceptable likelihood for events falling within a range of severity categories. FAA Order 8040.4A prescribes the FAA's *Safety Risk Management Policy*, provides a risk matrix for use by subordinate offices, and supports *Safety Management System Guidance* found in FAA Order 8000.369 (FAA 2012), (FAA 2016a). It should be noted that Order 8040.4 is currently under revision and a new version is expected to be released in the spring of 2017. One of the most significant updates is a new distinction between general and commercial aviation and the establishment of a new risk matrix that will apply only to general aviation. Also, the new risk matrices will be consistent with the matrix found in the FAA Air Traffic Organization Safety Management System Manual and the FAA Safety Risk Management Guidance for Systems Acquisitions, a pair of documents that may contain relevant policy for establishing safety objectives for MBT (FAA 2016d), (FAA 2014b). Figure 10 is a representation of the applicable risk matrix.

Figure 10: FAA Risk Matrix

An alternative method of establishing an aviation safety objective is more commonly found in use by commercial air carriers. The method involves assessing the current level of risk and

establishing an objective of meeting or improving upon the current risk level without reference to a numeric target. The rationale for this method is business oriented. Commercial airlines value their safety reputation with the flying public and attribute substantial cost with potential accidents that not only include the cost of the accident itself, but also the reduction in consumer demand that may result in the wake of an accident. Therefore, they are generally unwilling to accept the cost associated with an increase in the expected frequency of accidents even if the likelihood of an accident meets the criteria for acceptability as defined in government regulations.

5.2   Influence of Safety on MBT

In reviewing literature associated with trajectory based operations and related applications, no documents have been found that report an unacceptable level of safety risk as a direct barrier to implementation of the concept. However, safety risk has consistently influenced the feasibility of implementing concepts associated with time-based or trajectory-based operations. In general, safety assessments supporting TBO concepts have led to the introduction of new hazards, or an increase in the likelihood of accidents due to existing hazards. In both cases, mitigation strategies have been developed to reduce risk to an acceptable level, but these strategies often lead to the concept itself becoming infeasible either due to the level of investment that would be necessary to achieve acceptable risk, the need to create more complex exclusionary airspace in the absence of full equipage, or due to the negative impact the mitigation strategy would have on system efficiency. Selected issues and lessons learned from previous attempts at TBO implementation that may be relevant to the current initiative are described below.

5.2.1   Mixed Equipage

In the US, most discussions of TBO concepts include an implied or explicitly stated requirement for new or enhanced automation on the ground and in the air as well as for data communications between ground and airborne systems. In a paper produced by MITRE documenting results of the 2011 TBO flight trials in Seattle, the introduction states more research is needed in the areas of "mixed equipage operations, pilot/controller workload impacts, automation requirements, standards, certification, and training needs …" (Wynnyk et al. 2013). The remainder of the paper is generally positive in its tone, but implies that in order for TBO to be feasible, these areas will have to be developed. More specifically, assertions are made that all aircraft will need to be equipped with a full phase FMS that includes RTA capability as well as data communication technology to support trajectory negotiation; automation systems will need to be replaced or updated; and finally, additional training for aircrew and controllers will be necessary.

Since the dawn of aviation, aircraft operating in the airspace system have been equipped with different systems that deliver different capabilities. However, throughout most of that history, this condition did not represent a *mixed equipage* problem. This is because throughout the twentieth century, air traffic management system design accounted for operation of all aircraft to allow safe sequencing and separation through consistent application of a common set of standards and procedures. When technology emerged that became essential to the management of all air traffic, such as the transponder, and more recently ADS-B, that equipage was mandated for all IFR aircraft through Federal regulation. In other cases, air traffic management concepts have been developed that require systems with certain performance characteristics to safely achieve design objectives, yet do not rise to a level that supports an equipage mandate. While this approach may deliver benefits for operators that meet the equipage requirements, the benefits come at the expense of excluding operators who are not able to equip, or simply decide not to equip, from being able to use the airspace. Examples of

this design philosophy include the North Atlantic Track System and Reduced Vertical Separation Minima. Today, this airspace is only used by commercial aircraft or high-end general aviation aircraft that have made business decisions to equip with systems meeting the minimum requirements for operation in these areas. Since MBT is being designed to support management of all IFR traffic, it follows that if the concept is designed to rely on equipage of specific systems, concept success will depend heavily on an equipage mandate, or alternatively, on operators voluntarily investing in new systems for their aircraft. If a mandate requiring equipage beyond ADS-B is not possible due to political constraints, feasibility of the MBT design will largely be determined by the business case for the operator. Thus, if the safety case for an MBT concept requires aircraft to equip with expensive systems to achieve a level of safety risk that is considered acceptable to both regulators and operators, the safety requirements may indirectly inhibit implementation.

Barring a mandate, it seems unlikely that operators of most general aviation aircraft, some military aircraft, and certain types of unmanned aircraft will equip with any of the systems expected to be necessary to execute the current vision associated with managing aircraft by trajectory. It seems reasonable to expect that aircraft will continue to include a variety of systems and capabilities, but so long as all aircraft can be managed regardless of their individual configuration, these variations will have little impact on the safety case. This was found to be true during 2009-2010 European flight trials designed to test the performance of aircraft in complying with RTA clearances in the vicinity of the Stockholm Arlanda Airport. During a series of flight tests, aircraft equipped with a full spectrum of flight management systems were tested, including aircraft equipped with systems that included RTA functionality as well as systems that did not. The results were summarized as follows:

The results show that aircraft equipped with the most advanced Flight Management Systems were able to meet an assigned time with 30 second accuracy in 88% of the CASSIS trials. Even MD80 pilots who adjusted speed manually to meet a CTA could do so with 30 second accuracy in 73% of the case (Swedavia 2009).

