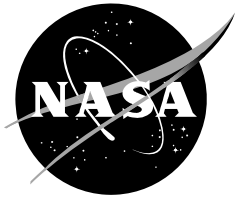


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# Concept of Operations for Management by Trajectory

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**September 2018**

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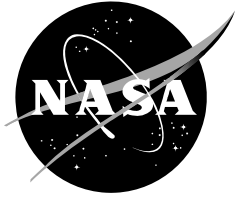
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## Executive Summary

This document describes Management by Trajectory (MBT), a concept for future air traffic management (ATM) in which every flight operates in accordance with a four-dimensional trajectory (4DT) that is negotiated between the airspace user and the Federal Aviation Administration (FAA) to respect the airspace user's goals while complying with National Airspace System (NAS) constraints.

In the present-day NAS, the ATM system attempts to predict the trajectory for each flight based on the approved flight plan and scheduled or controlled departure time. However, once the aircraft starts to move, controllers tactically manage the aircraft to implement traffic management restrictions, separate otherwise conflicting aircraft, and address arising NAS constraints. Tactical controller actions are not directly communicated to the automation systems or other stakeholders. Furthermore, the initial trajectory prediction does not anticipate these disruptions or how they will impact the flight. Consequently, and compounded by gaps in required data and models, trajectory predictions are less accurate than possible, which affects Traffic Flow Management (TFM) performance.

A cornerstone of the MBT concept is that all air vehicles have, at all times, an assigned 4DT from their current state to their destination. These assigned trajectories consist of trajectory constraints and descriptions. Pilots and air traffic controllers, with the aid of automation, operate the aircraft to comply with the assigned trajectory, unless first negotiating a revision. Equipped aircraft have substantial responsibility for complying with the assigned trajectory without controller intervention. To maximize the operational flexibility available to the airspace user, the assigned trajectory only imposes trajectory constraints as required to achieve the ATM goals of NAS constraint compliance and aircraft separation. Trajectory descriptions are added to the assigned trajectory to ensure sufficient predictability.

To further improve trajectory prediction accuracy, airspace users supplement the assigned trajectory by broadcasting intent information and updating it as necessary. Air vehicle intent is a more detailed description of the airspace user's plan for how the flight will fly the assigned trajectory. Air vehicle intent can change freely, without negotiation, as long as it remains in compliance with the assigned trajectory. Aircraft assigned trajectories, air vehicle intent, and predicted trajectories are shared, creating a common view among stakeholders.

A NAS Constraint Service gathers and publishes information about all known NAS constraints, enabling airspace users to be informed participants in trajectory negotiation. Trajectory constraints in the assigned trajectory are mapped to NAS constraints to facilitate identifying which aircraft are affected when NAS constraints change. To support efficient trajectory negotiation, all aircraft provide current information about air vehicle capabilities.

Assigned trajectories are constructed to satisfy all known NAS constraints, improving trajectory stability and predictability. Uncertainty and disruptions are handled by modifying the assigned trajectory as far in advance as possible. By proactively negotiating changes to the assigned trajectory, rather than relying on controller-selected tactical actions such as vectors to resolve traffic conflicts or implement miles-in-trail restrictions, MBT keeps aircraft on closed trajectories that are fully known to all stakeholders. Since reactive air traffic control actions cannot be predicted in advance, the downstream trajectory cannot be accurately predicted until they happen. Reliable trajectory predictions allow the system to identify needed modifications to trajectories further in advance, where they can be negotiated and communicated as amendments (i.e., additional or altered trajectory constraints) to the assigned trajectory. Decision Support Tools (DSTs) aid controllers in rapidly defining and communicating closed trajectories to the aircraft and support all stakeholders in trajectory negotiation.

Anticipated MBT benefit mechanisms include more accurate trajectory predictions, improved ATM performance and robustness to off-nominal conditions, increased flexibility and operational efficiency, reduced impediments to emerging classes of airspace users accessing NAS resources, reduced environmental impacts, and enhanced safety.

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## Abbreviations

<b>Abbreviation</b>	<b>Definition</b>
2D	2-Dimensional
3D	3-Dimensional
3DT	3-Dimensional Trajectory
4D	4-Dimensional
4DT	4-Dimensional Trajectory
ACAS	Airborne Collision Avoidance System
ADS-C	Automatic Dependent Surveillance-Contract
AFP	Airspace Flow Program
ANP	Actual Navigation Performance
AOC	Airline Operational Control
ARTCC	Air Route Traffic Control Center
ATC	Air Traffic Control
ATP	Actual Time Performance
A-IM	Advanced Interval Management
AT	Assigned Trajectory
ATM	Air Traffic Management
ATN-B2	Aeronautical Telecommunications Network – Baseline 2
AU	Airspace User
CDM	Collaborative Decision Making
CD&R	Conflict Detection and Resolution
ConOps	Concept of Operations
CPDLC	Controller-Pilot Data Link Communications
CTA	Controlled Time of Arrival
DHV	Debris Hazard Volume
DST	Decision Support Tool
DP	Departure Procedure
EA	Enterprise Architecture
EDCT	Expect Departure Clearance Time
EFB	Electronic Flight Bag
EPP	Extended Projected Profile
ERAM	En Route Automation Modernization
ETA	Estimated Time of Arrival
eVTOL	Electric Vertical Takeoff and Landing
FAA	Federal Aviation Administration
FIM	Flight-deck Interval Management
FMS	Flight Management System
FOC	Flight Operations Center
GA	General Aviation
GDP	Ground Delay Program
GPS	Global Positioning System
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
LOA	Letter of Agreement
MBT	Management By Trajectory
MCP	Mode Control Panel
MINIT	Minutes in Trail
MIT	Miles In Trail
NAS	National Airspace System

PBN	Performance Based Navigation
PIC	Pilot in Command
RF	Radius-To-Fix
RNP	Required Navigation Performance
RTA	Required Time of Arrival
RTP	Required Time Performance
SAA	Special Activity Airspace
SOP	Standard Operating Procedure
STA	Scheduled Time of Arrival
STAR	Standard Terminal Arrival Route
STARS	Standard Terminal Automation Replacement System
SUA	Special Use Airspace
SVO	Space Vehicle Operations
SWIM	System Wide Information Management
TBFM	Time Based Flow Management
TBO	Trajectory Based Operations
TCAS	Traffic Collision Avoidance System
TFDM	Terminal Flight Data Manager
TFM	Traffic Flow Management
TFMS	Traffic Flow Management System
TMC	Traffic Management Coordinator
TMI	Traffic Management Initiative
TMU	Traffic Management Unit
TOAC	Time Of Arrival Control
TOS	Trajectory Options Set
TRACON	Terminal Radar Approach Control
UA	Unmanned Aircraft
UAS	Unmanned Aircraft Systems
UPR	User Preferred Route
US	United States

# 1. Introduction

In the present day National Airspace System (NAS), the air traffic management (ATM) system has a predicted trajectory for each flight based on the approved flight plan and a scheduled or controlled departure time. Once the aircraft starts to move, controllers tactically manage the aircraft, using “open trajectory” vectors, altitude changes, and speed clearances, to implement traffic management restrictions, separate otherwise conflicting aircraft, and address arising NAS constraints. The current ATM system tends to be conservative in the strategic time frame, when changes are implemented via flight plan changes, to avoid delaying aircraft more than necessary. As a result, many problems are left to the controller to solve tactically (e.g., routing an aircraft around weather or complying with a new Traffic Flow Management [TFM] restriction). Tactical controller actions are not directly communicated to the automation systems or other stakeholders.

These aspects of the current system, coupled with gaps in trajectory prediction data and models, impede the ability to predict how NAS constraints will influence a flight’s trajectory. Ground Delay Programs (GDPs) and Airspace Flow Programs (AFPs) assign departure times designed to comply with a Controlled Time of Arrival (CTA) at a NAS constraint, based on the airspace user’s estimated time en route but without knowledge of controller actions to address other constraints. Time Based Flow Management (TBFM) makes a similar assumption that the estimated times of arrival (ETAs) to the constraint are correct, when a variety of disruptions can introduce unexpected delays that affect the flight’s ETA. Until the flight is affected, the impact of local traffic management decisions on individual flights is not known, and a flight may encounter several such disruptions en route to its destination. This makes NAS demand predictions at each NAS resource less accurate.

Management by Trajectory (MBT) is a concept for future ATM in which the Federal Aviation Administration (FAA) and airspace users negotiate four-dimensional trajectories (4DTs) for all flights that respect the airspace user’s goals while complying with NAS constraints.<sup>1</sup> By considering both airspace user and FAA objectives, and utilizing negotiated 4DTs to communicate the traffic management plan, the concept is highly flexible to different types of airspace users and trajectory characteristics. As a result, the baseline concept accommodates a broad and expanding spectrum of current and anticipated airspace operations, from traditional commercial aviation to emerging users such as Unmanned Aircraft Systems, space vehicles, and on-demand air transportation vehicles. Pilots and air traffic controllers use automation to keep the aircraft on its assigned trajectory, which includes complying with temporal or speed constraints. Equipped aircraft have substantial responsibility for complying with the assigned trajectory without controller intervention. Assigned trajectories are constructed to respect all of the known constraints from the aircraft’s current location to its destination, making the flight’s entire trajectory much more predictable than it is today. Where uncertainty or disruptions occur, resolutions are, to the extent possible, handled through trajectory modifications as far in advance as possible.

Future improvements in automation (ground-based and aircraft) and data communications (air-ground and among stakeholders on the ground) make the MBT concept possible. MBT eliminates most local, reactive control actions being applied to aircraft, which cannot be predicted in advance and which have impacts on the downstream trajectory that cannot be known until they happen. MBT does this by inserting the impact of all NAS constraints into the assigned trajectory in the form of trajectory constraints. Where uncertainty remains, necessary adjustments to the trajectory constraints are made proactively, maximizing trajectory predictability and delivering associated benefits.

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<sup>1</sup> In this way, MBT is similar to Trajectory Based Operations concepts that employ a 4D contract. The appendix “Comparison with ICAO TBO Concept” compares MBT with the International Civil Aviation Organization (ICAO) TBO concept.

In the past decade, the term Trajectory Based Operations (TBO) has been used widely. The term TBO has come to be used in two distinct ways. One meaning of TBO is as a high-level vision for the future of the NAS in which 4DTs are the core of air traffic control and air traffic management. The second meaning of TBO is an evolving set of specific endeavors intended to advance the NAS toward the future vision. MBT is one specific interpretation of the high-level TBO vision, and is the starting point from which specific challenges can be identified and studied, contributing to the refinement of the MBT concept and the overall body of knowledge related to TBO.

### 1.1 NAS Shortfalls Addressed by MBT

This section summarizes the shortfalls in the current NAS that are addressed by MBT, as shown in Table 1. These shortfalls are consistent with those identified in the International Civil Aviation Organization (ICAO) TBO Concept Document [1]. The ICAO TBO Concept Document provides high-level guidance for resolving these shortfalls, and the MBT concept provides a specific vision for resolving the shortfalls that is consistent with the ICAO TBO Concept.

**Table 1. NAS Shortfalls Addressed by MBT**

Shortfalls	MBT Improvements
Data exchanged between airspace users and the FAA are too sparse to support accurate trajectory prediction across all phases of flight and trajectory synchronization across automation systems.	The data needed by all relevant airspace users, aircraft, and FAA automation systems to develop accurate, consistent 4DT predictions are available to all relevant systems.
The use of open trajectories, including tactical maneuvers, causes poor trajectory predictability.	Aircraft operate on closed trajectories to the extent possible, which improves trajectory predictability.
Insufficient publication of trajectory changes and lack of trajectory synchronization result in poor trajectory predictability.	Publication of all trajectory changes and advanced exchange of trajectory information between ground automation systems and the aircraft allow for trajectory synchronization across systems, resulting in consistent trajectory predictions across systems.
Poor trajectory predictability inhibits strategic (longer look ahead) trajectory management.	Improved trajectory predictability, improved coordination capabilities, and use of 4DTs enable controllers to use strategic, closed clearances. A high level of trajectory predictability becomes the new norm. Enhanced predictability will improve TFM performance and provide a more consistent flow of air traffic, where demand will more accurately meet available capacity, reducing or eliminating delay.

<p>Lack of knowledge about certain types of constraints prevents airspace users from planning business-efficient, acceptable trajectories. Those constraints also are unknown to every ground automation system, causing aircraft to be handled with an open-ended clearance when the constraints are encountered.</p>	<p>All applicable NAS constraints, both dynamic (e.g., TFM) and static (e.g., crossing restrictions) are published such that they can be known by all airspace users and relevant automation systems. All constraints affecting a given aircraft are reflected in the 4DT.</p>
<p>Insufficient mechanisms to allow traffic managers and controllers to efficiently and effectively amend flights' routes cause route amendment backlogs during disruptive NAS events.</p>	<p>Traffic managers apply constraints to efficiently amend trajectories as NAS events evolve, enabling a more flexible and responsive ATM system that can take full advantage of available airspace and drastically reduce delay.<sup>2</sup></p>
<p>There is not a good mechanism that allows controllers and traffic managers to predict the downstream consequences of an action or decision on specific aircrafts' trajectories.</p>	<p>Downstream effects of actions on a trajectory are considered in decision making associated with a given trajectory, including tactical control actions.</p>
<p>Current time of arrival control (TOAC) standards establish a minimum performance requirement that some aircraft will be certified for while others will not. This type of standard may inadvertently introduce unacceptable safety risk into the NAS and creates a mixed equipage environment in which one ATM concept applies to those who meet the standard while another concept must be applied to those who do not.</p>	<p>By quantifying time-based performance as a metric that complements existing PBN metrics, all IFR aircraft may be managed by a single ATM concept that maximizes efficiency while maintaining an acceptable level of safety risk.</p>

**1.2 MBT Overview**

The MBT concept can be summarized by the following key points.

- MBT applies to all aircraft operating according to Instrument Flight Rules (IFR).
- Aircraft are assigned 4DTs, which are negotiated, closed trajectories, from their current state to their destination.
- A NAS Constraint Service publishes common information about NAS constraints to all stakeholders.
- Trajectory constraints can be mapped to NAS constraints to facilitate identifying affected aircraft when NAS constraints change.
- All aircraft follow their negotiated, assigned trajectories, complying with trajectory constraints.
- Trajectory constraints and associated tolerances are defined based on the flight's individual performance capabilities and the situational need for the constraint.

<sup>2</sup> This document does not describe the details of how traffic managers or traffic management automation determines what trajectory constraints to impose on each flight. Traffic management automation will identify which flights are affected by each TMI and translate that TMI into one or more trajectory constraints specific to the flight.

- Aircraft provide detailed information about their predicted 4DT (a.k.a. intent data) that is shared across stakeholders. Aircraft provide updates when intent data change.
- Conflicts can be detected further in advance due to improved predictability, and intervention can be accomplished through adding or modifying constraints in the assigned 4DT.
- Open trajectories (i.e., tactical vectoring by controllers) for which the controller's and/or pilot's intent is unknown by other actors in the system are minimized.
- MBT follows two paths to eliminating open trajectories: 1) introducing methods for planning tactical maneuvers as closed trajectory modifications and 2) eliminating the need for tactical maneuvers through improved predictability.
- Digital air-ground communication is used to deliver 4DTs to aircraft cockpits for easy loading and execution in the Flight Management System (FMS).
- Broadband air-ground communications and advanced electronic flight bag (EFB) applications are used to include the flight crew in the trajectory negotiation process.
- A *negotiating controller* subsumes the responsibilities of the D-side controller. Together, the negotiating controller and traffic management coordinators (TMCs), with their longer time horizon perspectives, proactively intervene to avoid conflicts and achieve TFM objectives, using automation enhancements that facilitate coordinating 4DT changes across multiple sectors.

### 1.3 Purpose

This document is intended to describe a far-term MBT concept. Far-term is not precisely defined but targets an operational environment in which the NAS, and the vast majority of aircraft, are capable of the advanced data exchange and automation capabilities associated with the Aeronautical Telecommunications Network-Baseline 2 (ATN-B2). The value of this document is to provide a vector to guide research.

### 1.4 Near- vs. Far-Term MBT

This MBT Concept of Operations (ConOps) presents an end-state vision for MBT, while beginning to identify what could be feasible in the more near-term timeframe. The near- and far-term MBT concepts differ in two ways. First, the near-term concept is constrained by the current NAS and currently planned changes to the NAS (i.e., changes that the FAA plans and are documented within the NAS Enterprise Architecture [EA] evolution within the NextGen timeframe), while the far-term concept may make assumptions about future enabling changes. Second, while the far-term concept encompasses the entirety of air traffic control (ATC) within the NAS, in the near-term a more limited set of TBO operations may be feasible and beneficial.

### 1.5 Assumptions

This section summarizes key assumptions about the near-term and far-term environments in which MBT would operate.

#### 1.5.1 Assumptions about the Near-Term MBT Environment

- Air traffic controllers will still be responsible for separation management and conflict avoidance; self-separation of IFR aircraft will not be the norm in the far-term MBT environment.
- Air vehicle capabilities and equipment will be consistent with the current progression of safety and performance standards.

- The capabilities of highly equipped aircraft will not change. For example, aircraft FMS that include Required Time of Arrival (RTA) functionality will remain limited to a single active RTA constraint at a time. Controller-pilot data link communications (CPDLC) with route clearances and trajectory intent output will be standard services supported by avionics.
- MBT will slowly seep into NAS operations; there will not be a step change in procedures. This will allow equipped aircraft to experience some benefit while operating among unequipped aircraft, and allow controllers with different perspectives on changing technologies and procedures to adapt to MBT at different paces.
- MBT tools will be introduced incrementally through upgrades to existing automation platforms and extensions to the information shared via System Wide Information Management (SWIM). Adoption of MBT will be varied around the NAS with some facilities and controllers more willing and able to adopt new capabilities than others. Benefits will initially be slow to accumulate as controllers become more comfortable with the technologies. Experience will allow the tools to be refined to improve performance and increase user acceptance. Eventually, a critical mass of usage will be reached, resulting in increased usage and benefits.
- Adoption of supporting technologies by airspace users will continue at its current pace. Equipped aircraft from participating operators will benefit from the ability to negotiate their trajectories and will be more likely to be left alone to follow the assigned trajectory.
- Current structured airspace will remain in use, although increased use of direct routing will be allowed in regions of low-to-medium operational density.
- Controllers will use automation support to define and issue closed trajectories in advance, rather than reverting to open-trajectory vectors issued via voice.

### **1.5.2 Assumptions about the Far-Term MBT Environment**

- EFBs will become much more capable and will have reliable, high-speed connectivity to ground-based systems. This will enable a rapid advance in air vehicle capabilities without requiring all of the changes to occur within legacy FMS architectures, which could be more expensive and slower to enter the fleet.
- All aircraft will be capable of receiving assigned trajectories via digital communication and flying these trajectories with known accuracies. Voice will continue to exist for cases when immediate feedback and action are required. While many aircraft will be capable of digitally receiving trajectories and automatically loading them into the FMS, others will require pilots to manually load trajectory data into the FMS or otherwise fly the assigned trajectory.
- The rapid advance of technologies and applications for unmanned aircraft systems (UAS) operations in the NAS will overflow into other categories of aviation operations. Current Traffic Collision Avoidance System/Airborne Collision Avoidance System (TCAS/ACAS) technology will experience a substantial evolution based on emerging UAS detect and avoid capabilities. This technology change will converge with technologies that support self-separation between aircraft (e.g., Advanced Interval Management [A-IM]). As a result, the long-term environment will be characterized by all IFR aircraft being equipped with coordinated tactical conflict avoidance capabilities that can detect and safely avoid complex conflict scenarios involving multiple aircraft of all types, while providing the planned avoidance maneuvers to ground automation via broadband communication. This will provide the final layer of safety in the MBT concept.
- TFM will evolve considerably. GDPs and AFPs will move toward controlling by CTA at the constrained NAS resource rather than departure time. The time horizon over which



TBFM is applied will expand further into the en route environment, and TBFM will be used to address airspace constraints as well as airport capacity constraints.

- Use of generic miles-in-trail (MIT) restrictions (i.e., the same restriction across many aircraft) will be eliminated. When metering is not required, aircraft will be spaced for safety and efficiency using either time-based management or A-IM.
- MBT facilitates a transition to time-based separation standards. Whether the NAS uses distance-based or time-based separation requirements, or a combination of both, to define minimum separation standards, is inconsequential to MBT. MBT is able to function for any type of separation requirements.
- Aircraft capability to meet TOAC constraints is described using a Required Time Performance (RTP) metric that serves as a complement to existing standards used to describe Required Navigation Performance (RNP). An aircraft's time-based performance is denoted by RTP-Y, where Y is a variable that describes the 95% confidence interval of the expected crossing time error distribution, in seconds, regardless of its shape. In an MBT environment, all aircraft will be certified to operate at some RTP level, including aircraft that are not equipped with automation systems that include RTA functionality.
- Airspace users' flight operations centers will develop advanced capabilities to fully participate in MBT. Software applications and private service providers will enable non-airline flights to fully participate in MBT.
- The NAS will accommodate new aircraft classes, including on-demand travel, personal mobility, UAS, space vehicle launch and return operations, airships, and loitering operations (e.g., to provide communication or ground surveillance services). Many of these newer, emerging users are expected to have the necessary capabilities to be fully compliant with MBT.

## 1.6 Document Scope

### 1.6.1 Surface Operations

This ConOps document focuses on the airborne phases of flight. However, MBT is applicable to all phases of flight. Although nothing in the MBT concept precludes including a surface trajectory as part of the aircraft's 4DT, defining the surface trajectory and the aircraft following it would require new ground and aircraft automation capabilities, distinct from those required for airborne MBT trajectories. Therefore, the application of MBT to surface operations will not be pursued in this effort unless the incremental benefits of including management of surface operations within the MBT concept is justified.

Application of TBO elements is still possible without the full application of MBT to surface operations. For example, the ATM system can plan and control pushback times based on scheduled takeoff times and with consideration of runway queue management, without needing to provide a closed trajectory on the surface. However, MBT is compatible with TBO concepts that do envision a closed trajectory on the surface such as [3].

What is most important for MBT, from the surface point of view, is exchange of the necessary data to provide an interface between surface and en route operations and an assigned trajectory that is consistent with a surface management plan that delivers expected surface event times that impact airborne operations [1]. For example, reliable takeoff and landing time predictions, runway assignments, and inclusion of the departure and arrival transitions in the assigned trajectory support coordination between en route and surface environments.

Surface operations will be very diverse for different types of users, further motivating treating MBT ground operations as a separate research topic. Emergent users may share traditional airports or operate to/from alternative sites. Space vehicles operate from special launch and

recovery sites and often have no surface movements. Rotorcraft are able to “air taxi” and therefore are not constrained by taxiways and do not require runways.

### **1.6.2 Traffic Flow Management**

Traffic flow management is separate from the MBT concept. TFM is responsible for selecting traffic management initiatives (TMIs), which impose constraints on trajectories. The MBT concept addresses the assignment of trajectories that are compliant with all TMIs, the modification of assigned trajectories as constraints change, and the satisfaction of the constraints as aircraft follow the assigned trajectories. Improved predictability resulting from MBT will allow TFM to select more-effective TMIs.

In the near-term, GDPs and AFPs will continue to function as they presently do. In the longer-term environment, GDPs/AFPs will move from controlling through the use of an Expect Departure Clearance Time (EDCT) constraining the departure time to enforcement of the CTA at the limited resource as a time constraint on the assigned trajectory. The operator will have flexibility to determine when the aircraft takes off, depending on how fast or slow it wants to fly to conform with the CTA and how the takeoff time will affect other constraints.

Mile-in-trail and minute-in-trail (MINIT) restrictions will be reduced in the near term and eventually eliminated as unnecessary when flights are following 4DTs that include time-based constraints where necessary. Increased use of self-separation techniques (e.g., A-IM) will allow efficient management of aircraft merging to a runway or other constrained airspace resource, without needing to repeatedly update time constraints in the assigned trajectories in response to residual uncertainty. By keeping all flights on closed trajectories that are de-conflicted over at least the next 30 minutes, MBT may increase sector capacities.

Uncertainty, which MBT will reduce, hampers current TFM performance. However, many TFM processes take advantage of the flexibility in current operations. In any TBO environment, if aircraft are more predictable and are scheduled accordingly, the reduction in uncertainty may be accompanied by a reduction in flexibility. However, some residual uncertainty will persist, creating the possibility that the TFM system might be more fragile to the remaining uncertainty. One area in which research will be required to validate the MBT concept is how TFM must adjust to the tradeoff between uncertainty and flexibility to achieve the anticipated TFM benefits. For example, if TFM continues to be conservative and initially absorb less delay than it expects will be required, to leave flexibility to fill an empty slot caused by another flight being late, then most flights will need their assigned trajectories to be updated, potentially multiple times, as the TFM system “releases” more and more of the expected necessary delay to the flights. How will this affect predictability and MBT benefits?

## **1.7 Document Structure**

The remainder of this document is organized as follows:

- Section 2 defines several terms that are key to the MBT ConOps.
- Section 3 describes the trajectory negotiation process.
- Section 4 presents the trajectory constraint language.
- Section 5 describes several elements of the MBT concept.
- Section 6 provides use cases that illustrate the MBT concept.
- Section 7 summarizes the MBT benefit mechanisms.
- Section 8 summarizes expected changes in roles and responsibilities in the NAS due to MBT.
- Section 9 provides a summary of the MBT concept.

## 2. Definitions

This chapter presents definitions and discussions of key terminology and concepts.

### 2.1 Trajectory

In the context of MBT, a three-dimensional trajectory (3DT) is a description of an aircraft's path in space. A 3DT is often visualized as a string or tube through space, and described by two dimensions in a horizontal plane (e.g., longitude and latitude) and one vertical dimension (the aircraft's altitude). Projected onto the two horizontal dimensions, the 3DT becomes the aircraft's two-dimensional (2D) route. A 4DT requires a starting time and speeds to be associated with every route segment or a time to be associated with each point along the aircraft's 3D path through space.

The term trajectory may be used for the continuous path in four dimensions (space-time) that an aircraft will or has flown, or it may be used for a description of such a continuous path or portion thereof. When referring to a description, a trajectory is often defined as: a series of waypoints (which define a 2D route); a set of assumptions about the path that connects these waypoints; a description of altitude at each waypoint; a set of descriptions or assumptions about the vertical profile between these waypoints; a starting time at the origin; and information about the time at which the aircraft will be at various waypoints or the speed the aircraft will travel along various segments. To support emerging airspace users, trajectories may also be described using additional conventions, such as an airspace volume in which the air vehicle will operate and the time period during which the vehicle will occupy that region. A trajectory describes a subset of the aircraft's state vector at each point in time. For example, the trajectory generally does not include the aircraft's pitch or roll angles.

A trajectory may be historical or prescriptive of the future. A historical 4DT describes the point in space at which the aircraft was located for every point in time between the start and end of the trajectory. Historical 4DTs are often measured by surveillance systems that record the aircraft's location and time at a periodic rate. This discrete sampling of what is actually a continuous path in four dimensions is generally still considered a trajectory.

The MBT concept uses several types of trajectories. Initially, the airspace user provides a *business trajectory* that describes the operator's preferences for when and where the flight will fly. A trajectory negotiation process between the operator and FAA produces an *assigned trajectory*, which is a contract for what the aircraft has agreed to and is required to do. This negotiation process may (or may not) require iteration between the operator and FAA. The FAA indicates how the operator's business trajectory must be adjusted and what additional *trajectory constraints* are required to comply with all *NAS constraints*, avoid other aircraft, and be sufficiently predictable. The operator may adjust its business trajectory to influence the applicable trajectory constraints. Once negotiated, the assigned trajectory contains two parts: a *trajectory description* that defines the 3D path to be flown and *trajectory constraints* that are required to meet FAA objectives, including at least a departure time to support TFM demand prediction. The aircraft must conform to both parts of the assigned trajectory unless the airspace user renegotiates; both parts are subject to the negotiation process.

Various automation systems calculate *predicted trajectories* based on the functional needs of those systems. Trajectory prediction uses the business trajectory (initially) and assigned trajectory, other information contained in the *assigned trajectory object*, as well as other information such as wind forecasts and aircraft models contained in the automation systems.

As time progresses, assigned trajectories are modified as needed, using the trajectory negotiation process, which may be initiated by either the airspace user or the FAA. The airspace user may update the business trajectory, which would initiate trajectory negotiation. Automation systems that predict the trajectory will update their predictions according to their functional requirements.

## 2.2 Assigned Trajectory Object

The assigned trajectory object, a key concept element in MBT, consists of several parts, listed in Table 2. The assigned trajectory object allows efficient exchange of all the flight-specific data that instruct the aircraft how it may fly and that are needed to predict the trajectory that the aircraft will fly. Trajectory prediction also requires other data, such as wind forecasts and air temperature, as well as aircraft models, that are not included in the assigned trajectory object.

The negotiation process transforms the business trajectory into the assigned trajectory; the flight must conform to everything in the assigned trajectory. To maximize airspace user flexibility and minimize negotiation requirements, the assigned trajectory should be a minimal set of requirements (trajectory description and trajectory constraints) to meet FAA objectives and enable prediction of the aircraft's trajectory.

The assigned trajectory should not over constrain the aircraft's trajectory and, therefore, will not describe every detail of the aircraft's plan for how it will fly. Additional information about how the aircraft plans to fly is contained in the air vehicle intent. For example, the assigned trajectory may specify that the aircraft will fly through a waypoint, but may not require the flight to cross that waypoint at any particular time. The air vehicle intent will indicate the estimated time the flight will cross that waypoint. The air vehicle intent data may also include additional points of interest not included as waypoints in the assigned trajectory, such as the top of descent, which may change during the flight.

ETAs that are not trajectory constraints are included in the air vehicle intent data, while time constraints (e.g., resulting from TBFM Scheduled Times of Arrival [STAs]) are included in the assigned trajectory. The aircraft can change its intent data (e.g., ETAs) without renegotiation, as long as it still conforms with the assigned trajectory. The aircraft must inform the FAA when its intent changes by a significant amount.<sup>3</sup> Time constraints, like all other trajectory constraints, must be changed through the negotiation process.

If the airspace user provided very minimal information in the business trajectory (e.g., only an origin and destination) then, through negotiation, the assigned trajectory will add waypoints defining a 3D path as well as time and/or speed trajectory constraints as necessary. If the airspace user provided a very dense description of how the aircraft will fly, the assigned trajectory may omit some details, which will be included in the air vehicle intent. The assigned trajectory and air vehicle intent are complementary. The assigned trajectory describes what the flight is required to do unless changed through negotiation and the air vehicle intent provides more detail about how the aircraft plans to fly in compliance with the assigned trajectory.

**Table 2. Assigned Trajectory Object**

Component	Description
Assigned Trajectory	<p>The assigned trajectory comprises the trajectory constraints and a trajectory description.</p> <ul style="list-style-type: none"> <li>• The trajectory constraints are the minimum set of requirements that achieve FAA conflict avoidance and TFM objectives.</li> <li>• The trajectory description provides the additional information about how the aircraft will fly, in compliance with the trajectory constraints, necessary to support trajectory prediction.</li> </ul>

<sup>3</sup> To strategically avoid conflicts, the FAA relies on both the assigned trajectory and air vehicle intent. If the air vehicle intent changes, the FAA may add a time constraint or otherwise modify the assigned trajectory to prevent a conflict. This represents an FAA-initiated trajectory negotiation.

	<p>The assigned trajectory, described through a defined schema that includes the use of published procedures, is the result of a negotiation process that begins with the airspace user’s business trajectory. Both the trajectory constraints and trajectory description are negotiable. The aircraft agrees to conform with everything in the assigned trajectory unless first negotiating a change.</p> <p>Some trajectory constraints result from NAS constraints; the NAS constraints (e.g., a region of dangerous weather) cannot be changed. Negotiation of trajectory constraints that result from a NAS constraint would mean finding a different set of requirements that still avoids the unchangeable NAS constraint (e.g., flying around the other side of the weather region).</p>
<p>Air Vehicle Intent</p>	<p>The air vehicle intent is a description, provided by the airspace user, of the operator’s plan for how the aircraft will fly. The assigned trajectory, together with the air vehicle intent, enable accurate prediction of the trajectory that the aircraft will fly from its current location to the destination.</p> <p>Air vehicle intent can change freely, while assigned trajectory changes require negotiation. Therefore, the assigned trajectory is the minimal necessary set of requirements on the aircraft’s trajectory. Air vehicle intent provides more detail. The air vehicle intent should fully conform to the assigned trajectory.</p> <p>The air vehicle intent data will include Extended Projected Profile (EPP) data, which is a currently emerging capability for aircraft FMS to send certain information about the trajectory the aircraft will actually fly to ground-based automation [2]. Air vehicle intent may extend beyond the current EPP specification. For example, air vehicle intent may include the planned speed profile on each route segment.</p> <p>MBT requires all IFR flights to provide air vehicle intent data, which can be accomplished by the FMS, EFB, ground automation,<sup>4</sup> or a combination thereof.</p>
<p>Flight Plan</p>	<p>The airspace user’s flight plan or business trajectory is included as a part of the assigned trajectory object to capture data elements that describe how the aircraft will operate but that are not included within the assigned trajectory or air vehicle intent.<sup>5</sup> The business trajectory may also include a Trajectory Options Set (TOS).</p>
<p>Air Vehicle Capabilities</p>	<p>Knowledge of the aircraft’s capabilities and limitations is essential to planning efficient and feasible assigned trajectories. If air vehicle capabilities change during a flight, the aircraft or airspace user must update this information.</p>

<sup>4</sup> In the long term, airspace users will have broadband communication between ground automation systems and aircraft (e.g., EFBs). The same modeling that currently resides within the aircraft’s FMS could be duplicated within the EFB and airspace user ground automation. In this vision of the future, air vehicle intent data could be provided by any of these systems.

<sup>5</sup> If all of the necessary flight plan and business trajectory data are included in the assigned trajectory and the air vehicle intent, then this part of the assigned trajectory object may be eliminated.

## 2.3 Assigned Trajectory

The MBT concept uses an assigned trajectory as the plan for the trajectory that the aircraft will fly, which includes the data elements that require coordination to achieve FAA objectives. This is distinct from air vehicle intent, which more fully describes the trajectory that is planned (by the airspace user) to be flown. Other literature refers to similar concept elements using terminology such as the controlled trajectory, the negotiated trajectory [4], or the agreed trajectory [5, 1].

The assigned trajectory is an agreement between the FAA and airspace user as to where and when the aircraft will fly. The aircraft is cleared to fly the assigned trajectory to the destination.<sup>6</sup> A clearance limit is not used within United States (US) airspace. The FAA may know that the assigned trajectory is not conflict free beyond some point, or will require other changes (e.g., due to TMIs that cannot yet be translated to a specific trajectory constraint). However, the flight is cleared to fly the current assigned trajectory unless and until the trajectory is modified via the negotiation process. In accordance with the ICAO TBO concept (currently under development), there is always a clearance limit associated with international boundaries [1].

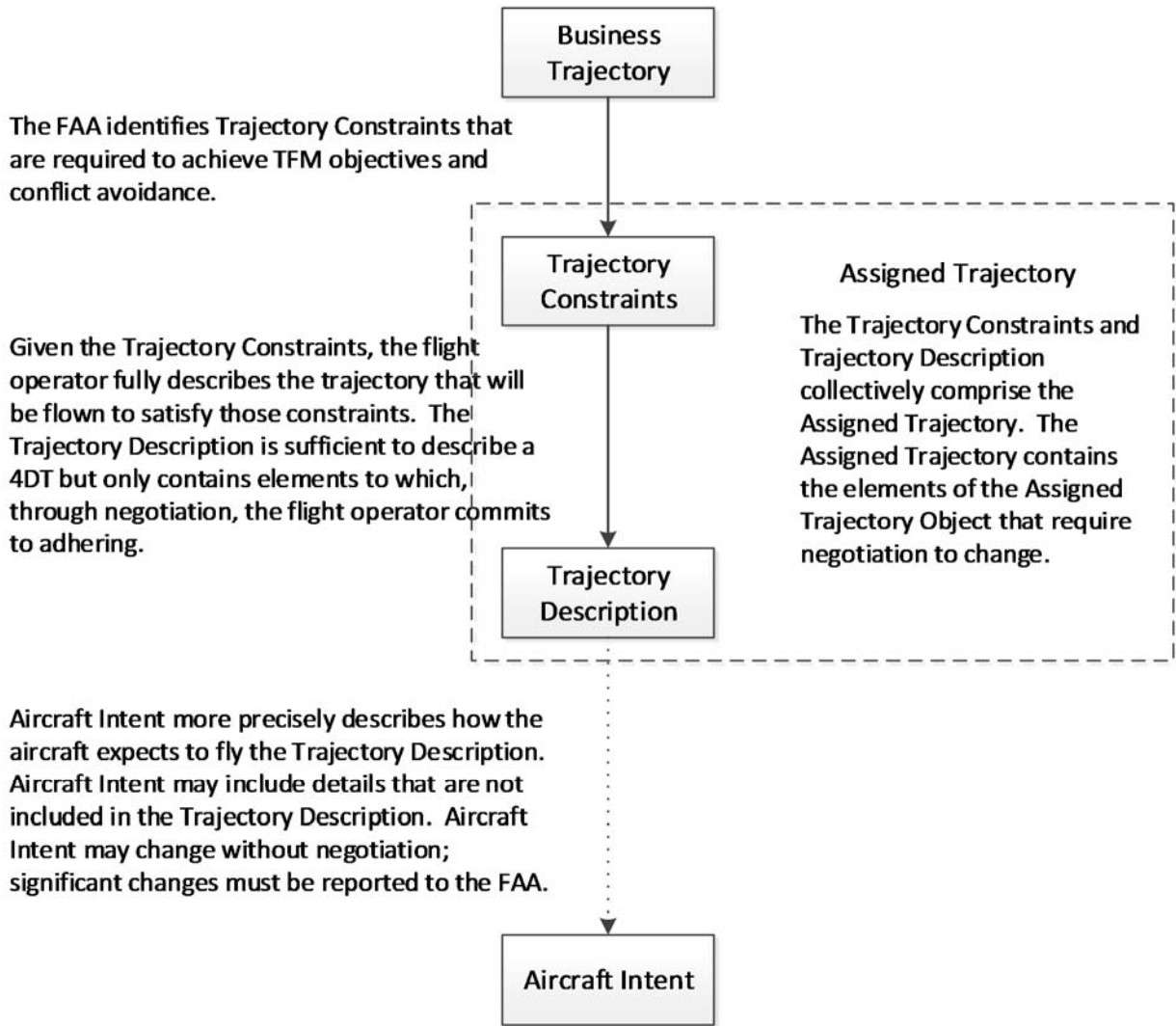
The assigned trajectory is constructed in two parts: trajectory constraints and a trajectory description.<sup>7</sup> The trajectory constraints are the minimum set of requirements that achieve ATM needs (i.e., conflict avoidance) and TFM needs [1]. Being the minimum required set, the trajectory constraints may not fully (or with sufficient precision) describe where and when the aircraft will fly. The trajectory description provides the additional information necessary to support trajectory prediction. Collectively, the assigned trajectory is a transformation of the airspace user's business trajectory into requirements to achieve FAA objectives and descriptive elements to ensure predictability.

Figure 1 illustrates how the business trajectory, trajectory constraints, trajectory description, and air vehicle intent provide information about the aircraft's trajectory.

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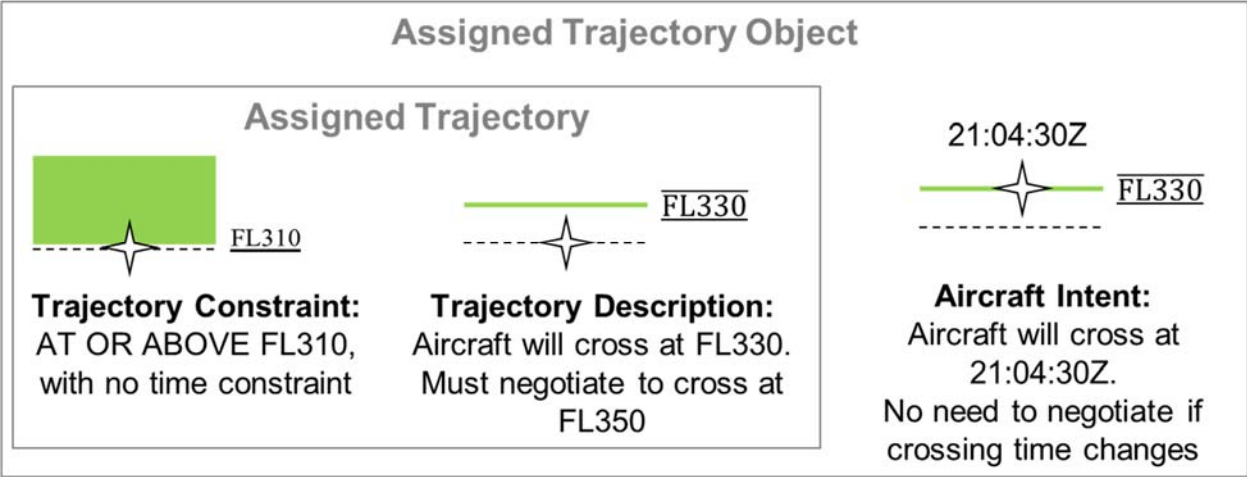
<sup>6</sup> The term "clearance" is not explicitly used in the MBT concept. The assigned trajectory is effectively the clearance, and could, alternatively, be referred to as the "cleared trajectory." The clearance given to the aircraft would only differ from the assigned trajectory if there is a clearance limit.

<sup>7</sup> The trajectory description is defined as a clearance in the ICAO TBO Concept Document [1, p. 12]: "Clearances are structured, as performance-needs dictate, to more precisely deliver the Agreed [Assigned] Trajectory by unambiguously describing the plan."



**Figure 1. Notional Relationship between Assigned Trajectory Object Elements**

An example of a trajectory constraint is to fly at or above FL310. An example of the corresponding part of the trajectory description might be that the aircraft will fly at FL330. Once trajectory negotiation is completed, the airspace user cannot choose to fly at FL350, for example, without first negotiating that change (see Figure 2).



**Figure 2. Example of Trajectory Constraint, Trajectory Description, and Aircraft Intent**

In some cases, the trajectory constraints may be sufficiently specific (e.g., cross a waypoint at a specified time) that the trajectory description would not add any more detail or precision. The trajectory description is not required to duplicate such trajectory constraints and, therefore, the trajectory constraints remain a necessary part of the assigned trajectory even after the trajectory description is specified.

The business trajectory will, among other things, define the desired 2D route. If there happen to be no trajectory constraints affecting the route, then only the trajectory description would provide information about the route.

