Integrated Trajectory-Based Operations for Traffic Flow Management in an Increasingly Diverse Future Air Traffic Operations

Paul U. Lee
Human-Systems Integration Division
NASA Ames Research Center
Moffett Field, CA
paul.u.lee@nasa.gov

Husni Idris
Aviation Systems Division
NASA Ames Research Center
Moffett Field, CA
husni.r.idris@nasa.gov

Douglas Helton
Crown Consulting
NASA Ames Research Center
Moffett Field, CA
dhelton@crownci.com

Thomas Davis
Crown Consulting
NASA Ames Research Center
Moffett Field, CA
tdavis@crownci.com

Gary Lohr
Crew Systems and Aviation Operations Branch
NASA Langley Research Center
Hampton, VA
gary.lohr@nasa.gov

Rosa Oseguera-Lohr
Crew Systems and Aviation Operations Branch
NASA Langley Research Center
Hampton, VA
rosa.oseguera-lohr@nasa.gov

***Abstract*— Integration of new flight operations, such as urban air mobility vehicles and commercial space flights, into the National Airspace System (NAS) will require accommodation of new vehicles with different performance and mission profiles into an established traditional commercial and general aviation aircraft operational framework. For example, in this increasingly diverse future air traffic operations, the interaction and integration of on-demand operations with traditional, largely scheduled operations will lead them to share existing commercial airspace with increased requirements on data exchange and control schemes to ensure adequate safety margins. In this new paradigm, the traditional operations will need to transform from current vector-based operation to a more integrated trajectory-based operation (TBO) in which the aircraft's trajectory intents are more strategically planned, precisely tracked, and collaboratively coordinated. Over the years, NASA has been developing, demonstrating and transferring air traffic management concepts to the FAA to support surface, departure and arrival metering, as well as dynamic reroutes for weather avoidance. This paper describes a framework for combining and advancing those NASA efforts to improve arrival and departure demand management by integrating select NASA TBO capabilities with the Traffic Flow Management System (TFMS), Time-Based Flow Management (TBFM), and the Terminal Flight Data Manager (TFDM) tools to enable TBO across the NAS. The overall concept incorporates operator priorities and preferences in a service-oriented approach to managing complex, high demand airports.**

Keywords*— *trajectory-based operations, increasing diverse operations, access to traditional airspace, TFMS, TBFM, TFDM, service-oriented system

I. Introduction

In recent years, there has been an emergence of new vehicles with different performance and mission profiles that are anticipated to enter the same airspace as the existing traditional commercial and general aviation operations. These new operations, ranging from urban air mobility [1] to commercial space flights [2], provide a glimpse into the future in which the current airspace, dominated by existing aircraft and operations, will need to accommodate and co-exist with new vehicle types and operations. NASA's ATM-X (Air Traffic Management - Exploration) Project [3] is focused on expanding air traffic management (ATM) operations to achieve these goals. The sub-project Increasing Diverse Operations (IDO) is expected to develop service-based ATM architecture and concept solutions that will accommodate to the extent possible all users in increasing numbers, with a focus on accommodating traditional users as well as new entrants [4].

In the increasingly diverse future air traffic operations, on-demand access is expected to increase dramatically due to new operations such as urban air mobility vehicles [5]. The interaction and integration of on-demand operations with traditional, largely scheduled operations will likely require them to share existing commercial airspace that are dominated by traditional operations today. The integration of such diverse operations requires the traditional air traffic operations to evolve, by expanding and transforming the current and NextGen infrastructure, but also to develop a new, more automated and scalable architecture to handle the potentially exponential growth for the newer vehicles and operations.

In order for these two types of vehicles / operations to co-exist in a shared airspace, there will need to be seamless data exchange and coordination between them to keep track of each vehicle's location, intent and other relevant information and to provide adequate safety margins between them at any potential interaction points. With this assumption, the traditional operations will need to transform from current "volume-based" operation, in which the aircraft are often vectored off of their trajectories by the air traffic controllers to a trajectory-based operation (TBO). In TBO, the aircraft file/update their trajectory intent and fly their trajectories in order for the underlying air traffic system to track them.

A transition from traditional operations to TBO is identified in the NextGen 2025 baseline, in the FAA document titled "NextGen Vision for Trajectory Based Operations", version 2.0 [6]. Over the years, NASA has been collaborating with the FAA to realize the NextGen vision of TBO. NASA has been developing, demonstrating, and transferring air traffic management concepts to the FAA to support surface, departure and arrival metering, as well as dynamic reroutes for weather avoidance [7][8][9][10]. NASA has also developed new concept, procedures, and tools to better utilize existing capabilities in Traffic Flow Management System (TFMS) and Time-Based Flow Management (TBFM) to coordinate strategic and tactical traffic flow management tools for better arrival demand management into complex airspace/airports [11].

