



Initial Concept of Operations for Full Management by Trajectory

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Executive Summary

This document describes Management by Trajectory (MBT), a concept for future air traffic management (ATM) in which flights are assigned four-dimensional trajectories (4DTs) through a negotiation process between the Federal Aviation Administration (FAA) and flight operators that respects the flight operator's goals while complying with National Airspace System (NAS) constraints.

In the present day NAS, the ATM system has a predicted trajectory for each flight based on the approved flight plan and scheduled or controlled departure time. 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.

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. This makes NAS demand predictions less accurate.

A cornerstone of MBT is that all aircraft are assigned a 4D trajectory from their current state to their destination. 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. Equipped aircraft have substantial responsibility for complying with the assigned trajectory without controller intervention. All aircraft also maintain current and accurate information about aircraft capabilities and intent.

A NAS constraint service gathers and publishes information about all known NAS constraints, so that flight operators can make informed decisions when negotiating 4DTs with the FAA. Trajectory constraints are mapped to NAS constraints to facilitate identifying affected aircraft when NAS constraints change.

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. MBT eliminates most local, reactive control actions being applied to aircraft, which both cannot be predicted in advance and the impact of which on the downstream trajectory are not 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 done proactively, maximizing trajectory predictability and delivering associated benefits.

Flight operators share aircraft intent with the FAA, which is a description of the operator's plan for how the flight will fly the assigned trajectory. The assigned trajectory, together with the aircraft intent, enable accurate prediction of the 4DT that the aircraft will fly. Aircraft intent can change freely, without negotiation, as long as it is still in compliance with the assigned trajectory. A change to any part of the assigned trajectory requires negotiation. Aircraft assigned trajectories, intent, and predicted trajectories are shared, creating a common view among stakeholders.

In addition to maintaining assigned trajectories and aircraft intent to improve predictability, MBT strives to keep aircraft on closed trajectories that are fully known to all stakeholders. In particular, tactical controller actions, such as vectors to resolve traffic conflicts, are minimized. For the most part, this is accomplished through the ability to use reliable trajectory predictions to adjust assigned trajectory constraints in order to resolve conflicts earlier than is possible today. In addition, controller tools for easily building and communicating closed trajectories to the aircraft in place of open-ended vectors are proposed.

Anticipated MBT benefits include improved efficiency (i.e., capacity increases, delay reductions, and reduced operational costs), increased flexibility, better predictability, greater robustness to off-nominal conditions, reduced environmental impacts, and enhanced safety.

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Acronyms

| Acronym | Definition |
|---------|--|
| 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 |
| ATC | Air Traffic Control |
| A-IM | Advanced Interval Management |
| ATM | Air Traffic Management |
| ATN-B2 | Aeronautical Telecommunications Network – Baseline 2 |
| ConOps | Concept of Operations |
| CPDLC | Controller-Pilot Data Link Communications |
| CTA | Controlled Time of Arrival |
| EA | Enterprise Architecture |
| EDCT | Expect Departure Clearance Time |
| EFB | Electronic Flight Bag |
| ERAM | En Route Automation Modernization |
| ETA | Estimated Time of Arrival |
| FAA | Federal Aviation Administration |
| FMS | Flight Management System |
| FOC | Flight Operations Center |
| GDP | Ground Delay Program |
| ICAO | International Civil Aviation Organization |
| IFR | Instrument Flight Rules |
| LOA | Letter of Agreement |
| MBT | Management By Trajectory |
| MINIT | Minutes in Trail |
| MIT | Miles In Trail |
| NAS | National Airspace System |
| 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 |
| SWIM | System Wide Information Management |
| TBFM | Time Based Flow Management |
| TBO | Trajectory Based Operations |
| TCAS | Traffic Collision Avoidance System |
| TFM | Traffic Flow Management |
| TFMS | Traffic Flow Management System |
| TMC | Traffic Management Coordinator |
| TMI | Traffic Management Initiative |
| TOAC | Time Of Arrival Control |
| TOS | Trajectory Options Set |
| TRACON | Terminal Radar Approach Control |
| UAS | Unmanned Aircraft Systems |

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 scheduled or controlled departure time. Once the aircraft starts to move, controllers tactically manage the aircraft, using vectors, altitude changes, and speed clearances, to implement traffic management restrictions, separate otherwise conflicting aircraft, and address arising NAS constraints. The current system tends to be conservative 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 flight operator'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 flights are assigned four-dimensional trajectories (4DTs) through a negotiation process between the Federal Aviation Administration (FAA) and flight operators that respects the flight operator's goals while complying with NAS constraints.¹ 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 both cannot be predicted in advance and the impact of which on the downstream trajectory are not 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 done proactively, maximizing trajectory predictability and delivering associated benefits.

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

¹ In this way, MBT is similar to TBO concepts that employ a 4D contract.

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.

Table 1. NAS Shortfalls Addressed by MBT

| Shortfalls | MBT Improvements |
|---|---|
| Data exchanged between flight operators and the FAA is too sparse to support accurate trajectory prediction across all phases of flight and trajectory synchronization across automation systems. | The data needed by all relevant flight operator, aircraft, and FAA automation systems to develop accurate, consistent 4D trajectory predictions is 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 results 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 4D trajectories 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 costly unrecoverable delay. |
| Lack of knowledge about certain types of constraints prevent flight operators 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. | All applicable NAS constraints, both dynamic (e.g., TFM) and static (such as crossing restrictions) are published such that they can be known by all flight operators and relevant automation systems. All constraints affecting a given aircraft are reflected in the 4D trajectory. |
| Insufficient mechanisms to allow traffic managers and controllers to efficiently and effectively amend flights' routes cause route amendment backlogs during disruptive NAS events. | Traffic managers apply constraints to efficiently amend trajectories as NAS events evolve, enabling a more flexible and responsive FAA that |

| | |
|---|---|
| | can take full advantage of available airspace and drastically reduce unrecoverable delay. ² |
| 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. | Downstream effects of actions on a trajectory are considered in decision making associated with a given trajectory, including tactical control actions. |
| "Bookend" time of arrival control (TOAC) standards create a mixed equipage environment in which some aircraft cannot be assigned a Required Time of Arrival (RTA). | Performance-based time standards allow all aircraft to be assigned an RTA, eliminating mixed equipage and enabling TBO. |

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 from their current state to their destination.
- 4DTs are influenced by specifying requirements (in the lateral, vertical, and longitudinal/temporal dimensions) to achieve TFM objectives and maintain aircraft separation.
- 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.
- Aircraft operators have the opportunity to negotiate the assigned 4DT, and relevant information to inform negotiation is available to all stakeholders.
- Assigned 4DTs are accessible to all stakeholders.
- All aircraft follow assigned 4DTs, complying with trajectory constraints.
- Trajectory constraints and associated tolerances are defined based on the flight's individual performance capabilities.
- Aircraft provide detailed information about their predicted 4DT (a.k.a. intent data) which is shared across stakeholders. Aircraft provide updates when intent data changes.
- Sharing aircraft-predicted trajectories with ground-based automation systems improves conflict detection and TFM applications, since all systems have access to more consistent trajectory predictions.
- Closed trajectory operations emphasize the use of time constraints to achieve strategic TFM initiatives. Interval management will be integrated into assigned trajectories in dense and complex airspace.
- Conflicts can be detected farther in advance due to improved predictability and intervention can be accomplished through adding or modifying constraints in the assigned 4DT.
- Tactical vectoring by controllers (for which the controller's intent is unknown by other actors in the system) is minimized.
- Pilot-initiated open-trajectory aircraft deviations around weather (for which the pilot's intent is unknown by other actors in the system) are minimized.