Some trajectory constraints assume other parts of the trajectory. For example, a trajectory constraint to fly at a particular altitude (e.g., to avoid a conflict) assumes the 2D route and potentially the speed/time along that route. If other parts of the trajectory constraints or trajectory description were changed, this trajectory constraint may change.

Both parts of the assigned trajectory are subject to negotiation and result from the negotiation process. While the FAA initially identifies the trajectory constraints, the airspace user may negotiate to alter them. Similarly, while the airspace user initially proposes the trajectory description, the FAA may negotiate, for example, to add detail as needed for 4DT prediction or to indicate elements are not required in the trajectory description and can be provided through air vehicle intent.

Assigned trajectories are described using a set of established trajectory attributes (i.e., a trajectory schema). The assigned trajectory describes the lateral route (e.g., using published NAS waypoints and unpublished latitude/longitude waypoints, RNP levels, precision turns, and published procedures); the vertical profile (e.g., using altitude assignments which may have tolerances); the longitudinal trajectory (e.g., using speed assignments, specific times, and tolerances); and TFM constraints (e.g., STAs and CTAs at waypoints, and aircraft in-trail spacing requirements associated with A-IM).

Through trajectory negotiation, the airspace user has the opportunity to be aware of NAS constraints, including TFM programs, and participate in selecting the assigned trajectory. A minimum requirement on the assigned trajectory is that (prior to takeoff) it include a planned takeoff time as a time constraint. This anchors the assigned trajectory in the time dimension. The assigned trajectory must define a continuous 2D route. The assigned trajectory must also define how the aircraft will fly in the vertical dimension, although a continuous vertical profile is probably not required. Specific points, such as the top of descent, may not be in the assigned trajectory, but rather provided in the air vehicle intent. Details of what level of information will be in the trajectory constraints, trajectory description, and air vehicle intent remain a research topic. The answer will likely be different for near-term MBT and end-state MBT operations. The assigned trajectory is also required to have a longitudinal profile. The longitudinal profile



provides a speed profile or planned times at waypoints, to describe how the aircraft will progress in time along the route.

An aircraft cannot have inconsistent time (e.g., RTA) and speed constraints/descriptions affecting the same route segment. For example, there should not, in general, be a time constraint on a waypoint and a speed constraint on the segment ending at that waypoint. There may be a trajectory time constraint at a waypoint, while the trajectory description provides planned speeds that will allow the aircraft to comply with the time constraints. Estimated times at each waypoint are not required to be included in the assigned trajectory, but are included in the air vehicle intent and the predicted trajectory.

As time passes, the assigned trajectory may need to be modified, since uncertainty will exist when the assigned trajectory is first negotiated. The FAA may negotiate to modify, add, or remove trajectory constraints, which could also affect the trajectory description, based on the flight's actual progress and changes in NAS constraints. The airspace user may negotiate to change the assigned trajectory for business reasons.

## **2.4 Constraints**

A constraint is defined as “a limitation to free maneuvering of the aircraft” [1, p. 14]. MBT considers multiple types of constraints. Most notably, NAS constraints are treated separately from trajectory constraints, as discussed below.

### **2.4.1 NAS Constraint**

A NAS constraint is an element of the NAS that affects the selection of assigned trajectories.<sup>8</sup> ATM configuration information [1] is included in the set of NAS constraints, such as a region of special activity airspace (SAA) that is closed during some period of time or a procedure that defines elements of the trajectory that must be used to fly an approach to some runway. A region of bad weather that has limited capacity and the resulting TMs are also examples of NAS constraints. Strong turbulence or unfavorable winds may also be considered NAS constraints.

### **2.4.2 Trajectory Constraint**

A trajectory constraint is a requirement, specific to a flight, with which the aircraft's trajectory must comply. A flight's assigned trajectory contains the set of trajectory constraints for that flight. All trajectory constraints are negotiable.

The airspace user has no ability to change NAS constraints (e.g., the TFM system determines when to use a GDP). In contrast, the airspace user may negotiate a change in trajectory constraints (e.g., negotiate to change a flight's departure time to avoid the GDP or negotiate using CDM to swap the EDCT resulting from the GDP that applies to that flight).

Some trajectory constraints are flight-specific requirements that result from NAS constraints. For example, a particular route may be selected because it avoids an active SAA. The airspace user can choose/negotiate the initial route and negotiate subsequent changes to the route, but all allowable routes avoid the NAS constraint. Moreover, once the route is negotiated, the route becomes part of the assigned trajectory and any change must be negotiated.

Similarly, a flight may have a trajectory constraint to cross an arrival fix at a specific time due to a TFM arrival metering program; the arrival metering program is a NAS constraint. While the TFM system may not have a lot of flexibility, the airspace user can try to negotiate for a different crossing time, perhaps by swapping times with another one of its flights over that fix.

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<sup>8</sup> Not all factors that affect trajectory selection are NAS constraints. For example, aircraft performance capabilities affect trajectory selection (and could be called a constraint) but would not be considered a NAS constraint. In addition, FAA objectives such as aircraft separation are not NAS constraints but do create trajectory constraints.

Some trajectory constraints are flight-specific requirements that result from the need to avoid conflicts with other aircraft. The flight's route, altitude, or time crossing a waypoint may be constrained to ensure separation relative to another aircraft. These trajectory constraints can also be negotiated; for example, the flight may prefer to change altitude rather than slow down.

A third possible cause for trajectory constraints is the need to ensure trajectory predictability. For example, if there are no trajectory constraints for a long period of flight time, and the flight is not able to provide accurate intent data, then an intermediate trajectory constraint might be used to bound the trajectory prediction error. Such "constraints" are accounted for in the Trajectory Description portion of the Assigned Trajectory.

Section 4 describes the language for trajectory constraints and the assigned trajectory.

### **2.4.3 Other Constraints**

There are other types of constraints that affect aircraft trajectories. For example, aircraft performance limitations and crew duty length rules may affect what trajectory the aircraft can accept and fly. An example of how aircraft performance might affect the trajectory is as follows: as the aircraft flies higher, the feasible true airspeed and Mach range narrows, reducing the amount by which speed control can vary the aircraft's time of arrival at a waypoint. If the aircraft encounters turbulence, it may have a limited ability to slow down to reduce the effect of the turbulence on ride comfort, forcing the aircraft to descend. As a result, the airspace user may reject a higher altitude to avoid the situation where it is unable to slow down in turbulence. The aircraft's RNP and RTP capabilities are also constraints that affect trajectory selection. The fuel remaining onboard can limit the amount of path stretching or speed changes away from efficient speeds that can be tolerated by a flight.

### **2.4.4 NAS Constraint Service**

MBT includes the concept of a NAS Constraint Service that maintains information about NAS constraints and publishes it to all stakeholders. In this way, airspace users and FAA automation systems have access to the NAS constraints that may affect a flight's assigned trajectory, without the need to repeat NAS constraint information within every assigned trajectory.

Each NAS constraint will have a unique identifier. The airspace user can identify which NAS constraints affect the assigned trajectory, or specifically which NAS constraints result in each trajectory constraint. If any of those NAS constraints change, the airspace user will know to consider changing the business trajectory, which could happen pre-departure or after takeoff. The airspace user must make this determination, since the FAA cannot know how a change in a NAS constraint will change an operator's business trajectory. If the operator has provided a TOS, the FAA can automatically evaluate the alternative trajectories in response to the change in the NAS constraint. See Section 5.13 for a discussion of how NAS constraint changes and TOSs will interact.

The NAS Constraint Service is likely to exist prior to MBT, as an extension of the NAS Common Reference (NCR) and United Flight Planning and Filing (UFPF) capabilities that the FAA is planning to deploy. Any constraints that are not known at the time of pre-departure flight planning and trajectory negotiation will be shared with the airspace user as soon as they are known. For example, if an En Route Automation Modernization (ERAM) required routing is not known as a standard NAS constraint, it will be provided to the airspace user as soon as the FAA knows that the flight's requested route will need to be changed.

### **2.4.5 References to NAS Constraints in Assigned Trajectory**

The assigned trajectory comprises the trajectory description and constraints with which the flight must comply. As optional data, the assigned trajectory may also contain references to the NAS constraints that resulted in the trajectory constraints. For example, a flight may be assigned a time constraint at a point along its route due to an STA from a metering program.

That metering program would be a NAS constraint uniquely identified within the NAS Constraint Service. The flight's assigned trajectory may include a reference to that metering program. In this way, the flights that may be affected by changes to NAS constraints can easily be identified. When a NAS constraint changes or is removed, affected flights can be alerted and re-evaluated to determine if their assigned trajectories can be changed closer to their business trajectories. Since the business trajectory may have changed, the operator may need to re-plan the flight based on its current location to provide a new business trajectory after the NAS constraint change, and initiate negotiation if desired.

Labeling the assigned trajectories with these references is a shared responsibility between the airspace user and the FAA. If the FAA assigned a time constraint due to a TFM program, the FAA could attach the corresponding NAS constraint reference. However, if the airspace user chose a route due to an area of bad weather, the airspace user would need to reference the NAS constraint representing the weather, since the FAA could not know why the airspace user chose that particular route.

#### **2.4.6 Navigation and Guidance/Control Performance Capabilities**

An aircraft's navigation and guidance/control performance capability is the accuracy with which it can achieve a target value in some dimension of navigation. For example, the aircraft's RNP level defines how accurately it can follow a lateral path. Similarly, aircraft capable of Reduced Vertical Separation Minimum (RVSM) meet a standard for vertical navigation performance.<sup>9</sup> In the future, aircraft will have a performance level similar to RNP for temporal navigation. The aircraft's performance capabilities in each dimension will be part of the air vehicle capabilities component of the assigned trajectory object.

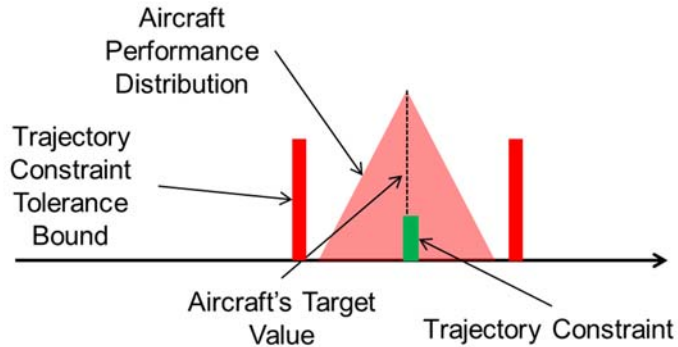
In the assigned trajectory, constraints can be defined as a specific value or a range of allowed values (i.e., a window). If a constraint is defined as a range of permitted values, any value within the range is considered to be fully compliant with the constraint. For example, a constraint may be "cross a particular point between 15:32:00 and 15:33:00," which is a closed range that describes a one-minute window of time. Another example constraint is "cross a particular point at or before 15:33:00," which is a range that is open on one end.

The purpose of providing a constraint as a range rather than a specific value is to allow the airspace user flexibility where doing so may benefit the operator and will not affect other NAS operations.

When a trajectory constraint is expressed as a route or a specific time (e.g., an RTA), the aircraft will have some error relative to the route centerline or specific time (see Figure 3). The aircraft's navigation capability (e.g., RNP level) is a metric that defines the maximum navigation error within which the aircraft will usually operate; on rare occasions the aircraft's error may be larger. In current RNP procedures, all aircraft using the RNP procedure are expected to operate according to the same performance capability equal to the RNP level, although many aircraft may actually be able to navigate more accurately.

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<sup>9</sup> [https://www.faa.gov/air\\_traffic/separation\\_standards/rvsm/](https://www.faa.gov/air_traffic/separation_standards/rvsm/)



**Figure 3. Aircraft Performance Capability Relative to Trajectory Constraint Tolerance**

In MBT, the tolerance on a trajectory constraint is equal to that flight's performance capability in that dimension, and each aircraft may have unique performance capabilities. Therefore, the tolerance may be different for each aircraft operating on a given route. The conformance monitoring function must be aware of the expected aircraft performance and alert if the error is (or is predicted to be) larger than allowed by the expected aircraft performance.

A trajectory constraint that includes a range of acceptable values must be defined with awareness of the aircraft's performance capability. The aircraft is permitted to target the edge of the constrained range such that with expected error the aircraft may operate outside of the range. Therefore, the trajectory constraint must be defined so that with the aircraft's possible navigation error, the aircraft will still be separated from the other aircraft or airspace that necessitate the trajectory constraint.

#### **2.4.7 Tradeoff Between Flexibility and Certainty**

Trajectory constraints provide certainty regarding where the aircraft will be and when it will be there. From a traffic management perspective, more trajectory constraints provide more certainty in the predicted future location of the aircraft. However, trajectory constraints limit the airspace user's flexibility (by requiring negotiation prior to a change) and, potentially, the efficiency of the flight. For example, an intermediate time constraint might cause a flight to have to speed up and then slow down for the next time constraint, rather than flying a constant speed. Trajectory constraints should be avoided when not required.

Trajectory predictability can also be improved by receiving the aircraft's intent data. While intent data provide a snapshot of how the aircraft will use the available flexibility, the snapshot does not guarantee predictability since intent can change without negotiation. However, confidence in the prediction can be achieved if the aircraft is required to provide an update whenever its intent changes. Intent data with guaranteed updates can reduce the number of trajectory constraints that are required, providing both flexibility and certainty.

## **2.5 Predicted Trajectory**

A predicted trajectory is a prediction of how the aircraft will fly from the current position to the destination, or a portion thereof. Predicted trajectories are descriptions of what the aircraft is expected to do, computed by various mathematical models (a.k.a. predictors), using the assigned trajectory, air vehicle intent, and other information, including measured and forecast atmospheric data, equations of motion, and the aircraft's characteristics.

The assigned trajectory will, prior to takeoff, have a time constraint representing the planned takeoff time, and may have additional time constraints along the route. The assigned trajectory will not, in general, have a time constraint at every waypoint along the route. The predicted trajectories will include an ETA for each waypoint along the route, and potentially many additional points closer together along the route, depending on the intended application of the prediction.

Multiple predicted trajectories are allowed for a flight because different automation systems may have distinct requirements for the predicted trajectory and, therefore, compute a prediction focused on the needs of that application. For example, the conflict detection function requires predicted trajectories that are spatially dense and frequently updated based on the most recent surveillance data, but only extend over a limited time horizon. In contrast, TFM functions do not require predictions that are as spatially or temporally dense and can tolerate lower update rates, but require predictions that extend to the flight's destination. For this reason, multiple predicted trajectories are permitted, where each ground automation system may have its own mathematical model used to calculate the predicted trajectory from the common assigned trajectory and air vehicle intent.

For in-bound international flights and longer-horizon TFM planning, a predicted trajectory may be generated prior to an assigned trajectory being negotiated and assigned, using the business trajectory. The negotiated assigned trajectory would start at a boundary crossing point and contain a planned crossing time at that point.

## 2.6 Business Trajectory

The business trajectory (a.k.a. reference trajectory, preferred trajectory, desired trajectory) is the trajectory that the airspace user would have the aircraft fly if that were the only aircraft operating in the NAS.<sup>10</sup> This is the trajectory preferred by the airspace user when considering NAS constraints that would still exist independent of other traffic (e.g., weather and procedures that do not vary with traffic level such as SAA), but exclusive of NAS constraints resulting from TMs or other aircraft.

The NAS Constraint Service will provide the airspace user with information about all known NAS constraints. In response to traffic-related NAS constraints, the airspace user may request, or begin negotiation, with a trajectory different than the business trajectory. The use of a requested trajectory that differs from the business trajectory allows the airspace user more self-determination over how a NAS constraint will be translated into trajectory constraints. For example, if, during trajectory negotiation, the FAA proposes an assigned trajectory that the operator does not like for some reason, the operator may respond with a requested trajectory that represents the operator's preferred trajectory subject to additional traffic-related NAS constraints.

The remainder of this document will use the term business trajectory to mean either the business trajectory or the requested trajectory. Where a distinction is required and not clear from the context, the text will clarify the usage.

The use of business trajectories (or trajectory options sets) and negotiation are essential because the FAA cannot know what trajectories will be efficient and acceptable for the airspace user. During a cognitive walkthrough of the MBT concept involving a range of ATM experts as participants, a pilot provided an anecdote that a controller had once issued a "short cut" to a flight that took the flight out of the jet stream, adding 45 minutes to the flight time and almost causing the aircraft to run out of fuel. A controller provided an example that he may work to climb an aircraft to a higher altitude but, due to the air temperature, the altitude is above the aircraft's maximum operating altitude for those conditions, which the controller does not currently know.

The filed flight plan is the initial description of the airspace user's business trajectory. During trajectory negotiation for the initial assigned trajectory, the airspace user may provide a more-detailed business trajectory as the starting point for negotiation. During operation, the airspace

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<sup>10</sup> The business trajectory may consider other flights operated by the same airspace user. For example, an airspace user with four flights scheduled to depart from Chicago (ORD) at the same time may provide business trajectories with different proposed takeoff times to express the relative priority between the flights or may leave this necessary de-confliction at the runway for the FAA to apply in the assigned trajectories.

user may update its business trajectory as part of a negotiation to change the assigned trajectory.

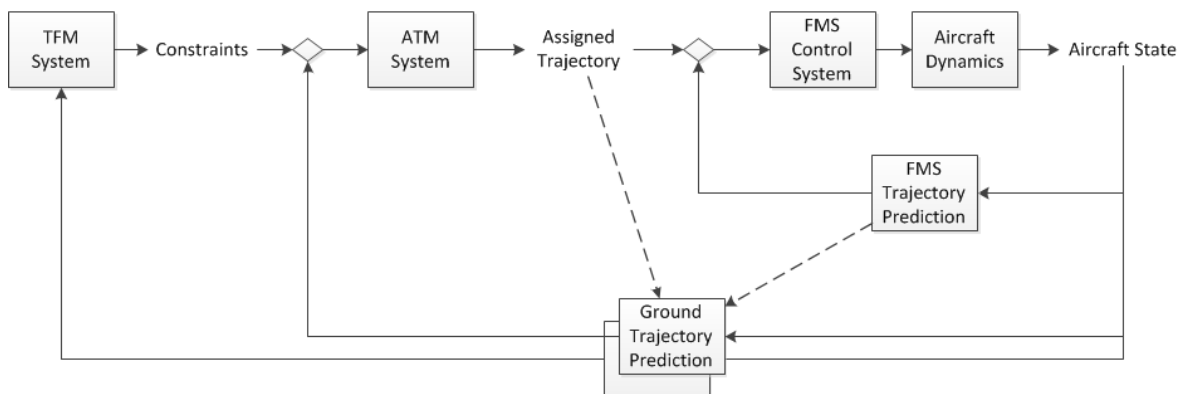
## 2.7 Closed vs. Open Trajectories

The concept of a closed trajectory has been used in various literature with slightly differing definitions. This document defines “closed trajectory” in the following way.

“The aircraft is flying a closed trajectory” means that the aircraft is using a closed-loop control system to follow an assigned trajectory, where the assigned trajectory extends from the aircraft’s current state to the aircraft’s destination; the assigned trajectory is fully known to the ground automation; and the trajectory that the aircraft will actually fly is sufficiently predictable.

The characteristics of a closed-loop control system are: the control system has a plan, the control system issues commands to achieve that plan, and there is feedback in terms of an estimate that is compared to the plan and is used to calculate new commands, so that error is driven toward zero. This control system may be on the aircraft (e.g., in the FMS) or may be distributed between the aircraft and ground and include a controller manually comparing surveillance to the target aircraft state and issuing commands to the pilot.

In the MBT concept, a closed trajectory is an assigned trajectory that is being followed by the aircraft such that the aircraft’s actual trajectory is sufficiently predictable from its current location to its destination, as illustrated in Figure 4.



**Figure 4. Notional Closed-Loop Control System following an MBT Assigned Trajectory**

The assigned trajectory is always fully known by the ATM system’s ground automation.<sup>11</sup> This is ensured by the mechanisms through which the assigned trajectory can be negotiated and selected. The assigned trajectory being known by the ground automation is not sufficient for it to be considered closed within the MBT concept. The ATM system must be able to sufficiently predict the trajectory that will be flown by the aircraft. How “sufficiently” is defined will be discussed further below.

The concepts of open and closed trajectories are defined to be mutually exclusive and collectively exhaustive across the set of all trajectories. Therefore, any trajectory that is not closed is, by definition, open. An aircraft flying an open trajectory means that at least one of the requirements for a closed trajectory has been violated.

<sup>11</sup> The assigned trajectory being known by the aircraft’s FMS is not a requirement in the definition of a closed trajectory. For unequipped aircraft, or when a controller’s command must be delivered via voice for expediency, the trajectory is still considered closed when the controller’s plan has been entered into the ground automation and shared with the airspace user, even if by voice.

### **2.7.1 Sufficiently Predictable**

Assume an aircraft is instructed by a controller to perform a tactical maneuver (e.g., to turn to some heading or change its speed) where the controller subsequently instructs the aircraft to return to its previous assigned trajectory. Further assume the aircraft will continue to comply with all downstream constraints and does not require its assigned trajectory to be modified. For example, the assigned trajectory may not include any downstream RTAs or the aircraft may still be able to comply with the next RTA.

First, consider the near-term conflict detection functionality. The ground automation does not have sufficient information about the period of time over which the tactical “vector” is to be maintained and, therefore, cannot produce a sufficiently accurate trajectory prediction. The aircraft’s FMS also does not know the controller’s intent. Only the controller who issued the tactical maneuver knows (and, possibly, only in a general sense) what he/she will instruct the aircraft to do during the remainder of the tactical maneuver. The controller relies on real-time feedback from the display to complete the maneuver. Thus, even if it was possible to extract the initial intent from the controller’s mental model, this would only be approximate. Since the near-term trajectory cannot be predicted sufficiently well to perform the necessary ATM conflict detection function, the flight is considered to be on an open trajectory.

However, the aircraft’s trajectory over a longer horizon could still be predicted sufficiently accurately based on the assigned trajectory. Despite not being closed for the purposes of conflict detection, the TFM benefits of a closed trajectory may not be affected by the temporary opening of the trajectory, especially if there is a downstream time constraint and the tactical maneuver does not affect the aircraft’s ability to comply with that constraint.

Now assume that an aircraft is following an assigned trajectory that has very sparse constraints. An extreme example is “Depart LAX at 0900; arrive JFK at 1430.” The assigned trajectory might be sufficient to predict the to-be-flown trajectory well enough to support some TFM decisions. However, the assigned trajectory by itself would not be sufficient to predict the to-be-flown trajectory to perform TBO conflict detection.

This example introduces the question of what the aircraft is allowed to do between the trajectory constraints comprising the assigned trajectory. If the aircraft is permitted to do almost anything (e.g., fly circles or zig-zag) as long as it satisfies downstream constraints, the trajectory that will be flown would not be sufficiently predictable and would be considered open despite satisfying the other requirements of a closed trajectory.

Currently in the NAS, there are rules defining how a flight must fly between consecutive waypoints in its cleared flight plan. In MBT, the trajectory description will define the flight’s continuous route (e.g., straight segments, great circle arc, or precise curves between waypoints). Some future vehicle types and business models may require other trajectory descriptions, for example to freely loiter within a defined region, at a specified altitude or altitude range, for a period of time. In the MBT concept, the lateral dimensions of the assigned trajectory must describe a continuous path or area within which the aircraft will remain (i.e., the assigned trajectory does not only create requirements at the listed waypoints but also continuously between the waypoints). The tolerance should be defined as the least restrictive navigation requirement for each segment that meets separation and TFM requirements.<sup>12</sup> In the vertical dimension, the assigned trajectory must describe the altitudes at which the aircraft will fly, but is not required to be a continuous vertical profile in the way that the 2D lateral route is defined.

The longitudinal/time dimension is handled differently since requiring exactly how far along the route the aircraft must be at every point in time would be too restrictive and inconsistent with how FMSs currently operate. The approach also depends on the air vehicle capabilities. The

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<sup>12</sup> Auxiliary waypoints may need to be added to a sparsely defined trajectory in order for the automation to provide ETAs for when the flight will enter a new ARTCC. Currently, there is an ERAM requirement that a flight has at least one waypoint in each ARTCC that it traverses.

assigned trajectory may include time constraints, which specify the time at which the aircraft should be at a specific point, or speed constraints. Note that time constraints may be asymmetric, such as “AT OR BEFORE”. All of the requirements in the assigned trajectory must be feasible for the aircraft (e.g., only some aircraft are capable of complying with a speed constraint on a route segment that ends with an RTA).<sup>13</sup>

The business trajectory must describe the speed profile the aircraft wants to fly along each route segment. Once time constraints are identified, the negotiation process will identify for which route segments the trajectory description will not specify a speed profile, since the aircraft will be adjusting speed to meet a time constraint, and for which route segments the trajectory description will specify a speed profile. When the aircraft is not operating to meet a time constraint, the aircraft is required to conform to the speed profile in the trajectory description within the specified tolerance. When the aircraft is operating to meet a time constraint, the speed schedule will be available in the air vehicle intent, but the aircraft is free to change its speed as needed to meet the constraint without negotiation.

Predictability in the time dimension is affected both by the constraints and the availability of air vehicle intent data. A sufficiently equipped aircraft that is supplying FMS-calculated ETAs at waypoints can be sufficiently predictable with fewer time or speed constraints than an aircraft that is less equipped. The combination of constraints, tolerances, air vehicle intent data, and ground-based modeling performance will be managed so that the aircraft satisfies the predictability requirement for a closed trajectory.

To be beneficial, MBT does not only need aircraft to follow closed trajectories; MBT needs aircraft to fly stable, closed trajectories. If the assigned trajectory will keep changing because of downstream uncertainty (e.g., due to weather uncertainty), then the trajectory that will be flown is not predictable. Residual uncertainty (i.e., the uncertainty that remains after implementing TBO) will be critical to determining MBT feasibility and benefits. How frequently constraints can change and still have stable, closed trajectories is an important research question.

## 2.8 Trajectory Compliance

Trajectory compliance is also distinct from whether or not the trajectory is closed. Three types of trajectory compliance issues can be defined.

1. Non-conformance: An aircraft can be out of compliance with the assigned trajectory, meaning it has failed to comply with a trajectory constraint within the required accuracy (where the required accuracy is part of the assigned trajectory specification).
2. Predicted Non-conformance: A system can predict that an aircraft will not comply with the assigned trajectory. An automation system predicts that an aircraft either will not comply with a trajectory constraint or will be unable to comply with a trajectory constraint.
3. Prediction Error: An aircraft can be out of compliance with the predicted trajectory, meaning it has deviated from the predicted trajectory by more than an assumed uncertainty envelope, even though no requirement in the assigned trajectory has been violated. For example, the predicted trajectory may have an error if the aircraft has provided ETAs via air vehicle intent but has not updated the ETAs, and then arrived at a waypoint at a different time than the ETA. Prediction errors will trigger an updated prediction that assesses whether any requirements of the assigned trajectory will be violated and whether any conflicts exist.

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<sup>13</sup> Most current FMS technology cannot accept a simultaneous speed constraint and RTA goal. Therefore, within current technology, speed constraints generally should not be used over the portion of route that the aircraft is flying to achieve an RTA.



The system attempts to avoid non-conformance events by proactively intervening to prevent predicted non-conformance events. Prediction error events may also be used to alert to a potential future non-conformance event.

### **3. Trajectory Negotiation**

In the preflight phase, FAA planning automation will handle negotiation as required to meet ICAO FF-ICE step 1 [5]. As such, negotiation may be an existing part of the future NAS and not a new capability added by MBT. However, MBT extends the concept of trajectory negotiation to support the use of higher-level objectives for the aircraft's trajectory. The MBT concept requires that every flight have an assigned trajectory at all times, and relies on modifying these trajectories in response to NAS constraints changes and uncertainty that existed at the time the previous version of the assigned trajectory was created. In the MBT concept, the process by which an assigned trajectory is initially assigned to a flight and subsequently updated as needed is referred to as "assigned trajectory negotiation." The quantity and concurrence of trajectory negotiations in MBT, as well as the urgency in some cases, requires that the negotiation process be fast and efficient.

To facilitate this high volume of negotiation events, as much of the negotiation as possible will be carried out using automated systems, as opposed to negotiating via voice and then entering the agreed trajectory into an automated system. Several different actors may participate in trajectory negotiation, including controllers, TFM personnel on the FAA side, and flight crews and airline operational control (AOC) facility personnel, such as flight dispatchers, on the airspace user side. In current operations, controllers may provide a pilot with several options to resolve a conflict, which is easily accomplished via voice. Trajectory negotiation in MBT must be more effective than current voice-based methods. In MBT, the language for trajectory negotiation will expand on the CPDLC message set to include exchanges such as a controller or traffic manager offering the airspace user a choice between two or more trajectory options, or providing parameters defining preferences for an amended trajectory that meets a modified set of constraints. The former allows digital data exchange to support interactions that are natural and easily accomplished via voice, while the latter allows airspace users and the FAA to make greater use of automation in carrying out negotiations to achieve efficient, desirable trajectories that comply with all constraints.

Such automated negotiation requires a language that can be used by computers to propose, evaluate, and agree upon trajectories that are feasible and efficient for the air vehicles and desirable to the airspace users, controllers, and ATM system. The language of negotiation requires two general components: the assigned trajectory and negotiation parameters that facilitate the negotiation process. In addition, other parts of the MBT assigned trajectory object, such as the air vehicle capabilities, must be available to all participants of the negotiation. In addition to automated negotiation, each stakeholder that participates in negotiation requires an automation system that visualizes the current and proposed assigned trajectories and allows the stakeholder to initiate negotiation and respond to negotiation requests.

This chapter describes the process and language used in negotiating assigned trajectories.

#### **3.1 Parties and Stakeholders to Assigned Trajectory Negotiation**

The following stakeholders may represent a flight in the negotiation process.

- Pilot (includes remote pilot for unmanned aircraft)
- Avionics (EFB, other on-board automation, or remote pilot's ground automation)
- Ground Flight Representative (dispatcher for an airline, ground service for a subscribing General Aviation (GA) pilot or other private airspace user, etc.)

- Ground Automation (AOC automation, etc.)

The following stakeholders may represent the FAA in the negotiation process.

- Controller (Air Route Traffic Control Center [ARTCC] sector controller, Terminal Radar Approach Control [TRACON] controller, Tower controller)
- ATC Automation (ERAM, Standard Terminal Automation Replacement System [STARS], Terminal Flight Data Manager [TFDM])
- Traffic Management Coordinator (ARTCC Traffic Management Unit [TMU], TRACON TMU, Tower TMU)
- Traffic Flow Management System (TFMS)

Each of the parties will be represented by a single stakeholder authorized to commit the flight and airspace user to an agreement. For example, the FAA does not need to negotiate with both (either independently or simultaneously) the airline pilot and that flight's dispatcher, who may disagree with one another. Instead, the FAA will negotiate with the pilot, in this example, and the pilot is responsible for acquiring approval from the relevant dispatcher if necessary.

Each party will select which stakeholder will represent the party in the negotiation. This decision may depend on the type of negotiation and, therefore, may be based on some of the meta information that accompanies the negotiation initiation. The selection of the representing stakeholder will depend on factors such as the time available for the negotiation, the magnitude of the proposed change, the type of negotiation (e.g., to avoid a conflict or to avoid downstream congestion delays). This concept extends to the participation of automation; automation may have the authority to negotiate and accept an assigned trajectory, internally accepting responsibility for informing and obtaining agreement from human actors. Although the MBT concept allows this, some airspace users may choose to never authorize automation to negotiate independently from a human representative. The MBT roles and responsibilities research [6] delves deeper into the relationships between humans and their automation regarding negotiation.

### 3.2 Negotiation Goals

The FAA's and flight's goals in a negotiation will differ. While a pilot's and dispatcher's goals may also differ, MBT expects the airspace user to internally handle those differences. Similarly, the differences in goals between a controller and traffic manager should not be visible to the airspace user during negotiation.

Examples of FAA objectives include safety (separating aircraft from other aircraft, separating aircraft from dangerous weather, controller workload), equity in access to airspace resources by all users, and efficiency in use of airspace resources. Examples of airspace user objectives for the flight include: minimum distance, minimum time, minimum fuel consumption, arrive at a specific time, avoid turbulence (passenger comfort), and efficient fleet management. Note that the FAA priorities tend to be more aggregate in nature than the airspace user priority examples. Since the FAA ensures safety, the airspace user can assume that will always be the highest priority. Aircraft performance constraints, such as the maximum speed for an altitude, are considered constraints that will always be respected and, therefore, are not included as priorities.

The FAA and airspace user will each, in general, have multiple objectives that are important and some notion of the relative priority of those objectives.

### 3.3 Negotiation Process

The airspace user initially informs the FAA of its intent to operate a flight and then or at a later time provides additional details about the flight in the form of a flight plan. Closer to the scheduled departure time, the airspace user may submit a business trajectory, a proposed

trajectory that the operator would like to fly considering TFM NAS constraints, or a TOS. This submission, or a time-based trigger, begins the initial negotiation process that produces the initial version of the assigned trajectory. There will always be at least one negotiation for each flight prior to departure to solidify the initial assigned trajectory. The FAA uses the business trajectory, proposed trajectory, or TOS and determines what trajectory constraints are necessary to comply with NAS constraints. This includes modifying routing to avoid closed airspace and applying time constraints associated with TFM programs. FAA automation tools work both automatically and as controller and traffic manager decision aids to identify appropriate constraints to add to trajectories, and in reviewing, modifying, and accepting the trajectories generated by airspace users or other Air Navigation Service Providers. This constrained trajectory is returned to the airspace user for acceptance or further negotiation. The airspace user (flight crew or flight operations center [FOC]) must be able to review and accept the new or modified assigned trajectory in a timely, effective manner. Once the airspace user has accepted the trajectory, it represents the assigned trajectory and is published to the assigned trajectory repository to be available to all stakeholders.

Figure 5 illustrates the normal negotiation process. In general, either the FAA or the airspace user (abbreviated AU in the diagram) may initiate a negotiation. The figure depicts how a removal or reduction of a NAS constraint may cause the airspace user to begin a negotiation. Similarly, an expansion of a NAS constraint or addition of a new NAS constraint may necessitate an assigned trajectory modification, initiated through negotiation by the FAA.

1. A negotiation begins with the initiating party sending a proposal for an assigned trajectory. This could be a proposal for the flight's initial assigned trajectory, or a modification of the flight's current assigned trajectory. A modification to an existing assigned trajectory could be sent as a complete assigned trajectory starting from the origin (i.e., identical to the current assigned trajectory between the origin and the current aircraft location), or a partial assigned trajectory starting from a defined point along the current assigned trajectory and extending to the destination, or as a partial assigned trajectory that diverges from the current assigned trajectory but then rejoins the assigned trajectory with no changes further downstream.
2. The receiving party<sup>14</sup> reviews the proposed assigned trajectory<sup>15</sup> and sends a response.
  - The receiving party may accept the proposed assigned trajectory with no changes. In this case, the negotiation ends and the proposed assigned trajectory becomes the flight's new assigned trajectory. If the proposed trajectory begins downstream of the flight's current location, then the new assigned trajectory follows the a priori assigned trajectory from the current location to the starting point of the proposed trajectory.
  - The receiving party may reject the proposed trajectory by responding that it is unable to comply with the proposed trajectory and provide a reason that the proposed trajectory is infeasible. If the airspace user is replying, the reason may relate to the aircraft's performance capabilities. If the FAA is replying, the reason may relate to a NAS constraint or conflict with other aircraft.
  - The receiving party may reject the proposed trajectory by responding that it does not like the proposed trajectory as much as the current trajectory and providing a reason that the proposed trajectory is less preferable. Note that the proposed trajectory may include a reason, such as "necessary to avoid traffic" and the receiving party should consider this reason when deciding how to respond.

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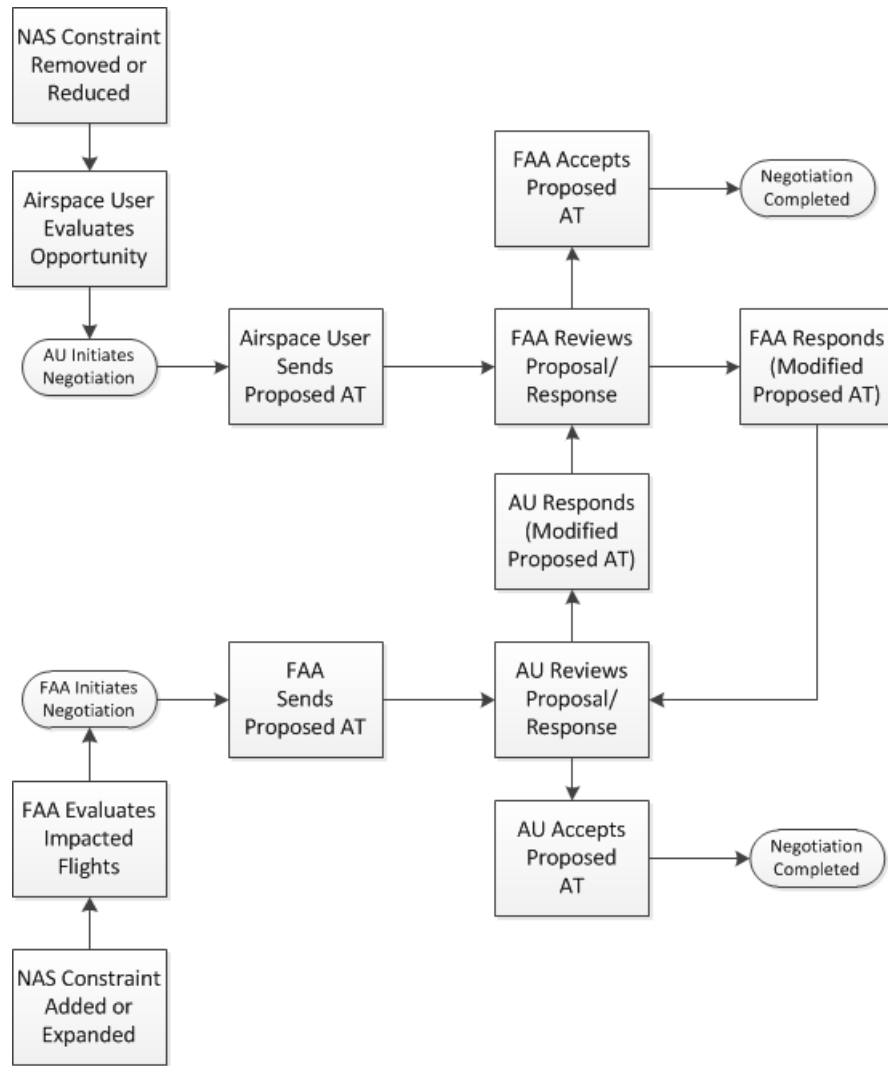
<sup>14</sup> If the FAA initiates the negotiation, then the airspace user is the receiving party (i.e., it receives the proposed AT). If the airspace user initiates the negotiation, then the FAA is the receiving party.

<sup>15</sup> Various versions of the Assigned Trajectory may be referred to as the Active Assigned Trajectory, a Proposed Assigned Trajectory, and a Supplanted (i.e., old version) Assigned Trajectory.

- If the receiving party rejects the proposed trajectory, either as infeasible or non-preferable, then the receiving party may also provide an alternative proposed trajectory. This alternative proposed trajectory (i.e., v2) should be a modification to proposed trajectory (i.e., v1 that initiated the negotiation) that would be feasible.<sup>16</sup>
  - The receiving party may accept, with no changes, a trajectory that was proposed by the initiating party earlier in the negotiation. In this case, the negotiation ends and the accepted proposed trajectory becomes the flight's new assigned trajectory.
3. Once the receiving party has responded, the initiating party (i.e., the party that originally initiated the negotiation) assumes the role of reviewing the receiving party's response or alternative proposed trajectory. The specific options depend on whether the receiving party proposed an alternative trajectory or simply rejected the proposed trajectory with a reason.
- If the receiving party rejected the proposed trajectory with a reason, the initiating party must consider the reason, modify the proposed trajectory, and send a new proposed trajectory to the receiving party for consideration.
  - If the receiving party provided an alternative proposed trajectory, then the initiating party must respond in one of the following ways.
    - The initiating party may accept the receiving party's alternative proposed trajectory with no changes. In this case, the negotiation ends and the alternative proposed trajectory becomes the flight's new assigned trajectory.
    - The initiating party may reject the receiving party's alternative proposed trajectory, providing a type of rejection (i.e., infeasible or non-preferred) and an associated reason. The initiating party must also provide a new proposed trajectory. The newly proposed trajectory should not be the same as that proposed when the negotiation was initiated. The initiating party should not reject the receiving party's alternative proposed trajectory without providing a counter-proposal (i.e., a new proposed trajectory); since the initiating party initiated the negotiation, it should take responsibility for suggesting a proposed trajectory that achieves its objectives and may be more likely to be accepted by the receiving party.
    - The initiating party may accept, with no changes, a proposed assigned trajectory that was proposed as a response by the receiving party earlier in the negotiation. In this case, the negotiation ends and the accepted proposed assigned trajectory becomes the flight's new assigned trajectory.
4. This back-and-forth process of proposal, consideration, and response or counter-proposal continues until one party accepts a proposed trajectory or the negotiation otherwise ends.
- Either party, while one party is considering the other party's most recent response or counter-proposal, may accept, with no changes, a proposed trajectory that was proposed earlier in the negotiation. In this case, the negotiation ends and the accepted proposed assigned trajectory becomes the flight's new assigned trajectory.
  - The initiating party may, at any time, end the negotiation. In this case the trajectory does not change.

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<sup>16</sup> There may be no easy way to prevent the responding party from proposing some completely different assigned trajectory.



**Figure 5. Notional Negotiation Process**

This process does not guarantee convergence to an agreed-upon trajectory. If the airspace user initiated the negotiation and the FAA never agrees to any proposed changes to the current assigned trajectory, then the current assigned trajectory remains in effect; the airspace user may keep trying or eventually give up. For example, if the airspace user’s proposal diverged from the current assigned trajectory at a certain waypoint, and the flight has reached or passed that waypoint such that the proposed assigned trajectory is no longer valid, then the airspace user will end that negotiation without any change to the assigned trajectory. In the process, the airspace user may abandon the electronic negotiation system and call (via radio or phone) the FAA to ask for help identifying an acceptable trajectory modification that achieves the airspace user’s goal. The airspace user would then need to resume negotiation, submitting an acceptable proposal, or the FAA participant could initiate a new negotiation with a proposed trajectory that is acceptable to the FAA and achieves the airspace user’s goal.