A concept that depends exclusively on specific automation capabilities will necessarily create a *mixed equipage* environment in which some aircraft are considered "haves" while others are considered "have nots." From an ATM perspective, this creates a new requirement for ATC to manage at least two different classes of aircraft that are executing two fundamentally different processes, and this seemingly subtle difference may have a significant influence on the safety case.

In considering the expected safety case for introducing a new *mixed equipage* environment, a requirement would emerge for controllers to maintain proficiency in all of the current skillsets necessary to safely manage traffic as equipped in today's environment, and then add to that by learning to manage aircraft by trajectory as well. The ATM environment will become more complex as both existing and MBT processes will be in place at the same time with no reasonable expectation that legacy procedures will be retired. A *mixed equipage* concept may also lead to a perceived requirement for airspace redesign accommodating or excluding different types of operations based on equipage, adding additional complexity to the airspace system. Historically, proposals of this nature have been accompanied by risk assessments that cite expected increases in controller workload, cognitive demands, and vigilance as safety concerns. A similar safety concern is an expected increase in the level of controller proficiency that would be necessary to support the vision. In this regard, the timing of implementation can be relevant to the safety case as the air traffic control community is not uniformly populated by age, and concern has been expressed at recent safety panels that large numbers of retirements will occur during relatively short periods of time. As the retired controllers are replaced, the

overall experience level of the ATC community could be significantly reduced at a time when a transition to new ATM concepts requires a high level of performance by controllers.

It is virtually certain that a concept would not be proposed if it introduced an inherently high risk, but instead, it should be expected that an attempt would be made to mitigate the risk in some way to achieve an acceptable level of risk. In general, risk mitigation efforts have typically led to either reductions in capacity to the point where the future system state is expected to be less efficient than the current system, or the level of investment necessary to achieve an acceptable level of risk exceeds any expectation of benefits. One of many examples of this from the literature is found in a paper delivered by Joel Klooster and David De Smedt at the Ninth USA/Europe ATM R&D Seminar in 2011. The paper reports the results of a study in which over 30,000 simulated flights were sequenced by time across a meter fix to assess the benefit of using the RTA function of a modern FMS to achieve a reduction in the variance of crossing times when sequencing and spacing a stream of arrivals. One of the experimental objectives was to evaluate the frequency with which separation losses, defined as less than 5 NM separation and less than 1000 feet vertical separation, occur between pairs of aircraft assigned to cross the meter fix at 8,000 feet with a 90 second time interval scheduled between them. The study acknowledged that frequent separation loss events would inhibit acceptability and after observing initial disappointing results, the test was re-run with a 120 second interval. The results indicate that approximately five percent of the aircraft pairs suffered separation losses with a 90 second interval, and 2.5% when the interval was increased to 120 seconds (Klooster and De Smedt 2011). While the increased interval between aircraft reduced the number of separation loss events, a 2-minute interval between aircraft represents a significant reduction in capacity compared to the current system in which aircraft are routinely sequenced with 60-90 seconds between them. As another approach to mitigating the safety risk, the paper recommends development of an additional support tool to alert controllers to situations that may result in less than 5 NM of separation, effectively conceding that for the concept to provide a measurable improvement over today's system, its implementation will require substantial additional investment.

5.2.2   TBO Standards

An important influence on aviation safety is the standard that defines the minimum separation allowed between aircraft operating within a volume of airspace. With the benefit of hindsight and lessons learned through recent research, it is instructive to review previous attempts to evaluate trajectory based operational concepts and re-assess results and conclusions regarding the success or failure of previous trials and experiments.

Three-dimensional distance-based standards have been a pillar of separation assurance since the implementation of radar in the early 1950's. The objective of distance-based separation is to provide enough distance between aircraft to ensure there is adequate time to recognize a conflict and take action to avoid an accident. All previous attempts to implement elements of trajectory based operations have included either an explicit or implied assumption that distance-based standards would remain in place as part of the operational concept. However, recent research has led to a conclusion that due to inescapable properties of aerospace physics, if aircraft are to be sequenced in four dimensions, they cannot be separated in three dimensions.

5.2.2.1 FAA 4D FMS RTA Flight Trials

One of the most compelling examples found within the literature supporting a requirement for four-dimensional separation is associated with a series of flight trials and HITL simulations sponsored by the FAA between 2010 and 2013. During initial simulation and flight trials in the vicinity of Seattle, Washington, and in partnership with Alaska Airlines, Boeing 737 aircraft

equipped with General Electric FMS were issued RTA clearances at the Olympia fix on the Olympia Six Standard Arrival to Seattle-Tacoma International Airport. There have been several updates to this arrival since the flight trials, but a copy of the arrival used at that time is shown in Figure 11 (Amefia and Lowry 2010).
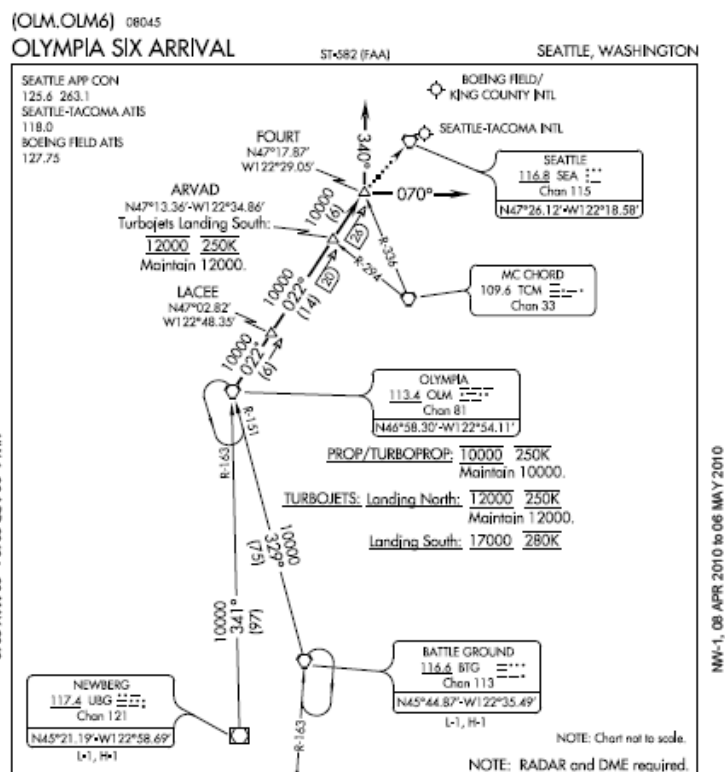