² 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.

- 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 FMS.
- Broadband air-ground communications and advanced electronic flight bag (EFB) applications are used to include the flight crew in the trajectory negotiation process.
- D-side sector controllers and traffic management coordinators (TMCs), with their longer time horizon perspectives, are increasingly important in proactively intervening 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. As such, this document describes more of a future vision than a focused concept; the line between what is part of the concept and what is part of the environment at that point in time is blurred since both the concept and the assumptions about the environment in which it operates are parts of the future vision.

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 will differ in two ways. First, the near-term concept is constrained by the current NAS and currently planned changes to the NAS, while the far-term concept may make assumptions about future enabling changes. Second, the far-term concept is intended to encompass the entirety of air traffic control (ATC) within the NAS. In contrast, the near-term concept describes particular TBO operations that could be feasible (and beneficial) within the constraints of the current NAS and changes that the FAA plans and are documented within the NAS Enterprise Architecture (EA) evolution within the NextGen timeframe.

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.

Aircraft capabilities and equipage will be consistent with the current progression of safety and performance standards.

The capabilities of highly-equipped aircraft will not change. For example, aircraft flight management systems (FMS) that include 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 flight operators will continue at its current pace. Equipped aircraft from participating operators will experience 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 voice-issued vectors (open trajectories).

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 aircraft 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 enroute 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 will have Required Time Performance (RTP) values similar to current-day Required Navigation Performance (RNP) levels. This will allow all aircraft, regardless of equipment, to be assigned an RTA. 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).

Flight operators' 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). New aircraft classes may initially have reliable digital communication and use MBT, even in non-IFR portions of the NAS.

The NAS automation systems will evolve toward a service-based architecture, in which ATC and ATM functions will be based on services rather than systems.

1.6 Document Scope

1.6.1 Airport Surface

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.

One of the unique challenges to the application of MBT on the airport surface is that aircraft autopilot systems are not designed to steer the aircraft during taxi, although some research has been done on cockpit aids, including EFB applications, to help pilots follow a 3-dimensional (3D) (horizontal position and time) assigned trajectory on the airport surface. There are also concept details that would need to be studied to apply MBT to surface operations. In current operations, aircraft begin taxiing when they are ready, unless excess demand for the runways requires gate holding to manage the runway queue. The uncertainty in when a flight will be ready to block out from its parking gate presents challenges in assigning a block-out time as part of a preplanned assigned surface trajectory. However, without a start time, a conflict free taxi trajectory to the runway cannot be determined. Finally, due to limitations associated with the use of datalink (e.g., the pilot needs time to receive and consider the information, transmission times are not required to be faster than 350 seconds [1]), trajectory changes via datalink must be done sufficiently far in advance that ground controllers would be unable to use datalink to provide changes to the taxi clearance once the aircraft is taxiing out. In combination, these issues require a different approach to applying MBT on the surface. Application of MBT on the surface is a candidate for future research.

Application of TBO elements are 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 [2].

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 enroute operations. 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 enroute and surface environments.

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 TMLs.

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 4D trajectories 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 in order 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 ConOps is organized as follows:

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

Note that this is a preliminary ConOps, and as such there are several open questions that have been identified and must be addressed in order to implement the concept. Some of these questions are denoted in text boxes in *italic text* starting with “**Open Question**” in **bold italic text**.

2. Definitions

This chapter presents definitions 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. 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.

Some TBO concepts define the trajectory to be the continuous path, while others define a trajectory as a series of waypoints (i.e., a continuous path could be drawn through the waypoints). In this document, we will use the term trajectory to mean a description of the continuous path that an aircraft may fly, will fly, or has flown, even where this description does not fully describe the continuous path.

The MBT concept uses several types of trajectories. Initially, the flight operator provides a *business trajectory* which 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 required 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 it 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 flight operator or the FAA. The flight operator 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 instructs the aircraft how it may fly and that is 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, or renegotiate before reaching that point along the trajectory. To maximize flight operator 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 aircraft 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 aircraft intent will indicate the estimated time the flight will cross that waypoint. The aircraft intent data may also include additional waypoints not included 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 aircraft intent data, while time constraints (e.g., resulting from TBFM Scheduled Times of Arrival, or 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.³ Time constraints must be changed through the negotiation process.

If the flight operator 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. If the flight operator provided a very dense description of how the aircraft will fly, the assigned trajectory may omit some details, which will be included in the aircraft intent.

Collectively, the assigned trajectory describes what the flight has committed to doing (i.e., is required to do unless changed through negotiation) and the aircraft 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 is comprised of the trajectory constraints and a trajectory description. The trajectory constraints are the minimum set of requirements that achieve FAA conflict avoidance and TFM objectives. The trajectory description provides the additional information about how the aircraft will fly, in compliance with the trajectory constraints, necessary to support trajectory prediction.</p> <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 flight operator'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 are the results of 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> |

³ To strategically avoid conflicts, the FAA relies on both the assigned trajectory and aircraft intent. If the aircraft 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.

| | |
|-----------------------|--|
| Aircraft Intent | <p>The aircraft intent is a description, provided by the flight operator, of the operator's plan for how the aircraft will fly. The assigned trajectory, together with the aircraft intent, enable accurate prediction of the trajectory that the aircraft will fly from its current location to the destination.</p> <p>Aircraft 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. Aircraft intent provides more detail. The aircraft intent should fully conform to the assigned trajectory.</p> <p>The aircraft intent data will include the 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 [1]. Aircraft intent will extend beyond the current EPP specification. For example, aircraft intent may include the planned speed profile on each route segment.</p> <p>MBT requires all IFR flights to provide aircraft intent data, which can be accomplished by the FMS, EFB, ground automation⁴, or a combination thereof.</p> |
| Flight Plan | <p>The flight operator'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 aircraft intent.⁵</p> |
| Aircraft Capabilities | <p>Knowledge of the aircraft's capabilities and limitations is essential to planning efficient and feasible assigned trajectories. If aircraft capabilities change during a flight, the aircraft or flight operator must update this information.</p> |

Open Research Topic

What trajectory constraint/description information needs to be negotiated versus provided through aircraft intent?

There is overlap between the trajectory description and the aircraft intent. The trajectory description is part of the assigned trajectory and, therefore, requires negotiation to change. The trajectory description does not contain anything that the aircraft intent could not also

⁴ In the long-term, flight operators 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 flight operator ground automation. In this vision of the future, aircraft intent data could be provided by any of these systems.

⁵ If all of the necessary flight plan and business trajectory data is included in the assigned trajectory and the aircraft intent, then this part of the assigned trajectory object may be eliminated.

contain. The aircraft intent potentially provides more detail and precision, and does not require negotiation to change. Due to the additional detail (e.g., top of descent point) and precision (e.g., specific planned speed rather than a 10 knot range), using the aircraft intent (or the full assigned trajectory object) will improve trajectory prediction, relative to only using the assigned trajectory. If the purpose of some of the content of the trajectory description is to support trajectory prediction, then this content might need to appear only in the aircraft intent, reducing the burden of negotiating changes to those trajectory elements. However, a consequence may be that the assigned trajectory by itself would no longer sufficiently describe the aircraft's trajectory. The assigned trajectory, by itself, might not be considered a 4DT; the combination of the assigned trajectory and aircraft intent would enable sufficient trajectory prediction to be considered a 4DT.