If the FAA initiated the negotiation and the airspace user continually rejects the FAA’s proposals, the FAA has the ability to declare the proposed trajectory to be essential for safety and efficiency, and unilaterally impose it as the flight’s new assigned trajectory. This is similar to current NAS operations where a controller can instruct an aircraft to turn or climb or change its speed and the aircraft is expected to comply. The pilot, then, has the option to respond that the

flight is unable, which essentially creates a critical situation requiring the controller to find another solution to the problem that motivated the vector clearance.<sup>17</sup>

If the FAA forces a new assigned trajectory on a flight, the flight must adhere to the new assigned trajectory if able. If the flight is able to comply with the immediate portion of the assigned trajectory, but will be unable to comply with a downstream trajectory constraint, then the airspace user should accept the assigned trajectory, and immediately initiate a negotiation because the flight will not be able to comply with the assigned trajectory. The flight should respond that it is unable to comply with the FAA's imposed assigned trajectory only if the flight is unable to comply with the immediate portion of the assigned trajectory.

If the airspace user initiates a negotiation because the flight will be unable to comply with the current assigned trajectory at some point in the future, then the FAA must assume the role of the initiating party and accept responsibility for finding a new AT that is feasible for the flight and achieves FAA goals.

Two negotiations affecting the same flight may not be active simultaneously. If the airspace user has initiated a negotiation that is ongoing when an external event occurs (e.g., a NAS constraint changes or a conflict is detected), the FAA may terminate the current negotiation (with no change to the assigned trajectory) and initiate a new negotiation due to the event. Once that negotiation has completed, the airspace user may re-initiate a negotiation for its original purpose.

Depending on what stakeholder initiates negotiation, various situations may occur. The pilot may initiate negotiation due to preference, changes to the operator's business objectives, relaxation of a NAS constraint that allows a trajectory closer to the operator's business trajectory, and/or weather or turbulence newly forecast or encountered by the aircraft.

- 1) The pilot's request will include a proposed change to the assigned trajectory.
- 2) FAA automation will evaluate the proposed trajectory and apply flight-specific trajectory constraints. This will require requesting specific constraints from TFM automation (e.g., metering times from TBFM).
- 3) A controller or traffic manager reviews, possibly modifies, and approves the new trajectory. Human review may be optional for some types of negotiation. The FAA provides the resulting trajectory to the pilot via automation (e.g., Data Comm to FMS or broadband to EFB).
- 4) If the pilot rejects the returned trajectory, the pilot may continue trajectory negotiation by submitting a modified request. The output of the trajectory negotiation process is a new assigned trajectory that should be acceptable to all stakeholders.

The flight dispatcher or other ground personnel responsible for the flight can initiate negotiation. Reasons for this include changes to the airspace user's business objectives, relaxation of a NAS constraint that allows a trajectory closer to the business trajectory, and/or updated weather forecasts or turbulence encountered by the flight. This case follows the same pattern as the case in which the pilot initiates trajectory negotiation. Once the dispatcher has approved a new assigned trajectory, if the flight has departed or the previous assigned trajectory was sent to the aircraft (near departure), then the pilot must also evaluate and accept (or could reject) the trajectory change.

A controller or traffic manager can initiate negotiation. Possible reasons for this include a predicted conflict or a change to a NAS constraint.

- 1) Automation will help the controller identify the need to amend the assigned trajectory and to construct the new assigned trajectory.

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<sup>17</sup> Future versions of the concept will also address how the flight's declaring an emergency is handled with respect to the assigned trajectory – whether the aircraft simply stops complying with the assigned trajectory or issues a new proposed trajectory which it declares as essential due to the flight's emergency.

- 2) Trajectory negotiation occurs as described above. The output of the trajectory negotiation process is a new assigned trajectory that should be acceptable to all stakeholders. If the assigned trajectory change must be coordinated with a traffic manager, the automation will facilitate this coordination. If the assigned trajectory change must be coordinated with another controller because the change will affect the trajectory in that controller's airspace, the automation will facilitate this coordination.
- 3) The controller or traffic manager takes an action that causes the updated assigned trajectory to be uplinked to the aircraft via Data Comm. The updated assigned trajectory is also provided to the dispatcher.
- 4) The pilot loads the clearance into the FMS and evaluates it. If the pilot accepts the new assigned trajectory:
  - (a) The pilot takes an action that executes it and confirms to the ground that the assigned trajectory has been accepted.
  - (b) The ground automation publishes the new assigned trajectory so that it is available to all stakeholders.
  - (c) The aircraft's FMS computes a predicted trajectory given the new assigned trajectory and downlinks the available intent information.
  - (d) The ground automation publishes the aircraft's intent information to be used in ground-based trajectory predictions, completing the trajectory synchronization process.
- 2) If the pilot does not accept the new assigned trajectory, then negotiation continues. If the pilot provides an alternative proposed trajectory, the FAA will evaluate it. If the pilot rejects the trajectory without indicating what is unacceptable, a controller likely will need to call the pilot and discuss the situation.

### **3.4 Negotiation Architecture**

The output of the negotiation is an assigned trajectory, either new or unchanged. The input to the negotiation includes the NAS constraints (via the NAS Constraint Service), static NAS elements (Standard Terminal Arrival Routes [STARs], Departure Procedures [DPs], sector boundaries, airport runways, etc.), other FAA goals (including conflict avoidance), the airspace user's objectives, the airspace user's requested trajectory or TOS, the air vehicle's performance capabilities (navigation, ceiling, speed range, etc.), and the current state of the aircraft.

Figure 6 illustrates a notional centralized negotiation architecture. In this approach, all negotiation between the parties is routed through centralized hubs at each party. In this way, each party may initiate a negotiation with the other party, but does not specify the stakeholder at the other party that will represent that party in the negotiation. Instead, the party's hub includes logic and a process by which the negotiation request is routed to the appropriate stakeholder. In contrast, Figure 7 illustrates a notional point-to-point architecture, in which a specific stakeholder at one party directly communicates with a specific stakeholder at the other party.

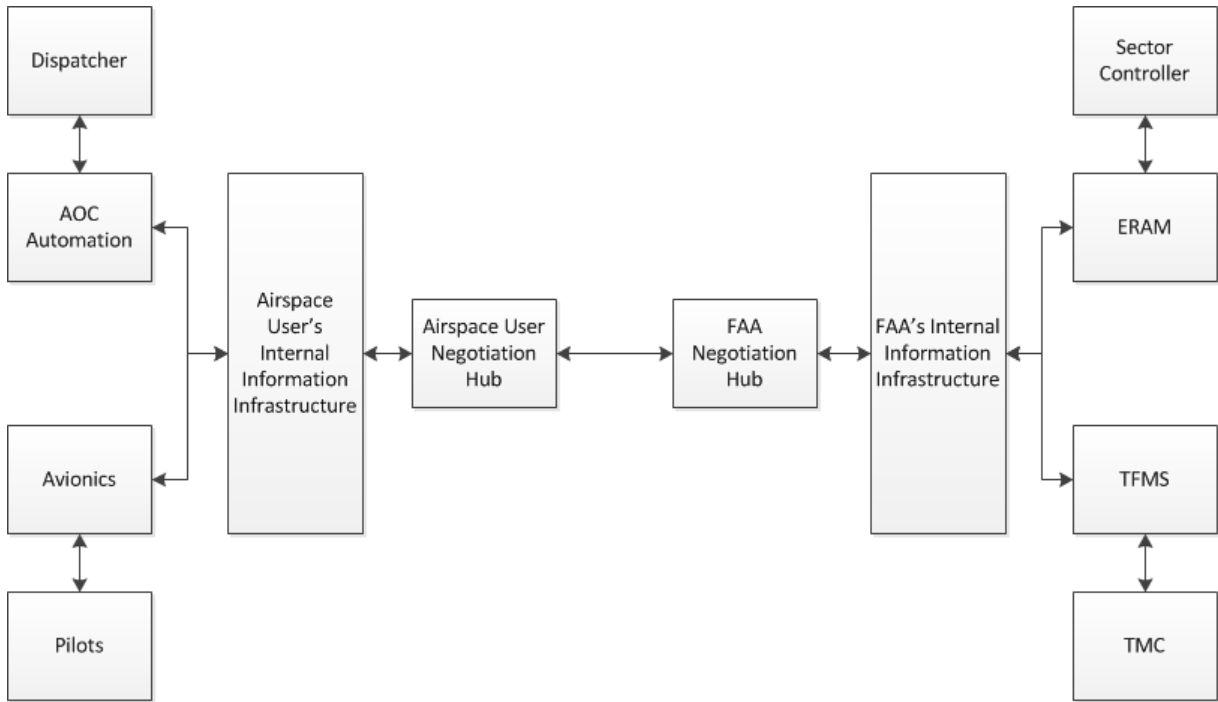
In Figure 6, the FAA Negotiation Hub also performs a validation service to ensure that proposed assigned trajectories are consistent, for example, with the flight's current location and current assigned trajectory. This capability would need to be distributed in the architectural approach shown in Figure 7.

Both figures share common features – the FAA and flight are the two parties to the negotiation and each may be represented in the negotiation by various stakeholders. Another commonality between the figures is that all negotiation is accomplished electronically. MBT assumes every flight will have the capability to electronically participate in the negotiation process.<sup>18</sup> This is most easily visualized in Figure 7. The communication occurs between an FAA automation system and an airspace user automation system. The human stakeholders use

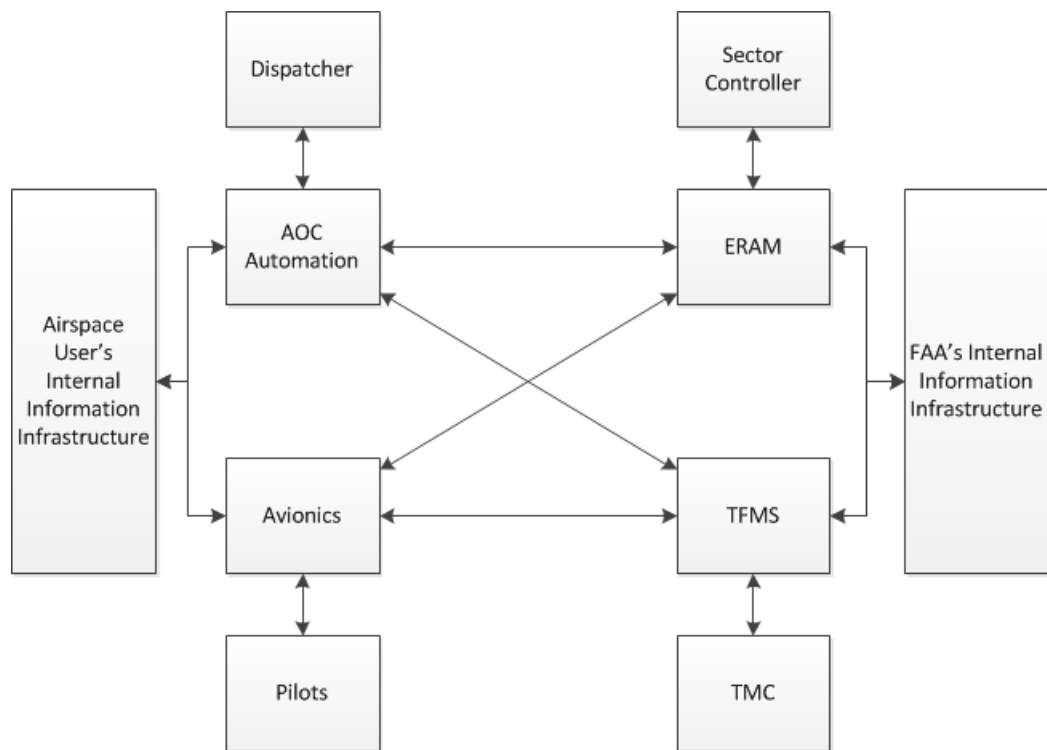
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<sup>18</sup> If necessary, the concept will be expanded to allow for voice-only negotiation.

these automation systems to receive negotiation requests and updates, as well as to generate responses or alternative proposals.



**Figure 6. Centralized Negotiation Architecture**



**Figure 7. Point-to-Point Negotiation Architecture**



### 3.5 Negotiation Systems

The MBT concept supports efficient creation and modification of assigned trajectories through automation, procedures, and roles/responsibilities. In the current NAS, multiple, separate automation systems manipulate the assigned trajectory. For example, En Route Automation Modernization (ERAM) modifies the filed flight plan by applying standard operating procedures (SOPs) and letters of agreement (LOAs), and then the TFMS applies TFM constraints such as an EDCT. MBT ensures that trajectories and constraints generated by different systems are consolidated and consistent with each other, identifying and iterating with those systems to resolve incompatibilities.

Technical innovations in personal computing and airborne-ground data transmission provide an opportunity to include highly capable software programs within arm's reach of the flight crew. To support trajectory evaluation and negotiation, the flight crew will require a software program with a robust graphical user interface to view, assess, create, and modify alternative assigned trajectories. Here, the flight crew should be able to view the assigned trajectory and flight objectives and quantitatively evaluate the assigned trajectory relative to those objectives. On the flight deck, the EFB is expected to be the hardware system used to host this application, since it provides the necessary computing power, user interface capabilities, and high-bandwidth communication connection to ground automation systems.

From a human-autonomy teaming perspective, the ideal approach for negotiation and assigned trajectory implementation is through one integrated system, such as the FMS. However, for the foreseeable future, FMS technological limitations preclude it as the hardware for hosting a highly capable negotiation application. The FMS will retain responsibility for automatic aircraft control. Therefore, a method for transferring the assigned trajectory from the EFB to the FMS will be required. Furthermore, to support trajectory negotiation, MBT requires a richer language than that provided by the CPDLC message set.

The avionics must be connected to the FAA, either directly or through the airspace user's ground automation. Some airspace users have ground personnel responsible for assisting the flight crew (e.g., airline dispatchers). Ground-based airspace user stakeholders also require an automation capability to support assigned trajectory negotiation. If the avionics communicates directly to the FAA, it must also be connected to the airspace user's ground automation.

Required FAA automation includes the functionality to host and manage the negotiation process, the capability to automatically handle simple negotiations, and the controller tools to support controllers and traffic managers in performing negotiation responsibilities. The controller tools must be sufficiently integrated with existing tools, without distracting from other responsibilities such as monitoring and maintaining aircraft separation.

### 3.6 Negotiation Parameters

Negotiation parameters entail other metadata that is necessary for stakeholders to communicate effectively during negotiation.

#### ***Type***

Negotiation may occur for various reasons, such as:

- Creating an initial assigned trajectory.
- The FAA needs the flight to make some small change (e.g., to avoid a conflict) that must be agreed to and executed quickly and is highly important. The FAA expects a positive reply with no changes.
- A new NAS constraint requires a flight's assigned trajectory to be substantially changed, but more time is available for negotiating the specific changes. The FAA proposes change with time for two-way negotiation.

- The airspace user requests an assigned trajectory change due to the relaxation of a NAS constraint or a change in the business objectives.
- The airspace user requires an assigned trajectory change because the flight will be unable to comply with one or more trajectory constraints in the current assigned trajectory.

The party initiating a negotiation should identify the type of assigned trajectory change being proposed. These types of negotiation have different levels of criticality. If necessary beyond the negotiation type, parameters that convey the level of criticality and the estimated value could be used to sort a controller's negotiation queue to prioritize flights needing immediate attention. Methods to preclude airspace users from gaming the system will be necessary.

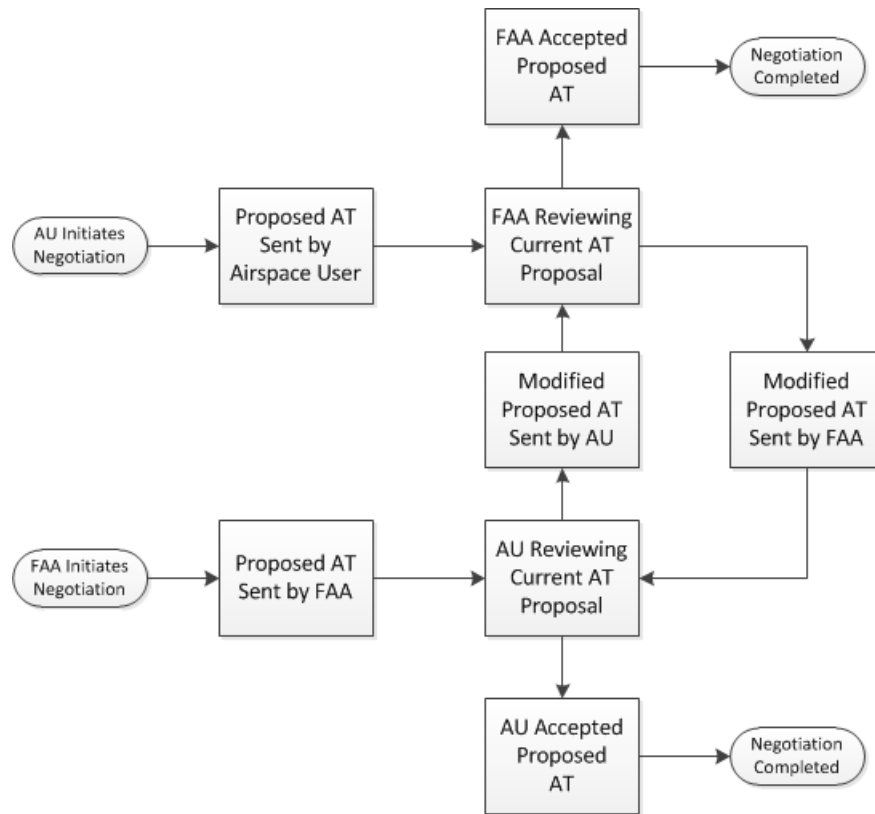
### ***Versioning***

Versioning, or configuration management, parameters facilitate the negotiation process by allowing the actors and their software to keep track of the current proposal for the assigned trajectory, as well as the history of proposed trajectories. During negotiation, a stakeholder may suggest a modification to the most recent proposed trajectory, or to a previously proposed trajectory if the negotiation has gone in a direction that stakeholder does not like. A robust method for tracking proposed trajectories that may branch along multiple paths is essential to allow all stakeholders to understand what proposal is being considered.

After negotiation is complete, versioning allows all stakeholders to know that they have the correct version of the active assigned trajectory. The versioning information is also shared between the negotiation software and the clearance issuance software. In this way, before execution of the clearance, the pilot can validate that the about-to-be-executed clearance is the same as the assigned trajectory finalized by the negotiation.

### ***Negotiation Status***

Negotiation status parameters identify the current status of the negotiation to all parties. This information would describe where a particular negotiation is with respect to the overall process using a state diagram (Figure 8). Additional data may record the start time of the negotiation, expected and actual wait times for responses, and any other data that may be useful in understanding the status and progress of the negotiation.



**Figure 8. Negotiation Process State Diagram**

### ***Fleet Management Preferences***

The MBT concept promises an added level of control and flexibility to airspace users. While each flight’s trajectory is negotiated individually, many situations will arise in which limited airspace resources must be shared among flights, including among flights belonging to the same airspace user (e.g., airline). Airspace users that have fleets of flights may require negotiation parameters that allow the airspace user to express the relative priorities of its flights. This may be especially relevant for hub operations where the AOC may want to favor strategic, connecting flights.

### ***Rationale***

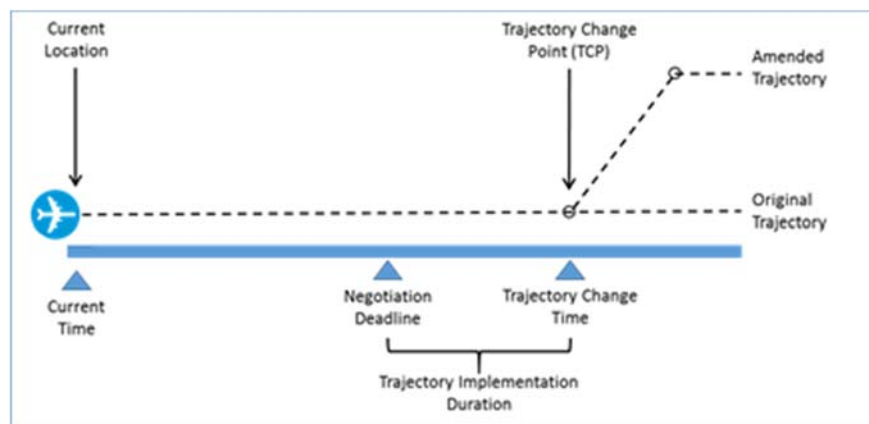
Negotiations tend to be more efficient if each party understands the objectives and constraints of the other party. Rationale information allows each stakeholder in a trajectory negotiation to communicate what they are trying to accomplish and their relative priority for various objectives. For example, a pilot could indicate the reason for initiating negotiation is to request a shorter path if weather has cleared or to request a different altitude or speed due to turbulence. A controller initiating negotiation could indicate that the proposed change is to avoid traffic, which indicates to the pilot the level of necessity and timeliness required.

The desire to enable automatic negotiation suggests that rationale be encoded through a pre-defined library of objectives, while a free text option may be available to handle unique situations. Rationale information could also include references to NAS constraints that have changed to motivate or necessitate the negotiation.

In addition to the rationale for initiating a negotiation, reasons for each response to a proposed assigned trajectory will help each stakeholder understand why the other negotiating party did not accept the current proposal.

## Negotiation Deadline

Further research is required to ensure a safe trajectory can be assigned to each aircraft in a reasonable amount of time, potentially limiting the ability of the operator to reject proposed trajectories and request alternatives. Every negotiation will have a time by which the negotiation process must be completed (i.e., the negotiation deadline). For example, pre-departure, the negotiation of the assigned trajectory must be completed prior to the scheduled departure time. For airborne flights, the negotiation to modify an assigned trajectory must be completed some amount of time before the trajectory change point (Figure 9). When a modification is essential to the FAA (e.g., to avoid a conflict) if the airspace user has not accepted a modified assigned trajectory by the negotiation deadline, then the last FAA-proposed assigned trajectory will automatically be the new assigned trajectory [4]. A proposed assigned trajectory may have an expiration time; after which it is no longer valid (e.g., the controller may have to move the other flight to avoid a conflict).



**Figure 9. Every Negotiation has a Deadline Associated with the Distance to the Trajectory Change Point**

## Free Text

A field for the negotiating parties to include free text to communicate other information that would facilitate negotiation may be of some value. While automation may not be able to make use of this, a pilot trying to express her objectives to a controller may find it easier to use free text (e.g., “I want to go north of the storm; I’m willing to fly close to it”) rather than specify a series of requested waypoints.

## 3.7 Trajectory Options Sets

The MBT concept employs Trajectory Options Sets provided by the airspace user to facilitate the negotiation process. The TOS supplies the FAA with a variety of trajectories or routes that the airspace user has indicated are preferable under different circumstances. The TOS can accelerate the negotiation process by helping the FAA understand what assigned trajectory the airspace user is likely to accept, confronted with various delays due to NAS constraints. An airspace user that submits a TOS must maintain it to be current with respect to the flight’s progress and changes to business considerations or remove it.

The TOS is communicated in the flight plan portion of the assigned trajectory object. The airspace user must also provide and maintain current the flight capabilities, resident in the Flight Capabilities portion of the assigned trajectory object. A language for communicating flight capabilities will be a future concept engineering activity.

### 3.8 Negotiating Assigned Trajectories with Time-Based Metering Constraints

The specifics of some NAS constraints cannot be known in advance. For example, the FAA cannot provide the airspace user with an STA at an arrival fix until TBFM has calculated and frozen the arrival schedule. To calculate the arrival schedule, TBFM requires ETAs for every flight at the arrival fixes. Computing ETAs requires knowing the demand (i.e., the proposed trajectories). Therefore, proposed trajectories must exist before specific time constraints can be added. MBT handles this cyclical problem through a service that publishes NAS constraints with estimated delays for each constraint that causes time-based delays. The airspace user uses this average delay information (e.g., the average delay for a TBFM metering program) to construct a requested trajectory that is cognizant of the NAS constraints, and then the FAA uses this requested trajectory to determine what the flight-specific constraints will need to be, generating a proposed assigned trajectory. The MBT concept also assumes that FAA TFM programs will be planned further in advance (e.g., the TBFM freeze horizon will be further into the future), enabled by the improved trajectory predictability provided by MBT. Therefore, a final step in the negotiation process will be to insert the specific time constraints associated with the TFM program. If TBFM arrival metering is not frozen further in advance, then as the flight crosses the freeze horizon, the time constraint will be updated from an estimate to a final value.

The concept for how Collaborative Decision Making (CDM) couples with trajectory negotiation will be expanded in future versions of the MBT concept. An airspace user may have two flights subject to a GDP. In MBT, GDPs will be managed through CTAs at the constrained resource, rather than EDCTs at the origin airports. The user may swap the CTAs between the two flights. When the airspace user decides to swap the CTAs, it will inform the FAA of the intention to swap CTAs, specifying the flights involved, and this will open separate negotiations for the two flights, assigning the new CTA to each flight and allowing any other necessary changes to be negotiated.

Some TFM programs, such as GDPs, are planned many hours in advance, before some airspace users have submitted business trajectories and negotiated an initial assigned trajectory. TFMS will continue to use scheduled information, as done today, to apportion the capacity into scheduled slots and allocate those slots to airspace users.

## 4. Trajectory Constraint Language

This section describes the components of the assigned trajectory and proposes a formalism for exchanging assigned trajectory data. Note that this format is intended for the purpose of describing the assigned trajectory and its data elements in a text document. Operationally, clearances will be issued using the CPDLC message set [6] and trajectory and constraint data will be exchanged using the FIXM, WXXM, and AIXM exchange models [7, 8, 9].

### 4.1 Trajectory Constraint Sequence

The assigned trajectory includes a set of trajectory constraints. To facilitate parsing of the trajectory constraints, each will be enclosed between opening and closing delimiters, such as: <CROSS *W1*> <CROSS *W2*> <CROSS *W3*>.

The sequence in which trajectory constraints appear in the assigned trajectory is significant. In the prior example, the flight is cleared to cross a series of three waypoints in the order *W1*, then *W2*, then *W3*. If the information contained in order of trajectory constraints is lost, then the flight could follow any of six different routes and still cross each waypoint once.

While the sequence of trajectory constraints is significant, the impact of trajectory constraints may overlap; a flight cannot consider only the next trajectory constraint and ignore all downstream trajectory constraints. For example, if the third trajectory constraint in the example

is changed to <CROSS W3 AT 10:45:20>, then the flight may need to start controlling its speed at or before the first waypoint to be able to comply with the time constraint.

## 4.2 Trajectory Constraints and Trajectory Description

Trajectory constraints exist to satisfy NAS constraints and other FAA goals such as separating aircraft. The trajectory description exists to provide a desired level of predictability/stability when there are not enough trajectory constraints to do this on their own. The flight must comply with both unless a change is negotiated. As a result, the format for trajectory constraints and trajectory description will be the same. The remainder of this chapter will be written in the context of trajectory constraints, but applies equally to the trajectory description.

When writing the assigned trajectory, the trajectory constraints and trajectory description will be mixed together. If the trajectory constraints and trajectory description were separated into two lists, then the aircraft would need some way to merge the lists in the correct order.

Since the trajectory constraints and trajectory description will be communicated as one combined list, every item will be marked as either a trajectory constraint or a trajectory description. While not all trajectory constraints will be mapped to a NAS constraint, no trajectory description will be mapped to a NAS constraint. Therefore, another labeling approach would be to mark trajectory constraints that are mapped to one or more NAS constraints with that reference, to mark other trajectory constraints with the reason for the constraint (e.g., aircraft separation), and all other elements of the assigned trajectory would be the trajectory description.

However, since the purpose of trajectory description is to improve trajectory predictability, and the purpose of trajectory constraints are to be minimally restrictive, trajectory description is likely to make more use of AT requirements rather than AT OR ABOVE/BELOW, whereas trajectory constraints may make more use of AT OR ABOVE/BELOW when a specific value is not required to avoid other traffic and NAS constraints. It is possible to have a trajectory constraint and a trajectory description that apply at the same point or overlap. However, this is not a problem since, if this occurs, the two will be consistent, with the trajectory constraint being more restrictive. If the flight complies with the trajectory description, it will also comply with the trajectory constraint.

## 4.3 Over Specification

An assigned trajectory could contain a set of trajectory constraints that would be infeasible for a flight to achieve, even though each constraint by itself would be feasible. To reduce the occurrence of this issue, the MBT concept will place some limits on the trajectory constraint vocabulary. However, this will not eliminate the potential for conflicting trajectory constraints. Therefore, the MBT concept requires that each party in the negotiation be responsible for evaluating the assigned trajectory and identifying trajectory constraints or groups of trajectory constraints that will create an infeasibility.

## 4.4 Logical Conditions

A trajectory constraint can require that some state of the flight match a specific value, be greater than or less than a specific value, or be between a range of values. Table 3 shows how these logical conditions apply to each of the primary state dimensions.

An open interval always includes the bounding value (i.e., greater than or equal to; less than or equal to) because the mathematical distinction between equaling the value and being arbitrarily close to the value has no operational significance. While not adhering to the typical mathematical meaning, in the context of MBT trajectory constraints, a closed interval "X BETWEEN A and B" always includes the bounding values A and B as conforming values of X

(i.e.,  $X \geq A$  and  $X \leq B$ , assuming  $A \leq B$ ). If a trajectory constraint is defined as a range of permitted values (i.e., an open or closed interval), any value within the range is fully compliant with the constraint. There is no implication that any point within the range is a preferred “target.” An excluded interval such as “ $X > A$  OR  $X < B$ , where  $A > B$ ” is not permitted in the language. Open and closed intervals are included to provide operational flexibility by permitting a range of valid values.

**Table 3. Types of Logical Conditions**

<b>Logical Type</b>	<b>Lateral</b>	<b>Altitude</b>	<b>Speed</b>	<b>Time</b>
Equal (=)	CROSS <i>Waypoint</i> FOLLOW <i>Procedure</i>	AT ALTITUDE A	AT SPEED S	AT TIME T
Greater Than Or Equal To ( $\geq$ )	N/A	AT OR ABOVE ALTITUDE A	AT OR ABOVE SPEED S	AT OR AFTER TIME T
Less Than Or Equal To ( $\leq$ )	N/A	AT OR BELOW ALTITUDE A	AT OR BELOW SPEED S	AT OR BEFORE TIME T
Between, Closed Interval ( $\geq$ & $\leq$ )	N/A	BETWEEN ALTITUDE A1 AND A2	BETWEEN SPEED S1 AND S2	BETWEEN TIME T1 AND T2

#### 4.5 Flight Specification

Each assigned trajectory will begin with some “header” information that will include a way to uniquely identify the flight. The GUFID is a Globally Unique Flight Identifier that is assigned by the FAA and used across all FAA automation systems to allow all data pertaining to a flight to be easily matched.

<FLIGHT CallSign GUFID *Gufid* DATE *Date*>

#### 4.6 Waypoint Trajectory Constraint

One of the most basic types of trajectory constraints is a specified waypoint (i.e., a point in two-dimensional space) over which the aircraft must pass, within defined tolerances.

<CROSS *Waypoint*>

The waypoint may be specified in various ways, including using a named point from the FAA’s database or specifying a longitude and latitude in a standard coordinate system.

In addition to specifying the waypoint to be crossed, the CROSS trajectory constraint may optionally specify altitude, speed, and/or time requirements that apply at that waypoint. While altitude and speed, or altitude and time, requirements may be included in the same CROSS constraint, the CROSS trajectory constraint will not include both a speed and a time requirement.<sup>19</sup> A speed requirement in a CROSS trajectory constraint applies at that waypoint, not along the preceding or following route segment.

<CROSS *Waypoint* AT ALTITUDE *Altitude*>

<sup>19</sup> Mathematically, it is possible for a flight to comply with both a speed and a time constraint at a point, or a speed constraint over a route segment and a time constraint at the end of that segment, by planning further in advance. However, in this version of the MBT concept, the CROSS trajectory constraint is limited to not include simultaneous speed and time constraints.

<CROSS *Waypoint* AT SPEED *Speed*>  
 <CROSS *Waypoint* AT TIME *Time*>  
 <CROSS *Waypoint* AT ALTITUDE *Altitude* AT SPEED *Speed*>  
 <CROSS *Waypoint* AT ALTITUDE *Altitude* AT TIME *Time*>

Rather than requiring a specific altitude, speed, or time, the CROSS trajectory constraint may permit an open interval or closed interval. Table 4 enumerates all of the available optional requirements.

**Table 4. Waypoint Trajectory Constraint<sup>20</sup>**

Waypoint	CROSS Waypoint
Altitude	AT ALTITUDE <i>Altitude</i> AT OR ABOVE ALTITUDE <i>Altitude</i> AT OR BELOW ALTITUDE <i>Altitude</i> BETWEEN ALTITUDE <i>Altitude1</i> AND <i>Altitude2</i>
Speed	AT SPEED <i>Speed</i> AT OR ABOVE SPEED <i>Speed</i> AT OR BELOW SPEED <i>Speed</i> BETWEEN SPEED <i>Speed1</i> AND <i>Speed2</i>
Time	AT TIME <i>Time</i> AT OR AFTER TIME <i>Time</i> AT OR BEFORE TIME <i>Time</i> BETWEEN TIME <i>Time1</i> AND <i>Time2</i>

A route may be defined through a series of CROSS trajectory constraints. In a future version of the MBT concept, the trajectory constraint language may be expanded to include a trajectory constraint “<ROUTE *Waypoint1 Waypoint2... WaypointN*>” although it is not considered necessary at this point.

#### 4.7 Tolerance

Consider the trajectory constraint <CROSS *Waypoint* AT ALTITUDE *Altitude*>. Mathematically, this constraint says that the flight’s altitude must be exactly *Altitude* when it crosses the waypoint *Waypoint*. All air vehicles will usually have some error in achieving a target value in any dimension, due to limitations in the performance of their navigation, guidance, and control systems. Therefore, trajectory constraints require tolerances to be achievable.

Required Navigation Performance refers to the level of performance required for a flight to use a specific procedure or region of airspace. In MBT, RNP used in the context of a specific trajectory constraint is equivalent to tolerance and describes how closely a flight must comply with the trajectory constraint. Actual Navigation Performance (ANP) is used to describe an aircraft’s navigation performance capability, which is unique to the aircraft. ANP is equivalent to accuracy and describes the flight’s capability of achieving a target value in some dimension of navigation.

In MBT, RTP and Actual Time Performance (ATP) similarly describe the tolerance on a time constraint and the aircraft’s performance capability to comply with time constraints, respectively. Every flight will have ANP and ATP values, shared as part of the air vehicle capabilities portion

<sup>20</sup> For all “BETWEEN X A AND B” requirements, the expected convention is that  $A < B$ .

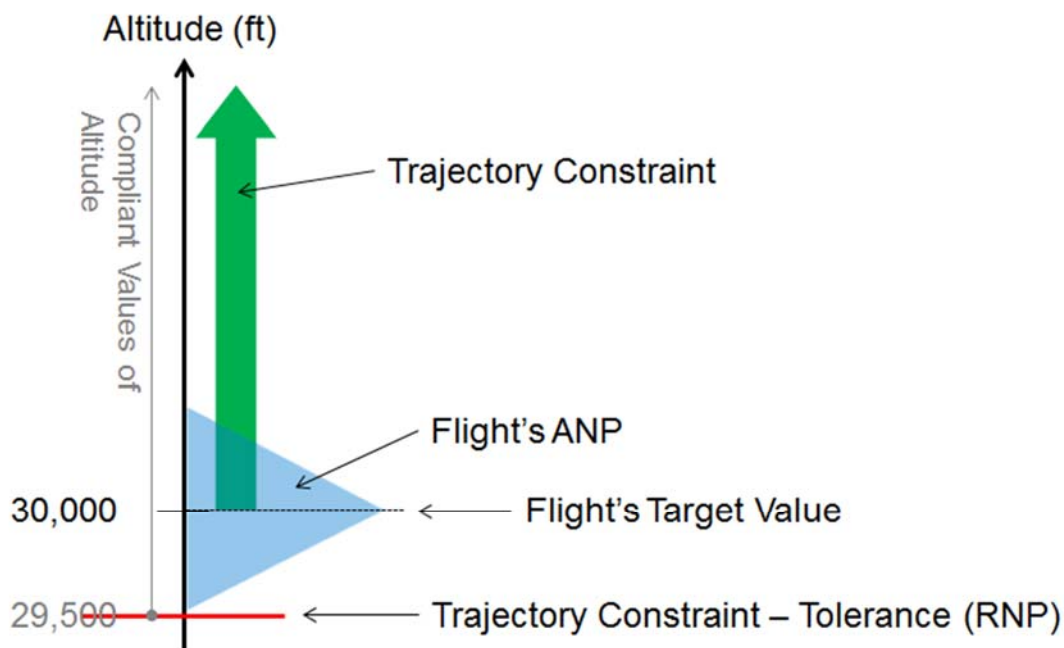


of the assigned trajectory object. The tolerance permitted on a trajectory constraint (RNP/RTP) is based on the flight's capability in that dimension (ANP/ATP).

<CROSS *Waypoint* AT ALTITUDE *Altitude* WITHIN *Tolerance*>

Tolerance will normally be expressed as a symmetric requirement about the target value, since the air vehicle's performance probability distribution will typically be symmetric. If necessary, the WITHIN notation could be extended <... WITHIN *POS\_TOL*, *NEG\_TOL*> to express separate tolerances greater than and less than the target value.

Tolerance also applies to open and closed interval constraints. In the trajectory constraint <CROSS *Waypoint* AT OR ABOVE ALTITUDE *Altitude* WITHIN *Tolerance*>, every value of altitude that is equal to *Altitude* or greater than *Altitude* is a valid target for the flight's guidance and control system. Similarly, in the trajectory constraint <CROSS *Waypoint* BETWEEN ALTITUDE *Altitude1* AND *Altitude2* WITHIN *Tolerance*>, the bounding values *Altitude1* and *Altitude2*, as well as every value in between, are valid targets for the flight. The tolerance defines how far outside the interval will be considered in compliance. The flight does not need to adjust the trajectory constraint by its known ANP/ATP to determine the range of acceptable target values. Therefore, the ATC system must consider the tolerance when specifying the trajectory constraint so that the result provides the intended separation from other aircraft.



<... AT OR ABOVE ALTITUDE 30,000 WITHIN 500>

**Figure 10. Tolerance Applied to an Open-Interval Trajectory Constraint**

Figure 10 illustrates a trajectory constraint (green) in altitude. The figure is equally applicable to any other dimension of navigation or time. Every value of altitude within the green range is a valid target for the flight's guidance and control system. The flight's performance distribution (ANP) depicts (blue) the likely actual values for the flight's altitude, where the dashed black line marks the target value the flight has chosen. The target is compliant with the trajectory constraint. The tolerance is shown as the distance between the edge of the trajectory constraint and the red line. A gray line shows the range of altitude values that are considered compliant with the trajectory constraint. The flight is considered to be in compliance with the

trajectory constraint as long as its actual altitude is within the tolerance of the constraint. The tolerance (RNP) must be equal to or greater than the flight's performance capability (ANP).

Figure 11 illustrates how tolerance applies to an AT trajectory constraint (i.e., the trajectory constraint specifies one specific value of altitude). Tolerance applies similarly to lateral position, speed, and time. Section 4.9 describes further how tolerance applies in the lateral (route) dimension.

<CROSS Waypoint AT SPEED *Speed* WITHIN *Tolerance*>

<CROSS Waypoint AT TIME *Time* WITHIN *Tolerance*>

<CROSS Waypoint WITHIN *Tolerance*>

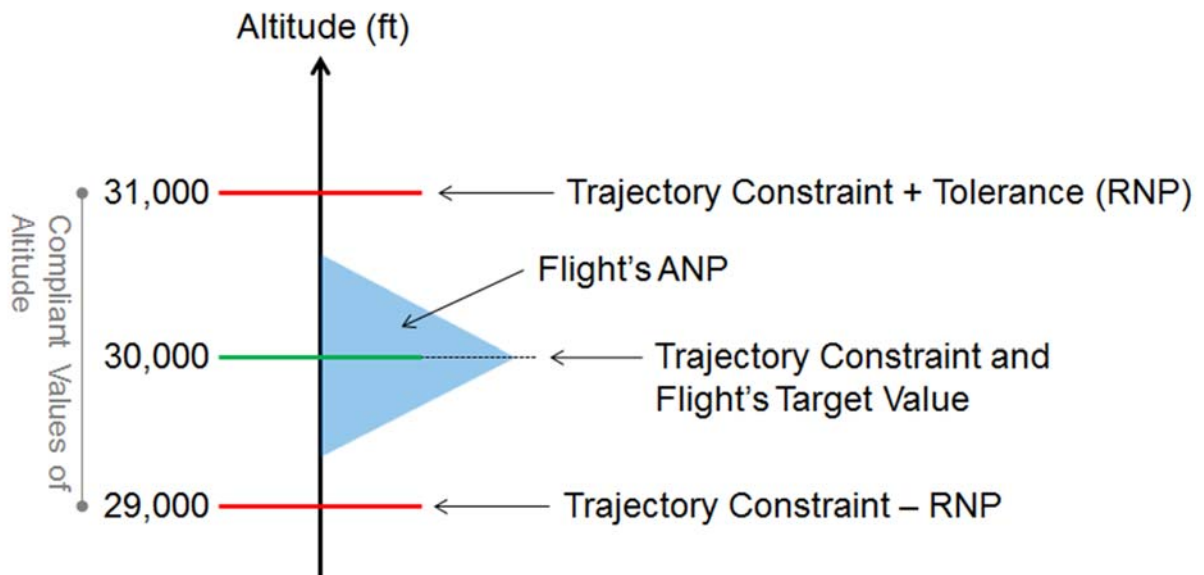
Rather than requiring a tolerance to be included for each dimension specified in a trajectory constraint, the assigned trajectory may specify default values for the RNP/RTP, that will apply to each trajectory constraint unless that constraint explicitly expresses an exception.

<TOLERANCE ROUTE *Default\_Lateral\_Tolerance* ALTITUDE *Default\_Altitude\_Tolerance* SPEED *Default\_Speed\_Tolerance* TIME *Default\_RTP*>

Each of the elements is optional. For example, to set only a default altitude tolerance:

<TOLERANCE ALTITUDE *Default\_Altitude\_Tolerance*>.

The location of the TOLERANCE statement within the assigned trajectory is significant. The statement sets the default values from that point in the assigned trajectory until the next point at which the default is set to a different value.



<... AT ALTITUDE 30,000 WITHIN 1000>

**Figure 11. Tolerance Applied to an AT Trajectory Constraint**

## 4.8 Origin and Destination<sup>21</sup>

The origin and destination of a flight are specified as trajectory constraints. The origin and destination may be expressed as airport identifiers from a published list of airports, or using another method, such as longitude and latitude. A small drone, for example, may take off from a field or building top that is not a designated airport.

<ORIGIN *Airport* RUNWAY *Runway* AT TIME *Time*>

<DESTINATION *Airport* RUNWAY *Runway* AT TIME *Time*>

The ORIGIN and DESTINATION trajectory constraints may optionally specify a runway that will be used. These trajectory constraints may also specify a takeoff time constraint and landing time constraint, respectively.