Figure 11: Olympia 6 STAR to SEATAC, 2010-2011

The important details on this arrival are that for turbojets landing north, the crossing limitation at Olympia is 12,000 feet and 250 knots (indicated or calibrated airspeed). However, landing south, the limit is 17,000 feet and 280 knots. In 2010, all participating aircraft were sequenced through Olympia while the airport was landing south.

The concept being tested was to issue RTAs to arrivals at Olympia in one minute intervals, and the test was successful with no safety concerns, and specifically, no separation loss events. However, the reason for this result was not fully understood at the time. On a standard day, an aircraft operating at 17,000 feet and 280 knots indicated airspeed will be flying at 364 knots *true airspeed,* the speed the aircraft is traveling through the air mass. The true airspeed is significantly higher than the indicated airspeed because of the density of the air. In general, as air density decreases at higher altitudes, true airspeed will increase.

When the airport is configured to use the south-flow runways, it is normally because prevailing winds are generally out of the south, meaning aircraft crossing Olympia would expect a tailwind (barring a wind shift somewhere below them). During the flight trial, this was routinely the case, and the winds at altitude were typically stronger than the surface winds. A fifty knot wind is not unusual at 17,000 feet. Also, aircraft are permitted to gradually reduce speed to cross the fix at the constrained speed, so they are often flying faster than the limit as they approach the fix. Thus, the aircraft ground speed, which is the speed it is traveling over the ground or the true airspeed corrected for wind, was approximately 420 knots, or 7 nm per minute. By sequencing the aircraft at one minute intervals, the result was about 7 nm of physical

distance between the aircraft as they crossed Olympia, and this separation is very comfortable for controllers who are required to maintain a 5 NM minimum separation in this sector. Also, from an airport capacity perspective, the concept was considered potentially feasible as this separation was roughly equal to what was being provided manually by controllers through assignment of vectors and speed constraints.

With the success of the 2010 trials, the 2011 trials were designed to be more robust. An important difference was that in 2011 aircraft could participate regardless of the airport runway configuration. Of particular interest, in addition to repeating the high/fast arrival profiles observed during the 2010 trails, aircraft in the 2011 trial would be able to cross Olympia at 12,000 feet and 250 KIAS. The important difference is found by comparing the aerospace physics. The indicated airspeed of an aircraft landing north would be 30 knots slower and altitude would be 5,000 feet lower than if it were landing south. As a result of flying this slower speed at a lower altitude, the true airspeed on a standard day would only be 300 knots. With prevailing winds out of the north, the aircraft would also have some headwind component, further reducing its ground speed. This would make the resulting ground speed closer to 4 nm per minute. When aircraft flying at this speed are separated by one minute intervals, the physical distance is only 4 nm, a distance that is classified as a loss of separation and one that would be considered a serious safety violation.

During simulation events conducted at the FAA W. J. Hughes Technical Center in preparation for the 2011 flight trials, procedures and flight profiles to be executed during the live flight trials were exercised with generally positive results in terms of human factors evaluations for both pilots and controllers (Teller 2011). However, concern arose during safety risk management panel proceedings regarding the amount of distance between aircraft separated by one minute at lower altitude meter fixes, and the potential for separation loss between aircraft became a significant safety issue that threatened to cancel the 2011 live flight trials. To mitigate the safety risk, documentation shows the flight trials team decided to increase the minimum interval from one minute to two minutes (FAA 2011). This mitigation solved the immediate safety concern and eliminated separation loss events in simulation, opening the door for execution of the live flight trial. However, it eventually resulted in the test (and in fact the entire concept) being considered operationally infeasible due to the excessive spacing between RTA aircraft. This was especially true for arrivals at Olympia when the airport was in a south flow configuration as they were routinely separated by approximately 15 nm, resulting in a significant reduction in airport capacity compared to existing methods that consistently delivered aircraft across the fix with between five and seven nautical miles of separation.

With the benefit of understanding the complex relationship between altitude, air density, wind, a variety of airspeed expressions, distance, and time, the results of the Klooster study cited in the previous section can now be explained more fully. The separation losses experienced during this study were largely the result of evaluating the concept at 8,000 feet and applying legacy distance-based standards. It is interesting to consider possible differences in results that would likely have been achieved if Klooster and De Smedt had chosen to use a high altitude meter fix. For example, these researchers might have selected the 19,000 foot crossing altitude at *Sayge* on the arrival to Denver (the same fix used in 2012-2013 FAA HITL simulations). If they had done so, the results would almost certainly have been different and the conclusions stated in that report would likely have been more optimistic.

5.2.2.2 Time-based separation for Wake Turbulence in Europe

While time-based concepts are being developed both in the United States and Europe, recent changes to separation standards indicates European regulatory agencies are keenly aware of the benefits of both sequencing and separating aircraft by time, leading to a progression toward implementation of time-based separation standards.

In January 2015, the United Kingdom issued an update to its separation standards through an Aeronautical Information Circular. This circular restated existing category standards for wake turbulence as well as the well-established time-based standards for departures and the distance-based standards for arrivals. However, this circular introduced a new time-based separation standard for arrivals as an alternative to the distance-based standards. The separation minima is reproduced from this circular in Figure 12 (UK Civil Aviation Authority 2015).