If the constraints – the things the aircraft has to do unless it negotiates – are to be the minimum set the NAS needs for trajectory prediction, then those constraints will not fully define the 4D trajectory that the aircraft will fly. If the assigned trajectory is required to include all of the data the NAS needs for trajectory prediction, then the assigned trajectory would be forced to include a certain amount of data that otherwise may not need to be negotiated.

Alternatively, if the assigned trajectory does not need to by itself constitute a trajectory (which may cause a change to its name), and the assigned trajectory object as a whole is what supports trajectory prediction, then flight operators will have more flexibility to manage their trajectories in compliance with the constraints.

2.3 Assigned Trajectory

The MBT concept uses an assigned trajectory as the plan for the trajectory that the aircraft will fly that includes the data elements that require coordination to achieve FAA objectives. This is distinct from aircraft intent that fully describes the trajectory that is planned to be flown. Other literature refers to similar concept elements using terminology such as the controlled trajectory, the negotiated trajectory [3], or the agreed trajectory [4].

The assigned trajectory is an agreement between the FAA and aircraft/flight operator as to where and when the aircraft will fly. The aircraft is cleared to fly the assigned trajectory to the destination. A clearance limit is not used within 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. In accordance with the International Civil Aviation Organization (ICAO) TBO concept (currently under development), there is always a clearance limit associated with international boundaries [5].

The assigned trajectory is constructed in two parts: trajectory constraints and a trajectory description. The trajectory constraints are the minimum set of requirements that achieve ATM needs (i.e., conflict avoidance) and TFM needs. 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 flight operator'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 aircraft intent provide information about the aircraft's trajectory.

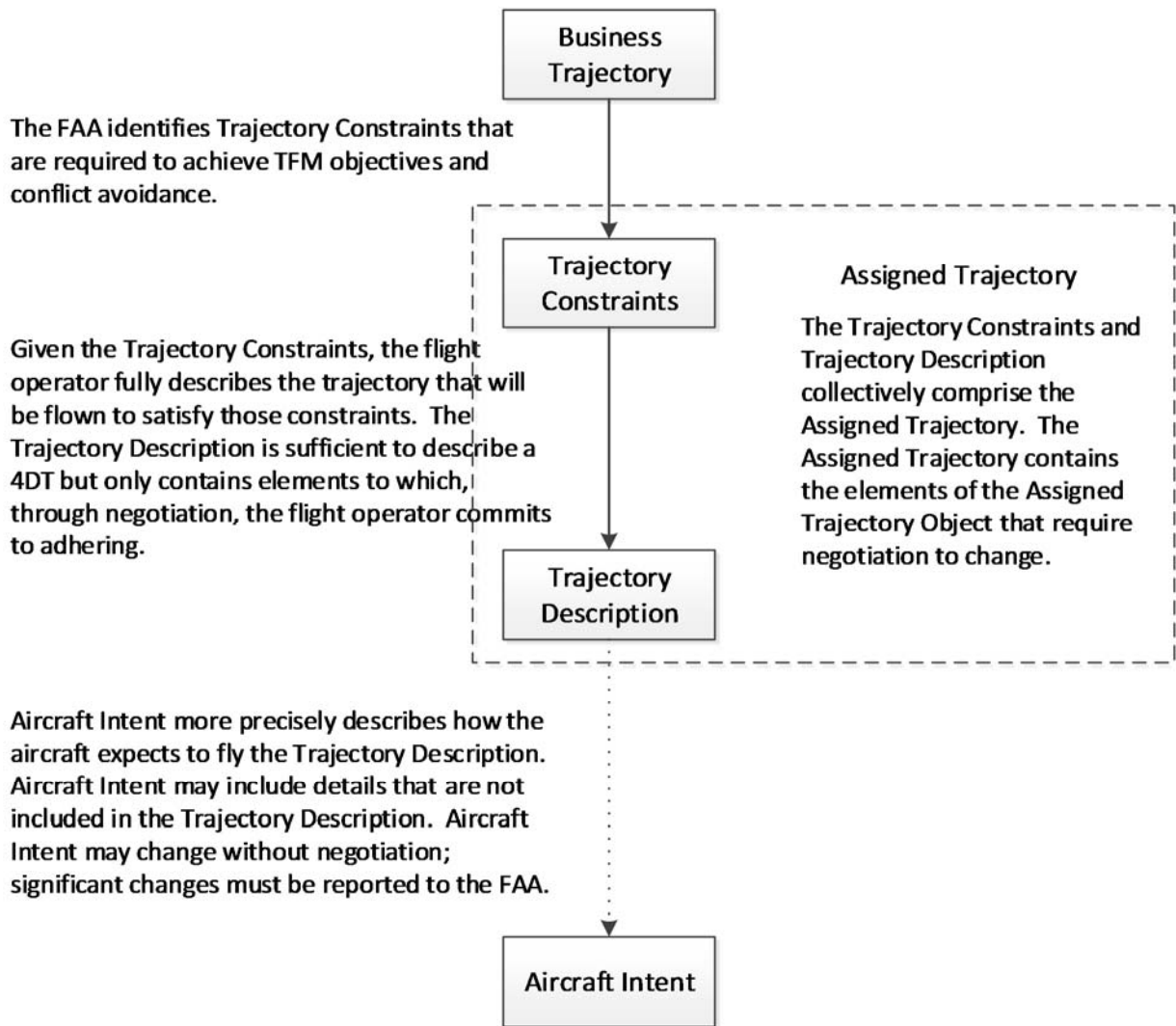


Figure 1. Notional Relationship between Assigned Trajectory Object Elements

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 flight operator cannot choose to fly at FL350, for example, without first negotiating that change.

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 flight

operator may negotiate to alter them. Similarly, while the flight operator 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 aircraft 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 flight operator 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 provided in the aircraft intent. Details of what level of information will be in the trajectory constraints, trajectory description, and aircraft intent remains 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 which 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 aircraft intent and the predicted trajectory.

As time passes, the assigned trajectory will 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 flight operator may negotiate to change the assigned trajectory for business reasons.

2.4 Constraints

The noun “constraint” is used in a few different ways in this document. 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 trajectories⁶. A region of special activity airspace (SAA) that is closed during some period of

⁶ 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.

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. Strong turbulence or unfavorable winds may also be considered to be 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 flight operator has no ability to change NAS constraints (e.g., the TFM system determines when to use a GDP). In contrast, the flight operator may change trajectory constraints through the trajectory negotiation process. Trajectory constraints are constraints in the sense that the aircraft must comply with them – the operator has agreed to them by agreeing to the assigned trajectory unless it negotiates a change to the assigned trajectory.

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 flight operator 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 flight operator can try to negotiate for a different crossing time, perhaps by swapping times with another one of its flights over that fix.

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.⁷

Table 3 shows common types of trajectory constraints. Strictly greater than (i.e., >, faster than, above, after) and strictly less than (i.e., <, slower than, below, before) are excluded because, while they could exist in a mathematical sense, there would be no operational use distinct from "equal to or greater than" and "equal to or less than."