## 4.9 Route Segments

A route segment (a.k.a. leg) is the path (i.e., ground track) a flight will follow between two waypoints. A segment may be flown as a straight path between the endpoints (excluding possible turns at each end) or as a defined curve (e.g., a specified radius of curvature).<sup>22</sup> Unless otherwise specified, a segment between two waypoints is assumed to be flown as a straight route, with the exception of completing a turn at the first waypoint and initiating a turn at the second waypoint. Figure 12 illustrates (from RTCA DO-350A) two radius-to-fix (RF) legs connecting three waypoints.

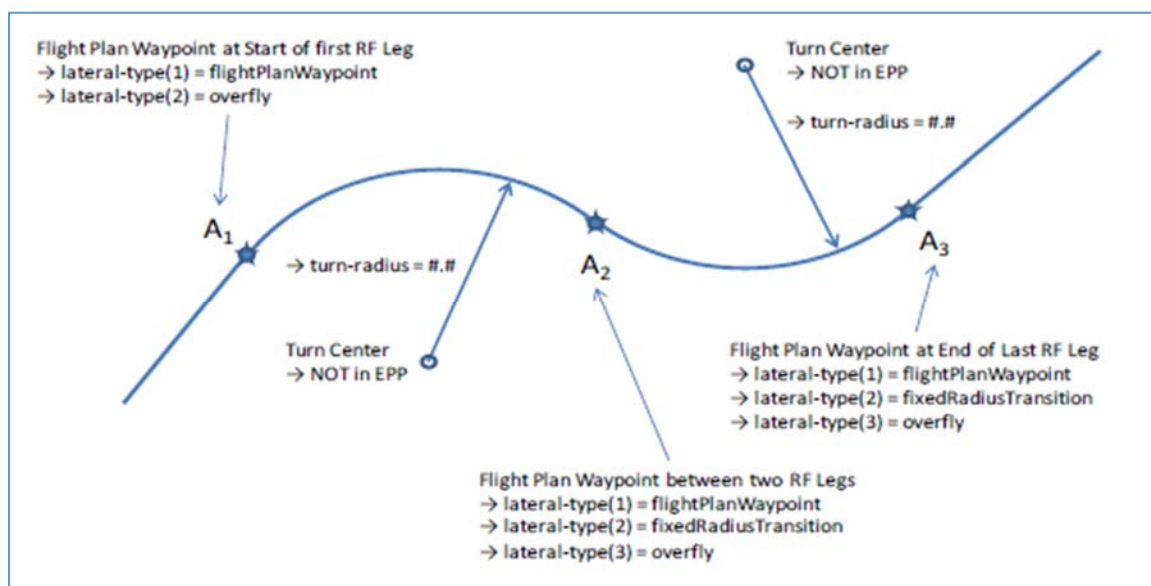


Figure 12. RF Legs<sup>23</sup>

A route SEGMENT trajectory constraint is implied between consecutive CROSS trajectory constraints. The assigned trajectory excerpt <CROSS *Waypoint1*> <CROSS *Waypoint2*> is

<sup>21</sup> This version of the MBT concept focuses on trajectories that start at takeoff and end at landing. Additional language may be added to support describing ground trajectories for taxiing aircraft. For example, a runway exit point could be an additional option within the DESTINATION constraint.

<sup>22</sup> Methods for describing curved segments will be expanded in future versions of the MBT concept. This version will assume the segment is a straight path.

<sup>23</sup> Figure copied from RTCA, Inc., DO-350A "Safety and Performance Requirements Standard for Baseline 2 ATS Data Communications (Baseline 2 SPR Standard)," 17 March 2016.

equivalent to <CROSS *Waypoint1*> <SEGMENT FROM *Waypoint1* TO *Waypoint2*> <CROSS *Waypoint2*>, which is also equivalent to <SEGMENT FROM *Waypoint1* TO *Waypoint2*>.

The SEGMENT trajectory constraint can be useful to apply other requirements on the flight over that segment. For example, <SEGMENT FROM *Waypoint1* TO *Waypoint2* IN TIME *Time*> indicates that the flight should fly the segment in an amount of time equal to *Time*.

The simplest route segment is a straight path between two waypoints, maintaining a constant altitude and speed. An aircraft may change altitude and/or speed along a segment. In addition, the time required to fly the segment may be constrained, or the time at which the flight crosses the starting and/or ending waypoints may be constrained.

**Table 5. Route Segment Trajectory Constraint**

Route Segment	SEGMENT FROM <i>Waypoint1</i> TO <i>Waypoint2</i>
Altitude	AT ALTITUDE <i>Altitude</i> AT OR ABOVE ALTITUDE <i>Altitude</i> AT OR BELOW ALTITUDE <i>Altitude</i> BETWEEN ALTITUDE <i>Altitude1</i> AND <i>Altitude2</i>
Speed	AT SPEED <i>Speed</i> AT OR ABOVE SPEED <i>Speed</i> AT OR BELOW SPEED <i>Speed</i> BETWEEN SPEED <i>Speed1</i> AND <i>Speed2</i>
Time <sup>24</sup>	IN TIME <i>Time</i> IN TIME GREATER OR EQUAL TO <i>Time</i> IN TIME LESS THAN OR EQUAL TO <i>Time</i> IN TIME BETWEEN <i>Time1</i> AND <i>Time2</i>

### **Time**

Section 4.5 introduced the trajectory constraint <CROSS *Waypoint* AT TIME *Time*> to define an absolute time constraint at a waypoint. The trajectory constraint <SEGMENT FROM *Waypoint1* TO *Waypoint2* IN TIME *Time*> creates a relative time constraint. The flight should fly the route segment in a duration equal to *Time*.

### **Speed**

The optional IN TIME expression is only used to describe the entire segment. In contrast, the AT SPEED expression could specify the speed at the first waypoint, the second waypoint, or along the entire segment.

<SEGMENT FROM *Waypoint1* AT SPEED *Speed* TO *Waypoint2*> specifies only a speed constraint effective at *Waypoint1*.

<SEGMENT FROM *Waypoint1* AT SPEED *Speed1* TO *Waypoint2* AT SPEED *Speed2*> specifies speed constraints at both waypoints. However, this trajectory constraint does not specify a required speed along the segment between the waypoints. If *Speed1* ≠ *Speed2*, the flight's speed must transition during the segment, with no constraint placed on how quickly the speed transitions or where along the segment.

<SEGMENT FROM *Waypoint1* TO *Waypoint2* AT SPEED *Speed*> specifies only a speed constraint effective at *Waypoint2*.

<sup>24</sup> In a SEGMENT trajectory constraint, a time value represents a duration (i.e., a length of time) rather than a specific point in time.

<SEGMENT AT SPEED *Speed* FROM *Waypoint1* TO *Waypoint2*> specifies a speed that should be followed at every point along the entire segment, including at the two waypoints.

In addition to specifying an absolute speed, the speed constraint could be described as a well-defined, though time-varying, property such as “econ cruise speed.” Additional details regarding this concept element will be included in future versions of the MBT concept.

Compliance for segment constraints must consider that if a different constraint exists on an adjoining route segment, then the flight cannot instantly change its speed and, therefore, there must be a transition period, which can start before the end of the first segment and/or extend into the second segment. How close to the shared waypoint the transition must begin and complete is left for a future version of the trajectory constraint language.

### **Altitude**

<SEGMENT FROM *Waypoint1* TO *Waypoint2*> specifies no altitude constraint.

<SEGMENT FROM *Waypoint1* AT ALTITUDE *Altitude1* TO *Waypoint2* AT ALTITUDE *Altitude2*> specifies altitude constraints that apply at each endpoint.

- If  $Altitude1 = Altitude2$ , then the trajectory constraint also implies that the altitude requirement applies at all points along the segment. <SEGMENT FROM *Waypoint1* AT ALTITUDE *Altitude1* TO *Waypoint2*> is equivalent for this case of constant altitude.
- If  $Altitude1 \neq Altitude2$ , then the flight must climb or descend during the segment. Assume  $Altitude1 > Altitude2$ , i.e., the flight will descend. Then the trajectory constraint also implies that at all points along the segment the flight’s altitude must be equal to or less than  $Altitude1$  and must be greater than or equal to  $Altitude2$ . This trajectory constraint does not restrict where along the segment the descent begins, nor where along the segment the descent is completed. The trajectory constraint does imply that the flight’s altitude will be monotonically decreasing (i.e., except for tolerance allowances, the flight will not descend, climb again, and then descend again).
- If  $Altitude1 < Altitude2$ , the same logic applies for a flight that will climb while on the segment.

<SEGMENT FROM *Waypoint1* TO *Waypoint2* AT ALTITUDE *Altitude2*> specifies an altitude constraint that applies at the end of the segment. Depending on the flight’s altitude when it enters the segment, this may require the flight climb, descend, or maintain a constant altitude.

Although not explicit, this trajectory constraint does constrain the altitude prior to the endpoint. In the lateral/route dimension, the MBT assigned trajectory language implies a constraint that a flight will fly a straight segment between consecutive waypoints unless otherwise specified. While the air vehicle intent may change freely without negotiation, the flight may not zig-zag horizontally between consecutive CROSS constraints, unless otherwise permitted. A similar implied constraint exists in the vertical dimension. The flight is expected to operate at the initial altitude, the final altitude, or smoothly transition between those altitudes. In order for the flight to have more vertical flexibility between explicit altitude constraints, either the tolerance needs to be set sufficiently large, or the vertical profile flexibility needs to be explicitly defined.<sup>25</sup>

As a result of these implied constraints in the altitude dimension, the language does not include an expression “SEGMENT AT ALTITUDE *Altitude* FROM *Waypoint1* TO *Waypoint2*,” parallel to that available in the speed dimension, that explicitly requires a constant altitude along the entire segment.

With the ability to specify an open interval or closed interval altitude constraint, at both the start and end of the segment, there are numerous possible combinations. The following

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<sup>25</sup> Future versions of the MBT concept will include language extensions to support this.

examples are intended to illustrate how any potential combination of altitude requirements should be interpreted.

If an altitude requirement is only expressed at the starting waypoint, that altitude requirement applies along the entire segment, except where a subsequent trajectory constraint requires the flight to begin a transition to another altitude.

<SEGMENT FROM *Waypoint1* AT OR ABOVE ALTITUDE *Altitude1* TO *Waypoint2*>

If an altitude requirement is only expressed at the ending waypoint, that altitude requirement applies only at that waypoint. However, per the above rules for an implied constraint, the altitude along the segment is constrained by the altitude at the first waypoint and the constraint for the altitude and the second waypoint.

<SEGMENT FROM *Waypoint1* TO *Waypoint2* AT OR ABOVE ALTITUDE *Altitude2*>

If altitude requirements are expressed at both endpoints, the interpretation depends on the relationship between the specific altitude values. In general, the assumptions described above for the “AT ALTITUDE” examples would be applied. Some additional situations can exist that will be clarified in a future version of the MBT concept. The following are a subset of the possible combinations.

<SEGMENT FROM *Waypoint1* AT OR ABOVE ALTITUDE *Altitude1* TO *Waypoint2* AT OR ABOVE ALTITUDE *Altitude2*>

<SEGMENT FROM *Waypoint1* AT OR ABOVE ALTITUDE *Altitude1* TO *Waypoint2* AT OR BELOW ALTITUDE *Altitude2*>

<SEGMENT FROM *Waypoint1* AT OR ABOVE ALTITUDE *Altitude1* TO *Waypoint2* BETWEEN ALTITUDE *Altitude2* AND *Altitude3*>

<SEGMENT FROM *Waypoint1* BETWEEN ALTITUDE *Altitude1* AND *Altitude2* TO *Waypoint2* BETWEEN ALTITUDE *Altitude3* AND *Altitude4*>

#### 4.10 Vertical Profile

MBT is a trajectory-based concept and, therefore, does not include “commands” such as “CLIMB TO *Altitude*.” The altitude change must be associated with a route segment, defined by two waypoints.

**Table 6. Vertical Speed Trajectory Constraint**

Vertical Speed	AT OR GREATER THAN VERTICAL SPEED <i>Vertical_Speed</i> THROUGH <i>Altitude</i>
----------------	---

<SEGMENT FROM *Waypoint1* AT ALTITUDE *Altitude1* TO *Waypoint2* AT ALTITUDE *Altitude2* AT OR GREATER THAN VERTICAL SPEED *Vertical\_Speed* THROUGH *Altitude3*>

This trajectory constraint specifies a route segment from *Waypoint1* to *Waypoint2*. The flight’s altitude must be *Altitude1* at the start of the segment and *Altitude2* at the end of the segment; assume *Altitude 2 > Altitude1*. The flight must climb at or greater than *Vertical\_Speed* feet per minute, until reaching *Altitude3*, which may be less than or equal to *Altitude2*. Finally, this constraint implies that the climb must start at *Waypoint1*. Otherwise, there would be undesirable ambiguity in the vertical portion of the trajectory segment between *Waypoint 1* and *Waypoint 2*.

Note that the vertical speed constraint is expressed as a speed (i.e., not a velocity vector). Therefore, the direction – climb or descent – is conveyed through the initial and final altitude; the speed constraint will always be positive.<sup>26</sup>

Similar requirements for climbing AT VERTICAL SPEED *Vertical\_Speed*, AT OR LESS THAN VERTICAL SPEED *Vertical\_Speed*, and BETWEEN VERTICAL SPEED *Vertical\_Speed1* AND *Vertical\_Speed2* are not particularly operationally useful for ATC of traditional aircraft. However, these constructs might be useful for some types of air vehicles (e.g., limiting the climb rate of a rotorcraft to ensure it passes below a crossing aircraft) and, therefore, are permitted in the language.

#### 4.11 Offset Segments

Segments connecting named waypoints are commonly used by many flights. In MBT, flights will have more flexibility to select arbitrary routes, rather than adhering to named jet routes. Still, there is a need to support current operations in which flights are assigned to follow a route, offset to one side by a certain distance.

<SEGMENT FROM *Waypoint1* TO *Waypoint2* OFFSET *Side Distance*> specifies that a flight should fly the segment between the waypoints, but offset to either the left or right (*Side*) by *Distance* in nautical miles.

#### 4.12 Turns

Aircraft do not turn instantaneously; waypoints mathematically have zero radius. Therefore, if two consecutive segments have different headings, then the aircraft must turn near the common waypoint; there are various options for how this turn can be described.

Often, a required type of turn will not be specified in a trajectory constraint; air vehicle intent data would indicate the type of turn that the flight will perform. However, the trajectory constraint language includes a method for specifying the turn type to support situations in which the type of turn is constrained. These statements specify the turn type at *Waypoint* and *Waypoint1*, respectively.

<CROSS *Waypoint* TURN *Turn\_Type*>

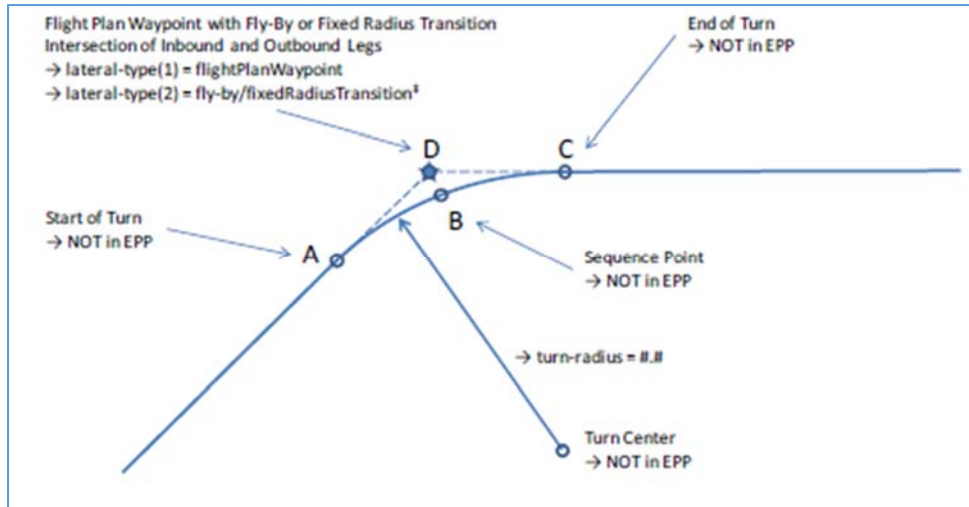
<SEGMENT FROM *Waypoint1* TO *Waypoint2* TURN *Turn\_Type*>

Future versions of the MBT concept will include additional details required for each turn type, such as the point by which the turn must end, and the point before which the turn may not begin. Some of the existing types of turns defined in current FMSs are illustrated in the following figures.

Figure 13 illustrates a fixed radius transition between two straight route segments. This is a special type of fly-by turn. In a fly-by turn, the air vehicle initiates the turn prior to reaching the waypoint and, therefore, passes the waypoint on the inside of the turn. The vehicle completes the turn after passing the waypoint, but smoothly captures the outbound segment without overshooting it. The fixed radius transition turn, which is a type of Performance Based Navigation (PBN) procedure, performs a fly-by turn using a constant radius of curvature and, therefore, can be precisely described and predicted.

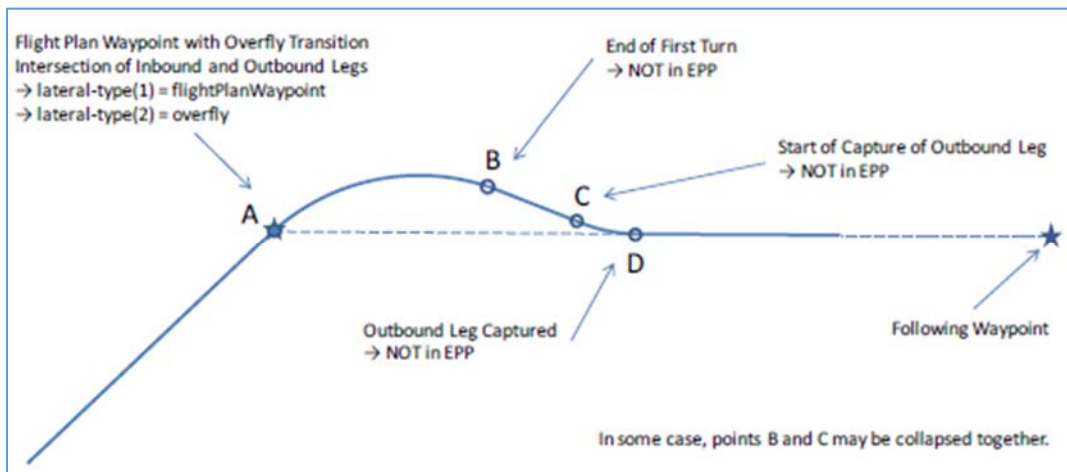
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<sup>26</sup> In this version of the MBT concept, a standard unit is assumed for each constraint type. If necessary, the language will be expanded to specify a default unit for each dimension and allow alternate units to be expressed explicitly. For example, vertical speed could be expressed in terms of flight level per a unit time, or as a climb angle (i.e., vertical distance relative to horizontal progress), rather than feet per minute.



**Figure 13. Fly-By or Fixed Radius Transition<sup>27</sup>**

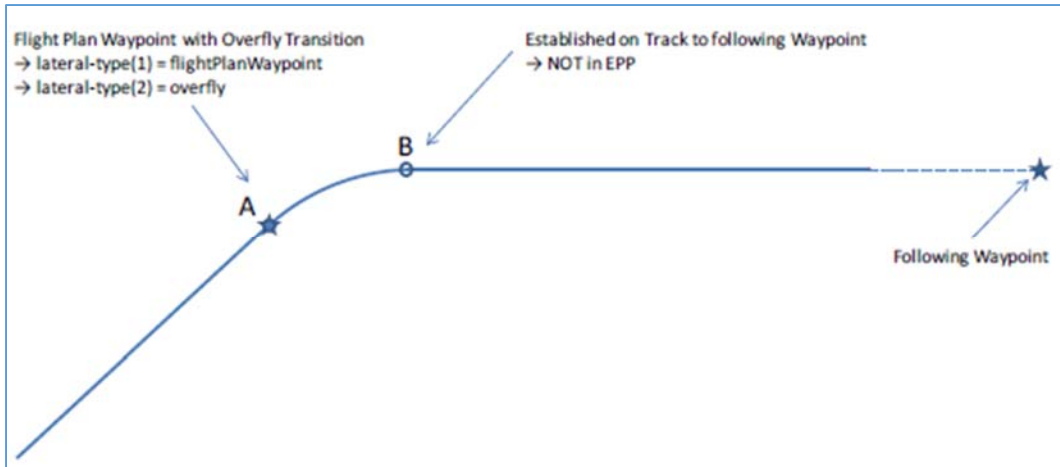
A fly-over (a.k.a. overfly) turn (Figure 14) is a turn in which the air vehicle flies directly to the waypoint, and then initiates the turn after crossing directly over the waypoint. As a result, the vehicle overshoots the outbound route segment and must smoothly recapture that segment. Figure 15 illustrates an alternate form of the fly-over turn in which the vehicle does not capture the segment between the initial waypoint at which the turn is made and the following waypoint until the following waypoint. The flight flies over the initial waypoint and then makes a turn toward the following waypoint and flies direct to that waypoint from the end of the turn.



**Figure 14. Standard Fly-Over Turn**

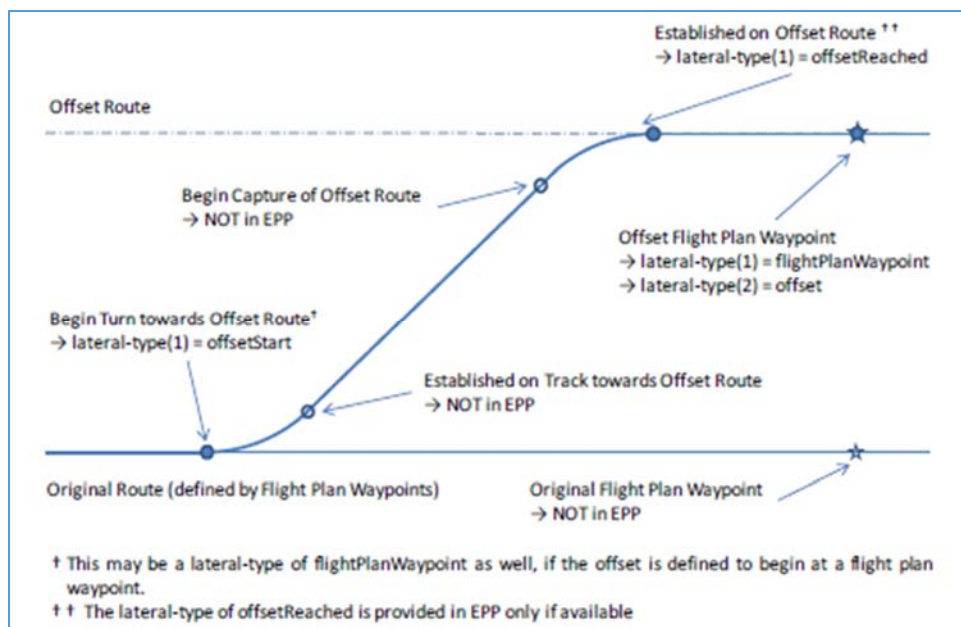
<sup>27</sup> Figures of turn types are copied from RTCA, Inc., DO-350A, "Safety and Performance Requirements Standard for Baseline 2 ATS Data Communications (Baseline 2 SPR Standard)," 17 March 2016.





**Figure 15. Alternate Fly-Over Turn**

Figure 16 illustrates turns to start a lateral offset from a defined straight route segment. The RTCA DO-350A standard also includes details for turns associated with changing the lateral offset amount and returning to the base route.



**Figure 16. Turns to Start Lateral Offset**

Emergent vehicle types and business models may require additional turn types. For example, rotorcraft and other vehicles that are capable of hovering can turn in place, while space vehicle operations fly mathematically prescribed trajectories but do not otherwise turn.

### 4.13 Tolerance Along Segment

Section 4.7 introduced tolerance in the context of the allowance on constraints at a waypoint. The trajectory constraint <CROSS *Waypoint* WITHIN *Tolerance*> specifies how close to the waypoint the aircraft must pass the waypoint. The tolerance at a waypoint may be specified separately from that along the inbound or outbound segment to accommodate an aircraft having a different ANP for turns as opposed to straight segments. Tolerance must be specified for each dimension in which a constraint exists, everywhere a constraint exists, such as lateral tolerance along the full segment connecting two waypoints. In the lateral dimension,

the trajectory constraint <SEGMENT WITHIN\_ROUTE *Tolerance* FROM *Waypoint1* TO *Waypoint2*> indicates that the flight should remain within the specified tolerance at every point along the segment, except at the waypoints as part of turns.

Similarly, <SEGMENT AT SPEED *Speed* WITHIN\_SPEED *Tolerance* FROM *Waypoint1* TO *Waypoint2*> specifies a speed that should be followed along the segment, and <SEGMENT FROM *Waypoint1* TO *Waypoint2* IN TIME *Time* WITHIN\_TIME *Tolerance*> specifies a tolerance for a relative time constraint.

<SEGMENT FROM *Waypoint1* AT ALTITUDE *Altitude1* TO *Waypoint2* AT ALTITUDE *Altitude2* AT OR GREATER THAN VERTICAL SPEED *Vertical\_Speed* THROUGH *Altitude3* WITHIN\_VERTICALSPEED *Tolerance*> adds a vertical speed tolerance to a segment used to expedite a climb or descent.

In the current version of MBT's trajectory constraint language, there is no explicit method to specify the altitude tolerance for a segment that includes an altitude change. This is because there is no explicit method for specifying where along the segment the flight will perform the altitude change. Altitude tolerance may be specified at waypoints with altitude constraints. If the segment is flown at constant altitude, then this tolerance is implied to be effective along the entire segment.

<SEGMENT FROM *Waypoint1* AT ALTITUDE *Altitude1* WITHIN\_ALTITUDE *Tolerance1* TO *Waypoint2* AT ALTITUDE *Altitude2*> WITHIN\_ALTITUDE *Tolerance2*>

#### 4.14 Procedure Constraints

The FOLLOW trajectory constraint specifies a published procedure that the flight must conform to in all dimensions (route, altitude, speed, time). The optional FROM and TO identifiers allow a portion of the procedure to be included in the assigned trajectory.

If additional requirements are to be added to the procedure, then separate CROSS or SEGMENT trajectory constraints should be included, in order after the FOLLOW constraint, to specify those altitude, speed, or time requirements. The procedure's published tolerances apply (i.e., have precedent over the flight's default values) unless explicitly overridden in the FOLLOW trajectory constraint.

**Table 7. Procedure Trajectory Constraint**

Procedure	FOLLOW <i>Procedure</i> FROM <i>Waypoint1</i> TO <i>Waypoint2</i>
-----------	---

#### 4.15 Region-based Trajectory Constraints

Some operations, such as surveying, crop dusting, sightseeing, law enforcement activities, and news activities, require a flight to loiter in a specific area for a period of time. For example, an aircraft performing crop dusting would not want to specify the back-and-forth flight path over the field using a series of waypoints. Instead, the assigned trajectory could be defined as the region over the field, within some range of altitudes, providing much greater flexibility for the flight. Air vehicles that may fly this type of operation include helicopters, small conventional aircraft, and unmanned aircraft (i.e., drones). The vehicle may take off from an airport or other launch site, fly to the region, dwell within that region for a period of time, and then return to the launch site.

To accommodate periods of loitering within a region, the assigned trajectory requires a type of trajectory constraint that defines a 3D volume of airspace within which a vehicle may operate flexibly, and the period of time during which the vehicle will remain in that region. If a flight wants to remain in a region longer or leave early, that would constitute an assigned trajectory change that requires negotiation.

In general, the shape of the region projected to the ground should be flexible (i.e., not constrained to be a circle or rectangle).

<DWELL START TIME *Time1* END TIME *Time2*  
LOW ALTITUDE *Altitude1* UPPER ALTITUDE *Altitude2*  
*Waypoint1, Waypoint2,... WaypointN*>

The preceding trajectory constraint could be used to define an arbitrary simple polygonal prism. Each waypoint could be a named, published point or another description such as a longitude and latitude pair. The mathematical definition of a prism requires that the top and bottom surfaces be parallel to one another. The start and end times define the period of time during which the flight will dwell in the region. The previous trajectory constraint in the assigned trajectory will identify where the flight enters the volume and the subsequent trajectory constraint will identify where the flight exits the volume.

#### 4.16 Specific Shapes

Some air vehicle missions do not require the full flexibility of dwelling in a region with no restriction on movement within that region, but still do not fit the paradigm of trying to fly from point A to point B as efficiently as possible. For example, a drone monitoring a particular point on the ground may want to fly in a known circular pattern that allows it to keep its camera or other sensors aimed at the point on the ground. In addition to circular paths, UASs often fly “race track” shapes, figure eights, and clover-leaf patterns. The trajectory constraint language should support these types of missions without requiring large numbers of waypoints.

Electric (and hybrid electric) Vertical Takeoff and Landing (eVTOL) air vehicles are expected to enter NAS operations, and they will be designed to perform agile operations in urban environments. Such vehicles transition between lift rotors for vertical takeoff and landing, to propellers and winged-flight for more efficient cruise. They may introduce new trajectory shape and constraint requirements, such as following surface roads, transitioning between mostly vertical motion to mostly cruise (forward) motion, and constraints relative to other air vehicles in regions where they are responsible for self-separation.

#### 4.17 Relative Trajectory Constraints

Many advanced ATM concepts control groups of in-trail aircraft by assigning responsibility to each aircraft to achieve and maintain a specific spacing behind the preceding aircraft in the line. To accommodate self-spacing ATM techniques, MBT requires relative trajectory constraints that describe a trajectory requirement in relationship to another aircraft. In addition, trajectory constraints that describe trajectory requirements relative to a region of airspace or a time that is not known in advance may be useful for supporting some operations.

Relative trajectory constraint types include:

- Follow behind another specified aircraft; maintain a specific spacing (either specified as a distance or a time, with a tolerance). This constraint assumes the two aircraft have been assigned the same route; this constraint only describes the progress along that route.
- Relative distance laterally offset from a defined route
- Cross behind (or ahead of) another specified aircraft at a specific point. This constraint assumes the two aircraft are on routes that cross at the specified point.
- Cross above (or below) another specified aircraft at a specific point. This constraint is similar to “cross behind/ahead of,” but in the vertical dimension.
- Cross a defined waypoint at a time relative to the time a previous waypoint was crossed.
- Cross a defined waypoint at a time relative to an RTA at a future waypoint.
- Fly a certain route segment in a certain amount of time (i.e., a relative start time).

- Avoid a particular region (e.g., NAS constraint). This type of constraint is atypical because it does not specify where the air vehicle will fly. However, it may be useful in combination with other constraints that provide flexibility. For example, if a flight has a trajectory constraint that allows it to operate freely within a region, this constraint could be used to exclude any overlap between the two regions.

### ***Flight-deck Interval Management***

Flight-deck Interval Management (FIM) may have a critical role in MBT. MBT will expand the use of time constraints to manage traffic. However, RTAs do not necessarily provide separation between aircraft at all points between waypoints. The use of FIM would potentially reduce a significant number of conflicts that would otherwise require assigned trajectory changes and additional trajectory constraints to resolve. A FIM trajectory constraint in MBT:

<FIM FLIGHT *Flight* AT DISTANCE *Distance*>

<FIM FLIGHT *Flight* AT TIME *Time*>, where *Time* is an amount of time, not a point in time.

An alternative form allows an open bound, specifying a minimum requirement but no maximum value. This is equivalent to specifying a “no closer than” constraint.

<FIM FLIGHT *Flight* AT OR MORE DISTANCE *Distance*>

<FIM FLIGHT *Flight* AT OR MORE TIME *Time*>

There is no equivalent form for following by less than a certain amount of distance or time with no lower bound (i.e., “BY LESS THAN DISTANCE”).

A closed bound may be specified.

<FIM FLIGHT *Flight* BETWEEN DISTANCE *Distance1* AND *Distance2*>

<FIM FLIGHT *Flight* BETWEEN TIME *Time1* AND *Time2*>

## **4.18 Relative to Moving Object on Ground**

Another category of air vehicle mission is to follow a moving target on the ground, such as a boat or truck. Typically, this is a government policing mission, but could also be a security mission for a high-value cargo or potentially observing wildlife. If the trajectory of the ground target is not known, the MBT assigned trajectory would need wider tolerances and possibly frequent modification.

## **4.19 Heading Constraints**

The MBT concept does not allow aircraft heading to be specified through a trajectory constraint. In current NAS operations, heading clearances are associated with vector control, which results in an open trajectory. MBT requires the desired heading be specified by assigning the flight to cross a specific waypoint. The lack of a heading constraint option is somewhat inconsistent with the inclusion of a vertical speed constraint option. While vertical speed could be constrained by providing altitude constraints at consecutive waypoints, there is a communications efficiency in allowing a vertical speed constraint and, thus, vertical speed is allowed in this version of the MBT concept.

## **4.20 Emergent Users and Other Novel Operations**

Emergent users, such as UASs and space vehicle operations (SVO), are becoming increasingly prevalent in the NAS. The MBT concept, the trajectory negotiation process, and the assigned trajectory construct and language must support these less conventional types of airspace users.

## ***Unmanned Aircraft Systems***

Unmanned Aircraft Systems encompass a wide range of vehicle types, sizes, and missions. Some UASs are very similar to conventional fixed-wing aircraft, some resemble traditional helicopters, some are much smaller fixed-wing aircraft or multiple-rotor copters. Some UASs operate individually, while others operate in swarms. Some operate at low altitudes, separate from passenger aircraft, while others want to share the busiest regions of the NAS. The size and performance characteristics will not affect the ability of MBT to accommodate their operations through the assigned trajectory construct. The inclusion of vehicle capabilities in the assigned trajectory object is essential to be able to design assigned trajectories that are feasible and will be appropriately spatially or temporally separated from vehicles with very different capabilities. Some mission types may require extensions to the AT language. For example, a group of vehicles flying in a formation could be assigned a single assigned trajectory that defines a moving “bubble” within which the group of aircraft must operate, with responsibility for conflict avoidance with the group fully allocated to the group.

## ***Space Vehicle Operations***

While space orbits are above the NAS, space vehicles climb through the NAS to reach orbit and again pass through the NAS for landing or recovery. One characteristic of a space vehicle is that its trajectory is largely defined by the operator; the FAA cannot negotiate for the vehicle to follow a different ground track or climb/descent profile. While the operator may have some flexibility in the launch or re-entry time, even in this dimension the vehicles mission requires a specific orbit from specific launch and landing/recovery locations, which requires a small range of launch times and re-entry times. Furthermore, once the trajectory, either ascent or descent, has begun, it cannot be modified since the vehicle does not have sufficient fuel or aerodynamic control to adjust its trajectory significantly.

While the space vehicle trajectories will be starkly different from those of traditional passenger aircraft – especially in speed and vertical speed – the assigned trajectory could be described using the same types of trajectory constraints. Alternatively, additional constraint types that better describe the vertical and speed profiles of these types of vehicles could be introduced into the AT language.

An additional operational consideration for SVO is protecting the potential debris field. The altitudes through which the vehicles climb, the amount of combustible fuel carried by the vehicles, and the frequency with which catastrophic failures occur create a potential for debris to be spread over a wide area, creating a hazard to other airspace users. Therefore, in addition to the assigned trajectory for the vehicle itself, the assigned trajectory must designate the time-varying volume of airspace that could be hazardous due to space vehicle debris. While this will require additional language, the MBT concept of an assigned trajectory can accommodate it.

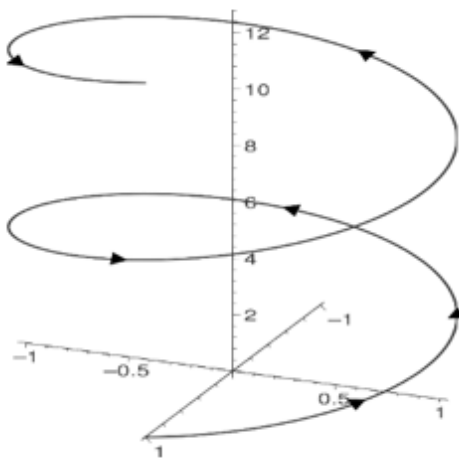
SVO have considerable impact on other airspace users. From the perspective of air traffic management and other airspace users, SVO appear similar to NAS constraints such as special use airspace (SUA), in which a region of airspace becomes closed to all other flights, and is not subject to negotiation. While the approximate timing of this closure will be known in advance, the precise timing will not be known until launch/re-entry, and there is a significant probability of a launch postponement. This suggests the idea of considering the probability of a NAS constraint when planning an assigned trajectory.

Space vehicle launch from an airborne aircraft represents an interesting case in which the launch vehicle would have an assigned trajectory starting and concluding at an airport, while the space vehicle would have an assigned trajectory through the NAS, originating at the location of the launch aircraft at the time of separation. Similarly, multi-stage space launch vehicles begin as a single vehicle and separate into multiple vehicles at various points in the launch, with one vehicle continuing to climb while the others return to Earth.

### **High-Altitude, Long-Endurance Flights**

One characteristic of long-endurance flights that operate at high altitude is that they often climb slowly, taking a long time to reach their operating altitude. In addition, their climb trajectory is often poorly predicted because of its dependence on atmospheric conditions. This type of flight often climbs while following a circular ground track, resulting in a helical path (Figure 17).

The ATC system would not want to reserve the entire column of airspace for the flight due to the vehicle's slow climb. However, the flight's position above the ground at a particular future time is not accurately predictable. One approach for the assigned trajectory for such a flight would be to define a series of 3D volumes – flat cylinders – with sequential time periods during which the flight could operate within each region. In this way, the ATC system would protect a minimal region of airspace for this one flight, while still supporting its unique requirements. This type of AT would provide the necessary volume of airspace for the operation while minimizing the impacts on other airspace users.



**Figure 17. Timed Regions of Airspace for Helical Ascent<sup>28</sup>**

### **Urban Air Mobility**

Urban air mobility promises to revolutionize the air transportation industry by offering affordable, point-to-point transportation within high-population regions and avoiding the delays associated with city surface traffic. Urban air mobility concepts are eyeing advances in electric batteries and hybrid air vehicles that blend the lift efficiencies of fixed-wing flight and the vertical agility of helicopters in eVTOL aircraft. The on-demand business models require flights to be able to operate with little advanced notification to the air traffic system. Although these vehicles have distinct performance capabilities and the ability to climb and descend along steep paths, the urban air mobility operations are not expected to require additional types of trajectory constraints beyond those for traditional aircraft. The idea of NAS constraints could be broadened to include buildings and towers that must be avoided by these low-altitude flights.

#### **4.21 Linking NAS Constraints to Trajectory Constraints**

The NAS Constraint Service allows both the FAA and airspace user to have complete knowledge of the current NAS constraints. Many of the trajectory constraints are due to NAS constraints. For example, time constraints at waypoints may be used to implement time-based metering TFM programs. When a NAS constraint expands in scope or severity, the FAA may need to modify assigned trajectories for flights affected by that change. Similarly, when a NAS

<sup>28</sup> <https://en.wikipedia.org/wiki/Helix>.

constraint is eliminated, shrinks, or becomes more severe (e.g., a longer time delay), the airspace user may want to adjust the assigned trajectory (e.g., take a more direct route if a region of airspace that was closed re-opens). Not all trajectory constraints result from NAS constraints. For example, if there were no NAS constraints, the flight would still need a route defined in the assigned trajectory. Some trajectory constraints are imposed to avoid conflicts with other flights.

Linking NAS constraints to trajectory constraints is optional but helps both parties identify when a flight's assigned trajectory should be revisited after a NAS constraint changes.<sup>29</sup> Each NAS constraint has a unique identifier. A trajectory constraint may be the result of multiple NAS constraints. The NASCONSTRAINT tag is used to link one or more NAS constraints, using their unique IDs, to a trajectory constraint or an assigned trajectory.

*<CROSS Waypoint NASCONSTRAINT ConstraintID1, ConstraintID2,...>*

When included within a trajectory constraint, the NASCONSTRAINT tag links one or more NAS constraints to that specific trajectory constraint. The same NAS constraint may be attached to multiple trajectory constraints. For example, if a portion of a route was selected to avoid a region of weather, and that weather moves differently than forecast, multiple waypoints and route segments will be affected.

*<NASCONSTRAINT ConstraintID1, ConstraintID2,...>*

When used as a separate trajectory constraint, the NASCONSTRAINT tag links one or more NAS constraints to the entire assigned trajectory. This format can be used to help identify that the flight is affected by a NAS constraint, without specifying which part of the assigned trajectory was affected by the constraint.

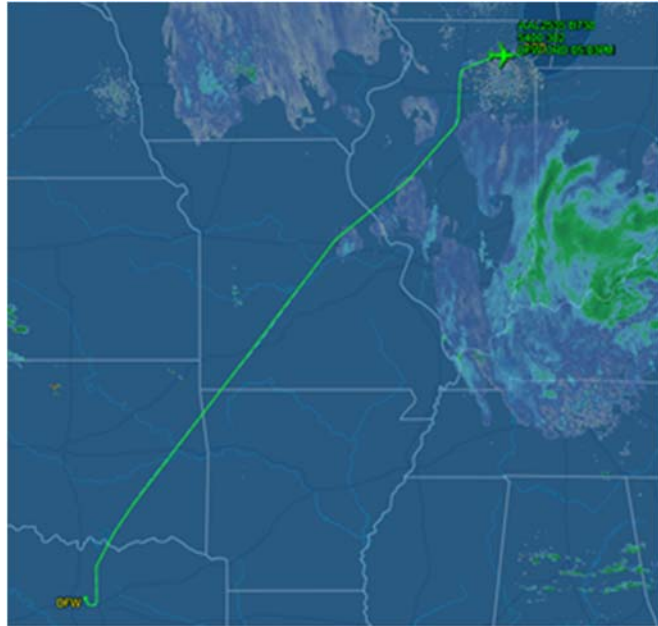
Linking NAS constraints to the assigned trajectory or trajectory constraints is a shared responsibility between the FAA and airspace user. While the FAA can identify trajectory constraints resulting from TFM programs, if the airspace user chooses a route due to a NAS constraint, only the user knows the reason for that route choice.

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<sup>29</sup> When a NAS constraint expands, it could now affect other flights that were not previously affected, so a method of identifying affected flights, in addition to linking in the assigned trajectory, will also be required.