		Follower					
		Super Heavy	Heavy	Upper Medium	Lower Medium	Small	Light
Leader	Super Heavy A380	#	135s	158s	158s	158s	158s
	Heavy > 136000 kg	#	90s	113s	113s	135s	158s
	136000 kg > Upper Medium > 104000 kg	#	#	68s	90s	90s	135s
	104000 kg ≥ Lower Medium > 40000 kg	#	#	#	#	68s	113s
	40000 kg ≥ Small > 17000 kg	#	#	#	#	68s	90s
	17000 kg ≥ Light	#	#	#	#	#	#

Note: # Signifies that separation for wake turbulence reasons alone is not necessary

Figure 12: UK Time-Based Separation Standard for Arrivals

According to the European Commission's website, headwinds are responsible for 44% of arrival delays at Heathrow, translating into nearly 3,000 hours of annual delay at that airport alone. The implementation of a time-based standard has eliminated approximately 60% of this delay and resulted in a measurable increase in airport capacity with increases being directly proportional to wind speed. As an example data point, with wind speeds of 20 knots, the airport is able to achieve approximately 3 additional arrivals per hour (European Commission 2017).

Beyond the direct benefits achieved by a time-based separation standard, opportunities for indirect benefits are also created. Runway optimization is an area of research that has generated a variety of innovative approaches to sequencing arrivals, but a review of the literature reveals that many of the algorithms are dependent upon application of time-based separation standard for both departures and arrivals, and adherence to distance-based standards has inhibited acceptance and implementation of many promising approaches. As one example, a simulation-based optimization approach was presented (Soykan and Rabadi 2016), but the metaheuristic algorithm proposed is based in part on a time-based separation standard for arrivals that is nearly identical to the one presented in Figure 12.

5.2.2.3 Required Time Performance and Time-of-Arrival Control Standards

Armed with the lessons learned from multiple studies conducted between 2010 and 2013, more recent research has focused on overcoming the inherent limitations of applying distance-based standards to time-based sequences of aircraft. A 2011 JPDO TBO Study Team report provided a detailed analysis of existing capabilities and an overview of implementation challenges. Among the areas of research identified as being needed to support implementation of a TBO concept is the development of a *Required Time Performance* (RTP) metric where "the objective is to meet the required time with a precision consistent with the density of traffic" (JPDO 2011b). The expected metric would also serve to complement the existing RNP standard, leading to concept implementation supported by a pair of metrics that would fully describe any aircraft's performance capability in four dimensions.

In 2014, RTCA Special Committee 227 developed an alternative to RTP and published a Time-of-Arrival Control (TOAC) standard in DO-236. Unfortunately, the TOAC standard falls

short of complementing the RNP standards and instead creates a "bookend" standard that creates a *mixed equipage* problem in which aircraft will either meet the standard or not. The key element of the RTCA standard is a requirement stating "the system shall be capable of meeting 10 seconds of TOAC accuracy for descent operations and 30 seconds of TOAC accuracy for cruise operations" (RTCA 2013). This standard was developed without reference to a mature concept of operations, and has several shortcomings. Data from multiple flight and simulation tests show that cruise TOAC is more accurate than TOAC in the descent environment, mainly because of the substantial uncertainty associated with descending through dramatically changing environmental conditions and descent procedures where jet aircraft are designed to operate their engines at very low power settings, making engines less responsive than when operated at higher settings in cruise flight. Any system capable of achieving a 10 second TOAC performance in descending flight should be expected to deliver at least the same if not better performance in cruise flight, yet the standard calls for a substantially higher performance in the descent phase. The standard also overlooks climbing flights altogether, and there is no justification cited for either the 10 or 30 second values.

As an alternative to a bookend standard, a categorical standard could be developed in the same way many other standards are expressed within the Federal Regulations. This would immediately provide benefits as categories could be established to describe aircraft performance over a full spectrum of the performance range such that all aircraft would fall into one of the categories. This would allow elimination of the mixed equipage problem created by the bookend standard as all IFR aircraft could be sequenced by time, but it would also allow progressively shorter intervals between aircraft as they are certified in higher performance categories.

In 2014, research funded by NASA through the Virginia Space Grant Consortium resulted in publication of a *Required Time Performance* metric that retains all of the benefits of a categorical standard, but adds additional capability (Bell and Gheorghe 2014). One of the main advantages of an RTP standard is a provision for the ability to address important variables that are unaccounted for in other types of standards. For example, if FMSs are developed by different manufacturers, it is reasonable to expect the algorithms driving TOAC performance to be different. Data from flight tests show trends in performance associated with different FMSs, especially with regard to mean crossing time errors. Simply put, some systems have a tendency to deliver aircraft early while others have shown a tendency to deliver aircraft late. If aircraft with dissimilar performance characteristics are sequenced at a fix with the late tendency aircraft preceding the early tendency aircraft, substantially less separation time and substantially higher collision risk will result even though both aircraft meet the bookend TOAC standard. In contrast, RTP standards have been developed to account for both mean crossing time error and variance.

The RTP metric complements the existing RNP metric by expressing time performance based on an underlying probability distribution in the same way RNP standards are expressed. That is, the performance of the aircraft is described in an RTP-x format, where x is a variable that quantifies the time-based performance of the system with a desired confidence level. The variable x is derived in such a way that it provides control over both the mean crossing time error and the standard deviation of that error, allowing manufacturers freedom to design algorithms that best support the needs of the operator while simultaneously providing a metric that is capable of governing aircraft sequencing with an acceptable level of safety risk as determined through application of collision risk models. Finally, whereas a decision to upgrade the performance of an aircraft's TOAC system may not be sufficient to achieve the requirement of a bookend standard, or to move to a different standard within a category system, the RTP-x

standard allows individual aircraft to achieve incremental benefits, allowing operators to measure the return on investment expected at any equipage level.