The operational need and benefit for "between" type constraints (> & <) is debatable and warrants focused research. There is some additional cost to including "between" constraints in the MBT concept, since support for this type of constraint does not currently exist in FMSs. Between type trajectory constraints could also be expressed as "At [*middle value*] ± [*tolerance*]". However, this format suggests that the middle value is the target. In a between type trajectory constraint, all values in the range are equally conforming to the constraint.

"Equal to or greater than" and "equal to or less than" are probably not applicable to lateral constraints, unless a constraint such as, "stay left of some point or path" is needed.

A not equal to (≠) constraint might be useful to avoid certain regions of airspace, although a more specific route to be followed is more likely to be used.

Additional types of trajectory constraints may be useful, based on further research. For example, traffic aware trajectory constraints, such as "cross safely behind" a specified aircraft,

⁷ 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 between the preceding and following trajectory constraints. Whether or not trajectory constraints will be required to improve trajectory predictability is uncertain and warrants focused research.

may be a more efficient way to manage dependent traffic while maintaining the flexibility necessary to handle uncertainty.

Table 3. Trajectory Requirement Types

| Type | Speed | Altitude | Time | Lateral | Interval Management |
|----------------|---|---|--|--|--|
| = | AT <i>speed</i> | AT <i>altitude</i> | AT <i>time</i> | CROSS <i>waypoint</i> FOLLOW <i>route</i> FOLLOW <i>procedure</i> | FOLLOW <i>aircraft</i> AT <i>distance/ time</i> |
| \geq | AT OR ABOVE <i>speed</i> | AT OR ABOVE <i>altitude</i> | AT OR AFTER <i>time</i> | N/A | FOLLOW <i>aircraft</i> BY AT LEAST <i>distance/time</i> |
| \leq | AT OR BELOW <i>speed</i> | AT OR BELOW <i>altitude</i> | AT OR BEFORE <i>time</i> | N/A | N/A |
| $\geq \& \leq$ | AT OR ABOVE <i>speed</i> ₁ and AT OR BELOW <i>speed</i> ₂ | AT OR ABOVE <i>altitude</i> ₁ and AT OR BELOW <i>altitude</i> ₂ | AT OR AFTER <i>time</i> ₁ and AT OR BEFORE <i>time</i> ₂ | CROSS <i>waypoint</i> WITHIN <i>tolerance</i> FOLLOW <i>route</i> WITHIN <i>tolerance</i> | FOLLOW <i>aircraft</i> BY AT LEAST <i>distance/time</i> ₁ and NOT MORE THAN <i>distance/time</i> ₂ |

2.4.3 Other Constraints

There are other types of constraints that affect the 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 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 aircraft 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.

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, flight operators 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 flight operator 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 flight operator will know to consider changing the business trajectory, which could happen pre-departure or after takeoff. The flight operator 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

Trajectory Options Set (TOS), the FAA can automatically evaluate the alternative trajectories in response to the change in the NAS constraint. See Section 3.16 for a discussion of how NAS constraint changes and TOSs will interact.

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 would be a shared responsibility between the operator 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 operator chose a route due to an area of bad weather, the operator would need to reference the NAS constraint representing the weather, since the FAA could not know why the operator chose that particular route.

2.4.6 Performance Capabilities

An aircraft's 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. In the future, aircraft will have similar performance levels for vertical navigation and temporal navigation. The aircraft's performance capabilities in each dimension will be part of the aircraft 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 flight operator 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. 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. The RNP value defines the tolerance on the constraint.

In MBT, each aircraft may have unique performance capabilities. Therefore, in MBT, 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. In MBT, the tolerance on a trajectory constraint is equal to that flight's performance capability in that dimension. 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.

Table 4 illustrates the assigned trajectory associated with a notional flight, AAL90, from Dallas-Fort Worth to Chicago O'Hare. Table 4 does not represent a proposed schema for the assigned trajectory; rather, it is intended to illustrate the concept described in this section.

Table 4. Notional Assigned Trajectory

| Waypoint/Route Segment/Procedure | Altitude | Crossing Time | Speed Constraint | Performance Requirement | IM | NAS Constraint Reference |
|----------------------------------|----------|--|-------------------------|-------------------------|----|--|
| DFW RWY 36L | | AT OR AFTER 09:53:00 AT OR BEFORE 09:55:00 | | | | #6879 Standard Procedure |
| AKUNA6 | | | | Standard | | #9232 Standard Procedure |
| MCL | At FL350 | AT OR AFTER 10:16:00 AT OR BEFORE 10:21:00 | | | | |
| SGF Extended Meter Point | AT FL350 | AT 10:54:00 | | RTP 10 sec | | #444 Extended Metering 3 min delay |
| WELTS | AT FL350 | AT OR AFTER 11:09:00 AT OR BEFORE 11:13:00 | | RNP 0.5 | | |
| SGF Coupled Meter Point | AT FL350 | AT 11:16 | | RTP 10 sec | | #555 Coupled Scheduling 2 min delay |
| VINCA | AT FL350 | | AT OR BELOW M0.78 | RNP 0.25 | | |
| TRTLL4 | | | | Standard | | |
| RINNO | | AT 11:50:00 | | RTP 10 sec | | #2228, ORD TSS |
| ORD RWY 27L | | AT 11:58:00 | | RTP 10 sec | | #468, ORD Reduced AAR (GDP) |

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

flight operator'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 provides 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

The assigned trajectory defines the requirements the aircraft's trajectory must meet (i.e., the trajectory constraints) as well as the trajectory description. The aircraft intent describes how the aircraft intends to fly. 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 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.

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 flight operator would have the aircraft fly if that were the only aircraft operating in the NAS.⁸ This is the trajectory preferred by the flight operator when considering

⁸ The business trajectory may consider other flights operated by the same flight operator. For example, a flight operator with four flights scheduled to depart from Chicago (ORD) at the same time may provide business

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 TMIs or other aircraft.

The constrained business trajectory is the trajectory preferred by the flight operator when considering whatever NAS constraints the operator chooses to consider. The NAS constraint service will provide the operator information about all known NAS constraints. The use of a constrained business trajectory allows the flight operator 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 which the operator does not like for some reason, the operator may respond with a new business trajectory, called a constrained business 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 constrained business 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 operator. During the MBT cognitive walkthrough, 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 flight operator's business trajectory. During trajectory negotiation for the initial assigned trajectory, the flight operator may provide a more detailed business trajectory as the starting point for negotiation. During operation, the flight operator 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 will continue to use it and define it 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.

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.

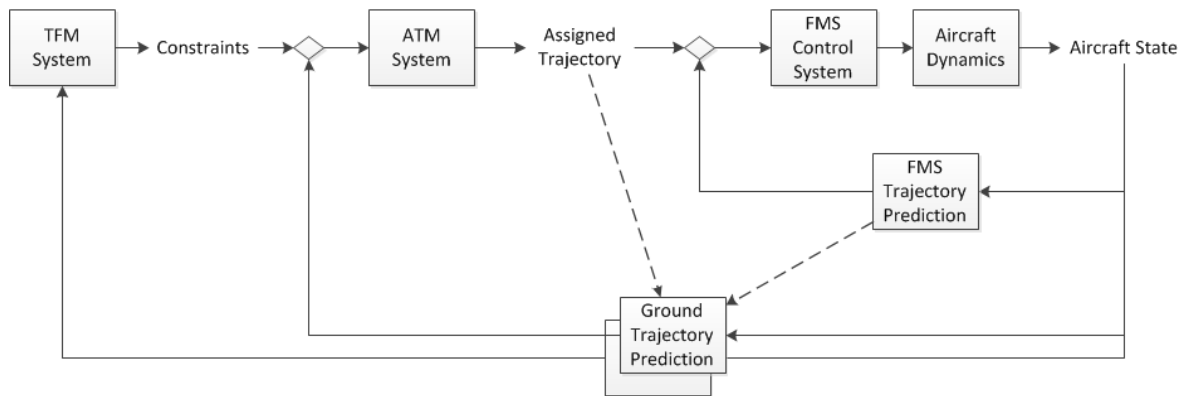


Figure 2. Notional Closed-Loop Control System following an MBT Assigned Trajectory

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.