## 4.22 Example Assigned Trajectory

<FLIGHT **AAL2535** DATE **03 21 2018**>

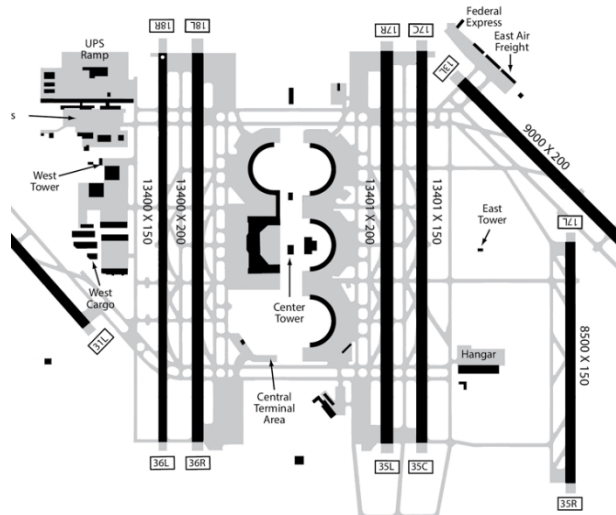


Identifies the flight.<sup>30</sup>

<TOLERANCE ROUTE **0.5** ALTITUDE **500** SPEED **10** TIME **30**>

The default tolerances for this flight are: lateral 0.5 nautical miles; altitude 500 feet; speed 10 knots; and time 30 seconds.

<ORIGIN **DFW** RUNWAY **17R** AT TIME **09:30:45**>

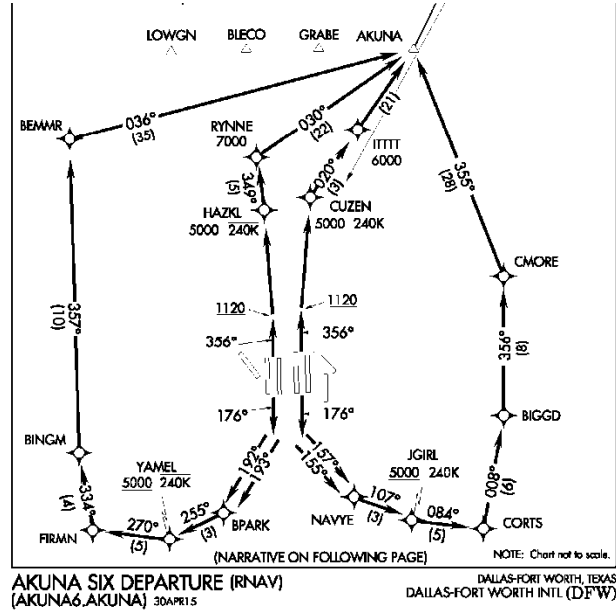


The flight's origin is the Dallas-Fort Worth airport. The flight has been assigned to runway 17R with a planned takeoff time of 09:30:45 GMT.

<sup>30</sup> Picture from FlightAware.com

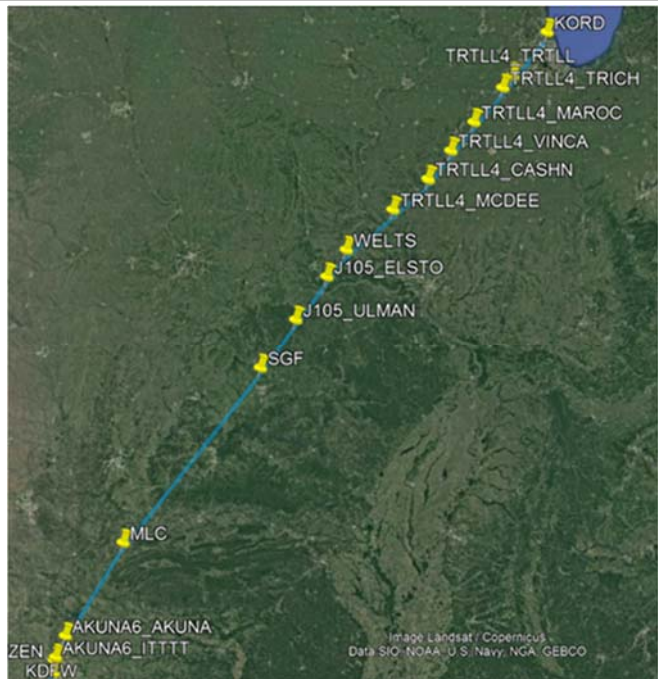


<FOLLOW AKUNA6>



Fly the AKUNA6 RNAV departure procedure. "TAKEOFF RWY 17R: Climb heading 176° to intercept course 155° to NAVYE, then on track 107° to cross JGIRL at or above 5000 and at or below 240K, then on depicted route to AKUNA, thence...."

<CROSS MCL AT ALTITUDE FL350 BETWEEN TIME 10:16:00 AND 10:21:00>



MCL is a VOR-TAC navigational aid (NAVAID)<sup>31</sup>

<sup>31</sup> Picture drawn using Google Earth.

<CROSS **SGF Extended Meter Point AT TIME 10:54:00 WITHIN 10 NASCONSTRAINT 8734**>

Specifies an RTA and a 10-second tolerance at the extended metering point for SGF. Identifies the reason for the RTA is a NAS constraint (extended metering). The RTA represents a 3-minute delay.

This example assumes that either the freeze horizon for TBFM metering has been expanded substantially, or an estimated time and delay is included in the initial assigned trajectory and will be updated when the aircraft reaches the freeze horizon.

<CROSS **WELTS WITHIN 0.5 BETWEEN TIME 11:09:00 AND 11:13:00**>

Specifies a time window and an RNP of 0.5 nautical miles at the Welts waypoint.

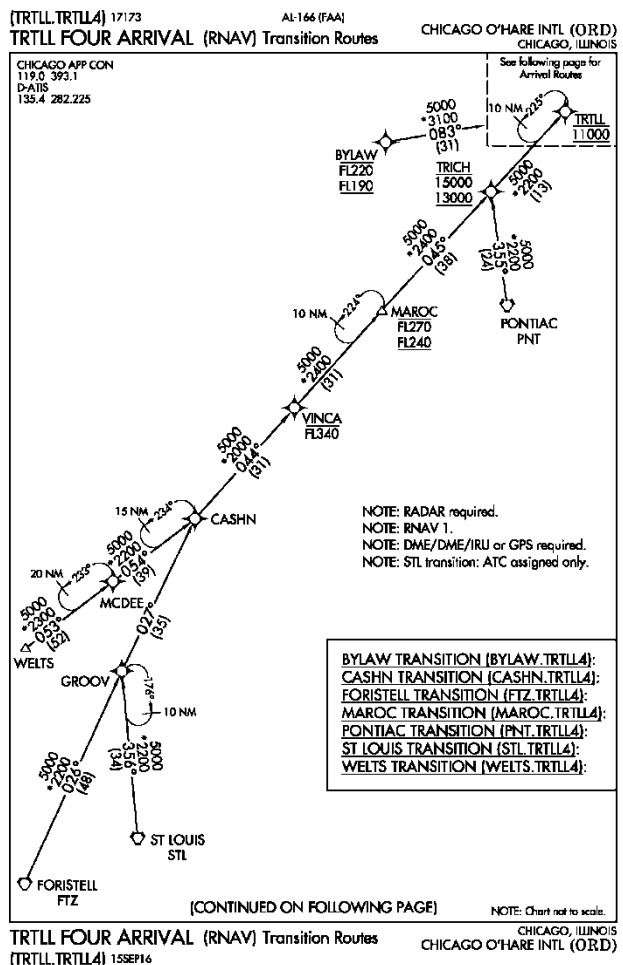
<CROSS **SGF Coupled Meter Point AT TIME 11:16:00 WITHIN 10 NASCONSTRAINT 8745**>

NAS constraint is coupled metering. RTA represents 2 minutes of delay.

<CROSS **VINCA WITHIN 0.25 AT ALTITUDE FL340 AT OR BELOW SPEED M0.78**>

The flight joins the TRTLL4 procedure at the VINCA waypoint.

<FOLLOW **TRTLL4**>

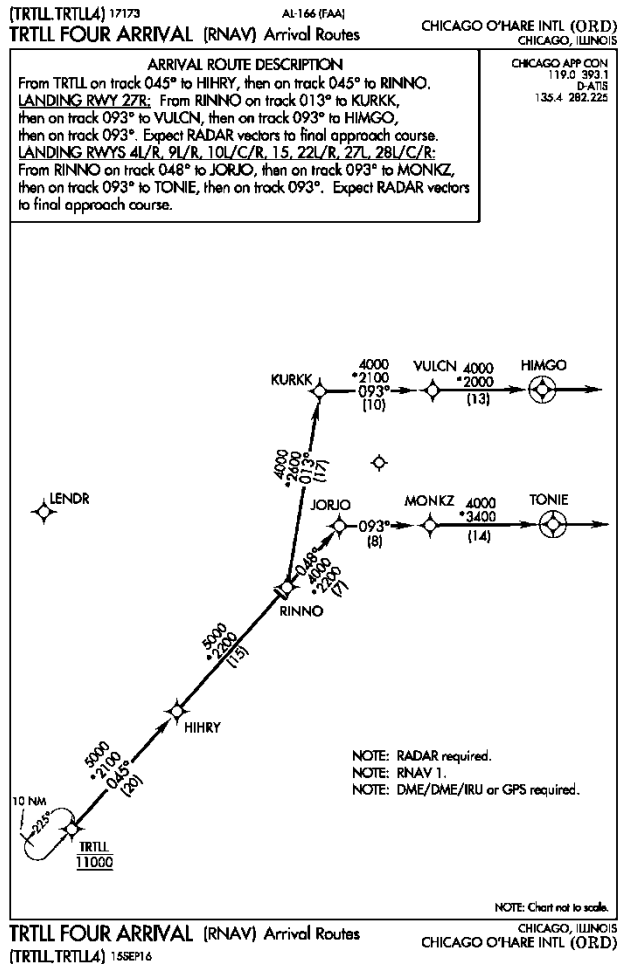


Follow the TRTLL FOUR RNAV Standard Terminal Arrival Procedure (STAR).

<CROSS TRTLL AT TIME 11:38:00>

Specifies an RTA at the TRTLL waypoint.

<CROSS RINNO AT TIME 11:50:00  
WITHIN 10 NASCONSTRAINT 3433>



RINNO is a waypoint on the TRTLL4 arrival procedure. The TRTLL4 procedure continues beyond RINNO, ending with “Expect radar vectors to final approach course.”

The RTA is due to a NAS constraint – a Terminal Scheduling and Spacing (TSS) program active at ORD.

<DESTINATION ORD RUNWAY 27L AT TIME 11:58:20 WITHIN 10 NASCONSTRAINT 468>

The flight’s destination is Chicago O’Hare International airport. At the time the initial assigned trajectory is negotiated, the arrival runway is not available. However, as the flight approaches ZAU (Chicago’s ARTCC), the FAA initiates a trajectory negotiation to add additional details to the assigned trajectory, including the assigned runway.

CTA at the runway is due to a GDP resulting from reduced arrival rate at ORD.

## **5. Concept Elements**

This section describes elements of the MBT concept and how they interact.

### **5.1 General**

MBT is a concept for air traffic control that fits within the FAA's vision of TBO. A cornerstone of the MBT concept is that each flight is, at all times, assigned a complete trajectory from its current location to its destination. TFM actions are applied to aircraft by modifying the assigned trajectory. Required tactical ATC interventions are applied by modifying the assigned trajectory to the extent possible.

MBT is intended to include all IFR flights. MBT is applicable to all phases of flight, but this ConOps focuses on airborne phases of flight. In the near term, MBT might be applied from the top of climb to the top of descent to reduce uncertainty and the scope of impact on current NAS operations.

### **5.2 Airspace Structure**

The MBT concept is not dependent on the airspace structure – whether there is a defined route network or whether free routing is allowed. In the long term, there may be fixed routing in some airspace (e.g., high-density airspace) and free routing in other airspace (low- and medium-density airspace), or there may be fixed routing during busy times of day and free routing at other times.

Airspace users would need to be informed of where/when their requested trajectories must conform to a published route structure as part of the NAS constraints. The density of the route structure could change based on the demand for that airspace region at that time. During certain periods of time, routes could require a minimum level of navigation accuracy for a flight to use that route, which would be communicated through the NAS Constraint Service. This is an example of how better-equipped aircraft will receive benefit.

### **5.3 Digital Air-Ground Communication**

MBT relies on digital communication between ground automation systems and aircraft. Near-term MBT will be consistent with current FAA and industry plans. The long term MBT concept assumes communication capabilities beyond current Data Comm plans and specifications. In particular, reliable, high-bandwidth communication will be available between the ground and flight deck, connecting the EFB and other advanced aircraft automation to the ground.

Aircraft adhering to assigned trajectories (and making intent information available) will improve predictability of future aircraft state and, thereby, enable “tactical” control for aircraft separation to be performed earlier relative to a conflict. Consequently, datalink communication of changes to the assigned trajectory will be able to be utilized to resolve more “tactical” conflicts despite the longer communication latency compared to voice. Datalink can also uplink more complex clearances to the FMS than can be easily transmitted over voice.

### **5.4 Closed Trajectories**

All flights will have an assigned closed trajectory at all times. Flights will follow these closed trajectories apart from in exceptional cases.

#### **5.4.1 Exceptions**

Most situations that require an assigned trajectory to be modified (e.g., a possible conflict with another aircraft, un-forecast weather that must be avoided, lower than forecast capacity

requiring delay absorption) will be detected far enough in advance (due to improved trajectory prediction) to allow an assigned trajectory modification to be negotiated and digitally communicated. There may be situations that require quicker action. If the controller needs to quickly communicate to the pilot that the aircraft needs to deviate from the assigned trajectory, then the controller will use voice rather than datalink. However, this does not necessarily prevent the trajectory from being closed. The ground automation will support the controller in identifying an appropriate trajectory modification and efficiently entering it into the ground automation. For example, the automation may suggest the trajectory modification for the controller to review and accept, or the controller may simply click on the display and the automation will identify the closest waypoint to use for a path stretch maneuver.

If the controller enters a modification to the flight's assigned trajectory into the ground automation (e.g., inserting a new waypoint to create a path stretch and then rejoining the original route at a subsequent waypoint), and then issues a clearance to the pilot via voice to follow this modified assigned trajectory, the trajectory is still closed (per the definition in Section 2.7), but the trajectory is not yet synchronized between the ground automation and the aircraft. The trajectory becomes synchronized when the pilot manually enters this modification into the FMS or receives the modification via datalink. However, the pilot may manually initiate the turn prior to synchronization. A recovery process synchronizes the new assigned trajectory (i.e., the previous assigned trajectory with the new modification applied) between the ground automation and the aircraft.

#### **5.4.2 Urgency Exception**

The ability for controllers to issue tactical commands – vector, altitude change, or speed change – for safety or other reasons continues to exist, but its use is limited to exceptional situations. If the controller needs to respond to a situation so quickly that there is not sufficient time to interact with the ground automation and synchronize a change to the assigned trajectory with the aircraft via datalink, then voice is used to issue a clearance to the pilot. Voice rather than datalink is used to avoid the potential delay in the flight crew receiving and accepting a change to the assigned trajectory.

A recovery process either returns the aircraft to the previous assigned trajectory or amends the assigned trajectory to include the voice commands, returning the aircraft to a closed trajectory as soon as possible.

The controller's automation will provide a mechanism for the controller to: 1) inform the automation that the aircraft has been taken off its assigned trajectory; 2) indicate to the automation what the aircraft's near-term trajectory will be; and 3) define a closed trajectory consistent with the voice commands that can be sent to the aircraft to get the aircraft back onto a closed trajectory. This mechanism might, for example, allow the controller to click on a point in the airspace and click where to return to the previous route as a way to quickly define the aircraft's new route. Unless the controller has some means to inform the automation that the aircraft is on an open trajectory, a conformance monitoring alert will likely be triggered because the trajectory predictions will start to violate assigned trajectory constraints.

#### **5.4.3 Delayed Acceptance of Conflict Avoidance Maneuver**

In current operations, a controller will issue an instruction to an aircraft via voice and expect the aircraft to execute the new clearance promptly. While the response time will vary, the controller will monitor the aircraft and express – by voice – the level of urgency if required. For tactical, voice-issued instructions, which are the exception, MBT would operate in the same manner. Conflict avoidance maneuvers effected through assigned trajectory modifications will be planned in advance of the time at which the new assigned trajectory diverges from the previous assigned trajectory, allowing flight crews sufficient time to receive the trajectory modification, negotiate as desired, and accept and execute the change. The concept may need to include a "respond by" time, after which the modification is void.

If the flight crew delays responding to a trajectory modification notice, there is the possibility that the controller or ground automation would “give up” on that aircraft and send trajectory modifications to other aircraft to resolve the same issue. The instruction to the first aircraft would then be rescinded. The situation would best be handled by follow up messages, since sufficient time was allowed for the necessary coordination, minimizing the number of aircraft whose assigned trajectories are affected.

#### **5.4.4 Pilot Rejects Assigned Trajectory Modification**

Knowledge of the air vehicle capabilities, which is part of the assigned trajectory data package, will reduce the occurrences of the FAA proposing trajectories that the aircraft is not capable of flying (e.g., a speed and altitude combination that is not feasible for that aircraft at the weight it will be at that time). However, a situation may occur in which a flight crew rejects an assigned trajectory modification. The trajectory negotiation process can be used to identify an acceptable trajectory modification, since sufficient time is allowed to complete the necessary coordination before the aircraft reaches the point at which the new and old trajectories diverge. If the situation becomes time critical, the controller may revert to voice and will have access to the same options that exist in the current NAS for handling an aircraft that rejects a clearance.

#### **5.4.5 Vertical Dimension**

In many aircraft, the autopilot and FMS may not be fully integrated in the vertical dimension. For historical reasons, vertical navigation has always been handled differently than lateral navigation and that difference is deeply imbedded in current operations and technologies. For example, the aircraft will not automatically initiate a pre-programmed vertical change in certain modes of flight; the pilot must initiate the change at the correct time, and only when given a clearance by the controller. Most modern-day airliners have vertical navigation (VNAV) available as a method to control the vertical flight. VNAV allows the aircraft to fly a vertical profile both in the climb and descent, which is calculated and displayed in the FMS. The FMS may be used solely to determine the appropriate angle to meet crossing and/or speed restrictions without VNAV engaged.

Notably missing, however, is the ability to pre-plan, coordinate, and execute a vertical profile in the cruise flight phase. The concept of a ‘cleared altitude’ is built in to the current cockpit philosophy, autopilot design (“altitude window”), and FMS / autopilot integration, and it precludes agreeing to a preplanned sequence of altitude changes in cruise (or continuously varying cruise altitude). Planning a vertical “route” like a lateral route would be an entirely new way of thinking for pilots and controllers. A change such as this would impact the cockpit design, FMS/autopilot integration, ATC controller tools, CPDLC message set, pilot/controller terminology, and procedures for how aircraft are cleared vertically.

In the near-term, vertical operations would resemble the current NAS; aircraft equipped with VNAV capability would execute the vertical profiles associated with arrival and departure procedures. In the end-state MBT concept, the assigned trajectory may include a vertical profile; aircraft will follow this vertical profile or request a trajectory amendment, in the same way the 2D route is negotiated and requires negotiation to amend. The flight crew would not need to request clearance to climb or descend in conformance to the assigned trajectory in any phase of flight, although the flight crew may need to manually execute the altitude change. This is in contrast to current operations, in which the flight crew must request clearance before executing a change in altitude.

The assigned trajectory is required to describe the altitudes at which the aircraft will fly, but is not required to define a continuous vertical profile. Aircraft intent can include additional waypoints (pseudo or other) defining where the aircraft will start climbing/descending, reach the new altitude, and, if needed, at any changes in vertical rate.

In current operations, a controller may instruct an aircraft to change altitude to avoid a conflict (e.g., crossing traffic) and then instruct the aircraft to return to its previous altitude after it

has passed the conflict traffic. In this operation, the aircraft is on an open trajectory because only the controller knows when the aircraft will be cleared to return to its previous altitude. In current automation systems, the conflict probe functionality can behave differently in different situations, either assuming the flight is still at the previous altitude or assuming the flight will stay at the new altitude instead of returning to the starting altitude. For example, current controller automation will not probe an interim altitude; it only probes the cleared altitude. A better approach might be to model the aircraft at both altitudes (and the range between them) for the short-term since the second change in altitude is uncertain.

In MBT, the altitude change would be issued as an assigned trajectory change, which could include the return to the starting altitude. Conflict probes could use the planned vertical profile and conformance monitoring could alert if the second altitude change is missed by the pilot.

#### **5.4.6 Longitudinal Tolerance**

While time constraints are used in the present NAS, they will be used more extensively in MBT operations. MBT will increase the use of time control at a common point (through speed changes) to separate crossing traffic, reducing the use of altitude changes and vectoring for conflict resolution.

At points where multiple aircraft merge onto a common route, such as where arrivals converge toward an airport, MBT will apply time constraints earlier, allowing aircraft to achieve those times more efficiently and accurately (i.e., more time to absorb delay through reduced speed or to speed up to achieve minimum separation). In contrast, current operations initially use gross flow rate control through inaccurate mechanisms such as GDPs and MIT, and then merge and separate the resulting flows of aircraft using tactical techniques including vectoring aircraft. Even TBFM's arrival schedule is implemented through tactical instructions from the individual controllers.

In the long term, all aircraft will be required to be capable of independently complying with time constraints with certain required levels of performance, which the aircraft must publish as part of the capabilities data in its flight plan. Furthermore, using an FMS or EFB, aircraft may be required to be able to handle multiple time constraints (e.g., time  $t_1$  at waypoint  $w_1$  and time  $t_2$  at waypoint  $w_2$ ). The aircraft will be required to determine if the time constraints can each be achieved as part of the trajectory negotiation process.

In the near-term, only one time constraint may be active at a time due to the limitations of existing FMSs, requiring pilots to activate each time constraint as an RTA after passing the previous one. This will inhibit the ability to determine if a string of RTAs is feasible for the aircraft. Some aircraft will be unable to independently comply with a time constraint, for example, if the aircraft does not have an FMS that can control to an RTA. Either pilots will have to manually fly the aircraft to attempt to comply with the time constraint, or controllers will have to issue speed clearances to unequipped aircraft to achieve compliance with time constraints; automation will compute and provide the necessary speed commands and the accuracy will not be as good as equipped aircraft.

There is a tradeoff between longitudinal flexibility and the frequency with which the assigned trajectory will need to be modified to prevent conflicts with other aircraft. For example, permitting larger speed variations and/or using fewer time constraints provides greater longitudinal flexibility to the aircraft. This tradeoff will be studied as part of concept validation exercises. Currently, pilots have discretion to vary aircraft speed by up to 10 knots or 5% relative to their cleared speed, whichever is greater, without coordinating with ATC. The impact of this flexibility on predictability and conflicts in MBT will need to be studied. MBT might allow less flexibility once the 4DT is negotiated.

## 5.5 Trajectory Synchronization

### 5.5.1 *Air vehicle intent*

All aircraft are required to provide predicted trajectory (a.k.a. intent) data via Automatic Dependent Surveillance-Contract (ADS-C) downlink or another datalink capability (e.g., broadband). The aircraft's FMS predicts the route the aircraft will fly, using an internal mathematical model, knowledge of the aircraft, and some additional data such as a wind forecast. The intent data contain 3D points along the aircraft's predicted route and the estimated times at which the aircraft will reach those points. Intent data also include parameters and data that could help improve the accuracy of ground-based predictors, such as planned vertical climb/descent rates, the updated top-of-descent point, and planned speeds along route segments.

In the mid-term, the content of these downlinked messages is defined by the existing EPP specification [2]. In the long term, these messages could be expanded to include additional information. The points at which ETAs are provided can be sparse (i.e., there can be large distances/times between consecutive points), but are intended to convey important points along the aircraft's trajectory. The frequency with which the FMS calculates the data and with which the aircraft sends the data may vary. In the end-state concept, airspace users will be required to send data that meet completeness, accuracy, and timeliness requirements.

Air vehicle intent data are distributed to stakeholders as described in Section 5.5.2. Ground automation will use the air vehicle intent data to improve and synchronize trajectory prediction. Some ground automation may directly use the aircraft-provided ETAs as the predicted trajectory within some functions.

In the near term, not all aircraft will be capable of providing detailed intent data automatically. For aircraft that do not provide this information, the predicted trajectory will have higher uncertainty, which will be recognized in trajectory planning. In rare cases, the controller could verbally request an ETA at a waypoint from a pilot and enter that information into the ground automation. Even if the aircraft cannot downlink intent data, the FMS can compute the ETA for the pilot. However, the manual effort required from the pilot to extract the information would exceed the operational value in most cases.

In the long term, every flight will be required to provide trajectory prediction data within a required accuracy performance. This can be computed by the FMS and communicated via EPP, computed by an EFB and communicated using an airborne broadband communication link (e.g. A/G SWIM), computed by FMS and communicated by EFB, or computed by the airspace user's flight dispatch system and communicated via SWIM.

Air vehicle intent is especially important if the trajectory constraints and description are relatively sparse or provide the aircraft flexibility because of large tolerances. If there is a large distance or time between two trajectory constraints, such that the aircraft could fly very different trajectories over that interval and still comply with the assigned trajectory, then the trajectory the aircraft will fly would not be very predictable using only the assigned trajectory. In the near term, flights that lack the ability to provide intent data will be assigned trajectories that include more constraints and detailed description, designed to make the trajectory sufficiently predictable. For capable aircraft, intent data provide the required predictability. An additional requirement is that the aircraft update its intent data when there are significant changes.

### 5.5.2 *Shared Awareness*

At any point in time, there is a single, common assigned trajectory for a flight. An FAA ground automation system will have the complete assigned trajectory and will make it available to other FAA, airspace user, and aircraft systems.

Most stakeholders, including sufficiently equipped aircraft, would receive the full assigned trajectory. However, some stakeholders with insufficient capabilities, such as the pilot of an aircraft with no FMS, may not be able to receive or handle the full details of the assigned



trajectory. These pilots would receive less detail about the assigned trajectory, via cumbersome voice procedures. In this case, automation would provide advisories to the controllers and controllers would provide incremental instructions to the pilot to keep the aircraft in conformance with the trajectory.

Different automation systems, including ground-based and aircraft-based, will have different trajectory predictors (i.e., mathematical models) that calculate system-specific predicted trajectories. At any point in time, there may be multiple predicted trajectories for a flight. MBT does not force there to be a single predicted trajectory for each flight, since different applications for predicted trajectories have different, incompatible requirements for those predictions.

Trajectory synchronization in the context of predicted trajectories implies that predicted trajectories and information relevant to predicting trajectories (e.g., wind and wind forecasts) are shared to reduce the undesirable differences between the predicted trajectories. For example, information from the aircraft's FMS-predicted trajectory, if available, will be shared to all of the ground automation systems that produce trajectory predictions. Moreover, ground automation systems may share predicted trajectories and some may use a prediction calculated by another system, rather than computing its own, depending on its requirements for the prediction.

## **5.6 Trajectory Prediction**

Different automation systems will calculate and use different predictions of the aircraft's future trajectory. For example, the conflict detection function needs a prediction that is accurate over a short planning horizon, is dense in position and time, and updates rapidly. In contrast, the TFM system needs a prediction that is good in a stochastic sense over all of the traffic 6+ hours into the future, can be sparser in position and time, and may update only once a minute. The distinct applications for the trajectory predictions create distinct requirements and motivate using different prediction models.

However, since all trajectory predictions will utilize the assigned trajectory as well as the flight's intent data, MBT will reduce the variations that exist between predictions compared to the present day. In general, the aircraft's intent data will be reliable, but a function may need to supplement it with predictions at additional points in space and time. However, if the aircraft is using different wind forecasts, for example, a ground function may favor a different model (although advanced EFBs are expected to receive better wind data than that provided to current FMSs). If the aircraft has deviated from the assigned trajectory and is not being flown by the FMS, the aircraft's intent could be misleading. Therefore, there are cases in which the intent data should not be used exclusively, and EPP messages may need to be disabled/discarded or indicate the mode in which the aircraft is operating.

### **5.6.1 Trajectory Uncertainty Considerations**

Assigned trajectories may have more detail close to where the aircraft is operating and less detail further in the future; this is a topic that warrants research. For example, an assigned trajectory might not include metering times at the destination airport; these times will be added as a trajectory modification when the flight gets closer to its destination. However, the trajectory will be specified enough to support TFM planning at the destination such that TFM functions can determine that metering is likely to be needed to balance demand with capacity. Furthermore, the NAS Constraint Service will indicate when a metering program is in effect, along with information about the affected airspace and average delay.

The MBT concept recognizes that uncertainty in an aircraft's future state can vary with the prediction horizon. When planning a modification to an assigned trajectory, the trajectory must be conflict free close to the aircraft's current location (e.g., within the conflict probe's look-ahead time) but is not required to be conflict free at longer time horizons. At longer time horizons, the TFM system will use stochastic forecasts. A flight's assigned trajectory may include a constraint intended to delay the flight's arrival to a constrained resource (e.g., related to managing sector

count) with the expectation that the constraint will be updated as uncertainty decreases and the flight gets closer to that resource.

When planning an initial assigned trajectory (perhaps more than an hour before takeoff), the system will not attempt to make the trajectory conflict free. As the departure time approaches, the assigned trajectory may be modified, revising the planned takeoff time and/or other constraints, to ensure the initial portion of the trajectory is conflict free.

Each automation system that computes a predicted trajectory will have different uncertainty based on the data and models that are used. The availability and content of data from the FMS describing the aircraft's prediction of the trajectory it will fly will affect the predicted trajectory uncertainty.

How trajectory prediction uncertainty varies with time into the future depends on characteristics of the assigned trajectory, including:

- The tolerances defined in the assigned trajectory will affect the uncertainty. For example, if there are no RTA constraints, a speed tolerance around an assigned speed will bound the longitudinal uncertainty.
- A trajectory with an RTA at a downstream waypoint may have uncertainty increase initially and then shrink as the aircraft approaches the waypoint. Ground system trajectory predictors may have uncertainty in speed or other attributes as the aircraft adjusts its trajectory to meet the RTA. The use of air vehicle intent will minimize this uncertainty.

Predicted trajectories may include a description of the trajectory uncertainty, which can be used for longer-term TFM planning.

## **5.7 Conformance Monitoring and Prediction**

The MBT concept includes conformance monitoring, conformance prediction, and conflict detection. These functions may be part of the future NAS and are not new capabilities introduced by MBT.

There are two separate but similar issues that the MBT concept must address. One is 'what happens if the predicted trajectory changes.' The other is 'what happens if the predicted trajectory will violate a constraint in the assigned trajectory.' The predicted trajectory will be recalculated repeatedly due to both periodic updates and asynchronous updates triggered by certain events. Detecting that the predicted trajectory has changed is accomplished simply by comparing consecutive predictions. Conformance monitoring addresses the second issue, when the predicted trajectory suggests the aircraft will at some point in the future violate assigned trajectory constraints. A third issue, also addressed by conformance monitoring, is 'what happens if the assigned trajectory is no longer conflict free.'

Every assigned trajectory must include a definition of the required conformance accuracy for each element (i.e., constraint) of the trajectory.

Automation will detect and alert when a flight deviates from its assigned trajectory by more than the required conformance accuracy. Automation will also attempt to predict when a flight is likely to deviate from its assigned trajectory by more than the required conformance accuracy.

An aircraft that is non-conforming (or predicted to become non-conforming) might on its own resume conformance, or it might mostly follow the trajectory with occasional conformance lapses (e.g., if it is unable to maintain a required RNP level), or it might entirely deviate from the assigned trajectory (e.g., if it experiences an emergency).

Both ground and aircraft automation will monitor for trajectory non-conformance due to their differing prediction algorithms. Aircraft automation will alert the pilot to non-conformance or predicted non-conformance, and provide the pilot time to resolve the non-conformance before notifying the ground automation (although the downlinked air vehicle intent may already alert the ground automation conformance monitoring capability).

The ground automation will alert the controller and the aircraft to the non-conformance or predicted non-conformance. The first step may be to require automation to compute new

trajectory predictions to determine whether the non-conformance does, in fact, exist. Due to the number of potential situations, a controller will likely be required to participate in determining the course of action after the non-conformance event or predicted non-conformance event.

If the aircraft will no longer be able to conform with the trajectory (e.g., it is no longer able to maintain the required RNP level), its assigned trajectory must be modified.

If the non-conformance causes a conflict, then in addition the conflict must be resolved using the standard method for resolving conflicts.

After the non-conformance event, aircraft-provided intent data can be used to update the predicted trajectory. In the absence of the aircraft providing updated intent data, the ground automation does not know with certainty what the aircraft will do next.

If the aircraft can resume conforming to its assigned trajectory without violating any other trajectory constraints, then the ground automation will continue monitoring and update the predicted trajectory.

If the flight will not be able to return to its assigned trajectory (e.g., it will be unable to comply with downstream constraints), then the assigned trajectory must be modified. The standard trajectory modification/negotiation method may be used.

Automation must also monitor and predict future instances where a flight may fail to conform to the assigned trajectory. For example, the flight may currently be complying with the assigned trajectory but automation is able to forecast that the flight will likely be unable to comply with a constraint (e.g., an RTA) further along the route. This situation should be addressed prior to the actual trajectory conformance violation.

## **5.8 Conflict Detection**

### **5.8.1 Conflict Detection Automation**

Automation will monitor for conflicts and initiate conflict resolution activities when necessary. The use of assigned trajectories and trajectory synchronization for predicted trajectories will permit conflict detection over time horizons that extend further into the future than is currently possible. This will allow most conflict resolution to be accomplished through a modification to the assigned trajectory (i.e., closed trajectory via Data Comm) rather than voice-based, open trajectory vector/speed/altitude commands.

Controllers may also manually perform conflict detection, especially in the near-term MBT concept. However, improved trajectory predictability is expected to allow them to reliably detect and resolve conflicts sooner than is feasible in current operations. This earlier conflict detection is likely to occur before aircraft enter the sector where the conflict takes place, placing responsibility for detecting and resolving the conflict onto the D-side controller or, for conflicts detected even earlier, onto an upstream controller (assuming a similar sector-based airspace organization to the current environment). Amending the assigned trajectory before an aircraft enters a downstream controller's planning horizon minimizes inter-sector coordination requirements [10].

### **5.8.2 Conflict Resolution**

If a conflict is detected, the trajectory for one or more flights must be modified to resolve the conflict. The method will depend on the time available to resolve the conflict. Sections 5.12 and 5.13 describe conflict resolution through a tactical response and changing the assigned trajectory.

## **5.9 Tactical Conflict Resolution Process**

When a conflict is detected between two or more flights (either by a controller or conflict detection automation) and intervention is required more quickly than can be accomplished

through an assigned trajectory change, then the immediate response must be via voice commands from the controller directly to the pilot.

Controllers retain discretion for selecting and implementing these actions.

Preferably, the controller provides the clearance in terms of a trajectory that the pilot can execute in the FMS, which will automatically update the downlinked air vehicle intent and close the aircraft's amended trajectory. One example of a simple FMS clearance might be: "CLEARED TO RMG (on current plan) VIA EVANS." This one waypoint instruction may be just as easy to enter into the FMS as modifying the autopilot to implement a heading/vector. Furthermore, the controller can quickly enter this clearance into the ground automation, so that all stakeholders remain synchronized and aircraft remain on a closed trajectory.

If automation has identified the conflict, the automation can provide a recommended trajectory-based solution to the controller. The automation should allow the controller an easy method of adjusting the recommended solution. If the controller accepts this solution, then the automation knows the intended trajectory and the aircraft remains on a closed trajectory, even though the normal method of synchronization with the aircraft via datalink has not occurred.

If the automation did not identify the conflict, or the controller rejects the recommended solution, the automation will provide a mechanism by which the controller can easily enter into the automation a trajectory change that rejoins the original assigned trajectory. Until the controller makes that entry, which may occur after the controller has initiated the aircraft maneuver, only the controller (and pilot/aircraft) knows the intended conflict resolution trajectory.

Once the aircraft has deviated from the assigned trajectory due to the controller's verbal clearance, the ground automation will continually search for and suggest a closed trajectory solution that brings the aircraft back to the original assigned trajectory.

If the controller uses a non-trajectory-based verbal clearance, the automation should have a quick method by which the controller can indicate to the automation that the aircraft is on an open trajectory. This information would be used by conformance monitoring and conflict detection functions to avoid alerting the pilot and/or controller when the automation does not have sufficient information to make accurate trajectory predictions.

Follow-up to further amend the assigned trajectory due to the conflict avoidance maneuver may be required. Regardless, trajectory predictions must be updated to reflect the temporal impact of the conflict resolution maneuver on the aircraft's downstream trajectory.

If the controller provides a vector command that is not trajectory-based to the aircraft, the aircraft's intent data will be erroneous. Ground-based functions that use the aircraft's intent must not use the air vehicle intent data until the aircraft has resumed following an assigned trajectory that is synchronized between the ground automation and the aircraft.

## **5.10 Conflict Resolution by Assigned Trajectory Changes**

If there is sufficient time to uplink a trajectory to the aircraft, a conflict may be resolved by changing the assigned trajectory. Two situations differ depending on the time available:

- Urgent Assigned Trajectory Change
- Assigned Trajectory Negotiation

An Urgent Assigned Trajectory Change occurs when the FAA identifies an issue with a flight's assigned trajectory that must be resolved quickly. Sufficient time exists to resolve the issue through an assigned trajectory change (i.e., the response does not need to be via a voice command directly to the pilot). However, there is not sufficient time to negotiate the change to the assigned trajectory. Urgent Changes are expected to be relatively small in their effect on the overall aircraft's trajectory.

Automation will provide recommended solutions to conflicts and will allow controllers to modify the recommended solution before accepting and issuing it.

## 5.11 Mixed Equipage

In the end-state concept, aircraft are expected to have a minimum set of capabilities (e.g., the ability to digitally receive and fly a 4DT), and the aircraft and airspace user collectively will have the ability to provide a minimum set of data. In the near term, aircraft that are equipped with at least a minimal set of capabilities will gain a greater benefit from the MBT concept. For example, aircraft that are able to participate in MBT may receive negotiated 4DTs and be allowed to follow them with little disruption, while controllers tactically manage other aircraft similarly to current operations to avoid conflicts. Some MBT benefits (e.g., improved TFM performance through improved trajectory predictability) may not be realized unless a minimal proportion of aircraft are sufficiently equipped.

While this issue requires further research, the intention is that during dynamically changing events, equipped aircraft will receive trajectory assignments that do not require further modifications. Controllers' procedures will be to use current-day voice-based techniques to manage unequipped aircraft clear of the aircraft following closed trajectories. If controllers choose to maneuver equipped aircraft instead (e.g., if that is less workload) then the equipped aircraft could be unintentionally penalized. It will be important to design automation and procedures to avoid this unintentional penalization.

In the near term, different aircraft equipage may be accommodated through knowledge of the air vehicle capabilities, limiting the assigned trajectory complexity based on air vehicle capabilities (e.g., whether RTA can be used or not), where responsibilities are allocated (e.g., controller providing speed commands or aircraft complying with RTA), assigned compliance margins, and, where appropriate, airspace segregation. Future flight plans will include a richer description of air vehicle capabilities than is available in the current system.

The MBT concept accommodates mixed equipage in various ways. The MBT assigned trajectory object will contain information about the aircraft's capabilities. The capabilities of less-equipped aircraft will constrain the assigned trajectory elements. For example, an aircraft that is not RNP-capable will not be assigned a trajectory that includes RNP segments. The flight crew of an aircraft without the ability to receive an assigned trajectory via datalink (or auto-load it into the FMS) may be limited in the amount of data that can be received via voice (and manually entered into the aircraft automation if the aircraft has any automation). The assigned trajectory may be less complex if possible and the complete assigned trajectory may not be communicated to the aircraft. In this case, controllers may provide incremental instructions to the pilot to keep the aircraft in conformance with the trajectory (e.g., speed commands to comply with a time constraint), using automation aids.

## 5.12 Reroute Coordination

In current operations, reroutes are seldom planned or implemented in advance. At the MBT cognitive walkthrough, controllers indicated that the controller assigned to the flight's current sector will often not identify and resolve a conflict in a downstream sector because he/she does not have reliable information that the conflict will, in fact, occur, and assumes that if he/she resolves it early, something else may change and the resolution may not work or may cause another conflict. Once the aircraft is in the sector in which the reroute needs to begin, that controller is responsible for planning the reroute, coordinating with downstream sectors if necessary, and implementing the reroute. This shortfall varies between ARTCCs. There are times when prior sectors will implement re-routes for downstream controllers. With coordination between the TMU and Area Supervisors, tactical re-routes may be implemented by numerous sectors upstream of a conflict. However, with MBT this process will consistently start earlier and be easier to disseminate and implement. The negotiation and assignment of trajectories in MBT will allow reroutes to be performed more proactively. The reroute may begin (i.e., first change the aircraft's route) in the current sector or a downstream sector, the reroute may affect the aircraft's route through several other downstream sectors, and the purpose of the reroute may

be to resolve a conflict in yet some other downstream sector. By addressing downstream issues through proactively planned assigned trajectory modifications, MBT enables more-efficient solutions and reduced tactical workload. Effort required to coordinate reroutes will shift to D-side controllers or traffic managers.

The current implementation of strategic Playbook re-routes have many negative consequences which MBT could help address. Playbook re-routes are planned well in advance, are often inefficient (i.e., they require aircraft to go well away from the impacted area due to forecast uncertainty) and require all aircraft to follow the same route (which creates capacity/demand issues on that route and does not allow for negotiation). Playbooks were developed primarily to speed the implementation of re-routes during severe weather by having pre-approved static routes available, reducing the per-aircraft voice communication workload. With MBT, the system will publish the constraint (as a CTOP or closed routes via the NAS Constraint Service) and allow users to file their requested alternate routing (via TOS or a negotiated flight plan). Every flight can receive a unique, user-preferred route due to the supporting automation and digital communication.

### **5.13 How NAS Constraint Changes Affect Assigned Trajectories**

A NAS Constraint Service exists as a central repository and source for all NAS constraints. The information on TMIs is available to all stakeholders and includes the expected timeframe for the restriction, the criteria for flights being subject to the restriction, and statistics such as the predicted average delay for flights affected by the TMI. Flight-specific impact is not possible for this constraint service since, for example, TBFM cannot be queried in a what-if manner to ask what scheduled time a particular flight would receive if it were to use the constrained resource, and these flight-specific constraints would be highly sensitive to all of the other flights' trajectories, which could be in flux. SWIM, or another network, provides access to the NAS service for all stakeholders. Airspace users can provide pilots with access to the constraint service via advanced aircraft automation using emerging high-bandwidth ground-air datalinks.

As time progresses, NAS constraints will change, both to the advantage and disadvantage of some flights. The TFM system is responsible for identifying when a flight's assigned trajectory must be modified if the assigned trajectory no longer satisfies the updated NAS constraints.

The NAS constraints may also change in a way that does not require changes to a flight's assigned trajectory. For example, if a region of bad weather dissipates and the airspace re-opens (i.e., a NAS constraint is removed or reduced), the flight's current assigned trajectory still satisfies all of the NAS constraints. However, the aircraft's assigned trajectory could now be modified to be closer to the airspace user's desired (business) trajectory.