5.2.3   Data Communications

The general rule for using CPDLC for ATC clearances is that the application should only be used for "non-time-critical" messaging or clearances.

The exact definition of time allocations for CPDLC in the domestic airspace is given in DO-350A (RTCA SC-214 2016a). When using ground initiated messages covered by the RCP130 requirement (RCP is Required Communications Performance), the overall transaction time including time to send the message, flight crew response time and downlink time is roughly two minutes for the 99.9% Continuity.[30] However most of the round trip transaction times will be a little over a minute, with 95% probability. The time required to send the clearance from the ground automation to the flight deck avionics, one-way, is well less than a minute. Therefore, CPDLC can be used for tactical clearances in some situations even though the latency is not instantaneous. CPDLC is especially useful for complex clearances that are difficult to transmit by voice.

Procedures will have to be developed for CPDLC for each of the relevant use cases and a safety analysis for be performed for each scenario.

5.2.3.1 Data Formats for Time

During HITL testing in 2013, researchers found that different systems applying time-based clearances and constraints used different formats to express portions of minutes. In general, either a minutes and seconds format is used or a minutes and tenths of minutes is used. This discrepancy can influence human factors in the cockpit or ATC facility as operators can become distracted if time is requested or provided in one format while an automation system requires it in another format. To address this concern, researchers found that limiting RTA clearances to 6 second intervals provided an effective mitigation by allowing easy mental conversion between the two formats (Alexander et al. 2013).

5.2.4   Shared Situation Awareness

Within the current ATM environment, a majority of communications are transmitted by voice. A benefit of this process is that all aircrew in a controller's sector hear all communications and gain awareness of their environment by listening to radio transmissions that are not directly intended for their aircraft. For instance, aircrew may overhear a conversation between ATC and an aircraft 100 miles in front of them regarding turbulence at their flight level and the success of a preceding crew in finding a smooth ride by descending to a lower flight level. By virtue of the communication being available to all aircrew, situation awareness is improved and leads to more efficient communications as subsequent aircrew can make a single request to descend to the smooth flight level. In contrast, if the first aircraft were to negotiate an altitude change via data communications, a process of trial and error might ensue in which each successive aircraft requests a series of climbs and descents in search of a smooth ride.

Similarly, there is a well-established culture of communications between pilots and controllers that provides intangible benefits. At times, voice inflection can be just as important as the words spoken on the radio. As an example, on the afternoon of January 15, 2009, US Airways flight 1549 departed La Guardia and lost both engines due to multiple bird strikes. The Captain of the aircraft never declared an emergency, but a subtle change in the tone of his voice communicated the seriousness of the circumstances. A more interesting observation that often goes overlooked is the response by other pilots operating in the same sector at that time.

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[30] Continuity is defined as the probability that the transaction completes within the expiration time

Routine communications all but stopped and none of the communications that took place during the emergency were initiated by aircrew (FAA 2009). They were all immediately aware of the gravity of the situation and understood that they could delay their communications to allow the air traffic controller to devote all of his attention to US Airways 1549.

As a final anecdotal example, a pilot departing a busy airport in a light Cessna might be issued clearance to climb to and maintain 7,000 feet. An opposite direction B737 could be cleared to descend and maintain 8,000 feet, providing acceptable vertical separation between IFR aircraft. However, while the minimum standards are met, an experienced controller would likely issue a vector to one of the aircraft to provide horizontal separation as well – something that is not required by instruction or policy – but due to his awareness that allowing a 737 to pass 1,000 feet directly over a Cessna could expose the smaller aircraft to severe wake turbulence effects. In previous HITL simulations, controllers have expressed concern that in today's environment they routinely provide these types of interventions, many of which may prevent accidents, but are not accounted for in any quantifiable way. The related concern is that in a more automated, data-centric environment, they may not be vigilant enough to detect and resolve these types of conflicts.

5.2.5   Vertical Profile

There are a number of possibilities with regard to vertical trajectories within an MBT concept. In the legacy system, altitudes are assigned and climb or descent clearance must be coordinated with ATC before changing altitudes. When climbing and descending aircraft are flying profiles that conflict in two dimensions, as is often the case in the vicinity of busy airports, controllers use altitude as a deconfliction tool by capping the maximum altitude a departing aircraft is cleared to climb to while establishing a minimum altitude an arrival may descend to until the aircraft are de-conflicted horizontally. However, even when aircraft are not necessarily in conflict, instances occur when a controller is only able to clear an aircraft to the top of the sector he controls, forcing a departing aircraft to temporarily level off before reaching its cruise altitude while awaiting handoff to a higher sector. An MBT concept may attempt to manage vertical trajectories to minimize the number of stair-step climbs on departure. No literature has been found discussing the safety case for such a concept, but in general, expectations for an MBT design that proposes changing the current methods of managing vertical movements of aircraft will need to include separation assurance as an integral part of the design.

Another related concept involves allowing aircraft to execute continuous climbs during the en route phase as a more optimum flight profile. The current system includes provisions for this technique by employing block altitudes, but these blocks are impractical due to the layered nature of the current flight level architecture. It is possible that the legacy flight level system could be changed to provide lateral separation over a block of altitudes by increasing the number of lateral route alternatives, giving aircraft the freedom to maneuver vertically without an explicit clearance needed to change altitudes. The safety case for such a design would be established through collision risk modeling and would largely depend on the navigation and time-based performance of the aircraft.

6.   Summary of key findings

This section summarizes the key findings of the study, with a particular focus on the implications for MBT. The section is arranged according to the topics in Sections 3, 4, and 5.

6.1   CPDLC/Data Comm

During the CPDLC program, FAA had identified airborne reroutes as a benefit mechanism, but did not have the modeling tools to assess the benefit. Instead, the benefit assessment focused on the reduced voice frequency congestion benefit mechanism and associated increase in en route sector capacity. However, en route sector capacity is not a major bottleneck in the NAS and it is also not a tangible benefit to users. Had the FAA included the reroutes benefit mechanism, the users may have seen a tangible benefit - particularly benefits to support equipping.