The MBT concept requires that the closed trajectory start from the aircraft's current state and extend to the aircraft's destination. This requirement results from the need to predict the trajectory all the way to the aircraft's destination.

The assigned trajectory is always fully known by the ATM system's ground automation.⁹ 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 have been violated.

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 previously 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-

⁹ 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.

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.¹⁰ 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 aircraft capabilities. The 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., speed constraints cannot exist on a route segment over which an aircraft is managing its speed to comply with an RTA).¹¹

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

¹⁰ 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.

¹¹ Current FMS technology cannot accept a simultaneous speed constraint and RTA goal. Therefore, within current technology, no speed constraints can be used over the portion of route that the aircraft is flying to achieve an RTA.

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 aircraft intent, but the aircraft is free to change its speed as needed without negotiation.

Predictability in the time dimension is affected both by the constraints and the availability of aircraft 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, aircraft 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 aircraft 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.

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. Concept Elements

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

3.1 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 to current NAS operations.

3.2 Airspace Structure and User Preferred Routes (UPRs)

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 areas of airspace (e.g., high density airspace) and free routing in other areas (low and medium density airspace), or there may be fixed routing during busy times of day and free routing at other times.

Flight operators would need to be informed of where/when their business trajectories must conform to a published route structure as part of the definition of 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.

3.3 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 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. Data link can also uplink more complex clearances to the FMS than can be easily transmitted over voice.

3.4 Closed Trajectories

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

3.4.1 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 the MBT concept improving 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 provide support for the controller 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 previously assigned trajectory with the new modification applied) between the ground automation and the aircraft.

3.4.2 Emergency 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.

3.4.3 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.

3.4.4 Pilot Rejects Assigned Trajectory Modification

Knowledge of the aircraft 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.

3.4.5 Vertical Dimension

In present-day aircraft, the autopilot and FMS are not 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. Planning a vertical profile, like planning a lateral route, would be an entirely new way of thinking for pilots and controllers. However, FMSs do assume a vertical profile. Changing how vertical trajectories are planned and flown may be the largest fundamental change proposed by MBT.

In the near-term, vertical operations would resemble the current NAS. In the end-state MBT concept, the negotiated 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 continuous 2D route is defined in the assigned trajectory; negotiation is required to change it. 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.

3.4.6 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 when arriving to an airport, MBT will apply time constraints earlier in time, 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.

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 relative to their cleared speed 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 4D trajectory is negotiated.

3.5 Trajectory Synchronization

3.5.1 Aircraft 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 contains 3D points along the aircraft's predicted route and the estimated times at which the aircraft will reach those points. Intent data also includes 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 near-term, the content of these downlinked messages is defined by the existing EPP specification [1]. 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, flight operators will be required to send data that meets completeness, accuracy, and timeliness requirements.

Aircraft intent data is distributed to stakeholders as described in Section 3.5.2. Ground automation will use the aircraft 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 some 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 may exceed the operational value in many 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, or computed by the flight operator's flight dispatch system and communicated via SWIM.

Aircraft 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 provides the required predictability. An additional requirement is that the aircraft update its intent data whenever it changes significantly.

3.5.2 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, flight operator, 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 forecasts) is 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.

3.6 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 or discarded, or indicate the mode in which the aircraft is operating.

3.6.1 *Trajectory Uncertainty*

Assigned trajectories may have more detail close to where the aircraft is operating and less detail farther 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 constraint 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 aircraft intent will minimize this uncertainty.

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

3.7 Initial Assigned Trajectory Creation and Acceptance

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 Traffic Flow Management System (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.

The flight operator initially informs the FAA of its intent to operate a flight and subsequently provides additional details about the flight in the form of a flight plan. Closer to the scheduled departure time, the flight operator may submit a business trajectory – a proposed trajectory that the operator would like to fly – or a TOS if national-level TMIs are already defined. This submission begins the initial negotiation process that produces the initial version of the assigned trajectory.

The FAA uses the business trajectory 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 will create constraints that flight operator-proposed trajectories must satisfy. FAA automation tools will support the controller and traffic manager in identifying appropriate constraints to add to trajectories, and in reviewing, modifying, and accepting the trajectories generated by flight operators, FAA automation, or other Air Navigation Service Providers.

This constrained trajectory is returned to the flight operator for acceptance or further negotiation. The flight operator (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 flight operator has accepted the trajectory, it represents the assigned trajectory and is published to the assigned trajectory repository to be available to all stakeholders. Whether ground automation trajectory predictions should be published to be available to all stakeholders is an open research question.

3.8 Assigned Trajectory Update Process

The MBT concept envisions that both controllers and traffic managers would have responsibility in different situations for creating and modifying the assigned trajectories. Pilots and FOC personnel may, but are not required to, initiate changes to the assigned trajectory through trajectory negotiation. The process for updating the assigned trajectory is described below.

- 1) The assigned trajectory update process is initiated in one of several ways:
 - (a) The pilot can initiate an update to the assigned trajectory by requesting a trajectory change. Reasons for this include 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.
 - i. The pilot's request will include a proposed change to the assigned trajectory. This represents a new business trajectory that is cognizant of the NAS constraints.
 - ii. 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).
 - iii. A controller or traffic manager approves the new assigned trajectory (first making changes if necessary). (This might

become automatic at some point in the long-term, subject to parameters set by the controller and/or traffic manager.) Then the FAA provides the resulting proposed trajectory to the pilot via automation (e.g., Data Comm to FMS or broadband to EFB).

- iv. If the pilot rejects the proposed trajectory, the pilot may continue trajectory negotiation by submitting a request for a modified trajectory, either based on the most recent proposal or based on the currently assigned trajectory. The output of the trajectory negotiation process is a new assigned trajectory that should be acceptable to all stakeholders.
 - v. If the pilot accepts the proposed trajectory, continue at step 4 below.
- (b) The flight dispatcher can initiate an update to the assigned trajectory by requesting a trajectory change. Reasons for this include 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 updated weather forecasts or turbulence encountered by the aircraft.
- i. 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.
- (c) A controller or traffic manager can initiate an update to the assigned trajectory. Possible reasons for this include a predicted conflict or a change to a NAS constraint.
- i. Automation will help the controller identify the need to amend the assigned trajectory and to construct the new assigned trajectory.
 - ii. 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.
 - iii. If the assigned trajectory change must be coordinated with a traffic manager, the automation will facilitate this coordination.
 - iv. 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.
- 2) The controller or traffic manager takes an action which causes the updated assigned trajectory to be uplinked to the aircraft via Data Comm. The updated assigned trajectory is also provided to the dispatcher.
- 3) The pilot loads the clearance into the FMS and evaluates it.
- 4) 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.
- 5) 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.