Both the FAA and the airspace user can detect this situation. In addition, the airspace user may detect an opportunity resulting from other environmental or business changes. Prior to departure and during flight, in either the operator's flight dispatch center or the aircraft's EFB (or both), flight planning applications are re-run, either periodically or on an event basis, to identify possibly advantageous changes to the flight's current assigned trajectory. This process will identify how changes to NAS constraints may allow the flight's assigned trajectory to be modified in an advantageous way. When an advantageous change is detected, the airspace user (either pilot or dispatcher) would begin the negotiation process to request the change.

If the flight's trajectory constraints have been mapped to the NAS constraints that caused them, then when a NAS constraint changes, the FAA can easily identify which flights may be affected by that change. However, the airspace user's business trajectory may have changed since it was initially provided to the FAA; there is no requirement for the airspace user to maintain a current business trajectory for every flight. Therefore, the FAA cannot unilaterally know whether the airspace user would want any particular trajectory modification enabled by the change in a NAS constraint. Therefore, the FAA is limited to notifying the airspace user of the flights potentially affected and allowing the airspace user to evaluate the situation and request a trajectory modification through the negotiation process if desired.

### **5.13.1 Use of TOS to Reduce Necessary Negotiation**

The MBT concept imagines expanding the use of TOSs to beyond CTOP programs, to allow the airspace user to express their preferences in a way that will expedite negotiation. In the case that the airspace user is maintaining a TOS for the flight, the FAA is able to evaluate whether a NAS constraint change would make an alternative trajectory more favorable to the airspace user, since the TOS can include criteria that indicate under what conditions each alternate trajectory would become preferred.

Providing a TOS for a flight (pre-departure or en route) is optional, but if the operator provides a TOS, the operator must update the TOS so that it always reflects the airspace user's business objectives or otherwise remove the TOS. The first option in the TOS will be the current assigned trajectory, unless the airspace user wishes to alter the current assigned trajectory.

When the operator (dispatcher or pilot) requests a new trajectory or modification to the current assigned trajectory, the FAA processes the requested change and returns the specific constraints (e.g., TBFM STAs and time constraints for deconfliction) that would be required. If the operator accepts the resulting trajectory, then it will become the new assigned trajectory for the flight. The TOS should be updated accordingly.

If a TOS is provided for a flight, the FAA could periodically evaluate the alternate trajectories in the TOS to determine whether an alternate trajectory has become preferred. This evaluation is done based on changes to NAS constraints and delay statistics for the applicable TMLs. Identifying a new preferred trajectory alternative causes the FAA to process that trajectory as a requested trajectory to compute flight-specific constraints. The resulting allowable trajectory is presented to the airspace user for approval. If the operator accepts the allowable trajectory, it becomes the new assigned trajectory. If the operator rejects the change, the alternative trajectory is removed from the TOS. Similarly, if a NAS constraint changes and the FAA needs to reroute a flight, it will use the TOS, if provided, for the start of the negotiation.

## **5.14 Piloting**

To achieve the envisioned benefits, the MBT concept is designed to reduce variance in aircraft tracking their assigned trajectories. Therefore, the MBT concept intends for equipped aircraft to utilize their FMS to fly the assigned trajectory. The MBT concept assumes that the FMSs are capable of following the assigned trajectories in four dimensions within defined tolerances.

For aircraft with less-capable FMSs, the assigned trajectory tolerance bounds are based on the air vehicle capabilities. The complexity of the trajectory constraints could be limited based on the air vehicle capabilities. The ground automation will need to know the air vehicle capabilities as part of the assigned trajectory object.

To accommodate different levels of aircraft equipage, the MBT concept does not require that the aircraft be flown by FMS. Less-equipped aircraft will receive less complex assigned trajectories and can be flown by autopilot or manually. The required conformance accuracy for such flights would also be less. The ground automation would be designed to avoid situations in which equipped aircraft are moved off their preferred trajectory to make way for unequipped aircraft.

Entirely unequipped aircraft would operate similar to how they operate in today's NAS, with a cleared flight plan representing a clearance to the destination. While the complete flight plan would be provided to the pilot, the pilot may not know the full assigned trajectory that includes necessary constraints that are not in the flight plan. However, the ground automation system would know all the constraints. Controller automation will provide instructions that controllers are to issue to the pilots of unequipped aircraft to conform to the assigned trajectory.

### 5.14.1 Pilot Requests Deviation Around Weather

Controllers generating lateral flight paths to support weather deviations is inefficient because, although the controller has weather information showing the precipitation, he/she cannot see the storm cells that the pilot can see out the window. Therefore, the controller is often not able to determine which way the aircraft will want or need to deviate or by how far. Once thunderstorms start to mature, the top of the storm takes on an “anvil” shape. Pilots will almost always want to give the downwind side (pointy part of the anvil) a wide berth if they have to go that way, as the storm can spit hail many miles in that direction and turbulence on that side is usually severe. The idea behind a “clearance” is that the controller is telling the pilots that a path is clear and safe to fly. However, in the case of severe weather, the controller and ground automation do not have the necessary information to define a precise closed trajectory that will avoid the weather. Given this lack of information, controllers will not want to get into the business of trying to determine which path around a storm cell is clear, be pressured to use a published waypoint that is in a grey area, or be held accountable if they send an aircraft through hail or if passengers are injured due to severe turbulence.<sup>32</sup> However, when a controller must allow a line of aircraft to deviate around weather, he/she would like to keep the traffic organized so as to avoid conflicts. The roles each stakeholder plays in various weather deviation scenarios is a topic that will need to be addressed in detailed research.

In current operations, when a pilot requests to deviate around weather, there is a limited set of possible responses from the controller. In the lateral environment, the controller might provide one of the following types of clearances:

- “Deviate as necessary, direct [*flight plan waypoint*] when able.” This represents an open trajectory until flight advises it is turning direct to the indicated waypoint.
- “Turn xx degrees left/right, advise when able to proceed direct to [*flight plan waypoint*].” This represents an open trajectory until the controller clears the aircraft direct to the indicated waypoint.
- “Deviate up to [xx] degrees [left/right] of route.”
- “Deviate up to [xx] miles [left/right] of route until clear of weather. Report when clear.”
- “Offset [xx] miles [left/right] of route.”
- “Cleared direct [*waypoint 1*], direct [*waypoint 2*].” This represents a closed trajectory, if entered into ERAM. However, the controller needs to know what deviation will clear the weather but still be as efficient as possible, and the controller must know that the pilot can identify the given waypoints if they are not already on the flight plan.
- “Unable [*reason*]”, such as due to traffic, etc., with anticipation of allowing later. This represents a continuation of the closed trajectory, but only delays the weather avoidance problem.

In MBT, the controller could modify the assigned trajectory to expand the lateral conformance bound along a portion of the aircraft’s route, allowing the pilot to select a path around the weather while conforming to the assigned trajectory. This will affect downstream ETAs and may affect the aircraft’s ability to conform to downstream time constraints. While this may technically still be a closed trajectory, there is a reduction in downstream predictability. Air vehicle intent may not provide the desired predictability because the pilot may not have a complete plan and, therefore, the intent may keep changing. The goal of using a closed trajectory is not achieved. Even if the aircraft is constantly broadcasting intent data, the aircraft itself may not know how it will maneuver through the weather; the intent data will provide little

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<sup>32</sup> In the current environment, when controllers do provide weather avoidance routes, such as to organize a flow of traffic deviating around the weather, the weather avoidance routes tend to be conservative and less efficient than is possible. This ensures that all pilots can remain as clear of the weather as they are comfortable operating and minimizes the number of subsequent requests for further deviation that the controller must manage.



value because it is based on assumptions that may not be correct about the aircraft's future decisions to avoid the weather and return to the original route.

Therefore, this approach may have no advantage over allowing the flight to temporarily operate on an open trajectory until clear of the weather. In either case, the system will have to handle the increased uncertainty. By using a time constraint after the weather, the trajectory beyond that time constraint can remain predictable (but the aircraft may not be able to predict whether it is able to conform to the time constraint).

If the traffic is very sparse, either approach may be feasible. If many aircraft need to maneuver through a region of weather, the TFM system will have needed to reduce the airspace capacity for the region, so that aircraft can maneuver without conflicts (i.e., two aircraft separated in time works but two aircraft with only lateral separation require the expanded conformance bound to not overlap).

If the weather is known well enough that a safe trajectory can be planned in advance, then the weather can be handled in MBT like any other NAS constraint. However, there may be a tradeoff between efficiency of the deviation trajectory and maintaining a closed trajectory. The pre-planned trajectory may need to be farther than necessary from the weather due to uncertainty that could be handled more flexibly with an open trajectory.

If the extent of the weather is not known, advanced trajectory planning will not be possible and an aircraft may, in a tactical way, request a deviation from the assigned trajectory. The closest storm will mask everything behind it, so while the initial deviation may be fairly easy to plan, especially during daytime conditions, the end game of getting back on the filed route will be uncertain. This topic of how MBT accommodates deviations around weather that cannot be planned in advance will require more detailed research.

#### **5.14.2 Aircraft Responds to TCAS Alert**

In normal operations, conflicts are handled through proactive modification of the assigned trajectory or through tactical but closed trajectory modifications or, if necessary, open trajectory, voice-issued clearances. Aircraft-based safety systems, such as TCAS, ACAS, or a future system, are the last layer in conflict avoidance.

In the near-term MBT concept, TCAS will continue to operate as it does in the current NAS. Aircraft will respond to TCAS advisories. Controllers will not immediately be aware of the TCAS maneuver due to the lack of information sharing that currently exists.

In the end-state MBT concept, we expect that aircraft-based separation technologies will mature to support self-separation in merging, following, and emergency avoidance situations. These future capabilities will automatically provide the maneuver advised to each aircraft to the ground automation.

Recovery from the TCAS alert event will be the same as from any case in which the aircraft stops following its assigned trajectory, which includes the case in which a controller issues a "vector" to the aircraft. Today, the aircraft recover to the assigned flight plan as soon as the collision has been avoided. In most cases aircraft should be able to still meet all downstream constraints because of the very short duration of these events.

### **5.15 Advanced Interval Management (AIM)**

MBT must be compatible with other NextGen and beyond concepts for improved efficiency and safety. MBT allows a flight to be assigned a trajectory that is coordinated with another flight's assigned trajectory where the flights follow the same route and the trailing aircraft is, within its assigned trajectory, told to use AIM to follow the lead aircraft.

The MBT assigned trajectory could assign an RTA for each aircraft at its entry point to the procedure, establishing both the sequence of crossings at each point in the procedure, as well as the desired intervals between the aircraft. The procedure would define a relative crossing time at each subsequent waypoint in the procedure (e.g., +9 minutes) or a time to fly each

segment. The entry times would be computed so that all downstream merges occur smoothly. Such an arrival procedure would effectively establish an RTA at each downstream fix, but the set of sequential RTAs would be determined by a single absolute time. The downstream constraints would be automatic, and for FMS-equipped aircraft, those constraints could be included in the FMS database, allowing the aircraft to determine the trajectory it needs to achieve the constraints.

AIM's role would be to run concurrently to monitor the interval established by the RTAs as the aircraft fly along the segments between the time-constrained fixes, and maintain at least a minimum interval. In this approach, RTA would be the control mechanism that strategically manages the aircraft in accordance with the schedule of crossings at key points, while AIM would be the desired interval maintenance mechanism (and a safety barrier), ensuring the minimum acceptable separation between aircraft is not violated between time-constrained fixes.

### **5.16 Weather Uncertainty**

When the weather changes unexpectedly and the airport capacity will be less than had been predicted, all of the 4DTs to that airport or through that region of airspace no longer satisfy the NAS constraints and need to be amended. This happens today in a very distributed way – TMs get changed, which cause TMs to be “passed back” to upstream facilities, and each facility deals with the aircraft in their airspace. MBT handles this in a similar but more centralized way. The first step is still the TFM system reacting to the weather uncertainty by modifying the set of TMs and publishing those NAS constraints. The airspace users can react to the changed TMs by providing new business trajectories. Negotiation happens (which could result in some cancellations, long ground delays, and diversions, just like today) and new trajectory assignments are issued. In the absence of new business trajectories, the FAA identifies how the a priori assigned trajectories would need to change to satisfy the new constraints and issues these as trajectory changes, which can be accepted by the airspace user or used as a starting point for negotiation.

As in the present day, the TFM system will predict resource capacities and impose NAS constraints to address demand-capacity imbalances. TFM and MBT then translate these NAS constraints into trajectory constraints. The TFM system will increasingly use stochastic forecasts and decision making to better handle uncertainty in capacity and demand. However, uncertainty will remain, especially on the capacity side. TFM will continue to hedge TFM plans in case the realized capacity differs from the forecast capacity.

TFM wants to apply some pressure to a constrained resource (e.g., airport capacity) because the forecast capacity may be wrong and the actual capacity may be higher than predicted. If there is no demand, this additional capacity will be wasted and delays will be higher than they needed to be. However, if the capacity turns out to be as forecast or lower than forecast, then some additional delay will be required of flights closer to the airport. In MBT, this means that assigned trajectories will be updated to reflect the evolving TFM constraints.

### **5.17 Graceful Degradation**

Through advanced automation, new ATM concepts such as MBT are expected to increase airspace throughput and capacity by means of reduced separation standards and/or reduced buffers associated with those standards. When controller automation supporting these new concepts fails or is degraded, there are serious concerns that controllers experiencing elevated traffic levels and complexity will not be able to manually manage all of their traffic in a safe manner. Furthermore, controllers may be ‘out of the loop’ due to their supervisory role over the automation, which may require more time to build a picture of the current situation, identify problems, and implement a solution. This results in slower response times that may have safety critical implications compared to if they were fully engaged in the control task. Due to these safety considerations, there is an increased emphasis on designing graceful degradation into

future NAS concepts. Graceful degradation refers to the ability of NAS systems to maintain safety in the presence of degraded modes of operations until demand can be reduced to performance levels commensurate with the degraded capabilities.

It is anticipated that the MBT concept will reduce trajectory uncertainty and increase trajectory predictability, enabling time horizons for managing constraints (including conflicts) to increase to a range of 30 minutes or longer. Beyond this time horizon, residual trajectory uncertainty due to uncertainty in wind, weather, and popup demand may become a factor in accurately predicting conflicts. With time horizons this long, MBT operations are more resilient to degraded modes of operation than current operations, which require a high level of tactical involvement. Under MBT, if a ground automation system should fail, the trajectories are in a stable state without controller involvement for some period of time (e.g., 20-25 minutes), essentially 'buying time' for the human operators and technicians to address the degraded mode. If the degraded system is recoverable during this time period, there is little impact on the NAS.

If the degraded system cannot be recovered in this time period, the stable state of the trajectories enables human operators to begin to implement contingency plans without an immediate concern for loss of separation. While the contingency plan will be dependent on the degraded mode, for contingency plans that require the transfer of flight responsibility to other sectors/areas in the facility or to separate facilities (e.g., Chicago Center fire), MBT is able to facilitate the transfer. MBT includes all NAS constraints, including facility-specific SOP and LOA constraints, enabling controllers in other areas or at other facilities to be aware of these constraints despite a lack of training on the impacted airspace. While ensuring safety during degraded modes of operation involves more than including these types of constraints, their inclusion is a positive step toward graceful degradation.

Another key contribution of MBT in enabling graceful degradation is the linkage of every trajectory constraint in the assigned trajectory to a NAS constraint. If the NAS constraint is related to a degraded mode, the linking mechanism identifies which trajectory constraints may need updating. For example, when degraded modes reduce capacity at constrained airports or airspace, MBT expedites the implementation of trajectory constraints that support the new TFM constraint associated with the degraded capacity.

The integration of certain classes of emergent users into the NAS, such as UASs and SVO, is another conceptual area where graceful degradation should be considered. Fortunately, the UAS and SVO concepts have proposed capabilities that implicitly support graceful degradation. For example, the integration of UAS into the NAS requires that unmanned aircraft (UA) execute known and predictable trajectories in response to a loss of control link or loss of communication that exceed requirements [11]. UAS-contingent responses are predetermined based on factors required by the situation, including class of airspace, phase of flight, and proximity to other aircraft. Pilot-in-command (PIC) and ATC training strive to ensure that UAS-contingent responses are executed at the appropriate time and that both the PIC and ATC can predict the UA flight trajectory. During the contingency, separation is maintained by requiring other aircraft in the vicinity to deviate away from the UA. If appropriate control link connectivity/communication is restored, the PIC requests and receives a revised ATC clearance before the UAS flight trajectory is changed from the contingency trajectory to the desired trajectory. If not, the UA will eventually lose power while maintaining its contingency trajectory, giving ATC time to clear the airspace beneath the trajectory.

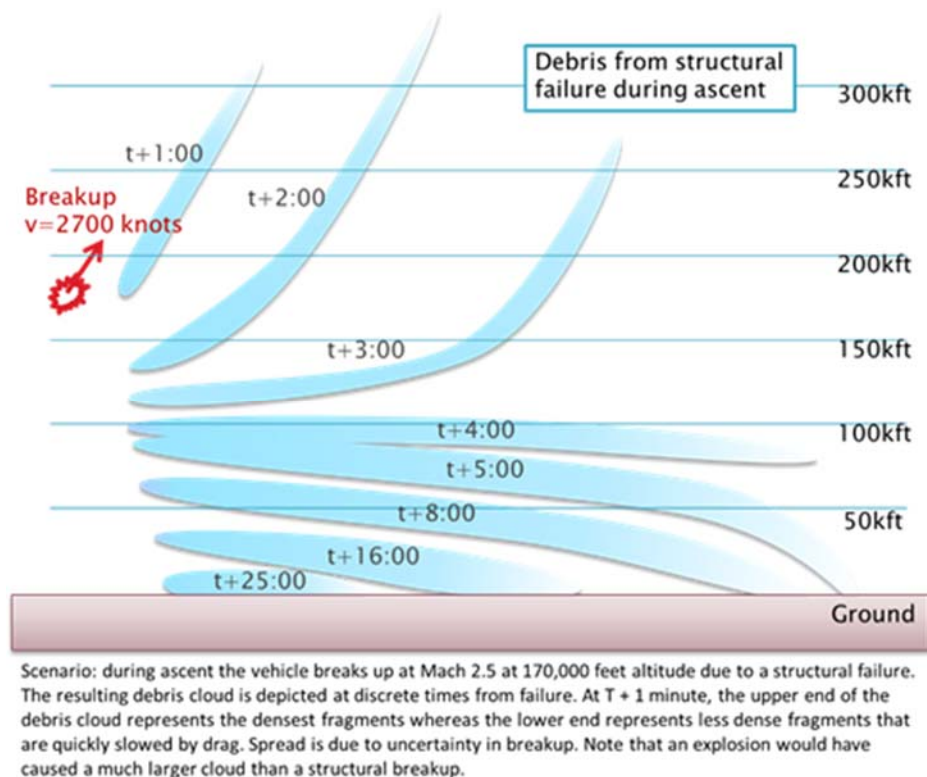
Regarding the integration of SVO and aircraft operations, the SVO ConOps proposes multiple levels of integration where the degree of integration is inversely related to the potential hazard posed by SVO [12, 13]. For example, aircraft safety cannot be ensured for high-risk SVO launches and thus the only feasible level of integration is complete airspace segregation. If the degraded mode in this context is the need for segregated airspace, then graceful degradation in this context can be to minimize the number of aircraft impacted by the airspace segregation. This can be achieved by just-in-time activation and deactivation of segregated airspace, as described in the SVO ConOps.

To address more complete integration of SVO and aircraft operations, the real-time debris hazard volume (DHV) concept was introduced. At any point in time along a nominal space vehicle trajectory, ANSP automation is capable of calculating and displaying DHVs in response to a failure. The DHVs are propagated as a function of time to identify where risk to aircraft and/or human casualty exceeds some threshold (Figure 18). If a failure occurs at some point, ANSP automation provides the following to the controller:

- Trajectory solutions that prevent flights outside the DHVs from entering the DHVs.
- Ranked trajectory solutions for clearing affected NAS traffic already residing in the DHVs. These solutions are based on giving priority to flights with the highest risk and time urgency while ensuring that none of the solutions compromise separation or the safety of any NAS user.

The real-time DHV concept facilitates graceful degradation because it both supports integration of SVO and airspace operations and provides a seamless response to a degraded mode (space vehicle catastrophic failure) during and after the degraded mode.

Lastly, concepts to address ATC Zero events, while outside the scope of MBT, could be greatly facilitated by the increased predictability enabled by closed trajectories of MBT. For example, flights within the impacted facility could be automatically reassigned closed, conflict-free trajectories out of the impacted facility's airspace into adjacent Center or terminal facilities. While controller workload would be extremely high in such situations, the closed trajectories would mitigate some of the workload impact and facilitate, to some degree, graceful degradation.



**Figure 18. Real-time Debris Hazard Volumes Shown as a Function of Time from Space Vehicle Failure [3]<sup>33</sup>**

<sup>33</sup> Figure provided by ACTA, Inc.

## 6. Use Cases

This section explains the MBT concept through a series of use cases. Use cases are an effective way of explaining a concept. However, use cases do not fully cover a concept; gaps exist where no use case describes some aspect of the concept. Therefore, use cases help explain the MBT concept but are not the only method to describe MBT.

### 6.1 Generic Use Case

- 1) The airspace user files a flight plan that describes where/when he/she would like to fly. This happens several hours before departure.
  - (a) The requested flight plan will include the lateral route, vertical profile, and anticipated speed profile.
  - (b) Optionally, the airspace user may provide a 4DT business trajectory or TOS.
- 2) The FAA receives the business trajectory and evaluates it against NAS constraints.
  - (a) If the route violates regions of closed airspace, the FAA will adjust the route, using the TOS if provided.
  - (b) If the business trajectory is affected by TFM programs, the FAA will “trial plan” to determine specific trajectory constraints that satisfy the TFM program (e.g., time constraints that achieve TBFM STAs). If TBFM is not able to provide an STA for a flight because of the time/distance of the flight from the constrained resource, then that constraint will be added through an assigned trajectory amendment process at a later time.
  - (c) The FAA replies with the initial assigned trajectory (i.e., the approved flight plan). This happens 30-60 minutes before departure.
  - (d) The assigned trajectory defines the constraints and other requirements that the aircraft must satisfy, including the required tolerances for conformance.
- 3) Negotiation occurs between the operator and the FAA regarding the assigned trajectory. Ultimately the airspace user and FAA agree on an assigned trajectory.
  - (a) The assigned trajectory is published to a trajectory service to be available to all stakeholders (e.g., other FAA automation systems).
- 4) The aircraft follows current procedures for blocking out from its parking stand and taxiing toward the runway.
  - (a) The assigned trajectory includes a planned takeoff time as a time constraint, and the airspace user manages the block-out time based on this planned takeoff time.
  - (b) The assigned trajectory starts at a runway at the origin airport and ends at a runway at the destination airport. In the initial assigned trajectory, the arrival runway may not yet be specified, or an estimate may be included that may be updated when the aircraft approaches the arrival airport.
- 5) While taxiing to the runway, the TFM system schedules the flight at a congested en route merge point (defining an STA for the flight at that point), and requesting the achievable range of times using Data Comm to ensure the STA is achievable). The assigned trajectory is modified to include a time constraint at the point the departure will join a jet route in en route airspace.
  - (a) The scheduled departure is updated to reflect the new en route time constraint.
  - (b) The flight crew receives, loads into the FMS, evaluates, accepts, and engages the new assigned trajectory.
  - (c) If the flight crew rejects the trajectory modification because the aircraft will not be able to comply with it, then negotiation adjusts the takeoff time and merge time constraints so that they are both feasible and satisfy TFM restrictions.

- (d) If the flight crew is slow to respond to the modification, the controller is alerted that the flight has a pending trajectory modification and the flight could be removed from the queue until a new assigned trajectory is negotiated.
- 6) Immediately following takeoff, while climbing, a ground-based automation system identifies that the departure may conflict at a departure fix with another departure from a different airport within the metroplex.
  - (a) The TRACON departure controller receives an alert from the automation system.
  - (b) The automation system allows the controller to quickly define a small path extension that will ensure separation.
  - (c) The trajectory modification is sent to the aircraft.
  - (d) The flight crew receives, loads into the FMS, evaluates, accepts, and engages the modified assigned trajectory, and the aircraft flies the modified assigned trajectory.
  - (e) If the assigned trajectory cannot be modified during this phase of flight, or in sufficient time, then the controller will revert to voice, entering the clearance given to the aircraft into the automation so that the trajectory remains closed.
  - (f) If the modification affects the aircraft's ability to still comply with the downstream time constraint from step 5, the flight crew will need to accept the near-term portion of the new trajectory and subsequently reject the previously accepted downstream time constraint.
- 7) Using its FMS, the aircraft continues to fly the assigned trajectory.
  - (a) The aircraft's FMS or EFB continuously predicts the aircraft's future trajectory, based on the assigned trajectory, models built into the avionics, parameters set in the FMS/EFB, and external data such as wind information.
  - (b) The aircraft downlinks (via ADS-C EPP for FMS or via another broadband air-ground datalink for EFB) an air vehicle intent message that provides its expected times at key points along the assigned trajectory.
- 8) All ground-based automation systems receive the initial assigned trajectory and each modification to the assigned trajectory via SWIM.
  - (a) SWIM also disseminates the air vehicle intent to all ground-based automation systems that need the information.
- 9) A ground-based automation system responsible for conflict detection and conformance monitoring uses an internal model, along with the assigned trajectory and external data such as wind information and air vehicle intent data, to calculate a predicted trajectory for the aircraft.
  - (a) This predicted trajectory identifies the aircraft's state (e.g., 3D location, velocity) at each point in time, where the points in time may be 1 second apart or less. This automation system is only interested in a limited time horizon (e.g., the next 30-60 minutes).
  - (b) The ground automation uses the air vehicle intent data so that its predicted trajectory better matches the predicted trajectory in the FMS/EFB.
  - (c) This automation system uses the predicted trajectory to monitor for conflicts with other aircraft.
  - (d) Nominally, aircraft will be on closed trajectories. If a controller issues a tactical instruction that results in an open trajectory, the ground conformance monitoring automation needs to know. This may happen through conformance monitoring or manual entry by the controller.
- 10) Ground automation detects a conflict 30 minutes into the future when the aircraft will be in a different sector.
  - (a) Ground automation alerts the controller currently responsible for the flight and suggests a trajectory modification that will avoid the conflict by applying a crossing time constraint near the location where the conflict occurs.

- (b) The controller evaluates the proposed trajectory modification and approves it without change. Improved predictability allows the controller to be confident that this change will not result in other conflicts or traffic complexity.
  - (c) The modified assigned trajectory is sent to the aircraft. The flight crew receives, loads into the FMS, evaluates, accepts, and engages the new assigned trajectory. All ground automation systems also receive the modified assigned trajectory via SWIM.
- 11) A second ground-based automation system (e.g., TFMS) uses its own internal model, along with the assigned trajectory and external data such as wind information and air vehicle intent data, to calculate a predicted trajectory for the aircraft.
- (a) This predicted trajectory identifies the aircraft's state at each point in time, where the points in time may be 1 minute apart. This automation system is interested in the full remaining trajectory.
  - (b) The ground automation uses the air vehicle intent data so that its predicted trajectory better matches the predicted trajectory in the FMS.
  - (c) This automation system uses the predicted trajectory to make TFM decisions.
- 12) The ground automation system (e.g., TFMS) identifies that a region of airspace is likely to be overcrowded an hour from now, when the flight would be in that airspace.
- (a) The automation alerts a TMC to the predicted demand exceeding the forecast capacity for the airspace region. Due to reliable trajectory prediction, the overload situation is predicted far enough in advance that the response can be strategic.
  - (b) The TMC decides to reroute some aircraft, since the automation predicts that slowing aircraft will simply delay the over-capacity situation to a later time.
  - (c) Focusing on one of the aircraft, using tools in the automation, the TMC creates a modified trajectory for the aircraft that avoids the congested airspace. The automation tools facilitate coordination with the facilities in which the trajectory change would be initiated.
  - (d) The assigned trajectory change is sent to the aircraft and dispatcher. The flight crew receives, loads into the FMS/EFB, evaluates, accepts, and engages the new assigned trajectory.
  - (e) All ground automation systems also receive the modified assigned trajectory via SWIM.
- 13) Wind forecast data are uplinked to the aircraft's FMS. With an advanced EFB, the aircraft will receive continuous updates of high-quality wind forecast data. Loading this into the FMS will depend on the FMS capabilities.
- 14) The metering arc crossing point is a key point in the trajectory and the FMS's ETA at that point becomes part of the air vehicle intent message. The FMS calculates a predicted trajectory that includes an ETA for when the aircraft will arrive at the point along the trajectory that crosses the metering arc, as well as the top of descent location.
- (a) The aircraft uses uplinked wind data to improve the accuracy of the FMS's predicted trajectory.
- 15) As the aircraft approaches its destination airport, TBFM calculates a predicted trajectory for the flight to determine the flight's ETA at an outer metering arc, a meter fix, and the runway.
- (a) TBFM uses wind forecast data to improve the accuracy of the ETAs.
  - (b) TBFM assigns an STA at the outer meter arc and an STA at the meter fix, using the range of achievable times from the airspace user). TBFM also assigns an expected arrival runway. TSS assigns a landing time as part of a planned sequence and schedule at the runway.
  - (c) Assigned trajectory modifications, including the assigned runway and RTAs at the metering arc, meter fix, and runway, are sent to the aircraft.

- (d) The flight crew receives, loads into the FMS, evaluates, accepts, and engages the new assigned trajectory, activating the first RTA in the sequence.
  - (e) This airport is not using AIM for arrival spacing for this period of time.
  - (f) The FMS adjusts the aircraft's speed to comply with the RTA at the metering arc. This is a continuous, closed-loop control system.
- 16) TBFM computes a predicted trajectory for the aircraft to determine ETAs at the metering fix.
- (a) TBFM uses the air vehicle intent data to determine the flight's ETA at the metering arc and meter fix.
  - (b) In response to an unexpected reduction in the estimated runway capacity, TBFM adjusts the flight's STA at the metering fix and runway, and the flight's assigned trajectory is modified to include the new STAs.
  - (c) The flight crew receives, loads into the FMS, evaluates, accepts, and engages the new assigned trajectory.
- 17) The flight crosses the metering arc and fix at the assigned times, and lands on the assigned runway at the assigned time.

## **6.2 Emergency Runway Closure**

This scenario describes a situation in which a runway unexpectedly closes while there is a line of flights headed toward it to land. In the case of a sudden runway closure (i.e., drop in airport capacity), the TFM system would react on several levels, using a Ground Stop and then possibly a GDP to handle strategic demand, slowing airborne flights, and using holding patterns, alternate runways, and possibly diversions to handle aircraft closest to the airport.

There is plenty of time to handle the back of the line because they can just keep following their trajectory toward the now-closed runway. Aircraft not close to final approach would receive updated assigned trajectories to reflect the new TFM constraints. Those airspace users could then negotiate to further modify the assigned trajectories.

The flights closest to the now-closed runway would have to be handled initially via voice-issued clearances. However, the automation could have a standard procedure, which the controller issues via voice and then "presses a button" to notify the automation of the new assigned trajectory, keeping these aircraft on closed trajectories. As time permits, the trajectories would be updated to direct the aircraft to a different runway or holding pattern. Aircraft that need to divert would select a diversion airport and negotiate a trajectory to that new destination.

## **6.3 Controller Provides Options for Conflict Resolution**

The negotiating controller receives an alert of a pending separation issue between two aircraft (AAL262 and AAL1516) 32 minutes before loss of separation. The controller automation provides a resolution advisory involving a lateral path maneuver, and the negotiating controller also identifies an altitude adjustment that would resolve the conflict.

The controller offers the pilot of AAL262 the option of stopping its planned flight level change at FL310 until clear of traffic (Climb and Maintain FL310. At ROD, Resume Climb to FL 360.) or adjusting its lateral path (At ABC, Direct DEF, Direct RMG, where RMG is already on the assigned trajectory).

The pilot uses the trajectory negotiation automation capability on the EFB to compare the two options and evaluate their effect on fuel burn, flight time, etc., and chooses the lateral path maneuver. The pilot downlinks the preference from the EFB to the controller automation via SWIM.

The controller receives the pilot's preference and indicates to the controller automation that the lateral path maneuver is the accepted solution. The controller automation converts the completed negotiation into a clearance that can be uplinked to the FMS. The negotiating



controller uplinks the amended clearance (At ABC, Direct DEF, Direct RMG, Cleared as Filed) to the aircraft. The pilot receives the clearance, loads it into the FMS, ensures that it matches the negotiated trajectory, and accepts the clearance. The aircraft downlinks the WILCO message and executes the amended trajectory.

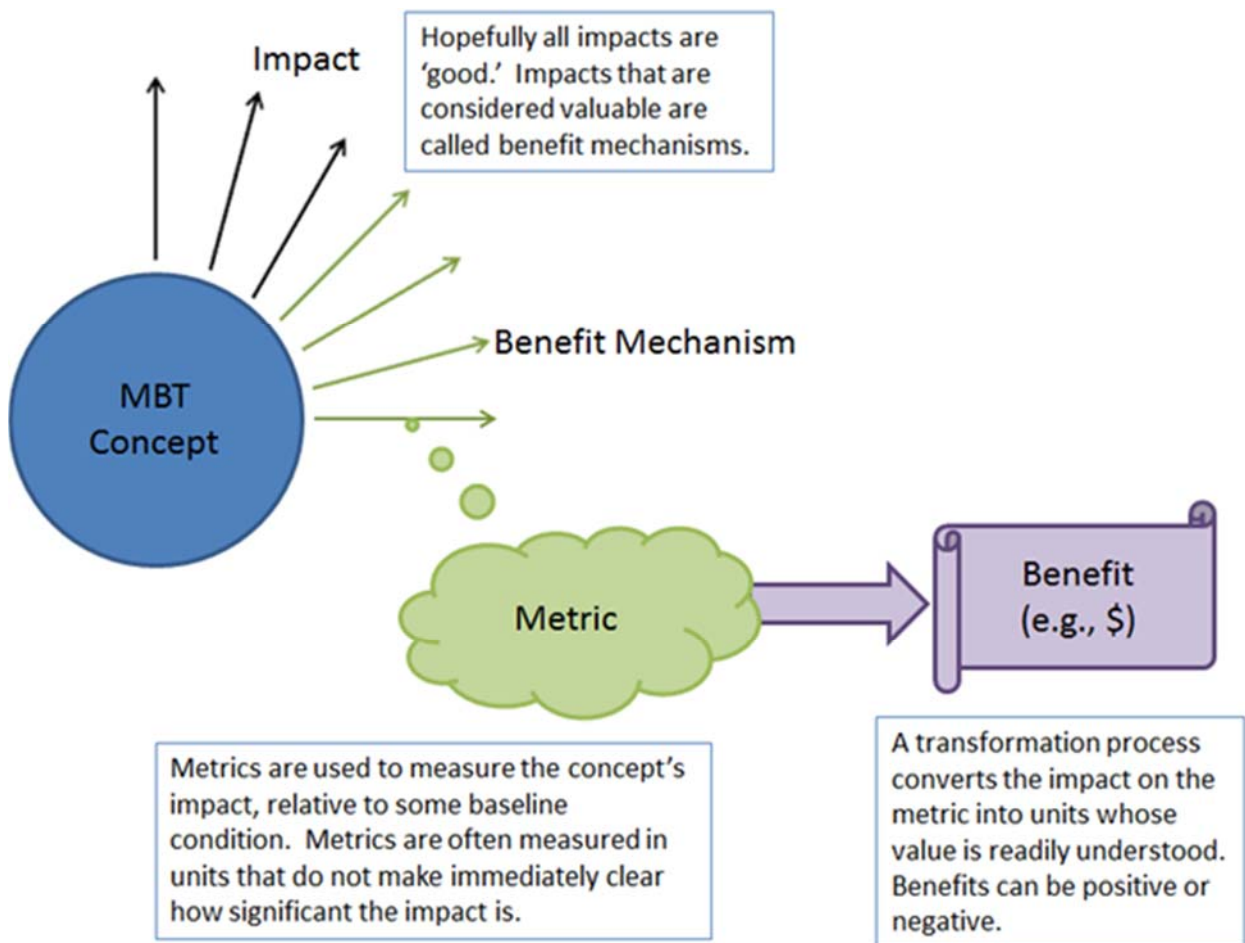
The controller automation receives the WILCO response and updates the assigned trajectory, which is published to all relevant stakeholders. When AAL262 reaches ABC, the aircraft turns to fix DEF, and turns back to the original route upon reaching DEF.

## 7. Benefit Mechanisms

The MBT concept transforms significant aspects of how aircraft operate and are managed in the NAS. Consequently, MBT impacts many NAS performance metrics through a variety of mechanisms. The anticipated MBT benefits include improved air transportation efficiency, which is manifest as increased capacity for constrained NAS resource, reduced delays, and reduced operational costs; increased flexibility; better predictability; greater robustness to off-nominal conditions; reduced environmental impacts; and enhanced safety. Recipients of these benefits include the direct airspace users, the airspace users' customers (e.g., flying public, companies utilizing air transportation services, and companies and recreationalists using airspace resources), the FAA and other service providers (e.g., airport authorities), and other economic and pleasure activities that rely on access to the NAS.

### 7.1 Understanding Benefit Mechanisms and Quantifying Benefits

This chapter adopts a classic model to explain the relationship between a concept's impacts, benefits mechanisms, metrics, and benefits (Figure 19).



**Figure 19. Relationship between Concept Impacts, Benefit Mechanisms, Metrics, and Benefits**

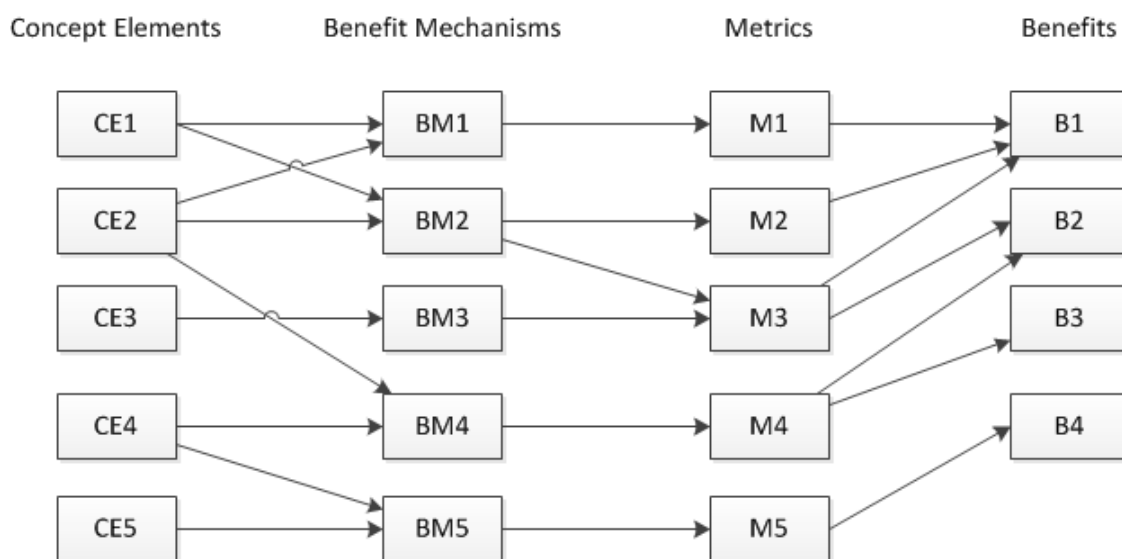
One or more concept elements produce an effect; if the effect may have value, we call it a benefit mechanism. Understanding the benefit mechanisms is essential because the concept engineers need to know how the concept is providing benefits. Understanding the trace

between concept elements and benefit mechanisms is useful for determining the relative benefits and costs of different parts of the overall concept.

Metrics are the measurable changes, such as flight time and compliance accuracy with an RTA, that result from benefit mechanisms. Benefits are the system improvements that are readily recognizable to the stakeholders. Benefits transform the metrics into units that are more useful for making investment decisions.

Ideally, there would be a one-to-one-to-one-to-one relationship between concept elements, benefit mechanisms, metrics, and benefits. However, this is rarely the case. A concept element may contribute to several system impacts that are considered benefit mechanisms, or multiple concept elements may combine to produce a benefit mechanism. Two benefit mechanisms may produce changes to the same metric, or a benefit mechanism may be evaluated through more than one metric. Many metrics may ultimately be valued in terms of dollars.

Figure 20 notionally illustrates the potentially complex relationship between elements of the concept, benefit mechanisms, metrics, and the ultimate benefits.



**Figure 20. Relationship between Concept Elements, Benefit Mechanisms, Metrics, and Benefits**

A large concept such as MBT has a large number of stakeholders – people, organizations, or other agents that will experience the benefit mechanisms and other impacts. Benefits are not experienced equally by all stakeholders. Some benefits, such as those related to safety improvements, might be considered system benefits since all stakeholders have a vested interest in NAS safety, whereas other benefits related to reduced fuel consumption are primarily valuable to the air vehicle operators and their customers. This report begins to trace benefit mechanisms to the participants that receive the value.

The benefits ascribed to ATM concepts are often grouped into categories of impacts on efficiency, safety, access, and the environment. This chapter includes subsections that discuss the benefit categories of efficiency, safety, and access. At the current level of detail, environmental benefits are considered to be directly related to the efficiency benefits of reduced fuel burn, and are not otherwise discussed.

## 7.2 Efficiency Benefit Mechanisms

Anticipated MBT benefits related to improved air transportation efficiency result from various impacts that increase capacity for constrained NAS resources, which result in reduced delays. Many of these efficiency benefits result from improved performance of TFM programs to manage demand relative to the forecast or actual capacity of various NAS resources, and these

TFM improvements primarily result from improved trajectory predictability. Other benefit mechanisms are related to trajectories that more efficiently avoid NAS constraints and conflicts with other air vehicles. The use of negotiated 4DTs that reflect shared awareness of NAS constraints is also expected to increase robustness to off-nominal conditions. Most efficiency benefits are realized in the form of reduced operational costs.

Table 8 lists benefit mechanisms related to MBT’s impact on NAS efficiency. With each benefit mechanism is listed a key MBT concept element responsible for that impact, a potential metric that could measure the impact, and the resulting benefit (i.e., how the impact is valuable).

The primary direct recipients of efficiency benefits manifest as reduced operational costs are the airspace users. However, many of these benefits will be passed along to the airspace users’ customers (e.g., flying public, companies utilizing air transportation services, and companies and recreationalists using airspace resources). The FAA and other service providers (e.g., airport authorities) may also experience benefits where more-efficient traffic management allows for reduced costs of providing services and reduced costs of developing alternative technologies to achieve the same efficiency benefits. For example, an airport may not need to build a new runway if the existing runways can be used more effectively. The NAS stakeholder(s) that experience the benefit are identified in the discussion of each benefit mechanism following the table.