6.1.1   Specific implications for MBT

Voice communication of complex reroutes is impractical for widespread use in the NAS. The nine-year deferment of data link capabilities has slowed MBT concept element progress. History may repeat itself if the MBT cost/benefits assessment makes the same mistake as the original CPDLC cost/benefits assessment. To mitigate these concerns, MBT should:

- Identify benefit mechanisms that are tangible to users.

- Identify methods for determining hard-to-assess benefit mechanisms.

- Consider providing financial incentives for flight operators to equip with capabilities that are foundational to the MBT concept if the benefits are not clear cut for flight operators (as was done with the 2012 Data Comm program and with the European Link 2000+ Programme).

6.2   Baseline 2 ADS-C EPP

ADS-C EPP appears to be the only capability on the horizon with any momentum that can be utilized for sharing complete (or near-complete) FMS trajectory intent with ANSP ground systems. However, there is no mandate for ADS-C EPP. Aircraft that are equipped with FANS 1/A, which supports basic ADS-C, will need to upgrade to what is referred to as Baseline 2 for an EPP capability, which Boeing says *"is going to be prohibitively expensive."* The FAA has not committed to widespread ground deployment, and without that, Boeing does not believe there is a business case for B2 (Nguyen 2016).

6.2.1   Specific implications for MBT

The MBT ConOps should include a concept variant that assumes ADS-C EPP intent will not be available for high percentage of aircraft. For aircraft without EPP, managing aircraft trajectory prediction uncertainty will be more difficult, lessening the effectiveness of MBT.

6.3   ADS-B In

While ADS-B Out is mandated, ADS-B In is not so what will entice users to equip? The NextGen Equipage Paradox refers to the following:

Despite the potential for significant benefits from NextGen, airlines and other operators are not making the needed aircraft equipage investments. There are still uncertainties in NextGen requirements and benefits. This means that in the end, those operators who

are last to equip with NextGen avionics will reap the most financial benefit, while those operators who are first will get the lowest returns at a far greater risk. [31]

6.3.1 Specific implications for MBT

Any MBT concept elements that require self-spacing, self-merging, and/or self-separating will not be feasible for aircraft without ADS-B In.

6.4   Advanced FMS capabilities

For older aircraft with older avionics, FMS upgrades are not possible because of the inherent differences with newer technology. Looking to the future, Boeing says Baseline 2B *"is going to be prohibitively expensive."* Air carriers have had bad experiences in the past where their investment in avionics upgrade have not been utilized and thus not provided any benefit because the corresponding investments on the ANSP side did not materialize. The FAA has not committed to widespread ground deployment, and without that, Boeing does not believe there is a business case for Baseline 2 (Nguyen 2016).

6.4.1 Specific implications for MBT

The wide range of FMS capabilities in the NAS that currently exists and will continue to exist for decades into the future results in a mixed capability environment. The MBT concept will have to consider the best approach for addressing the mixed capability environment on a concept element by concept element basis. In other words, what does best equipped, best served mean for each MBT concept element?

6.5   SWIM

SWIM has vast potential for improving information sharing across stakeholders that has been impossible until recently. However, the US definition of SWIM differs significantly from European SWIM, which has consequences for its implementation and use.

6.5.1 Specific implications for MBT

Existing concept elements should be reexamined to determine if newly available information can be leveraged to improve the concept element. However, dual standards for SWIM may limit international air carrier effectiveness with respect to certain MBT concept elements such as trajectory negotiations because of incomplete information.

6.6   IFC

High cost inhibits low-cost carriers from implementing IFC.

6.6.1 Specific implications for MBT

Low-cost carriers may not be able to leverage EFB applications and SWIM information. Thus, certain benefits of MBT (e.g., effective trajectory negotiation) that rely on dynamic information will not be attainable to them.

6.7   AAtS

Slow adoption of the AAtS approach may result in many interim sub-optimal, often competing stove piped solutions that impede the rate of AAtS implementation and take up.

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[31] http://www.rtca.org/Files/NAC%20Recommendations/NAC%20EquipAdHoc%20FinalApprvd.pdf

6.7.1 Specific implications for MBT

Certain benefits of MBT such as effective trajectory negotiation may not be fully realized if adoption rate of AAtS is slow.

6.8 Pilot/FMS information needs

There are many ATC LOAs and SOPs that can change the FMS trajectory that are unknown to the pilot and are not available in an FMS database. Furthermore, trajectory changes due to these procedures often put the aircraft on an open trajectory. However, FMSs have limited database capacity to add the data associated with these SOPs and LOAs.

6.8.1 Specific implications for MBT

LOAs and SOPs place constraints on aircraft trajectories that today are not published. MBT should account for these constraints and their effect on trajectories and trajectory negotiation.

6.9 The FOC's role in NextGen

In the JPDO's FOC report (JPDO 2012), the following shortcomings were identified regarding the FOC's limited role in NextGen.

Finding 4: The rules and content for data sharing are not clearly defined. While NextGen stresses the importance of "distributed decision making," increased user focus, and provisioning information to users, the current NGIP does not address the data availability, rules, and related processes that will be required to bring this to fruition.

Finding 5: There is a lack of appreciation for and incorporation of the role of the FOC to ensure the success of the FAA Data Communications (Data Comm) program.

6.9.1 Specific implications for MBT

MBT needs to consider not only the functions ascribed to the FOC, but also specify the data to be exchanged or rules for data exchange.

6.10 Closed trajectories

Trajectory uncertainty causes controllers to use tactical clearances, which tend to be open trajectory clearances. Consider that automated conflict resolution advisories have been discussed for over two decades and still have not been implemented in ERAM.[32] Without the automation support for closed trajectories, controllers will continue to use open trajectory techniques.