This paper describes a framework for combining and advancing those NASA efforts to improve arrival and departure demand management by integrating select NASA TBO capabilities with the TFMS, TBFM, and the Terminal Flight Data Manager (TFDM) tools. The goal is to better manage arrival and departure demand at constrained airports by integrating the strategic and tactical control of that demand from origin to destination and performing this control more precisely and collaboratively. Therefore, this paper describes a potential evolutionary path towards the increasingly diverse future of the National Airspace System (NAS), by building on, integrating, and advancing the enabling TBO technologies. The following sections describe the motivation for integrated TBO solutions, descriptions of NASA developed TBO capabilities, and integration of these capabilities. In addition, the paper describes how operator priorities and preferences may be integrated in a service-oriented framework to provide a robust, scalable solution for the complex, high demand airports.

II. Motivation for Trajectory-Based Operations

A. *Trajectory-Based Operations Overview*

TBO is a method for planning and managing air traffic by extending the use of three main functionalities: (1) time-based management, (2) performance-based navigation (PBN), and (3) data exchange, both between airborne-to-ground systems and between ground-to-ground systems [5]. TBO involves trajectory planning, management, and optimization in the strategic and near-tactical timeframe. The air navigation service providers (ANSPs) and the flight operators agree on strategic flight plan trajectories. This plan is coordinated across all systems, air traffic facilities and flight operators, who work to achieve the strategic plan.

The TBO capabilities are envisioned to enable time-based flight trajectory negotiations using seamless data exchange and automation. Centered on time-based management and PBN, TBO enables four-dimensional trajectories that the ANSPs and the airspace users can negotiate to identify a solution that meets everyone's needs. It emphasizes predictability as an objective (in addition to efficiency), enabling increased users' confidence that they will be able to fly their desired trajectory and hence can better plan and optimize for their fleet concerns. It allows for integration and more cohesive and coupled relationships between air traffic control (ATC) and traffic flow management (TFM) [4][6].

Enabling full integration of TBO across all phases of flight will require scheduling and other related capabilities to be integrated or coordinated across multiple facilities. For example, a flight might reserve its place in a virtual queue while still at the departure gate while the ATC system plans its arrivals at its fixes and destinations. By predicting the traffic demand, capacity, and constraint points and sharing them across facilities in advance, the flight could merge and space more strategically with other traffic, with minor speed and route adjustments. Sharing of demand and constraint information allows for more collaboration and strategic planning between airline operators and ANSPs.

B. *Need for Integrated TBO and Time-Based Management in Current Day Traffic Flow Management*

When the capacity at high-volume airports or the surrounding airspace is constrained and demand exceeds the available resources, the resulting traffic bottlenecks often have a NAS-wide impact [11]. The reasons for these demand/capacity mismatches can vary from structural limitations (e.g. limited airport surface or airspace route capacity), to wind-related capacity changes, to the more severe and less predictable constraints such as convective weather.

Traffic managers limit demand into the airports and airspace by imposing Traffic Management Initiatives (TMIs) such as ground delay programs (GDPs), airspace flow programs (AFPs) and the new collaborative trajectory options programs (CTOPs). Although these forms of strategic management help divert excess demand, they are based on Airport Arrival Rate (AAR) and associated airspace congestion predictions made hours in advance, often using rules-of-thumb and best guesses. Consequently, their effectiveness varies with constraint uncertainty, and may compound demand-capacity imbalances when predictions are incorrect [12].

TFMS, TBFM, and TFDM traffic management tools and procedures are already used to address the problem of demand management within the NAS [13]. These systems represent a set of capabilities that manage flows into capacity-limited resources by modifying the routes and/or times of flights within those flows. They were developed for and continue to be used in different operational contexts and timeframes. TFMS is used by airline operators and traffic planners during pre-flight planning. TFDM is used just prior to gate pushback and during taxi-out and taxi-in phases. TBFM is used by controllers and local facility traffic managers within a horizon of the arrival of the flight. Plans for enhancing all three systems, many of which are in the FAA's implementation pipeline or already in use, suggest some overlap in functionality [14][15][16] and temporal solution space.. To a large extent, however, these three systems still provide separate and largely uncoordinated solutions for the traffic management problem.