**Table 8. Benefit Mechanisms Related to MBT Efficiency Impacts**

<b>Benefit Mechanism</b>	<b>Related Concept Element</b>	<b>Metric</b>	<b>Benefit</b>
Increased trajectory stability	Planning 4DTs that consider NAS constraints	Magnitude and frequency of assigned trajectory changes	Dollars (via cost of operations reductions due to improved certainty)
Improved trajectory prediction	Trajectory stability; closed trajectory modifications; use of air vehicle intent	Trajectory prediction accuracy	Dollars (via cost of operations reductions due to improved predictability)
Improved TFM performance	Improved trajectory prediction	Delays; throughput	Dollars (via cost of operations)
Reduction in unused slots in TFM programs	Improved trajectory prediction and sharing of updated trajectories	Underutilization of capacity	Dollars (via cost of operations)
TFM programs implemented further in advance	Increased use of multiple time constraints issued through assigned trajectory	Variation from aircraft preferred speed	Dollars (via cost of operations)

Increased conflict detection and resolution (CD&R) efficiency	Improved trajectory prediction	Magnitude of assigned trajectory changes; number of conflicts requiring resolution; time prior to conflict when resolution is implemented	Dollars (via cost of operations)
Availability of trajectories not practical to issue via voice enables better use of airspace	4DTs delivered via datalink and easily loaded into FMS	Airspace complexity based on assigned trajectories	Dollars (via cost of operations)
Earlier planning and improved coordination of assigned trajectory modifications across multiple airspace sectors/centers	Negotiated assigned 4DTs	Wind-adjusted flight distance relative to business trajectory	Dollars (via cost of operations)
Quicker response to changes in NAS constraints	Shared awareness of NAS constraints and assigned trajectories	Number of trajectory changes due to reduced/canceled NAS constraints	Dollars (via cost of operations)
Enable business opportunities not currently feasible	4DTs treat emergent and traditional users the same	Number of non-conventional trajectories	Dollars (via new economic activity using airspace resources)

### ***Trajectory Stability and Predictability***

One feature of the MBT concept is that the initial versions of the assigned trajectories will take into account more of the TFM restrictions and other NAS constraints that delay flights. Current operations in the NAS do not pre-plan how each flight will be handled relative to these disruptions to nominal operations, instead relying on individual controllers to invent tactical solutions for aircraft within their sectors or traffic managers to design and implement solutions as traffic enters their facility's airspace. As a result, MBT trajectories are expected to be more stable, having fewer and smaller changes during flight. Increased certainty of flight time, route, and distance may allow airspace users to reduce the amount of excess contingency fuel carried by the aircraft, reducing operating costs and fuel burn.

Trajectory stability combined with closed trajectory modifications, as opposed to open trajectory segments that are unpredictable, result in significant improvements to trajectory prediction accuracy. The inclusion of flight intent data also substantially contributes to trajectory prediction accuracy. Increased trajectory prediction accuracy enables improvements in both TFM performance and conflict detection and resolution (CD&R) efficiency.

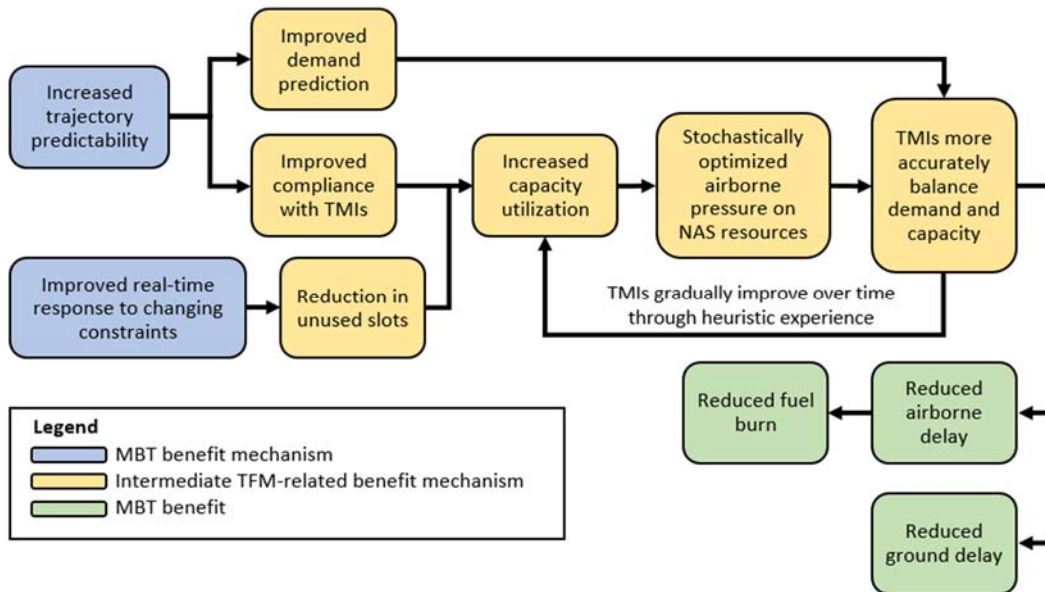
### ***Benefit Mechanisms Related to TFM***

MBT provides multiple benefit mechanisms that improve the efficiency of TFM, including increased trajectory predictability and improved real-time response to changing constraints (Figure 21). Increased trajectory predictability improves TMI compliance, which in turn improves capacity utilization. MBT achieves this result because the associated TMI constraints become part of the assigned trajectory (unlike a MIT restrictions in today's system) and must be feasible relative to the aircraft's performance (e.g., realizable speed ranges). Importantly, MBT's trajectory prediction improvements allow TMI constraints to be planned further in advance. Increased trajectory predictability also improves demand prediction, which enables less-conservative TFM programs. Improvements in demand prediction and TMI compliance both contribute to TMIs that more effectively balance capacity and demand and allow those TMIs to be achieved more efficiently. Trajectory negotiation allows those TMIs to be achieved in a manner that best matches the airspace user's business considerations. Planning TFM programs further in advance creates more opportunities for airlines to use CDM capabilities to optimize business decisions.

There is a tradeoff between the airborne delay associated with imposing airborne pressure on NAS resources and the potential of missing slots and thus not fully utilizing available capacity. As traffic managers gain experience with MBT and see the improvements that TMIs provide for balancing demand and capacity, they may reduce some of the need for airborne pressure on NAS resources. This is depicted by the feedback loop in Figure 21. Enhanced predictability will provide a more-consistent flow of air traffic, where demand will more accurately meet available capacity, reducing or eliminating delay.

Improved real-time response to changing constraints is primarily supported by MBT's NAS Constraint Service and refers to when an aircraft upstream of the TFM constraint must change its trajectory (e.g., due to weather) and this impacts its ability to meet its original TFM constraint. In MBT, the weather deviation is a closed trajectory so the new ETA is known by the TFM automation system as soon as the weather deviation becomes part of the assigned trajectory. When multiple aircraft are impacted by unexpected weather deviations, there is potential that arrival slots will go unutilized. The real-time identification of updated ETAs enables TFM programs to re-plan so that other aircraft can efficiently use those slots (e.g., departures that already require ground delay may be able to depart earlier and use those slots). In contrast, the same situation in today's system results in more time elapsing before accurate ETAs are available for weather-deviated flights. Thus, there may be missed opportunities for other aircraft to use those arrival slots in an efficient manner.

The anticipated dollar benefits (e.g., due to reduced ground delay, airborne delay, and fuel burn) of TFM-related mechanisms are expected to be the largest of the MBT benefit mechanisms.



**Figure 21. MBT Benefit Mechanisms Related to TFM Improvements**

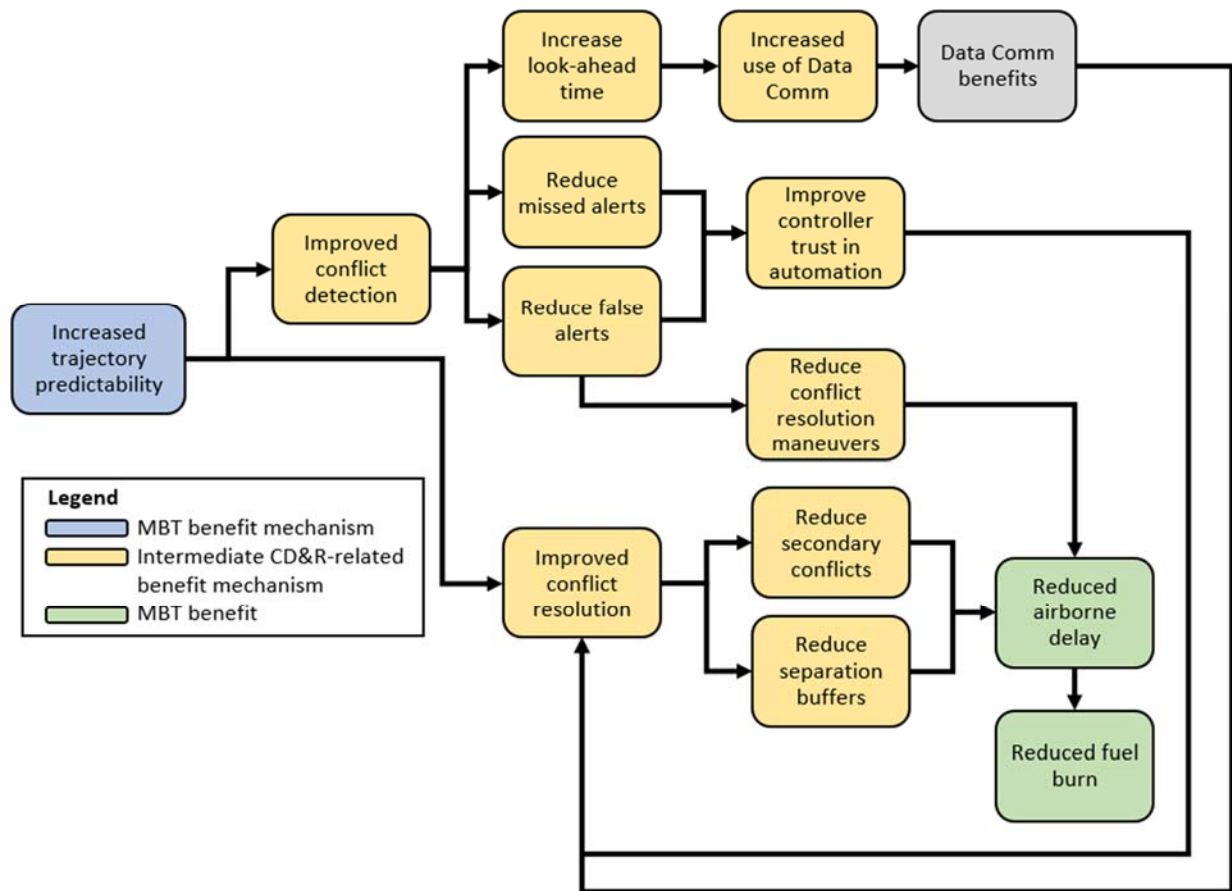
***Benefit Mechanisms Related to CD&R***

Closed trajectories, shared awareness of trajectory and NAS constraints among stakeholders, and trajectory synchronization will increase trajectory predictability under MBT. Figure 22 shows the relationship between increased trajectory predictability and CD&R functionality.

An expected MBT benefit mechanism is a reduction in missed alerts and false alerts, which may also improve controller trust in CD&R automation. Furthermore, MBT’s trajectory prediction improvements will enable longer look-ahead times, which will ensure that there is sufficient time to use Data Comm rather than voice communication and allow for more-efficient resolution maneuvers. The increased use of Data Comm provides benefits such as reduced readback errors (accounted under safety benefit mechanisms) and facilitates the closed trajectories on which MBT is predicated.

Secondary conflicts (i.e., conflicts that may occur downstream due to the resolution of the current conflict) are reduced due to more-accurate conflict probing resulting from improved trajectory predictability. Over time, controllers may reduce separation buffers (i.e., separation they maintain beyond the mandated separation minima) for conflict resolution as their confidence in the CD&R automation increases. Tangible MBT benefits can be measured through the reduction in false alerts, secondary conflicts, and separation buffer size.

As the FAA makes investment decisions in various NAS changes, it is careful not to double count benefits – i.e., attribute a benefit that will occur once to multiple different NAS changes when any one of those changes would result in that benefit. The FAA is researching many concepts and technologies related to trajectory based operations. The current MBT concept of operations does not present a design for how MBT would be integrated with various other candidate TBO solutions. Similarly, this section does not attempt to apportion benefits related to TBO between MBT and other concepts, technologies, or procedures. Future benefit studies could attribute some of the benefit mechanisms identified in this section to other NAS changes, such that those resulting benefits would not contribute to MBT’s investment case. For example, benefits attributed to Data Comm cannot also be attributed to MBT’s use of Data Comm.



**Figure 22. MBT Benefit Mechanisms Related to CD&R**

***Benefit Mechanisms Related to 4DTs***

Shared awareness of trajectory and NAS constraints among stakeholders supports the MBT benefit mechanism of improved real-time response to changing constraints. In particular, when NAS constraints are eliminated or relaxed, the real-time sharing of this information through the NAS Constraint Service is provided to the airspace user and flight crew. This enables the airspace user, flight crew, or FAA to initiate negotiation of a more-efficient trajectory. Furthermore, FAA solutions involving in-flight reroutes consider airspace user preferences. The resulting increased use of more-efficient trajectories will provide benefit through reduced airborne delay and fuel burn. In addition, negotiation allows the operator to fly trajectories that satisfy ATM requirements but are as close as possible to their business trajectories, providing economic benefit to the airspace users.

A key element of the MBT concept is the explicit inclusion of trajectory constraints in the time dimension, making the assigned trajectories four-dimensional. Increased use of time constraints will enable implementation of TFM programs further into the future and further improve trajectory prediction over longer time horizons.

Datalink delivery and FMS auto-load of assigned 4DTs will enable the use of trajectories that would not be practical to issue via voice clearances, allowing better use of airspace resources. Moreover, earlier planning and improved coordination of assigned trajectory modifications across multiple airspace sectors/centers will enable increased use of more-efficient trajectories and responses to constraints. Resulting benefits will include reduced delays and reduced flight cost.

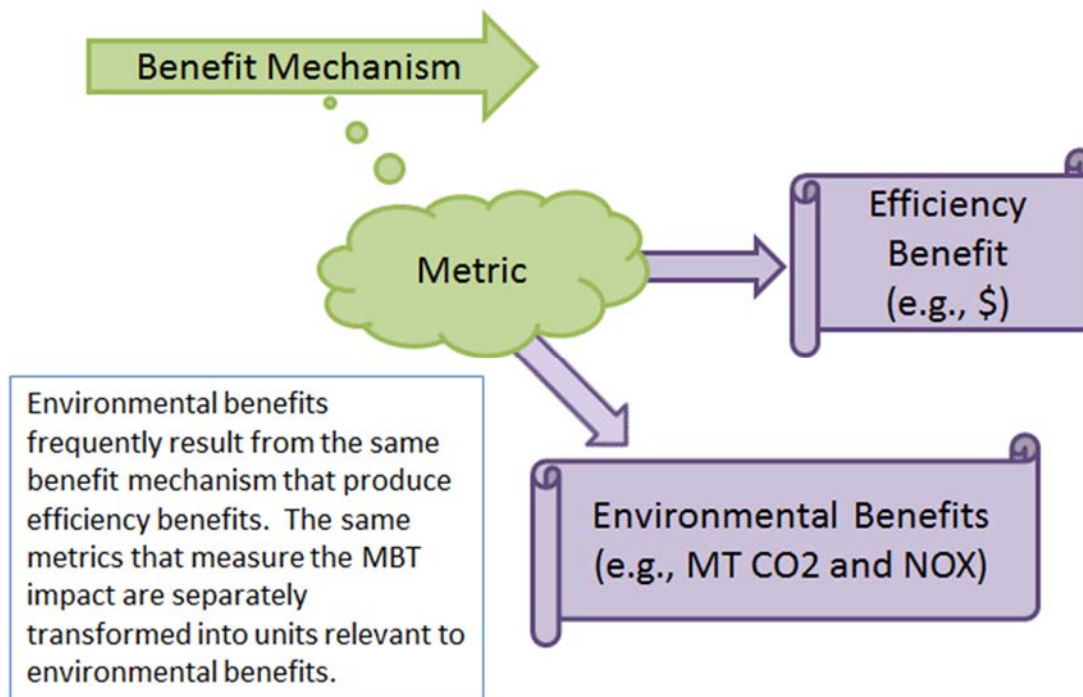
Emergent users – those with novel vehicle types and/or novel business models – that share NAS airspace with traditional air transportation users will benefit from each of the efficiency



MBT benefit mechanisms to the extent they compete for access to the same airspace resources. While MBT's use of assigned 4DTs facilitates access to the airspace (Section 7.4), the assigned 4DTs also enable business opportunities that might not otherwise exist. A 4DT can, for example, permit a vehicle to loiter in a defined volume of airspace. While possible in today's NAS, these operations require additional controller workload to monitor the aircraft.

### **Environmental Benefits**

Figure 23 illustrates the relationship that often exists between efficiency and environmental benefits. Two types of benefits occur when an aircraft burns less fuel – an operational cost savings measured in units of dollars (e.g., related to the cost of the fuel and the maintenance on the engines) and a reduction in combustion pollutants released into the atmosphere (measured as the mass of those pollutants). At this point in MBT benefits research, the environmental benefits are not explicitly identified, since the benefit mechanisms are the same as those categorized as efficiency impacts.



**Figure 23. Relationship between Efficiency and Environmental Benefits**

### **7.3 Safety Benefits Mechanisms**

Decisions to invest in new ATM technologies typically compare benefits with costs, where the costs represent the necessary economic investment to develop, deploy, and maintain the new technology. Where benefits are not measured in economic terms, this comparison can be less quantitative. Therefore, all benefits are often converted into economic units in the final investment decision-making process. While costs measure the size of the investment, a concept as broad as MBT could produce negative benefits from some benefit mechanisms, in addition to the positive benefits that justify the concept. This section does not make forecasts regarding the relative size of the benefits that will be produced by various mechanisms. Rather, it begins to catalog the benefit mechanisms for subsequent study.

MBT will need to undergo extensive testing to ensure that operations are at least as safe as in the current NAS. Some of the MBT concept elements could result in zero net benefit or even a negative benefit. Even a zero net benefit could denote improved performance in some

situations, offset by worsened performance in others, which may or may not be an acceptable impact in the context of a safety assessment. At this point in the MBT benefits research, identifying a potential impact as a benefit mechanism does not imply an expectation of a positive benefit.

Table 9 lists benefits mechanisms associated with MBT's impact on NAS safety. With each benefit mechanism is listed a key MBT concept element responsible for that impact, a potential metric that could measure the impact, and the resulting benefit (i.e., how the impact is valuable). Safety benefits are enjoyed by all of the NAS stakeholders, since all stakeholders have a vested interest in NAS safety.

**Table 9. Benefit Mechanisms Related to MBT Safety Impacts**

<b>Benefit Mechanism</b>	<b>Concept Element</b>	<b>Metric</b>	<b>Benefit</b>
Increased resilience to degraded modes	Assigned 4DTs where negotiated changes seldom affect the near future	Probability of hazardous event	Dollars (via cost of accidents and additional safety systems)
Improved trajectory prediction	Aircraft follow assigned 4DTs and update intent information	Number of conflicts that require action to resolve	Dollars (via reduced cost of resolutions); controller workload
Automation uses assigned 4DT to improve conflict detection and resolution planning	Automation assists controllers to identify need to negotiate assigned trajectory changes due to NAS constraints or objectives	Time prior to conflict at which resolution is planned	Dollars (via cost of accidents and additional safety systems)  Dollars (via reduced cost of resolutions through earlier planning)
Increased use of digital delivery of clearances	4DTs defined in digital systems and shared for common awareness	Number of incorrect FMS entries; time controllers spend issuing clearances	Dollars (via cost of accidents and additional safety systems); controller workload
Increased ability to monitor conformance with expected trajectory	Near 100% closed trajectories	Latency in detecting trajectory deviation	Dollars (via cost of accidents and additional safety systems)
Novel vehicle types and business trajectories share airspace with less disruption to traditional airspace users	Seamlessly handles emerging air vehicle types by using assigned 4DTs	Amount of communication spent to determine if an air vehicle is able to accept a specific trajectory change	Dollars (via cost of accidents and additional safety systems)

Possibly the most significant benefit mechanism relative to MBT's safety impact is an increased resilience to degraded modes of operation. In MBT operations, most assigned

trajectories will be stable (i.e., will not need to change) and conflict free for the next 30 minutes or longer. If a degraded mode of operation occurs within the NAS, such as a failure in a surveillance or communication system, MBT provides more time to address that degraded mode (e.g., switch over to backup system, implement manual procedures) while allowing flights to safely continue along their current assigned trajectories. The stable MBT trajectories, which de-conflict flights by planning ahead rather than waiting and tactically vectoring flights, provide more time for humans and automation to respond to degraded modes before any action to separate flights is required.

Consider the situation, common in today's NAS, in which two aircraft would conflict if the controller responsible for the airspace in which they are flying does not intervene. Today's airspace system is designed to create these scenarios, especially at places like meter fixes, and relies on controllers to separate the aircraft. In current operations, routine tactical separation is accomplished by the controller issuing an instruction to one of the pilots, which could be a speed, altitude, or heading change. The pilot must verbally acknowledge a vector instruction, switch navigation mode, turn the heading indicator on the mode control panel (MCP), and then later reengage the FMS to fly direct to the next fix in the existing flight plan. The controller must monitor that the aircraft does alter its trajectory and the conflict is avoided. Typically, conflicts are not addressed early because of trajectory prediction uncertainty, necessitating resolutions close to where the conflict would occur. MBT enables earlier resolution, due to earlier prediction confidence, and reduces the controller's workload in monitoring the execution of the solution. MBT is also able, through automation, to consider how various solutions affect the flight's efficiency and downstream traffic congestion.

A common situation under the MBT concept will be that an updated assigned trajectory is digitally delivered to the aircraft's FMS or EFB. The pilot must review and accept the modification or reply with an alternative; the avionics will help the pilot understand the change and its impact on the flight. The assigned trajectory change will also be available to the AOC, where automation or a dispatcher can check for any issues. With minimal pilot effort, and reduced chance of human error, the aircraft will fly the modified trajectory. This MBT change is anticipated to provide a safety benefit, including through a reduction in readback errors and improved verification that the trajectory modification is safe and feasible for the aircraft.

The consistent use of 4DTs will also improve automatic monitoring of aircraft compliance, compared to current operations in which controllers must often manually monitor that an aircraft is complying with a voice-issued clearance. The reduced reliance on vectoring to avoid conflicts, with aircraft staying on assigned, closed trajectories all or most of the time, may also improve safety. MBT's reduced reliance on voice-communicated vector commands may also allow more aircraft to be handled in each sector. The net safety impact of this significant MBT change in conjunction with the other MBT changes will need to be determined to enable this capacity benefit.

The introduction into the NAS of new types of air vehicles supporting novel business models will result in airspace being shared by vehicles with more widely varied performance characteristics. Controllers currently use their knowledge of aircraft characteristics to both forecast conflicts and design feasible solutions that will avoid the conflict. This mental problem will become increasingly hard as the controllers will be unfamiliar with the performance envelopes of large numbers of new vehicles. In MBT, every airspace user will follow their assigned 4DT, which will allow the controllers to use these 4DTs rather than their own internal predictions of the vehicles' trajectories. The negotiation process, supported by automation tools and an assigned trajectory object that includes information about the vehicle's capabilities, will allow 4DT modifications that are feasible for the vehicles, without the controller needing to know, for example, a reasonable climb speed for each model of unmanned aircraft (UA), which will also depend strongly on the vehicle's payload.

The estimation of benefits of MBT in the context of emergent airspace users will be somewhat unique because these airspace users do not operate in the current NAS, at least at the level of demand forecast for the future. While there are two changes – the introduction of

MBT and the introduction of new users – only the impact of transitioning to MBT is to be measured. Therefore, MBT benefit estimation will require estimating the associated metrics for the current NAS if that future type and level of demand existed and comparing those results with estimates of the metrics for the same demand in an MBT environment.

#### 7.4 Access Benefit Mechanisms

Within the access benefit mechanism category are concepts such as ATM flexibility, an airspace user’s ability to predict their own operations, and fairness (a.k.a. equity) in access to NAS resources. ATM flexibility entails capabilities such as airspace users having increased self-determination with respect to their own trajectories, including the ability to decide how to use limited-resource capacity that is allocated among their flights via CDM technologies.

Table 10 lists benefit mechanisms related to MBT’s impact on NAS access. With each benefit mechanism is listed a key MBT concept element responsible for that impact, a potential metric that could measure the impact, and the resulting benefit (i.e., how the impact is valuable). The NAS stakeholder(s) that experience the benefit are identified in the following discussion of each benefit mechanism.

**Table 10. Benefit Mechanisms Related to MBT’s Impact on Access**

<b>Benefit Mechanism</b>	<b>Concept Element</b>	<b>Metric</b>	<b>Benefit</b>
Users have increased self-determination over the trajectories they fly	Trajectory Negotiation	Difference between user-preferred trajectory and trajectory flown	Dollars (via cost of operations and customer satisfaction)
Increased predictability of trajectory flown	Aircraft follow assigned 4DTs	Trajectory prediction error	Dollars (via cost of operations and customer satisfaction)
Airspace user has shared awareness with FAA of constraints that ATM system must handle	Central repository of NAS constraints	Amount of pilot voice requests asking controllers for justification for a trajectory change	Dollars (via cost of operations); controller workload
New entrants gain access to NAS airspace resources	Seamlessly handles emerging air vehicle types by using assigned 4DTs	Equity in access measured by delays and available airspace resources	Dollars (via cost of operations and new entrant business opportunities)
Encourages equipage that enables larger efficiency and safety benefits	Air vehicles and airspace users that adopt new technologies will be better able to negotiate favorable trajectories and will need trajectory modifications less often	Percentage of aircraft participating in trajectory negotiation (vs. just accepting assigned trajectories)	Dollars (via cost of operations)

MBT provides airspace users with an opportunity to negotiate their assigned trajectory in a much more formal way than they can currently do in the NAS. This increased self-determination of how a flight will experience the various NAS constraints will provide various economic benefits. For example, an airspace user may choose whether to avoid a region of turbulence to provide customers with a smoother ride or transit the turbulence to maintain schedule without having to burn more fuel to fly faster. Furthermore, airspace users will have more flexibility to tradeoff between aircraft speed and fuel efficiency, based on business needs. Trajectory negotiation may also create more opportunities for CDM-based abilities for airspace users to swap access to NAS resources between flights within its fleet, providing additional economic benefits. Airspace users are the primary beneficiary for this benefit mechanism; end customers of those flight service providers may also receive the benefit as a flow through if the market is sufficiently competitive. Airspace users include both traditional passenger and cargo air transportation companies as well as emergent users.

There are many examples of how the increased trajectory predictability can result in economic benefits that could be measured. Airspace users can use reliably improved arrival time estimates to reduce the required ground infrastructure and staff needed to process arrival aircraft. Fewer arrivals will need to wait for marshals to guide aircraft to their parking gates. Furthermore, having more advanced notice of when flights will arrive could enable airlines to improve schedule connectivity, optimize the assignment of aircraft and crews to departure flights, reduce airline-caused delays, and potentially allow for fewer spares. In addition to reducing direct operating costs, these benefits will increase customer satisfaction, which also can be measured as an economic benefit. Again, airspace users are the direct beneficiary; their customers may in turn receive a portion of the benefit.

This section focuses on identifying benefit mechanisms. Understanding what metrics could be used to assess each benefit mechanism and ultimately in what form the benefit would be realized is important to validating the benefit mechanisms, but not this section's primary focus. This section does not attempt to develop the necessary models that would translate changes in metrics into the quantified benefits. The above examples of how increased trajectory predictability could benefit an airspace user illustrate why the benefit mechanism could provide an economic benefit, but modeling each of those mechanisms to estimate benefits would be extremely challenging. Benefit studies typically select a small number of example mechanisms and still make many significant assumptions.

By providing all airspace users with access to information about all NAS constraints, MBT enables users to make more-effective business decisions, providing economic benefit. In addition, the resulting shared awareness may reduce the voice communication between airspace user and air traffic controllers, reducing controller workload. Understanding NAS constraints may be especially important to some types of emergent NAS users, so that they may plan missions that will avoid impacting other users and, therefore, be accepted. All airspace users are likely to benefit from this mechanism. In addition, by reducing required controller workload, the FAA controllers may benefit through increased job enjoyment, or the FAA organization may realize a cost savings by reducing the required controller staff.

By treating all air vehicles in a similar manner – assigning negotiated trajectories that are feasible given their performance characteristics – MBT enables new entrants access to NAS airspace with minimal disruptions to traditional airspace users. The benefit of supporting new business models is expected to outweigh the impact of the increased demand. New classes of airspace users are the beneficiary of this mechanism since they will gain access to the NAS that would otherwise be more restricted.

The MBT concept provides access to all aircraft regardless of equipment. However, aircraft that are equipped with at least a minimal set of capabilities are anticipated to gain a greater direct benefit from MBT. For example, users that have not integrated with the NAS Constraint Service will not be aware of changing constraints that provide potential benefits. The subset of the airspace users that invest to be full participants in MBT will experience the largest economic benefit.

## 7.5 Summary

The MBT concept transforms significant aspects of how aircraft operate and are managed in the NAS. Consequently, MBT impacts many NAS performance metrics through a variety of mechanisms. This chapter provided an introduction to benefit mechanisms and their relationship to quantifiable benefits, and then summarizes the anticipated MBT benefit mechanisms and benefits. MBT benefits include:

- Improved air transportation efficiency
  - Due to increased trajectory stability and predictability
  - Related to TFM, CD&R, and 4DTs
  - Relationship to environmental benefits
- Enhanced safety
- Improved access to NAS resources for emergent users

Recipients of these benefits include airspace users, the airspace users' customers (e.g., flying public, companies utilizing air transportation services, and companies and recreationalists using airspace resources), the FAA and other service providers (e.g., airport authorities), and other economic and pleasure activities that rely on access to the NAS.

## 8. Roles and Responsibilities

The allocation of roles and responsibilities among the actors that participate in or are affected by MBT reflects a shift toward strategic planning and away from tactical decisions confined to geographic areas of responsibility. Accompanying this shift is an increase in automation to support negotiation, negotiated planning, and common awareness of NAS constraints, assigned trajectories, and predictions. The increasingly diverse airspace user community necessitates greater flexibility in how responsibilities are assigned to different participants (e.g., whether a pilot, flight dispatcher, or airspace user automation participates in negotiation in a particular situation).

The candidate allocations of roles and responsibilities are somewhat constrained by what is considered feasible based on the current system design. For example, assigning primary responsibility for separation management to any role other than a controller would be such a departure from the current system design that it would make implementation of the MBT concept much more difficult in the absence of significant justification. However, the workload associated with tactical separation management is anticipated to be sharply reduced in MBT due to the proactive adjustments to assigned trajectories to alleviate conflicts.

MBT envisions an environment in which humans use sophisticated automation to manage a complex system. In a system as dynamic and complex as the NAS, automated systems support many important functions and must help manage the workload and cognitive complexity associated with high-tempo, safety critical operations.

The key change in roles associated with MBT is the introduction of a negotiating controller, who is responsible for coordinating and negotiating trajectory amendments for aircraft operating within the sector but far enough from the trajectory change point that the trajectory amendment can be coordinated using Data Link. The negotiating controller also takes on responsibilities that are allocated to the D-side controller in the current NAS.

Key changes that MBT proposes in the allocation of responsibilities relative to the current NAS include:

- Requirement for airspace users to provide aircraft intent. The level of detail in the intent is determined by the aircraft capabilities to downlink intent. Ground automation uses aircraft intent to supplement information in the assigned trajectory and to support conformance monitoring. More detailed and accurate aircraft intent reports may support less constrained assigned trajectories.
- Trajectory negotiation is carried out by TFM personnel interacting with airspace users (FOC and/or pilots) for aircraft that are sufficiently far from the trajectory change point. The negotiating controller also engages in trajectory negotiation for aircraft that are operating within the same sector as the trajectory change point. The R-side controller is responsible for providing tactical control instructions by voice when the aircraft is too close to the trajectory change point to coordinate the trajectory amendment by Data Link. The R-side controller is responsible for ensuring that aircraft remain on closed trajectories, even if provided voice control instructions.
- The capability for the airspace user to engage in trajectory negotiation depends on equipage. Although airspace users are not required to equip with specific trajectory negotiation capabilities, unequipped airspace users have less capability to identify and negotiate optimal trajectories.
- All participants are responsible for trajectory conformance monitoring based on the information to which they have access.

Key automation capabilities to support MBT responsibilities include:

- A NAS constraint service that processes and publishes information about NAS constraints, including information about the specific effects on trajectories.
- As mentioned above, airspace users equipped with advanced trajectory negotiation capabilities will receive the greatest benefit from MBT trajectory negotiation. In particular,

MBT supports the exchange of preferences and offering alternatives as part of trajectory negotiation.

- With the help of more predictable MBT trajectories, controller trial planning capabilities support identification of downstream effects of proposed trajectory amendments. This helps prevent trajectory amendments that introduce downstream problems, which improves trajectory stability and manages workload for downstream controllers (and airspace users).
- Automation supporting R-side controllers that provide voice clearances supports them in easily and reliably providing closed trajectory clearances, and sharing controller intent with the automation when the clearance is ambiguous.

The document “Management by Trajectory: Refined Study of Roles and Responsibilities between Participants and Automation” [11] discusses MBT roles and responsibilities in more detail.



## 9. Summary

Although reachable through a logical evolution from the current NAS, the MBT concept represents a significant change in how air traffic is managed. Yet through this transformation, MBT achieves the FAA's goal of TBO, providing the associated benefits. Furthermore, MBT supports the inclusion of emerging vehicle classes and business models. Anticipated MBT benefit mechanisms include more-accurate trajectory predictions, improved ATM performance and robustness to off-nominal conditions, increased flexibility and operational efficiency, reduced impediments to emerging classes of airspace users accessing NAS resources, reduced environmental impacts, and enhanced safety.

Three cornerstone MBT concept elements are the negotiation of, communication of, and adherence to an assigned 4DT for every flight. These 4DTs extend from the flight's current state to its destination and are composed of a series of trajectory constraints and trajectory descriptions. Trajectory constraints are imposed to ensure or help ensure achievement of the FAA's goals of efficient traffic management and use of NAS resources, safety, and safe separation of proximate air vehicles. MBT also includes the notion of trajectory description elements so that the assigned 4DT is a complete 4DT, where few trajectory constraints are required. All aircraft are required to follow their assigned 4DTs, complying with all trajectory constraints and the trajectory description unless first negotiating a revision. Digital air-ground communication is used to deliver assigned 4DTs and subsequent amendments to aircraft cockpits for easy loading and execution in the FMS. Broadband air-ground communications and advanced EFB applications are used to include the flight crew in the trajectory negotiation process, reducing the required FMS technology evolution.

The MBT concept includes a NAS Constraint Service that gathers and publishes information about all known NAS constraints. Shared awareness of the NAS constraints enables the airspace user to better understand the FAA's goals as they negotiate an assigned 4DT with the FAA. The NAS constraints that required a particular trajectory constraint are referenced in the assigned trajectory to facilitate identifying aircraft affected by changes to or removal of NAS constraints.

MBT uses an assigned trajectory object that contains four parts: the assigned trajectory, air vehicle intent, flight plan, and air vehicle capabilities. All aircraft are required to provide, and refresh as necessary to remain current, information about their trajectory intent and air vehicle capabilities. This requirement may be accomplished by the vehicles FMS, EFB, ground automation, or a combination thereof. The air vehicle intent is a description, provided by the airspace user, of how the vehicle will fly the assigned trajectory, and may contain details such as ETAs at waypoints that are not trajectory constraints or more-precise data such as an ETA at a waypoint for which there is an RTA trajectory constraint. Together, the assigned trajectory and air vehicle intent enable accurate prediction, both near-term and to the destination, of the 4DT that the aircraft will fly. Air vehicle intent can change freely, but must fully conform to the assigned trajectory. The air vehicle intent data will include, and may extend beyond, the current specification for EPP data. For example, air vehicle intent may include the planned speed profile on each route segment. MBT requires all IFR flights to provide air vehicle intent data, which can be accomplished by the FMS, EFB, ground automation, or a combination thereof.

Assigned trajectories, air vehicle intent, and predicted trajectories are shared to create a common view among stakeholders. Assigned trajectories are constructed to satisfy all known NAS constraints, improving trajectory stability and predictability. Uncertainty and disruptions are handled by modifying the assigned trajectory as far in advance as possible. By proactively negotiating changes to the assigned trajectory, rather than relying on controller-selected tactical actions such as vectors to resolve traffic conflicts or implement MIT restrictions, MBT keeps aircraft on closed trajectories that are fully known to all stakeholders. Since reactive air traffic control actions cannot be predicted in advance, the downstream trajectory cannot be accurately predicted until they happen. Reliable trajectory predictions allow the system to identify needed modifications to trajectories further in advance, where they can be negotiated and

communicated as amendments (i.e., additional or altered trajectory constraints) to the assigned trajectory. DSTs will aid controllers in rapidly defining and communicating closed trajectories to the aircraft and will support all stakeholders in trajectory negotiation. D-side sector controllers and TMCs, with their longer time horizon perspectives, will be increasingly important in proactively intervening to avoid conflicts and achieve TFM objectives, using automation enhancements that facilitate assigned trajectory amendments that affect aircraft trajectories across multiple sectors or centers. While not necessary for MBT, time constraints are expected to be increasingly used, and over longer time horizons, to achieve strategic TFM initiatives. Interval management will be integrated into assigned trajectories in dense and complex airspace.

Considerable additional MBT research is needed to advance the concept. Future MBT concept engineering will develop more-detailed requirements for the assigned trajectory object and the assigned trajectory negotiation process. Prototype automation and decision support tools should be developed to validate roles and responsibilities. Extensive simulations are required to measure the achieved trajectory prediction improvement and understand the tradeoffs between the density of trajectory constraints and the types and frequency of trajectory modifications required in different airspace environments. Quantification of the benefits realizable by MBT is needed to support an investment case. The dependence of these benefits on TFM performance improvements requires validating that improved trajectory predictability will enable longer-term TFM planning. In addition, MBT has been developed as a longer-term concept. A transition plan is needed that carefully identifies what elements of MBT can be applied within current technological limitations (e.g., existing FMS capabilities).