3.9 Trajectory Negotiation

In the preflight phase, FAA planning automation will handle negotiation as required to meet ICAO FF-ICE step 1 [4]. As such, negotiation may be an existing part of the future NAS and not a new capability added by MBT. Regardless, negotiation is an important part of the overall MBT concept and, therefore, is included in this document.

Flight operators will, at their option, participate in determining the initial assigned trajectory and any modifications to the assigned trajectory, referred to as trajectory negotiation. Negotiation of trajectory modifications may be initiated by the flight operator (due to a business objectives change or to take advantage of a NAS constraint becoming less restrictive) or the FAA (due to a NAS constraint change or to avoid conflicts).

Trajectory negotiation needs to be more effective than current voice-based methods. In current operations, controllers may provide a pilot with several options to resolve a conflict, which is easily accomplished via voice, but is not a capability considered in the current vector of aircraft and data exchange automation standards development [1]. The FAA having knowledge of the aircraft capabilities and the original (or updated) business trajectory is expected to improve negotiation efficiency. The ability for the flight dispatcher or pilots using advanced EFBs to participate in negotiation is also expected to support efficient negotiation.

Trajectory negotiation requires that the FAA provide sufficient information about the constraints affecting each flight, so that flight operators can make informed decisions. Flight operators need information about the constraints to define their desired trajectory, but the constraints that ration access to a limited resource cannot be determined in detail without predictions of the demand on each resource at each time, which requires a predicted trajectory. MBT handles this cyclical problem through a service that publishes NAS constraints with estimated delays for each constraint that causes time-based delays. The flight operator 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.

In complex situations, such as reroutes around dynamic weather where there is limited capacity on the ad-hoc defined routes, convergence of negotiation to a user-accepted solution is not guaranteed. 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. A possible fail-safe approach is to set an end time by which the negotiation must be completed; if the flight operator has not accepted a modified assigned trajectory at that time, then the last FAA-proposed assigned trajectory will automatically be the new assigned trajectory [3].

Since the NAS constraint service will provide information on the NAS constraints, the flight operator's business trajectory should avoid closed airspace regions. However, if the operator submits a business trajectory that penetrates a region of unsafe weather, for example, and does not provide a TOS, then the FAA will modify the route to avoid the NAS constraint. The FAA will make its best guess as to which side of the weather the operator would prefer. The operator can

continue negotiating by submitting a different proposed trajectory, such as on the other side of the weather, if it prefers.

3.10 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 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 nonconforming (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 aircraft 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.

3.11 Conflict Detection

3.11.1 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.

3.11.2 Manual Conflict Detection

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 [6].

3.11.3 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 3.12 and 3.13 describe conflict resolution through a tactical response and changing the assigned trajectory.

3.12 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 aircraft 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 aircraft intent data until the aircraft has resumed following an assigned trajectory that is synchronized between the ground automation and the aircraft.

3.13 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 (Section 3.8)

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 does not exist 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.

3.14 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 flight operator 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 though knowledge of the aircraft capabilities, limiting the assigned trajectory complexity based on aircraft 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 aircraft capabilities than is available in the current system.

The MBT concept accommodates mixed equipage in various ways. Separate from the assigned trajectory, the MBT 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.

3.15 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 generally not identify and resolve a conflict in a downstream sector because they do not have reliable information that the conflict will, in fact, occur, and assume that if they resolve 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 be begin, that controller is responsible for planning the reroute, coordinating with downstream sectors if necessary, and implementing the reroute.

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 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 though 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.

3.16 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. Flight operators 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 flight operator's desired (business) trajectory.

Both the FAA and the flight operator can detect this situation. The flight operator detecting an opportunity resulting from a NAS constraint change could be done as follows. 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 any advantageous changes to the flight's currently 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 flight operator (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 flight operator's business trajectory may have changed since it was initially provided to the FAA; there is no requirement for the flight operator to maintain a current business trajectory for every flight. Therefore, the FAA cannot unilaterally know whether the flight operator would want any particular trajectory modification enabled by the change in a NAS constraint. Therefore, the FAA is limited to notifying the flight operator of the flights potentially affected and allowing the flight operator to evaluate the situation and request a trajectory modification through the negotiation process if desired.

3.16.1 Use of TOS to Reduce Necessary Negotiation

In the case that the flight operator is maintaining a TOS for the flight, the FAA is able to evaluate whether the NAS constraint change would make an alternative trajectory more favorable to the flight operator, 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 enroute) is optional, but if the operator provides a TOS, the operator must update the TOS so that it always reflects the flight operator's business objectives or remove the TOS. The first option in the TOS will be the currently assigned trajectory, unless the flight operator wishes to alter the currently assigned trajectory.

When the operator (dispatcher or pilot) requests a new trajectory or modification to the currently 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 alternative 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 TMs. 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 flight operator 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.

3.17 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 FMS, the assigned trajectory tolerance bounds are based on the aircraft capabilities. The complexity of the trajectory constraints could be limited based on the aircraft capabilities. The ground automation will need to know the aircraft 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 an 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.

3.17.1 Pilot Requests Deviation Around Weather

Controllers generating lateral flight paths to support weather deviations is inefficient since the controller has weather information showing the precipitation but cannot see the storm cells seen by the pilot 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 whole idea behind a "clearance" is that ATC is telling an aircraft the path is clear. Controllers and ground automation do not have the necessary information to define a precise closed trajectory that will avoid the weather.

Controllers will not want to get into the business of trying to determine which path around a storm cell is clear, be under pressure to use a published waypoint that is in a grey area, or be held accountable if they send an aircraft through hail or get passengers hurt due to severe turbulence.¹² 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.

¹² 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 therefore minimizes the number of subsequent requests for further deviation that the controller must manage.

- “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, to allow 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. Aircraft 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 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 in 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 with 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.

3.17.2 Aircraft Responds to TCAS Alert

In normal operations, conflicts are handled through proactive modification to 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.

3.18 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.

Arrival procedures currently use indicated airspeed crossing constraints at fixes. In the future, time constraints may be more effective. 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. The aircraft would then have to fly the indicated airspeed necessary to achieve the ground speed needed to meet the time constraint (which is not difficult today if the aircraft has GPS which provides ground speed directly). 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 clearance issued via datalink or voice. 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 determines the order of crossings at each point as well as the desired intervals between aircraft, while AIM would be the maintenance mechanism (and a safety barrier) allowing the aircraft to ensure the minimum acceptable separation between aircraft is not violated between time-constrained fixes.

3.19 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 – TMLs get changed, which cause TMLs 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 TMLs and publishing those NAS constraints. The flight operators can react to the changed TMLs by providing new business trajectories. Negotiation happens (which could result in some cancelations, 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 issue these as trajectory changes, which can be accepted by the flight operator 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.

3.20 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 cannot manually manage 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 time 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 NAS systems being able 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 the range of 30 minutes or longer. Beyond this time horizon, residual trajectory uncertainty due to wind uncertainty 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 other 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 safely manage the impacted flights (compared to today's tactical paradigm) despite a lack of training on the impacted airspace.

Another key contribution of MBT in enabling graceful degradation is that every trajectory constraint in the assigned trajectory is linked 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.

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.