TFDM schedules and meters gate pushback, based on airport surface congestion and controlled departures times (CDTs), or Expect Departure Clearance Times (EDCT) for flights subject to TMI. However, departure rates and times are not yet synchronized by the tool to schedule the departures into slots in the overhead traffic stream. Overhead time slots are manually allocated dynamically by traffic management as they become available. They are not synchronized to other schedules along the flight such as the takeoff time or the TBFM meter fix times. Therefore, there is no assurance that an overhead time slot will be available when a flight reaches its scheduled departure time, which may cause the departure time to be rescheduled. If the flight is departing from an airport within the TBFM horizon, its original departure time may have been scheduled by TBFM. Hence the rescheduling causes further cascading effects where TBFM needs to match the flight with a new arrival slot at the destination [7].

Departure metering is currently managed differently depending on whether or not the departure airport is within the planning horizon of a destination airport at which TBFM is being used to meter arrivals. All flights subject to an AFP or GDP are issued EDCTs through TFMS, but flights departing from close-in airports are also subject to TBFM arrival metering at their planned destination and are issued CDTs based on the scheduled time of arrival (STA) assigned by TBFM. These scheduled departure times issued by TFMS and TBFM systems are not well coordinated with each other and can subject some flights to inequitable compounded delays. Additionally, TBFM schedules are based on the actual AAR being achieved, and TFMS schedules are based on the predicted acceptance rate of the airport or airspace and the scheduled traffic demand. There is no direct coordination between TBFM departure metering and TFMS departure metering for flights bound for the same destination airport, and consequently, limited responsiveness to changes between them, such as when the AAR used by TBFM is different than the one that had been used by the GDP [11].

Furthermore, flights may or may not depart at their scheduled EDCT due to other factors impacting the departure airport, e.g. congested airport surface or overhead stream, or simply non-compliance by the operator or local traffic management. Even when a flight departs at its scheduled EDCT, there is little monitoring or control over its conformance to its planned arrival schedule until it reaches airspace that is covered by TBFM metering. Finally, en route constraints and miles-in-trail (MIT) restrictions unrelated to TBFM metering may delay flights, resulting in periods of under or over demand at the destination.

TBFM also provides little in the way of flight/delay prioritization. Aircraft en route from external airports outside of the TBFM planning horizon of the destination airport are given priority over departure flights from close-in airports when assigning delay. Although this is advantageous in terms of reducing fuel costs associated with airborne delays, departures scheduled from close-in airports often receive a disproportionate share of the overall delay. Consequently, costs associated with disruption to airline schedules and excessive ground delay may result in higher costs for those operators than those solely based on fuel consumption [17]. In addition, operator flight priorities and preferences are not easily incorporated in TBFM departure scheduling at close-in airports.

Another problem in today's TFM system is that flights may be subject to multiple uncoordinated departure delays. When significant convective weather or widespread congestion within the NAS arise, traffic managers in different facilities typically issue multiple TMIs to deal with the various problems in their airspace, impacting many flights to encounter multiple uncoordinated TMIs. For example, a flight may be held on the ground through a GDP, before being rerouted around a thunderstorm, and then subject to MIT caused by congested arrival sectors or airports. The joint impact of all three initiatives together results in inequities, in part because tools currently available to traffic managers are not well integrated.

Once flights get closer to the destination, traffic managers impose more tactical TMIs such as MIT restrictions to the meter fixes, time-based metering and other airborne delay maneuvers. These restrictions may also be based on rules of thumb but are increasingly based on TBFM metering. TBFM automatically meters and sequences arriving flights by assigning each flight with an STA at the metering point, and automatically calculating any delay controllers must apply to each flight in order to comply with the STA. Enhancements to TBFM enable a new capability called extended metering, which permits multiple planning and freeze horizons to be used to more accurately meter traffic at greater distances from the destination airport or airspace constraint. However, the throughput rate and resulting demand profile are not shared with TFMS, and therefore, EDCTs issued by TFMS to flights departing within the TBFM horizon are not automatically adjusted. There is also no automated coordination between planning functions to adjust flight progress for flights once they depart but have yet to enter into TBFM metering [11].

TBFM is also not currently capable of efficiently redistributing excess arrival demand from one arrival fix to another. That remains a manual process, which may result in inefficient trajectories or added delays at one arrival fix while another arrival fix has unused excess capacity. Additionally, any interruption in a flight's defined trajectory, such as radar vectors, results in inaccurate estimated times of arrival (ETAs), which in turn causes erroneous STAs and sequencing. Controllers and traffic managers must resort to use manual judgement and processes to distribute and meter traffic. This is particularly problematic during dynamic convective weather, which can make TBFM unusable [9].

Another cause of significant delays at metroplex airports is the interaction of flows between adjacent airports that compete for airspace. Currently the competed airspace is delegated to one flow or the other by the standard operating procedures (SOP). This often results in blocking flows from using the airspace and often from using the runways that need to use the airspace for the approach. Additional impacts include significantly extending arrival and departure routes, capping departures below arrivals resulting in level segments, and limiting runway throughput by preventing divergent headings after take-off.