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## Appendix A: Comparison with ICAO TBO Concept

	<b>MBT ConOps v2.0</b>	<b>ICAO TBO Concept Document v10.0</b>
<b>TBO definition</b>	<p>“Management by Trajectory (MBT) is a concept for future ATM in which flights are assigned four-dimensional trajectories (4DTs) through a negotiation process between the Federal Aviation Administration (FAA) and airspace users that respects the airspace user’s goals while complying with NAS constraints. Pilots and air traffic controllers use automation to keep the aircraft on its assigned trajectory, which includes complying with temporal or speed constraints. Equipped aircraft have substantial responsibility for complying with the assigned trajectory without controller intervention. Assigned trajectories are constructed to respect all of the known constraints from the aircraft’s current location to its destination, making the flight’s entire trajectory much more predictable than it is today.”</p>	<p>"A concept enabling globally consistent performance-based 4D trajectory management by sharing and managing trajectory information. TBO will enhance planning and execution of efficient flights, reducing potential conflicts and resolving upcoming network and system demand/capacity imbalances early. It covers ATM processes starting at the point an individual flight is being planned through flight execution to post flight activities."</p>

<p><b>Regional Scope</b></p>	<p>FAA is the primary ANSP considered, with some discussion of flights to and from international destinations. "Negotiated assigned trajectory would start at a boundary crossing point and contain a planned crossing time at that point"</p>	<p>Discusses global application and issues related to different ASPs modifying the trajectory and applying constraints – "Developed and deployed in globally harmonized manner."</p> <p>"... constraints may originate from different ASPs along their intended trajectory. TBO seeks to coordinate among global participants to ensure valid flight-specific constraints are met and deliver trajectories for improved ATM System performance including stability and robustness of the ATM network. ... While different ASPs interact with a flight, each ASP may also instantiate multiple GATMOC Components relating to various time-horizons of a trajectory."</p> <p>"... adding or removing a trajectory constraint on one part of the trajectory will often impact another part of the trajectory. In turn, the modified trajectory may alter the decision of another GATMOC Component. This level of coupling requires that a flight's trajectory be managed for consistency across participants."</p> <p>Section 3.4 "multi-ASP considerations" goes into depth on issues and strategies. user responsible for end-to-end trajectory consistency. boundary conditions used to link between ASP specified flight segments.</p>
<p><b>Constraints – Non-flight specific</b></p>	<p>Section 2.4.1. "A NAS constraint is an element of the NAS that affects the selection of assigned trajectories. A region of special activity airspace (SAA) that is closed during some period of time is a NAS constraint, as is a procedure that defines elements of the trajectory that must be used to fly an approach to some runway. A region of bad weather that has limited capacity and the resulting TMIs are also examples of NAS constraints.</p>	<p>"A generic constraint consists of known information that limits the solution space for defining a trajectory. Examples include aeronautical information like predefined airspace structures, availability of military airspace for civil use, availability of conditional routes, night curfews, etc. A generic constraint, often caused by restrictions or regulation, may result in a trajectory constraint." "... continuous sharing and updating is enabled through information management and automation." (page 15)</p>

	Strong turbulence or unfavorable winds may also be considered to be NAS constraints."	
<b>Constraints - Flight specific</b>	Section 2.4.2. "A trajectory constraint is a requirement, specific to a flight, with which the aircraft's trajectory must comply. A flight's assigned trajectory contains the set of trajectory constraints for that flight. All trajectory constraints are negotiable."	"A trajectory constraint limits the freedom of a trajectory by fixing one of its 4D points or segments in one or more dimensions (vertical, lateral, time), with corresponding bounds ("between boundary values") or direction ("before", "after", "above", etc.) An example is an altitude constraint to avoid restricted airspace." (page 15)
<b>Constraint service &amp; reference</b>	Sections 2.4.4 and 2.4.5 describe how users can learn about NAS constraints and reference them in the assigned trajectory. If the constraint is relaxed later then the linkage allows finding flights that might benefit and need revising.	"Trajectory information to be shared consists of the following types of information: The sharing of environmental factors affecting trajectories (e.g., winds, airspace configuration, aerodrome capacities, generic constraints)" (Section 2.2.1)
<b>Time Constraint</b>	The term "CTA" is used similar to "Controlled Time". "Time constraint" usage is similar to ICAO.	Distinguishes between a "Controlled Time," for which "feedback control may be via aircraft systems or ground-based", and a "Target Time," which expresses the time the ASP wants a flight to arrive to a given point, within a tolerance. If the aircraft will miss the target time, the assigned trajectory may be revised. The "Controlled Time" can be issued as a "Trajectory Constraint", but this is not required. (page 15)

<p><b>Assigned Trajectory</b></p>	<p>"Assigned trajectory" contains the cleared lateral route, trajectory constraints, and NAS constraints - not the air vehicle intent. It's analogous to a flight plan (including route, cruise altitude and speed) plus trajectory constraints and NAS constraints. (Section 2.2.)</p>	<p>"TBO involves the development of an Agreed Trajectory, coordinated across participants that extends through all phases of flight. Under TBO, principles are developed to ensure that the Agreed Trajectory and associated constraints are known to relevant participants. For example, ATC instructions should minimize the need for open-ended vectors, and their impact should be reflected as an update to the Agreed Trajectory in a timely manner. While TBO shares an Agreed Trajectory, accuracy of and control to this trajectory is tailored to the performance needs of the circumstances. In other words, not every aspect of a flight needs to be predetermined and captured precisely in the Agreed Trajectory at the time of departure."</p> <p>"Agreed trajectory" includes intent, so it's more like the assigned trajectory object.</p> <p>"It is expected that TBO will make it possible for the ATM system to use a wider set of clearances than we have today (e.g. different types of time constraints, 2D routes to be followed with vertical and/or speed constraints, etc.) This wider set of clearances will allow the more accurate delivery of an Agreed Trajectory when circumstances warrant."</p>
<p><b>Assigned Trajectory Object</b></p>	<p>Contains Assigned trajectory, air vehicle intent, (flight plan), air vehicle capabilities. (section 2.2)</p>	<p>"Agreed trajectory" contains agreement on constraints and intent, but not air vehicle capabilities.</p> <p>"... each flight's Agreed Trajectory as a unique, common reference for decision-making across concept components."</p>
<p><b>Business Trajectory</b></p>	<p>"The airspace user provides a business trajectory which describes the operator's preferences for when and where the flight will fly. "</p>	<p>Describes the Desired Trajectory thusly: "The current trajectory that is requested and generated by the airspace user with knowledge of the ATM system's operational constraints and resource contention." (page 14)</p>



	<p>"The FAA indicates how the operator's business trajectory must be adjusted and what additional trajectory constraints are required to comply with all NAS constraints, avoid other aircraft, and be sufficiently predictable. The operator may adjust its business trajectory to influence the required trajectory constraints."</p>	<p><i>"Explanation:</i> The airspace user determines the trajectory that is best suited to meet their mission objectives. The airspace user may elect to pre-emptively circumvent operational constraints and resource contention — or engage in collaboration on the trajectory. With full knowledge of constraints and resource contention, an AU may wish to engage in collaboration when they are aware that the ASP has some flexibility on constraints. For example, as part of the negotiation process, the ASP may modify some constraints as more demand information is made available.</p>
	<p>"The airspace user may update the business trajectory, which would initiate trajectory negotiation."</p>	<p>"There is only one desired trajectory for any given flight at any time. To allow for flexibility and as the ATM system has unpredictable or uncontrollable events, it is likely that it will be necessary to renegotiate trajectories leading to a revision in the agreed trajectory. The desired trajectory reflects the most recent AU request. Where the agreed trajectory is not the desired trajectory then the ASP will negotiate to obtain a revised agreed trajectory."</p>
<p><b>Updates / Revisions</b></p>	<p>Section 3.8 and 3.9 describe trajectory update and negotiation process. It is very similar to the ICAO process with slightly different terminology. One distinction is that the MBT concept allows for the possibility of sending multiple options with requests, which might result in fewer negotiation rounds.</p>	<p>Defines separate processes for "update" and "revision" of the agreed trajectory. An update seems similar to the MBT update of intent (coordination across participants "need not be required"), whereas a revision involves modification of constraints or re-optimization of the flight (coordination is required and the revision is shared). (page 13).  See also pages 21, 23, and 30-31 regarding "update" and "revision" process.  Page 23 has a detailed process and flowchart for how revisions are managed.  Pages 30-31 describe the process in high level, and the role of each actor in using and modifying the trajectory.  Page 37 talks about tolerances when "update" and "revision" will need to occur.</p>

<p><b>Rules</b></p>	<p>MBT outlines updating trajectories but does not discuss collaboration between ASPs to update different regions of the trajectory like ICAO describes.</p>	<p>"Management of the trajectory requires a collaboratively agreed-to set of rules governing the process. The processes must be established for updating and sharing of the Agreed Trajectory, setting tolerances, detecting deviations from an Agreed Trajectory, and collaborating between ASPs and concept components to obtain or revise an Agreed Trajectory." Section 2.3.2 and 3.4 have more detail.</p>
<p><b>Trajectory Options Set</b></p>	<p>"If the operator has provided a Trajectory Options Set (TOS), the FAA can automatically evaluate the alternative trajectories in response to the change in the NAS constraint. "</p>	<p>Page 14 describes "ranked trajectories" as "A series of trajectories, with tolerances supplied if necessary by the airspace user to define when the next ranked trajectory should be considered the preferred one.</p>
	<p>"The use of business trajectories (or trajectory options sets) and negotiation are essential because the FAA cannot know what trajectories will be efficient and acceptable for the operator. "</p>	<p><i>"Explanation:</i> Ranked trajectories are not mandatory. However, there can be ATM system performance benefits in some circumstances. Tolerances are used to express the bounds of variation on the trajectory triggering a preference for the next ranked trajectory.</p>
	<p>Section 3.16.1, "3.16.1 Use of TOS to Reduce Necessary Negotiation", describes TOS usage in detail.</p>	<p><i>"Note — The AU may use ranked trajectories to express an ordered series of trajectories meeting their mission objectives (e.g., best, second-best, etc.) The ASP can use ranked trajectories in a similar manner by providing a set of negotiating trajectories that are acceptable."</i></p>
		<p>Note the additional option of the ASP proposing multiple trajectories that would be acceptable, which is somewhat different from the airspace user's TOS.</p>
<p><b>Open Trajectory</b></p>	<p>"...any trajectory that is not closed is, by definition, open. An aircraft flying an open trajectory means that at least one of the requirements for a closed trajectory have been violated."</p>	<p>Page 16 defines an open clearance: "Open clearances authorize or instruct an aircraft to deviate from compliance with a 4D Trajectory without additional authorization or instruction allowing a new 4DT to be defined. Examples of open clearances include: the assignment of a heading without a turn-back, or the assignment of an interim altitude on climb.</p>
	<p>Widespread discussion of avoiding open trajectories due</p>	<p>"Note 1: Open clearances produce greater uncertainty in the resulting 4DT,</p>

	to the associated prediction uncertainty.	affecting decisions based upon these trajectories.”
<b>Closed Trajectory</b>	"The aircraft is flying a closed trajectory” means that the aircraft is using a closed-loop control system to follow an assigned trajectory, where the assigned trajectory extends from the aircraft’s current state to the aircraft’s destination; the assigned trajectory is fully known to the ground automation; and the trajectory that the aircraft will actually fly is sufficiently predictable."	Page 16 defines a closed <i>clearance</i> (not a closed trajectory): “Closed clearances are issued by ATC units to authorise the flight to proceed in accordance with a 4D trajectory.”
	"MBT follows two paths to eliminating open trajectories: 1) introducing methods for planning tactical maneuvers as closed trajectory modifications; and 2) eliminating the need for tactical maneuvers through improved predictability."	“Note 1: Closed clearances are preferred for trajectory-based operations. Closed clearances allow the coordination of trajectory intent between operational stakeholders and a reduction in trajectory prediction uncertainty for downstream trajectory synchronisation and demand-capacity balancing activities.”
	"Required tactical ATC interventions are applied by modifying the assigned trajectory to the extent possible."	“Note 2: Ideally the closed clearance should be compliant with the Agreed Trajectory; however, a closed clearance issued for tactical purposes may require an update or revision to the Agreed Trajectory.”
	"Every assigned trajectory must include a definition of the required conformance accuracy for each element (i.e., constraint) of the trajectory. Automation will detect and alert when a flight deviates from its assigned trajectory by more than the required conformance accuracy. "	“Note 3: Through judicious selection of the clearance (e.g., use of PBN Procedures), a resulting 4DT, consistent with the Agreed Trajectory, can be obtained to varying levels of accuracy, within the capabilities of the aircraft and flight crew.”
<b>Control</b>	Pilots and air traffic controllers use automation to keep the aircraft on its assigned trajectory, complying with all trajectory constraints unless first negotiating a revision	"While flight execution is based on the Agreed Trajectory, this does not mean that the flight must be precisely controlled to all dimensions of the trajectory. For example, an Agreed Trajectory may have no time constraints along the path requiring no time control along-path; however, the flight will continue to operate to a cleared or filed speed shared with

		<p>relevant stakeholders."</p> <p>"Trajectory constraints typically must be achieved within a required accuracy through the use of feedback control. This may be through a ground-based and/or an aircraft-based closed-loop control process."</p>
<b>RTA</b>	<p>"Performance-based time standards allow all aircraft to be assigned an RTA, eliminating mixed equipage and enabling TBO."</p> <p>"... using an FMS or EFB, aircraft may be required to be able to handle multiple time constraints"</p>	<p>"... time trajectory constraints may be implemented through active management by ATC through speed instructions or CTA/CTO, but could also be managed by the flight crew through an FMS RTA."</p> <p>"TBO does not restrict the methods through which control is to be executed. A clearance may be provided for the flight deck to use onboard Required Time of Arrival (RTA) capabilities, or ATC may monitor the flight to provide speed instructions as required to meet the time."</p>
<b>Interval management</b>	<p>Interval management will be integrated into assigned trajectories in dense and complex airspace</p>	<p>IM is only briefly mentioned – "When necessary, monitoring is impacted by the performance of the underlying surveillance function whether this is ground-to-air, or air-to-air for interval management."</p>
<b>Vertical profile</b>	<p>Section 3.4.5 describes that assigned trajectory will contain a plan for multiple altitude changes that can be flown without individual clearances at each transition. The vertical profile can be flown like a lateral route.</p>	<p>Mostly only describes vertical constraints with respect to climb and descent, but does state "Vertical constraints may be specified on the Agreed Trajectory in the form of altitude constraints to be met or initiated at a specified location or time" (page 36), however there is no further explanation for how this idea would be implemented or impact pilot/controller procedures.</p>

<p><b>Uncertainty Management</b></p>	<p>"Where uncertainty or disruptions occur, resolutions are, to the extent possible, handled through trajectory modifications as far in advance as possible."          "Where uncertainty remains, necessary adjustments to the trajectory constraints are done proactively, maximizing trajectory predictability and delivering associated benefits."          "At longer time horizons, the TFM system will use stochastic forecasts. "</p>	<p>"Decision-making at appropriate time frames commensurate with the accuracy of information available"          "Control of individual flights to trajectory constraints within performance bounds"          "Dynamic re-planning and coordination of trajectories for optimal ATM System performance"          "Increasing performance of the overall system ... requires planned trajectories to be updated and revised ... based on latest data, observations and predictions, in order to find the optimum balance between ... different stakeholder perspectives"          "One of the important decisions of this interaction is to determine how much control should be applied when, given anticipated uncertainty in capacity and demand estimation"          "In this uncertain case, DCB should defer some of the delay absorption, if required, to a future decision with more certain information"          "When this point occurs should be determined based upon a variety of factors such as the balance between cheaper early control ..., and unnecessary early control due to uncertainty..." (Section 2.3.3.2)</p>
<p><b>Uncertainty vs. flexibility</b></p>	<p>"One area in which research will be required to validate the MBT concept is how TFM must adjust to the tradeoff between uncertainty and flexibility to achieve the anticipated TFM benefits."</p>	<p>"... some level of flexibility is required ... for optimization in an environment that contains uncertainty. This flexibility is important to all classes of Airspace Users .... From an ATM perspective, a certain level of certainty of flight behaviour is also needed to ensure the required performance of the GATMOC Components 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."</p>

<p><b>Robustness to uncertainty</b></p>	<p>Robustness is described as a benefit, "The anticipated MBT benefits include improved efficiency (capacity increases, delay reductions, reduced operational costs), increased flexibility, better predictability, greater robustness to off-nominal conditions, reduced environmental impacts, and enhanced safety." No discussion of choosing constraints to impact desired level of robustness.</p>	<p>"Application of bounds or margin to decisions thereby minimizing the impact of future perturbations and uncertainty"  section 3.3 "... perturbations must be considered when developing the Agreed Trajectory, with margin built-in for robustness."  "The Agreed Trajectory is developed to be robust to disturbances from separation provision"  section 3.3.5 "Having a robust Agreed Trajectory implies that expected perturbations to the trajectory do not result in frequent trajectory revisions."  "Margins may be placed on various variables in the Agreed Trajectory, some examples include: ..."  "...non-participating flights will require larger margins..."  "... estimates of the expected perturbation due to separation provision ... can be used to derive a margin to be incorporated into a time constraint."</p>
<p><b>Area of responsibility</b></p>	<p>"Downstream effects of actions on a trajectory are considered in decision making associated with a given trajectory, including tactical control actions. "</p>	<p>"Agreed Trajectory modifications beyond the conflict horizon or area-of-responsibility may be made without coordination with the separator or ATC if the modifications do not impact the Agreed Trajectory within the limits (Figure 11). Care must be taken to understand the modification being requested to properly evaluate whether the Agreed Trajectory is impacted within the conflict horizon. For example, the imposition of a required time of arrival 30 minutes hence will likely impact the speed selection now."</p>
<p><b>Controller tools</b></p>	<p>Proposes controller tools for easily building and communicating closed trajectories to the aircraft in place of open-ended vectors.</p>	<p>"...technical enablers on their own may not be sufficient to deliver the capability. In particular, development of automation enhancements and training to support the processes required by the capabilities would also be required." (Page 55)</p>

<p><b>Operational Scope - ground</b></p>	<p>"The application of MBT to surface operations will not be pursued in this effort unless the incremental benefits of including management of surface operations within the MBT concept is justified."</p>	<p>"gate to gate trajectory ... such detail is usually not required beyond local participants." "aerodrome operations [should] consider enroute view and manage surface to deliver expected surface event times with known impacts to the ATM system. Also monitor incoming flights to ensure plan is consistent with local surface plan." section 3.2 describes some aspects of surface constraints, but only briefly. "TBO allows for a "gate-to-gate" Agreed Trajectory to the level of fidelity required for ATM performance needs."</p>
<p><b>Operational Scope - TFM</b></p>	<p>"Traffic flow management is separate from the MBT concept."</p>	<p>Some aspects of TFM are discussed in this document. Section 3.1 describes managing the ATM configuration and flow at a macro level as well as managing individual trajectories. "These processes interact as changes to ATM configuration may constrain trajectories and changes to trajectories will impact the flows which affect the ATM configuration. Interactions also occur between ASPs; for example, changing a local ATM configuration may impact GATMOC Components in other regions further upstream or downstream through changes to trajectories." Figure 6 is useful.</p>
<p><b>Operational Scope - Unconventional Ops</b></p>	<p>Brief discussion in 2 places, e.g. "The NAS will accommodate new aircraft classes, including on-demand travel, personal mobility, UAS, space vehicle launch and return operations, airships, and loitering operations (e.g., to provide communication or ground surveillance services)."</p>	<p>Section 3.5 has about 1/2 page of discussion describing accommodation for each of formation flight, RPAS, and space vehicles.</p>
<p><b>Operational Scope - transition &amp; mixed equip</b></p>	<p>Section 3.14 describes mixed equipage challenges, near-term, far-term vision, and transitional ideas.</p>	<p>"The TBO Concept supports a mixed environment. This includes a mix of aircraft and supporting FOC that are equipped with a variety of capabilities and a mix of ASPs supporting and not supporting those capabilities." Section 4 addresses a range of issues and approaches.</p>

## Appendix B: MBT Glossary

Term	Definition
3D Trajectory (3DT)	A three-dimensional (3D) trajectory is a description of an aircraft's path in three-dimensional space. A 3DT is often visualized as a string or tube through space and is described by two dimensions in a horizontal plane (e.g., longitude and latitude) and one vertical dimension (the aircraft's altitude). Projected onto the two horizontal dimensions, the 3DT becomes the aircraft's two-dimensional route. In some cases, the term "trajectory" is reserved for a four-dimensional trajectory (4DT) and the term "three-dimensional path" is used.
4D Trajectory (4DT)	A four-dimensional (4D) trajectory adds the dimension of time to a three-dimensional trajectory. A 4DT includes a starting time as well as time and/or speed information along the three-dimensional trajectory (3DT), such that the time the air vehicle will be at any position along the 3DT, or the air vehicle's position along the 3DT at any point in time, can be calculated.
Actual Navigation Performance (ANP)	Describes the flight's performance capability in each dimension of navigation. Whereas Required Navigation Performance (RNP) describes the requirement the flight must comply with, ANP describes the flight's capability.
Actual Time Performance (ATP)	Equivalent to Actual Navigation Performance (ANP) for the time dimension.
Actual Trajectory	The four-dimensional trajectory (4DT) that an aircraft actually flew (and taxied). An approximation used to store or describe the actual trajectory. An historical 4DT describes the points in space at which the aircraft was located for every point in time between the start and end of the trajectory. Historical 4DTs are often measured by surveillance systems that record the aircraft's location and time at a periodic rate. This discrete sampling of what is actually a continuous path in four dimensions is generally still considered a trajectory. <i>Synonym:</i> Historical 4DT.
Advanced Interval Management (AIM)	"Advanced Interval Management consists of a set of ground and flight-deck capabilities and procedures that are used by air traffic controllers and flight crews to more efficiently and precisely manage spacing between aircraft in a stream of traffic." <i>Reference:</i> <a href="http://www.faa.gov/nextgen/programs/adsb/pilot/ima">www.faa.gov/nextgen/programs/adsb/pilot/ima</a> .
Air-Ground SWIM (A/G SWIM)	FAA concept for extending the information-sharing capabilities of System Wide Information Management (SWIM) to aircraft en route. In MBT, capabilities like Air-Ground SWIM facilitate flight deck participation in trajectory negotiation.
Air Vehicle Capabilities	An element of the Assigned Trajectory Object that carries current information about the air vehicle's capabilities and limitations. Knowledge of the air vehicle's performance is essential to plan efficient and feasible assigned trajectories. If an air vehicle's capabilities change during a flight, the air vehicle or airspace user must update this information.



<p>Air Vehicle Intent</p>	<p>A component of the assigned trajectory object; a description, provided by the airspace user, of the detailed plan for how the air vehicle will fly in conformance with the assigned trajectory. Since the assigned trajectory is the minimal necessary set of requirements on the air vehicle's trajectory, air vehicle intent is used to provide more detail. Together, the assigned trajectory and air vehicle intent enable accurate prediction (both near-term and to the destination) of the trajectory that the air vehicle will fly. Air vehicle intent can change freely, while assigned trajectory changes require negotiation. The air vehicle intent should fully conform to the assigned trajectory. The air vehicle intent will include Extended Projected Profile (EPP) data, which is a currently emerging capability for Flight Management Systems (FMSs) to send certain information about the trajectory that will actually be flown to ground-based automation. Air vehicle intent may extend beyond the current EPP specification depending on continued MBT concept engineering work. For example, air vehicle intent may include the planned speed profile on each route segment. MBT requires all flights to provide air vehicle intent data, which can be accomplished by the FMS, electronic flight bag, ground automation, or a combination thereof.</p>
<p>Airspace Flow Program (AFP)</p>	<p>Similar to a Ground Delay Program but used to control the flow of aircraft to a congested region of airspace, rather than a congested destination airport. <i>Reference:</i> <a href="http://cdm.fly.faa.gov/?page_id=285">cdm.fly.faa.gov/?page_id=285</a>.</p>
<p>Assigned Trajectory (AT)</p>	<p>Part of the Assigned Trajectory Object; comprises the trajectory constraints and trajectory description. The assigned trajectory, described through a defined schema that may include the use of published procedures, is the result of a negotiation process that begins with the airspace user's business trajectory. Once an initial assigned trajectory is established, any part of it may be renegotiated. The aircraft agrees to conform with everything in the assigned trajectory unless first negotiating a change.</p>
<p>Assigned Trajectory Object</p>	<p>Comprises the Assigned Trajectory, Air Vehicle Intent, Flight Plan, and Air Vehicle Capabilities. It is used for efficient exchange of all of the flight-specific data that instruct how the aircraft may fly, is needed to negotiate the assigned trajectory, and is needed to accurately predict the trajectory that the aircraft will fly.</p>
<p>Business Trajectory</p>	<p>The four-dimensional trajectory (or any partial information thereof) that the airspace user wants to fly and may request as a starting point for negotiation of the assigned trajectory. The business trajectory may change over time. The business trajectory is what the flight would follow if there were no constraints from other traffic. The business trajectory is the trajectory preferred by the airspace user when considering National Airspace System (NAS) constraints that would still exist independent of other traffic (e.g., forecast winds, weather and NAS procedures that do not vary with traffic level such as Special Activity Airspace), but exclusive of NAS constraints resulting from other aircraft or Traffic Management Initiatives resulting from traffic congestion. <i>Synonyms:</i> Reference Trajectory, Preferred Trajectory, Desired Trajectory</p>

Call For Release (CFR)	A type of Traffic Flow Management program that controls the takeoff time of flights that will use certain airborne or downstream resources. Managed by the local Air Route Traffic Control Center rather than the Air Traffic Control System Command Center. Flights are issued a Departure Release Time. <i>Synonym:</i> Approval Required (APREQ)
Closed Trajectory	An aircraft operating on a closed trajectory is following an assigned trajectory that extends from the aircraft's current location to the aircraft's destination; the assigned trajectory is fully known to the ground automation, and the trajectory that the aircraft will actually fly is sufficiently predictable.
Conflict	MBT uses the term conflict to indicate that the probability is greater than a defined threshold that the separation between two or more aircraft will, within some defined time horizon, be less than a defined separation minimum. Typically, both lateral and vertical separation must simultaneously be insufficient relative to lateral and vertical criteria.
Controlled Time of Arrival (CTA)	A scheduled time at which a Traffic Flow Management (TFM) program assigns a flight to use or begin to use a constrained resource. In current operations, a CTA is often converted into an Expected Departure Clearance Time (EDCT) or Departure Release Time. MBT is expected to enable increased use of CTAs to achieve TFM objectives, rather than allowing flights to fly open-loop relative to the TFM objective after an EDCT or Departure Release Time. This will improve compliance at the constrained resource, improved flexibility over where necessary delay is experienced, and increased compatibility between Time Based Flow Management and strategic TFM initiatives.
Controller-Pilot Data Link Communications (CPDLC)	"Application that allows ATC data communications between controllers and pilots." <i>Reference:</i> RTCA SC-214. (2016). DO-350A. Safety and Performance Requirements Standard for Baseline 2 ATS Data Communications (Baseline 2 SPR Standard). Washington, D.C.: RTCA.
Collaborative Trajectory Options Program (CTOP)	A Traffic Flow Management program that manages airspace demand for one or more flow constrained areas (FCAs) through automatic assignment of delays and reroutes. For added flexibility and collaboration, airspace users have the option to submit a set of desired reroute options, named a Trajectory Options Set (TOS), to the FAA. When a CTOP program is in place, automation will issue impacted flights one of two alternatives: 1) a route assignment, devised using the TOS, if submitted, that avoids the FCAs, or 2) a route assignment through the FCAs with a controlled departure time issued as an Expected Departure Clearance Time. Key features of the CTOP program include its capability to handle multiple constraints simultaneously and its capability to continuously monitor airspace conditions for any advantageous amendments, for example, rerouting a flight back to its original route after a constraint has been lifted. <i>Reference:</i> FAA AJR-1. (2014). AC No: 90-115. Advisory Circular. Subject: Collaborative Trajectory Options Program (CTOP). Washington, D.C.: DOT FAA.

Crossing Restriction	In MBT, element of an assigned trajectory that instructs an aircraft to cross a given waypoint at (or above or below) a specified altitude, and sometimes also at a specified airspeed.
Departure Release Time	Similar to an Expected Departure Clearance Time but for a Call For Release program. The flight is required to take off within a time window typically beginning 2 minutes before the departure release time and closing 1 minute after the departure release time. (Note that this is a 4-minute window from X-2:00 to X+1:59.)
Deviation	Deviation is defined in FAA Order 7110.65 as “A departure from a current clearance, such as an off course maneuver to avoid weather or turbulence.” In the MBT concept, the term deviation is used to mean a trajectory change, either open or closed, that takes the aircraft on a path to avoid a National Airspace System constraint (e.g., other aircraft, closed airspace, or a weather phenomenon).
Downstream	A non-specific future period in time of an air vehicle's flight, implying a different future geographic location. <i>Synonym: downpath</i>
Electronic Flight Bag (EFB)	“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. EFB devices can display a variety of aviation data or perform basic calculations (e.g., performance data, fuel calculations, etc.). In the past, some of these functions were traditionally accomplished using paper references or were based on data provided to the flightcrew by an airline’s flight dispatch function. The scope of the EFB functionality may include various other hosted databases and applications. Physical EFB displays may use various technologies, formats, and forms of communication.” <i>Reference: FAA AFS-400. (2014). AC No: 120-76C. Advisory Circular. Subject: Guidelines for the Certification, Airworthiness, and Operational Use of Electronic Flight Bags. Washington, D.C.: DOT FAA.</i>
Estimated Time of Arrival (ETA)	A prediction of the time at which an aircraft will reach a given point along its expected route. In MBT, ETAs are not trajectory constraints, but will be provided with air vehicle intent.
Expect Departure Clearance Time (EDCT)	The assigned takeoff time for a flight affected by a Ground Delay Program or Airspace Flow Program, and for those flights affected by a Collaborative Trajectory Options Program that travel through the program’s Flow Control Areas. The flight is required to take off within a time window beginning 2 minutes before the EDCT and closing 2 minutes after the EDCT (note this is a 5-minute window from X-2:00 to X+2:59). The EDCT is calculated based on an allocated slot at the constrained resource and the estimated flight time to reach that resource. Through Collaborative Decision Making, airspace users may adjust the EDCTs assigned to their flights by swapping their allocated slots at the constrained resource.

<p>Extended Projected Profile (EPP)</p>	<p>The EPP “indicates the aircraft’s trajectory intent for the next several waypoints as specified in the request either by a number of waypoints or period of time in the future. For each of the waypoints, it includes Latitude, Longitude, and, when available, waypoint name, Level, ETA, Airspeed, Vertical type(s), Lateral type(s), Level constraint, Time constraint, Speed constraint. When available, it includes the relevant data for the trajectory as current gross mass, and EPP trajectory intent status. Includes the date and time of computation.”  <i>Reference:</i> RTCA SC-214. (2016). DO-350A. Safety and Performance Requirements Standard for Baseline 2 ATS Data Communications (Baseline 2 SPR Standard). Washington, D.C.: RTCA.</p>
<p>Flight Management System (FMS)</p>	<p>A specialized computer system that automates a wide variety of piloting tasks. Using data from various sensors that indicate the aircraft’s location and state, the FMS can fly the aircraft along the flight plan. From the cockpit, the FMS is normally controlled through a Control Display Unit (CDU), which incorporates a small screen and keyboard or touchscreen.</p>
<p>Flight Plan</p>	<p>In current National Airspace System operations, the flight plan is the planned route, departure time, cruise altitude, speed, aircraft information, etc., for the flight, which is initially proposed by the operator and subsequently updated by the FAA. In MBT, the Assigned Trajectory Object contains an element called the Flight Plan that includes the airspace user’s business trajectory or Trajectory Options Set and any other information relevant to the requested trajectory that is not included in the other sections of the Assigned Trajectory Object.</p>
<p>Graceful Degradation</p>	<p>In Air Traffic Management operations, graceful degradation refers to systems being able to maintain safety in the presence of degraded modes of operations such that the system does not experience a sudden, steep decline in performance capability.</p>
<p>Ground Delay Program (GDP)</p>	<p>A type of strategic Traffic Flow Management program that delays aircraft going to a particular airport or metroplex at their origin airport, by controlling their takeoff time, in order to regulate the arrival demand as a function of time at a destination with limited capacity. Affected flights receive an Expected Departure Clearance Time. Managed by the Air Traffic Control System Command Center, GDPs utilize a ration-by-schedule methodology and Collaborative Decision Making techniques.</p>
<p>Look-ahead</p>	<p>The time horizon associated with a prediction. In the context of conflict detection, the look-ahead time indicates how far into the future conflict detection algorithms probe.</p>

<p>Management by Trajectory (MBT)</p>	<p>A concept for future Air Traffic Management in which flights are assigned four-dimensional trajectories through a negotiation process between the FAA and airspace users that respects the airspace user's goals while honoring National Airspace System (NAS) constraints and objectives. The pilots and air traffic controllers, each aided by automation, keep the aircraft on its assigned trajectory, which includes complying with temporal or speed constraints. Equipped aircraft have substantial responsibility for complying with the assigned trajectory without controller intervention. The assigned trajectories are constructed to respect all of the known constraints to the flight's destination, making the flight's entire trajectory much more predictable than it is today. Where uncertainty or disruptions occur, resolutions are, to the extent possible, handled through trajectory modifications as far in advance as possible. MBT targets an operational environment in which the NAS, and the vast majority of aircraft, are capable of the advanced data exchange and automation capabilities associated with the Aeronautical Telecommunications Network-Baseline 2.</p>
<p>Miles-in-Trail (MIT)</p>	<p>A traffic management technique in which a criterion for identifying subject flights is defined (such as all the flights flying over the same fix, to or on the same jet route, or that will enter the same sector on specific routes) and consecutive subject flights must be spaced at least the specified number of miles apart, often regardless of altitude. MIT is used to regulate the rate at which aircraft reach a constrained resource (e.g., to avoid overloading a sector or enable merging with another flow), as well as to provide spacing to enable merging additional traffic joining the flow. The MIT restriction technically applies at the fix or sector boundary, but due to the difficulty establishing and maintaining the spacing, the spacing is usually in effect over an extended distance. MIT is relatively easy for controllers since it can be visualized on their radar display. However, MIT is inefficient because, for a period of time, every pair of aircraft receives the same spacing. Time-based traffic management techniques are designed to reduce or eliminate the use of MIT, providing unique restrictions to each aircraft. FAA Order 7110.65 uses the following definition: "A specified distance between aircraft, normally, in the same stratum associated with the same destination or route of flight."</p>
<p>Minutes in Trail (MINIT)</p>	<p>A variation of MIT in which the minimum required separation between consecutive subject flights is expressed as a number of minutes. MINIT is normally used when aircraft are operating in a non-radar environment or transitioning to/from a non-radar environment. It may also be used to space aircraft deviating around weather, since the precise path the aircraft will follow may not be known, and between departures at a runway, since tower controllers can measure time more easily than distance due to the speed differences between a departed aircraft and one about to take off. FAA Order 7110.65 states, "A specified interval between aircraft expressed in time. This method would more likely be utilized regardless of altitude."</p>
<p>Mixed Equipage</p>	<p>An omnipresent condition of the National Airspace System (NAS) in which the avionics equipment and resulting capabilities of aircraft to participate in advanced Air Traffic Management are heterogeneous across the aircraft operating in the NAS.</p>

NAS Constraint	A National Airspace System (NAS) constraint is an element of the NAS that affects the selection of assigned trajectories. A region of special activity airspace that is closed during some period of time is a NAS constraint, as is a procedure that defines elements of the trajectory that must be used to fly an approach to some runway. A region of bad weather that limits capacity and the resulting Traffic Management Initiatives are also examples of NAS constraints. Strong turbulence or unfavorable winds may also be considered NAS constraints.
NAS Constraint Service	MBT includes the concept of a National Airspace System (NAS) Constraint Service that maintains information about all known NAS constraints and publishes it to all stakeholders. Through this service, airspace users and FAA automation systems have access to complete information about the NAS constraints that may affect a flight.
Navigation Capability	In MBT, an air vehicle's navigation capability is the accuracy with which it can achieve a target value in some dimension of navigation. The air vehicle will have some error relative to each trajectory constraint. The aircraft's navigation capability (e.g., Required Navigation Performance or Required Time Performance level) is a metric that defines the maximum navigation error within which the aircraft will usually operate (typically 95%); on rare occasions the aircraft's error may be larger.
Open Trajectory	In MBT, any trajectory that is not a closed trajectory is, by definition, an open trajectory. An aircraft flying an open trajectory implies that the full future trajectory is not described in a digital format and, therefore, is less predictable.
Performance-based Navigation (PBN)	<p>"The PBN concept specifies that aircraft RNAV system performance requirements be defined in terms of the accuracy, integrity, availability, continuity and functionality, which are needed for the proposed operations in the context of a particular airspace concept. The PBN concept represents a shift from sensor-based to performance-based navigation. Performance requirements are identified in navigation specifications, which also identify the choice of navigation sensors and equipment that may be used to meet the performance requirements. These navigation specifications are defined at a sufficient level of detail to facilitate global harmonization by providing specific implementation guidance for States and operators."</p> <p><i>Reference:</i> ICAO. Doc 9613, Performance-based Navigation (PBN) Manual, 2008. ISBN 978-92-9231-198-8. See "Navigation Capability" for added MBT context.</p>
Predicted Trajectory	A predicted trajectory describes the four-dimensional trajectory that a flight is forecast to follow. The predicted trajectory may extend from the flight's current position to its destination, or may be limited to a portion thereof. Predicted trajectories are computed by various mathematical models (a.k.a. trajectory predictors), using the assigned trajectory and other information, including measured and forecast atmospheric data, equations of motion, and the aircraft's characteristics. In MBT, predicted trajectories, as well as data used to generate predicted trajectories, are shared among stakeholders. Multiple predicted trajectories are possible since each may focus on a different application.

Requested Trajectory	The requested trajectory is the trajectory preferred by the airspace user when considering all National Airspace System (NAS) constraints. In response to traffic-related NAS constraints, the airspace user may request (i.e., begin negotiation) with a trajectory that is different than its business trajectory. The use of a requested trajectory that differs from the business trajectory allows the airspace user more self-determination over how a NAS constraint will be translated into trajectory constraints during negotiation.
Required Navigation Performance (RPN)	A type of performance-based navigation (PBN) that allows an aircraft to fly a specific path between points in three-dimensional space. RNP also refers to the level of performance required for a specific procedure or region of airspace. An RNP of 10 means that the air vehicle's navigation system must be able to calculate its position to within a square with a lateral dimension of 10 nautical miles. An RNP of 0.3 means the aircraft navigation system must be able to calculate its position to within a square with a lateral dimension of 3/10 of a nautical mile. In current RNP procedures, all aircraft using the RNP procedure are expected to operate according to the same performance capability equal to the RNP level, although many aircraft may actually be able to navigate more accurately. In MBT, each aircraft could be assigned a unique tolerance based on that air vehicle's performance capability.
Required Time of Arrival (RTA)	A system-determined time that can be assigned to an aircraft that defines the time at which the aircraft is required to cross a fix. "The time at which the system is required to cross a fix." <i>Reference:</i> RTCA SC-227. (2014). DO-236C, Change 1. Minimum Aviation System Performance Standards: Required Navigation Performance for Area Navigation. Washington, D.C.: RTCA.
Required Time Performance (RTP)	RTP is used in MBT as a concept similar to Required Navigation Performance (RNP), but for time. The MBT concept envisions that aircraft will have RTP values similar to current-day RNP levels. This will allow all aircraft, regardless of equipage, to be assigned a Required Time of Arrival. The aircraft's RTP value will be based on the precision with which it can meet an assigned time (e.g., +/- 10 sec, +/- 30 sec).
Residual Uncertainty	Trajectory prediction uncertainty that remains after the implementation of MBT.
Scheduled Time of Arrival (STA)	A type of time constraint produced by Time Based Flow Management that specifies the planned time at which a flight should cross a particular point or line/arc in the airspace (i.e., a metering point). STAs (and Controlled Times of Arrival) are constraints from the Traffic Flow Management system that the Air Traffic Control system could implement via various techniques such as speed restrictions or path stretch.
System Wide Information Management (SWIM)	An FAA platform that facilitates greater sharing of Air Traffic Management system information, such as airport operational status, weather information, flight data, status of special use airspace, and National Airspace System (NAS) restrictions. SWIM supports current and future NAS programs by providing a flexible and secure information management architecture for sharing NAS information.

<p>Time Based Flow Management (TBFM)</p>	<p>An FAA automation system used to manage arrival flows into congested Terminal Radar Approach Control airspace and airports, in which flights are assigned Schedule Times of Arrival (STAs) at metering points along their routes and required amounts of delay to comply with the next STA. In the current environment, controllers issue speed and vector commands to impose this delay. Also used to manage departures either joining metered arrival flows or merging at constrained airspace transitions into Air Route Traffic Control Center airspace. Also used to refer to the approach of using time-based rather than distance-based traffic management. Compared to miles-in-trail, TBFM provides a more-efficient traffic flow and increases capacity because the separation between pairs of aircraft can be uniquely set rather than all pairs needing the same MIT spacing.</p>
<p>Time Constraint</p>	<p>In MBT, a type of constraint used within the assigned trajectory to assign “an aircraft time requirement to be met at a specified downpath waypoint.” A time constraint may originate from a Scheduled Time of Arrival, Controlled Time of Arrival, Expected Departure Clearance Time, Departure Release Time, or to separate aircraft at a point in space, for example. <i>Reference:</i> RTCA SC-227. (2014). DO-236C, Change 1. Minimum Aviation System Performance Standards: Required Navigation Performance for Area Navigation. Washington, D.C.: RTCA.</p>
<p>Traffic Flow Management (TFM)</p>	<p>The set of systems, actors, and procedures by which the FAA manages air traffic to maximize efficiency, minimize delay, and maintain safe controller workload, given the traffic demand and status of National Airspace System (NAS) resources. In MBT, TFM determines many of the NAS constraints that affect trajectory negotiation. The Traffic Flow Management System is a suite of automation tools that serves as the FAA’s primary system for planning and implementing traffic management initiatives (TMI) to mitigate demand and capacity imbalances throughout the NAS. TFMS monitors demand and capacity information, assesses the impact of system constraints, provides alerts, and helps determine appropriate adjustments.</p>
<p>Trajectory</p>	<p>A description of the continuous path that an aircraft may fly, will fly, or has flown.</p>
<p>Trajectory Based Operations (TBO)</p>	<p>The FAA’s high-level vision for the future of the NAS in which four-dimensional trajectories and time-based management are the core of air traffic control and air traffic management. MBT is one specific interpretation of how the FAA’s TBO vision could be accomplished.</p>
<p>Trajectory Constraint</p>	<p>A trajectory constraint is a requirement, specific to a flight, with which the aircraft’s trajectory must comply. National Airspace System (NAS) constraints are non-negotiable; the trajectory constraints that result from NAS constraints may be negotiated. For example, a Controlled Time of Arrival (CTA) at a constrained airport is a trajectory constraint associated with reduced capacity at the destination airport (NAS constraint). The airspace user can negotiate a different CTA, but cannot negotiate a change to airport capacity. Trajectory constraints are included in the assigned trajectory.</p>



<p>Trajectory Description</p>	<p>The trajectory description and trajectory constraints fully define the assigned trajectory. Since the trajectory constraints are as minimal as possible to provide maximal airspace user flexibility, the set of trajectory constraints may not completely describe a four-dimensional trajectory (4DT); the trajectory description provides the remaining trajectory information needed to describe the aircraft’s 4DT. In cases where few trajectory constraints are required, the trajectory description is used so that that the assigned trajectory is a sufficiently detailed 4DT. The trajectory description provides additional information about how the aircraft will fly, in compliance with the trajectory constraints, necessary to support trajectory prediction and stability.</p>
<p>Trajectory Negotiation</p>	<p>In MBT, trajectory negotiation refers to a process between the airspace user and the FAA to select an assigned trajectory to which the airspace user agrees and the that satisfies National Airspace System constraints and other FAA objectives (such as efficient use of airspace resources and conflict avoidance). Both airspace users and the FAA may initiate negotiation to modify an assigned trajectory. Negotiation may involve multiple iterations back and forth or may be limited to the FAA providing a necessary modification and the airspace user accepting it (unless the proposed modification jeopardizes the safety of flight).</p>
<p>Trajectory Non-conformance</p>	<p>The MBT concept includes three types of trajectory compliance: non-conformance, predicted non-conformance, and deviation from trajectory prediction.</p> <ul style="list-style-type: none"> <li>• Non-conformance occurs when an aircraft is (e.g., a system has detected this condition) out of compliance with the assigned trajectory, meaning it has failed to comply with a trajectory constraint/description within the required accuracy (where the required accuracy is part of the assigned trajectory specification).</li> <li>• Predicted non-conformance occurs when a system predicts that a flight will not comply with (or will be unable to comply with) the assigned trajectory.</li> <li>• Deviation from trajectory prediction occurs when a flight has deviated from its predicted trajectory by more than a defined prediction uncertainty envelope, although the flight may still be in compliance (and predicted compliance) with its assigned trajectory. Deviation from the predicted trajectory requires updating the prediction and assessing whether the assigned trajectory will be violated and whether any conflicts exist.</li> </ul>
<p>Trajectory Options Set (TOS)</p>	<p>A ranked set of preferred trajectories for a flight, provided by the airspace user. The set includes information that describes when lower-ranked trajectories would be preferred over higher-ranked trajectories. In the current National Airspace System, TOSs are associated with the Collaborative Trajectory Options Program. In MBT, an airspace user providing and maintaining a TOS could improve negotiation efficiency.</p>
<p>Trajectory Predictability</p>	<p>A measurement of the accuracy with which an aircraft’s trajectory is predicted. Trajectory prediction errors result from modeling errors, changes in the aircraft’s intent, and changes in the assigned trajectory. Changes in air vehicle intent or the assigned trajectory are measures of trajectory stability.</p>

Trajectory Stability	A notional concept in MBT for a measurable property of a trajectory that describes the magnitude of changes in the aircraft's intent and the assigned trajectory. A trajectory that is not stable cannot be predictable.
Upstream	Refers to a non-specific previous period in time of a flight, implying a different geographic location from the aircraft's current location.
Vectoring	Tactical commands issued by a controller to a flight to attempt to achieve the controller's goals. Strictly, vectoring includes turning the aircraft's heading. Often the term refers to any tactical instructions, which could include speed commands or altitude changes, that are not implemented through a reroute or other flight plan amendment. Vectoring creates an open trajectory since the controller does not predefine in any digital form the complete and precise trajectory modification.

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<b>14. ABSTRACT</b> This document describes Management by Trajectory (MBT), a concept for future air traffic management (ATM) in which every flight operates in accordance with a four-dimensional trajectory (4DT) that is negotiated between the airspace user and the Federal Aviation Administration (FAA) to respect the airspace user's goals while complying with National Airspace System (NAS) constraints.					
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