4. 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 are used to help explain the MBT concept but are not used as the only method to describe MBT.

4.1 Generic Use Case

- 1) The operator files a flight plan that describes where/when they 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 flight operator 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 flight operator 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 flight operator 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 enroute merge point (defining an STA for the flight at that point). The assigned trajectory is modified to include a time constraint (the FMS uses an RTA to implement the time constraint) at the point the departure will join a jet route in enroute airspace.
 - (a) The scheduled departure is updated to reflect the new enroute 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 and 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 Terminal Radar Approach Control (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 would need to accept the near-term portion of the new trajectory but then 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 aircraft 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 aircraft 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 aircraft intent data, to calculate a predicted trajectory for the aircraft.
 - (a) This predicted trajectory identifies the aircraft's state (e.g., 3D location, velocity, etc.) 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 applies the aircraft intent to its trajectory prediction, resulting in its predicted trajectory better matching 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 which 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 aircraft 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 aircraft 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 (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 is 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 aircraft 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. 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 to include 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 aircraft 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 as revised RTAs.
 - (c) The flight crew receives, loads into the FMS, evaluates, accepts, and engages the new assigned trajectory. The new RTAs will not be activated until after the flight crosses the metering arc.
- 17) The flight crosses the metering arc and fix at the assigned times, and lands on the assigned runway at the assigned time.

4.2 Emergency Runway Closure

This scenario describes the 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 flight operators 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.

5. Benefit Mechanisms

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. The high-level benefit ascribed to ATM concepts are normally grouped into safety, efficiency, environment, and access categories. The benefit mechanisms for MBT discussed in this section are organized according to efficiency, safety, and access. Environmental benefit is directly related to the efficiency benefit of reduced fuel burn, but is otherwise not discussed.

5.1 Efficiency

MBT will improve efficiency mainly through efficiency improvements to conflict detection and resolution (CD&R), TFM, and trajectory negotiation as described in the following sub-sections.

5.1.1 MBT 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. The relationship between increased trajectory predictability and CD&R is shown in Figure 3. A key expected CD&R-related benefit mechanism is to improve controller trust in automation due to a reduction in missed and false alerts. Longer look-ahead times will ensure that there is sufficient time to use Data Comm rather than voice communication. The increased use of Data Comm provides benefits such as reduced readback errors that are independent of MBT, but Data Comm also facilitates the closed trajectories in which MBT is predicated. Secondary conflicts (conflicts that may occur downstream 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.

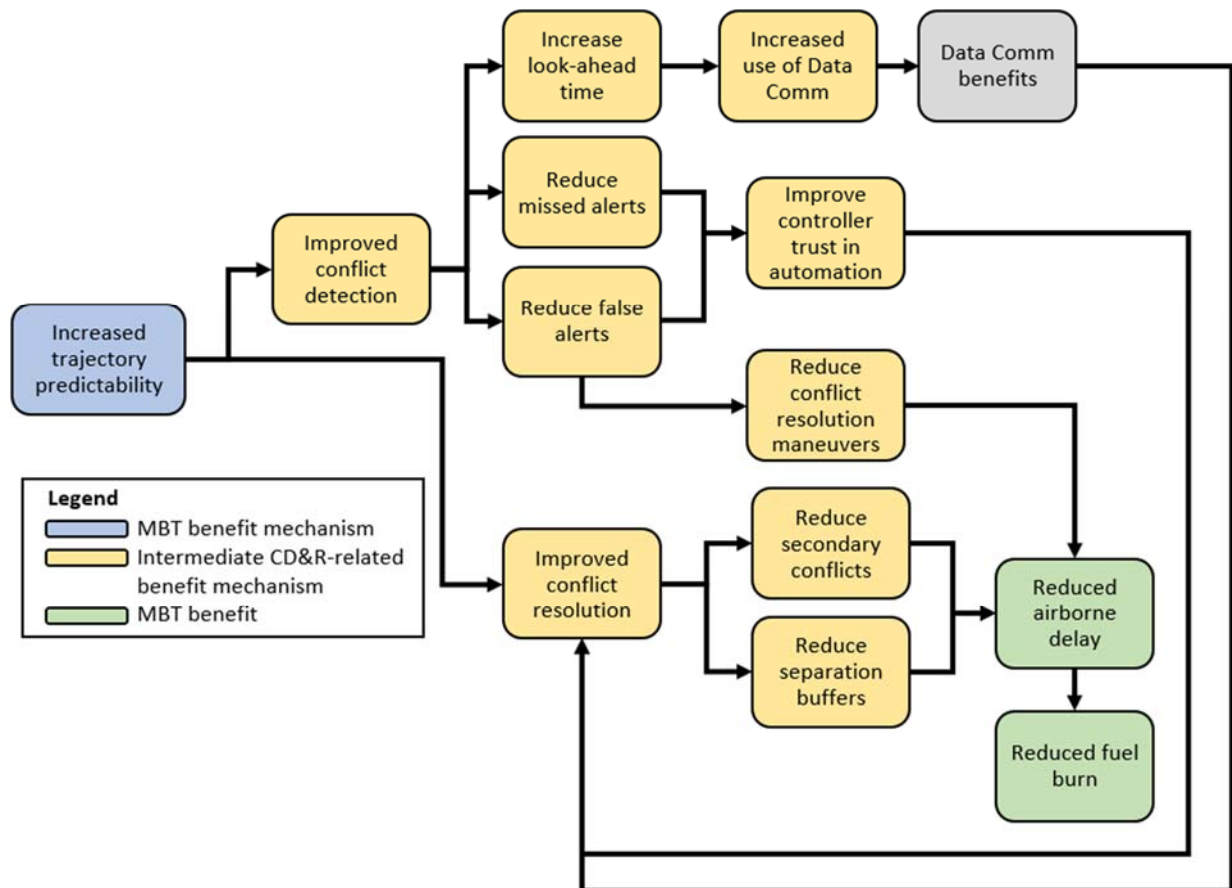


Figure 3. MBT benefit mechanisms related to CD&R.

5.1.2 MBT Benefit Mechanisms Related to TFM

When flights are constrained by TFM, MBT provides two benefit mechanisms that improve the efficiency of TFM: increased trajectory predictability and improved real-time response to changing constraints as shown in Figure 4. Increased trajectory predictability improves TMI

compliance and capacity utilization because the associated TMI constraint becomes part of the assigned trajectory (unlike a MIT restriction in today's system) and must be supported by the aircraft's performance (e.g., realizable speed ranges). Increased trajectory predictability also improves demand prediction because all known non-TFM constraints are incorporated into the demand predictions. Improvements in demand prediction and TMI compliance both contribute to TMIs that better balance capacity and demand.

The second MBT mechanism, improved real-time response to changing constraints, is primarily supported by the 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 through the NAS constraint service enables other aircraft to 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.

There is a tradeoff between the airborne delay associated with imposing airborne pressure on NAS resources versus 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 4. Enhanced predictability will provide a more consistent flow of air traffic, where demand will more accurately meet available capacity, reducing or eliminating costly unrecoverable delay.

The anticipated dollar benefits (i.e., reduced ground delay, airborne delay, and fuel burn) of TFM-related mechanisms are expected to outweigh the dollar benefits of CD&R-related mechanisms.