6.10.1 Specific implications for MBT

Open trajectory clearances exacerbate the trajectory uncertainty in the system. On the other hand, trajectory predictability enables controllers to use strategic, closed trajectory clearances, which then maintains a high level of trajectory predictability. Thus, the MBT concept needs to consider the set of technologies, procedures, and cultural changes that will be the *tipping point* that moves the NAS towards wide-spread use of closed trajectories and predictability to facilitate MBT. There is clearly cultural resistance to automated conflict resolution advisories.

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[32] https://www.caasd.org/library/papers/uret/

6.11 Trajectory negotiation

FMS capabilities do not support proposing a new trajectory, only to propose a flight-optimal way to achieve the given flight plan. EFB applications to support trajectory negotiation do not currently exist. While these applications will likely get developed when sufficient enablers are in place, the air carrier industry lack of interest in applications to leverage CTOP (which provide similar types of benefits as trajectory negotiation) is a cautionary tale for trajectory negotiation participation.

6.11.1 Specific implications for MBT

Trajectory negotiation is one of the MBT benefits that allows users to see direct, tangible benefits across the fleet or for individual flights. If users choose not to upgrade their capabilities to facilitate trajectory negotiation, it is indicator that they would not likely upgrade for other aspects of MBT. It will be difficult to make realistic estimates of user participation for trajectory negotiation, which will have a direct bearing on benefits.

6.12 Management of residual trajectory uncertainty

Residual uncertainty is not a primary reason why TBO adoption has been slow. Modern TBO concepts recognize the existence of residual uncertainty and include concept elements to accommodate it. These concept elements, while adding some complexity beyond the original "perfect world" concept that trajectories would be planned once and then followed precisely with no disturbances, are no more difficult to develop than other aspects of TBO concepts. Understanding how much residual uncertainty will exist, how to minimize it, and how to trade off between accommodating uncertainty and expending additional effort to reduce it, may have occupied some research effort that could have otherwise gone toward adopting TBO concepts operationally. In this way, residual uncertainty has contributed to "concept paralysis" in which not knowing which TBO concept should be pursued has prevented quicker adoption of TBO. For example, questions such as what types of trajectory synchronization should be included in the concept and are multiple trajectory predictions permitted or must there be only one trajectory prediction has allowed academics to write numerous papers without a consensus that encourages moving forward with concept validation.

The lack of a single concept of operation for TBO has led to many different opinions about what TBO should be with little convergence by the ATM research community. The FAA needs to clearly define the TBO concept and the NAS Enterprise Architecture evolution associated with the transition to TBO. This provides an opportunity for NASA to provide leadership to help the FAA define the TBO concept elements, of which MBT is one.

6.12.1 Specific implications for MBT

Weather will continue to be a major contributor to residual trajectory uncertainty as well as TFM uncertainty. Yet it is well known in the ATM community that many DSTs do not perform well in dynamic situations such as weather (Gong and Mcnally 2015). This is not a coincidence – rather it is because they have not been designed to handle dynamic situations. Weather problems are often "assumed away" in the concept description or just completely ignored. The underlying justification, whether stated or not, is that most days in the NAS do not have major weather disruptions. Furthermore, the complexity of addressing the dynamic weather situations during concept evaluations limits their assessment. Thus, while lateral and temporal trajectory constraints are seen as the interface between TFM and MBT, the validity of these constraints in addressing demand/capacity imbalances in the presence of weather will likely be degraded. If these constraints create inefficiencies, MBT can provide flexibility and agility when the constraints are updated to mitigate to some extent the initial inefficiencies.

6.13   UPR/UPT

- Controller complexity and traffic density in the eastern US will continue to prevent the use of UPRs in that region.

- No research has been performed to identify the traffic level threshold where UPR requests should be accepted or rejected.

- FMS database capacity limitations impact UPR flight planning capabilities and potential airborne rerouting.

- Human factors issues associated with the NRS grid can tip the scale towards denying UPRs.

- Misunderstanding between stakeholders about whether UPTs include constraints can delay progress.

- Many SOPs/LOAs contain trajectory constraints that are unknown to the navigation databases used by the FMS and FOC flight planning applications, which can result in flight plans getting amended to support ANSP needs.

6.13.1 Specific implications for MBT

Trajectory negotiation is one of the MBT benefits that allows users to see direct, tangible benefits across the fleet or for individual flights. If these roadblocks cannot be addressed, then it will limit user participation and the loss of a key benefit.

6.14   Growing consensus for aspects of MBT concept elements

There is growing consensus that the introduction of SWIM, AAtS, IFC, and EFBs has significant potential to disrupt *business as usual* in the ATM environment, particularly for MBT concepts such as trajectory negotiation, which provides a tangible benefit to the user. And the FAA is making important strides to enable more effective airborne reroutes. These are all predicated on Data Comm equipage. There is also the realization that a mixed equipage environment will exist on many fronts for the foreseeable future for Data Comm, ADS-B In, and ADS-C EPP. Each concept element will have to be evaluated to determine how best-equipped, best-served should be applied with an emphasis on identifying tangible benefit mechanisms.