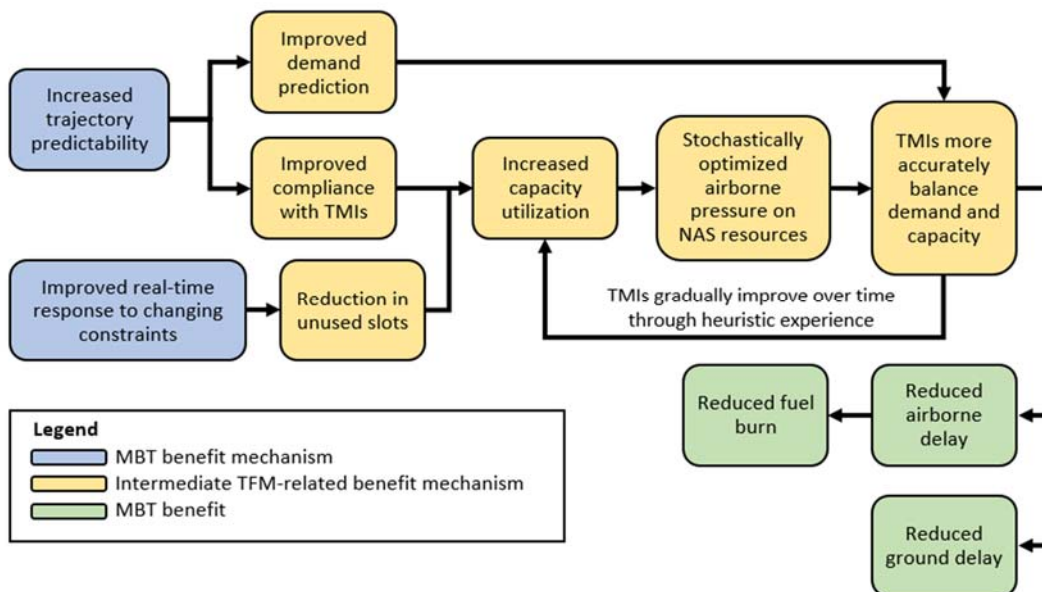


Figure 4. MBT benefit mechanisms related to TFM.

5.1.3 MBT Benefit Mechanisms Related to Trajectory Negotiation

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 flight operator and flight crew. This enables the flight operator, flight crew, or FAA to initiate negotiation of a more efficient trajectory. 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 flight operators.

5.2 Safety

The key benefit mechanism for improving safety in a MBT environment is the resilience to degraded modes of operation. It is expected that assigned trajectories will have stable predictions for 30 minutes or longer due to the inclusion of all trajectory constraints. If a degraded mode of operation occurs, there is generally more time to address the degraded mode (e.g., switch over to backup system, implement manual procedures) without an impact to flights for some period of time. The stable MBT trajectories essentially 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. From the pilot's perspective, for example, 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.

Under the MBT concept, an updated trajectory clearance will be digitally delivered to the FMS/EFB, the pilot will need to review and accept the modification, but the avionics will help the pilot understand the change and its impact on the flight. With minimal pilot effort, and reduced chance of human error, the aircraft will fly the modified trajectory. This change is anticipated to provide a safety benefit, including through a reduction in readback errors.

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 will also allow more aircraft to be handled in each sector, with higher monitor alert numbers without reducing safety.

5.3 Access

The MBT concept provides access to all aircraft regardless of equipage. However, aircraft that are equipped with at least a minimal set of capabilities will gain a greater direct benefit from MBT. For example, users that have not integrated with the NAS constraint service aircraft will not be aware of changing constraints that provide benefit.

Datalink delivery and FMS auto-load of assigned trajectories will enable the use of trajectories which would not be practical to issue via voice, 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 included reduced delays and reduced flight cost.

6. Roles and Responsibilities

The allocation of roles and responsibilities in MBT (described in the context of MBT concept elements in Section 3) reflects both increased automation capability to support many aviation functions, as well as increased flexibility to assign responsibilities to different participants – in many cases afforded by the increased automation.

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.

A key feature of the MBT allocation of roles and responsibilities is a vision for the D-side controller and traffic management specialist to take on a greater role for separation management. This is facilitated by the vision that separation management functions, in addition to traffic management functions, will be carried out as trajectory management functions. This creates an opportunity for flexibility, allowing the traffic management specialist to carry out tasks that today can only be carried out by the controller currently in contact with the aircraft.

7. Summary and Conclusions

The MBT concept represents a significant change from current operations. However, the concept would be reached through a logical evolution from the current NAS. MBT achieves the FAA's goal of trajectory based operations, providing all of the associated benefits and efficiencies. Furthermore, MBT supports the inclusion of emerging vehicle classes and business models.

The cornerstone MBT concept element is that all aircraft are assigned a 4D trajectory from their current state to their destination. All aircraft follow their assigned 4DTs, complying with all trajectory constraints and the trajectory description unless first negotiating a revision. All aircraft also maintain current and accurate information about intent and aircraft capabilities.

A NAS constraint service gathers and publishes information about all known NAS constraints, so that 4DTs that comply with these NAS constraints may be negotiated by the FAA and flight operator. Trajectory constraints are mapped to NAS constraints to facilitate identifying affected aircraft when NAS constraints change. MBT uses a trajectory object that contains several parts: the assigned trajectory, aircraft intent, flight plan, and aircraft capabilities. The assigned trajectory is comprised of the trajectory constraints and a trajectory description. The trajectory constraints are the minimum set of requirements that achieve FAA conflict avoidance and TFM objectives. However, the trajectory constraints by themselves are not sufficient to predict the aircraft's 4DT. The trajectory description provides the additional information about how the aircraft will fly, in compliance with the trajectory constraints, necessary to support trajectory prediction. Trajectory constraints and associated tolerances are based on the aircraft's capabilities.

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 flight operator'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. Some trajectory constraints are the results of 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).

The aircraft intent is a description, provided by the flight operator, of the operator's plan for how the flight will fly the assigned trajectory. The assigned trajectory, together with the aircraft intent, enable accurate prediction (both near-term and to the destination) of the 4DT that the aircraft will fly. Aircraft intent can change freely, while assigned trajectory changes require negotiation, but should fully conform to the assigned trajectory. The aircraft intent data will include and extend beyond the current specification for Extended Projected Profile (EPP) data. For example aircraft intent may include the planned speed profile on each route segment. MBT requires all IFR flights to provide aircraft intent data, which can be accomplished by the FMS, EFB, ground automation, or a combination thereof.

Aircraft assigned trajectories, intent, and predicted trajectories are shared creating a common view among stakeholders. D-side sector controllers and TMCs, with their longer time horizon perspectives, are increasingly important in proactively intervening to avoid conflicts and achieve TFM objectives, using automation enhancements that facilitate coordinating 4DT changes across multiple sectors. Conflicts can be detected farther in advance due to improved predictability and intervention can be accomplished through adding or modifying constraints in the assigned 4DT. Tactical vectoring by controllers and open trajectory deviations around weather are minimized. Closed trajectory operations emphasize the use of time constraints to achieve strategic TFM initiatives. Interval management will be integrated into assigned trajectories in dense and complex airspace.

Digital air-ground communication is used to deliver 4DTs 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 anticipated MBT benefits include improved efficiency (i.e., capacity increases, delay reductions, and reduced operational costs), increased flexibility, better predictability, greater robustness to off-nominal conditions, reduced environmental impacts, and enhanced safety.

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