Acronyms

Acronym	Definition
AAtS	Aircraft Access to SWIM
ABRR	Airborne Reroute
ACS	Aeronautical Common Services
ADS-B	Automatic Dependent Surveillance-Broadcast
ADS-C	Automatic Dependent Surveillance-Contract
ADS-R	Automatic Dependent Surveillance-Rebroadcast
AFP	Airspace Flow Program
AIAA	American Institute of Aeronautics and Astronautics
AID	Aircraft Interface Device
A-IM	Advanced Interval Management
AIM	Aeronautical Information Management
AIMM	AIM Modernization
ANSP	Air Navigation Service Provider
AOP	Autonomous Operations Planner
ARSI	Arrival Route Status and Impact
ARTCC	Air Route Traffic Control Center
ASDI	Aircraft Situation Display to Industry
ASPIRE	Asia Pacific Initiative to Reduce Emissions
ATC	Air Traffic Control
ATCSCC	Air Traffic Control System Command Center
ATM	Air Traffic Management
ATMRPP	Air Traffic Management Requirement and Performance Panel
ATN	Aeronautical Telecommunications Network
ATOP	Advanced Technologies & Oceanic Procedures
ATSU	Air Traffic Service Unit
CAR	Coded Airborne Reroute
CD&R	Conflict Detection & Resolution
CDM	Collaborative Decision Making
CDR	Coded Departure Route
CDTI	Cockpit Display of Traffic Information
CIWS	Corridor Integrated Weather System
CPDLC	Controller-Pilot Data Link Communications
ConOps	Concept of Operations
CSP	Communications Service Provider
CSS-Wx	Common Support Services-Weather
CTOP	Collaborative Trajectory Options Program
DAG-TM	Distributed Air/Ground Traffic Management
DARP	Dynamic Airborne Reroute Procedure

Acronym	Definition
Data Comm	Data Communications
DCL	Departure Clearance
DMS	Data Management Service
DSP	Departure Spacing Program
DST	Decision Support Tool
EDA	Efficient Descent Advisor
EDCT	Expect Departure Clearance Time
EET	Estimated Elapsed Time
EFB	Electronic Flight Bag
EPP	Extended Projected Profile
ERAM	En Route Automation Modernization
ERASMUS	En Route traffic Soft Management Ultimate System
ES	Extended Squitter
ET	Expiration Time
EWD	Enhanced WINS Dissemination
FAA	Federal Aviation Administration
FANS	Future Air Navigation System
FCA	Flow Constrained Area
FEA	Flow Evaluation Area
FIR	Flight Information Region
FIS-B	Flight Information Services-Broadcast
FMS	Flight Management System
FNS	Federal NOTAM System
FOC	Flight Operations Center
FSM	Flight Schedule Monitor
GDP	Ground Delay Program
GPS	Global Positioning System
GS	Ground Stop
HAR	High Altitude Routing
HITL	Human In The Loop
HMI	Human Machine Interaction
IAP	Instrument Approach Procedure
ICAO	International Civil Aviation Organization
IEEE	Institute of Electrical and Electronics Engineers
IFC	In-Flight Connectivity
IFR	Instrument Flight Rule
IPI	Intermediate Projected Intent
ITWS	Integrated Terminal Weather System
JPDO	Joint Planning and Development Office
LOA	Letter of Agreement

Acronym	Definition
MAP	Monitor Alert Parameter
MBT	Management by Trajectory
MCP	Mode Control Panel
MIT	Miles in Trail
NAS	National Airspace System
NAVAID	Navigational Aid
NCR	NAS Common Reference
NEMS	NAS Enterprise Messaging Service
NEXRAD	Next Generation Weather Radar
NextGen	Next Generation Air Transportation System
NGIP	NextGen Implementation Plan
NOAA	National Oceanographic and Atmospheric Administration
NOTAM	Notices to Airmen
NRP	North American Route Program
NRR	Non-Restrictive Routing
NRS	Navigation Reference System
NTML	National Traffic Management Log
NTN	NextGen Trajectory Negotiation
OPD	Optimized Profile Descent
OSS	One Stop Shop
PBN	Performance Based Navigation
PDMP	Pre-Defined Meter Point
PIREP	Pilot Report
RAPT	Route Availability Planning Tool
RCP	Required Communications Performance
RCTP	Required Communications Technical Performance
RNAV	Area Navigation
RNP	Required Navigation Performance
RTA	Required Time of Arrival
RTCA	Radio Technical Commission for Aeronautics
RTP	Required Time Performance
RVR	Runway Visual Range
SA	Situation Awareness
SAA	Special Activity Airspace
SFDPS	SWIM Flight Data Publication Service
SID	Standard Instrument Departure
SIGMET	Significant Meteorological Information
SOP	Standard Operating Procedure
STAR	Standard Terminal Arrival Route
STARS	Standard Terminal Automation Replacement System

Acronym	Definition
STDDS	SWIM Terminal Data Distribution System
SWIM	System Wide Information Management
TAP	Traffic Aware Planner
TASAR	Traffic Aware Strategic Aircrew Request
TBFM	Time Based Flow Management
TBO	Trajectory Based Operations
TCP	Trajectory Change Point
TFDM	Terminal Flight Data Manager
TFM	Traffic Flow Management
TFMData	Traffic Flow Management Data
TFMS	Traffic Flow Management System
TFR	Temporary Flight Restriction
TIS-B	Traffic Information Services-Broadcast
TLS	Target Level of Safety
TMC	Traffic Management Coordinator
TMI	Traffic Management Initiative
TMU	Traffic Management Unit
TO	Surveillance Overdue Delivery Time
TOAC	Time-of-Arrival Control
TOC	Top of Climb
TOD	Top of Descent
TRACON	Terminal Radar Control
TRN	Transaction
TRNET	Transaction Expiration Time
TSD	Traffic Situation Display
UAT	Universal Access Transceiver
UPR	User Preferred Route
UPS	United Parcel Service
UPT	User Preferred Trajectory
URL	Uniform Resource Locator
VDL	VHF Data Link
VHF	Very High Frequency
WAM	Wide Area Multilateration
WARP	Weather and Radar Processor
WINS	Weather Information Network Server
WMSCR	Weather Message Switching Center Replacement System

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14. ABSTRACT

In order to realize the full potential of the Next Generation Air Transportation System (NextGen), improved management along planned trajectories between air navigation service providers (ANSPs) and system users (e.g., pilots and airline dispatchers) is needed. Future automation improvements and increased data communications between aircraft and ground automation would make the concept of Management by Trajectory (MBT) possible.

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