For example, when JFK is in a configuration to land on ILS 13L (red flow in Fig. 1), LGA is forced to land on ILS 13 requiring arrivals from the south (yellow flow) to approach high and make an extended loop above TEB to approach runway 13. This configuration also requires EWR to release the lower altitudes of the airspace (highlighted in blue in Fig. 1) to LGA, and forces TEB to wait for gaps in the LGA flow. LGA is also blocked from using runway 4 for landing because it delegates the low altitude airspace highlighted in red to JFK. Additionally, the JFK departures to the east are capped below the JFK arrivals causing them to travel an extended level segment, and the LGA departures from runway 13 (not shown in the figure) are typically forced to only turn left to avoid the JFK arrivals. Greater use of TBO and PBN in the Terminal airspace has the potential to share the airspace across multiple flows that are headed to different destination airports.

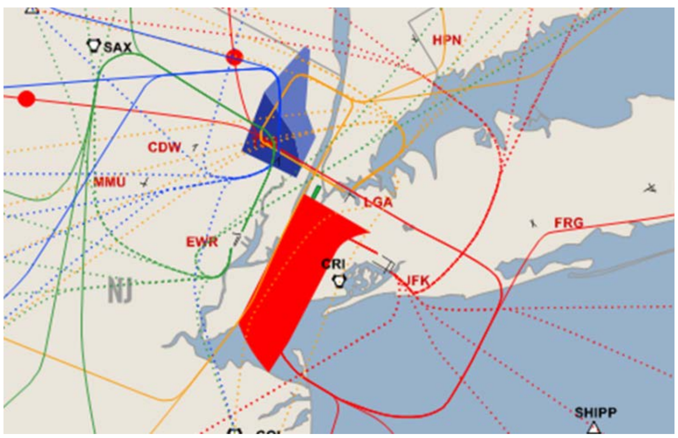

Fig. 1. Example of NYC Metroplex Conflicting Flows

Given that the current traffic management tools manage traffic flows into capacity-limited resources in a largely uncoordinated fashion, integrated TBO solutions that provide better time-based management along more precise trajectories has a potential to result in improved predictability, efficiency, and throughput while also improving the overall delay characteristics. The following section describes a set of TBO solutions that provide such benefits across all phases of flight.

III. Trajectory-Based Operations Solutions

In recent years, NASA has developed a number of TBO solutions for all phases of flight - i.e. pre-flight, departure, en route, and arrival. In the pre-flight phase, NASA's Integrated Demand Management (IDM) concept uses strategic TFMS tools to pre-condition the traffic demand prior to departure, in order to deliver an efficient and manageable traffic demand to more tactical traffic flow management capabilities, such as TBFM. The IDM concept uses predicted arrival rates to a target airport to develop capacity settings across TFMS and TBFM systems so that the delivery of the traffic demand is well coordinated between strategic and tactical traffic flow management systems [11].

In the departure phase, the capabilities of NASA's Airspace Technology Demonstration 2 (ATD-2) improves the efficiency of surface operations at the nation’s busiest airports through time-based metering of departures and improved sharing of flight operations information amongst the various airport surface stakeholders. The ATD-2 concept also couples a surface scheduling to en route scheduling such that an integrated time-based trajectory solution from takeoff to constrained overhead flow can be constructed prior to takeoff [7].

Once the aircraft reaches level flight in the en route phase, it prefers to fly at its optimal altitude and speed. However, it can be delayed or rerouted multiple times to avoid various airspace constraints due to adverse weather or traffic volume. NASA's Airspace Technology Demonstration 3 (ATD-3) developed ground and flight deck technologies to identify more efficient routes around adverse weather and other airspace constraints from en route [8] to arrival phases of flight [9]. These technologies enable time-based solutions in adverse weather conditions and enable the users to specify preferences in terms of saving time, fuel or both in optimizing their routes around weather.

As the flight approaches its destination airport, it enters the arrival phase. In this phase, NASA has developed an integrated set of technologies under Airspace Technology Demonstration-1 (ATD-1), that provides an efficient TBO solution for managing arrival aircraft beginning from just prior to top-of-descent, though the en route and Terminal airspace, all the way down to the airport runway [10]. These technologies enable precise tracking of continuous descent, time-based, and efficiently spaced trajectories.

In all phases of flight, a service-oriented architecture which enables user and/or third-party services for generating and negotiating user-preferred trajectories and allocating resources is highly desirable in order to mitigate capacity bottlenecks and improve scalability of services with increased operations.. In the future, trajectory management functions, including trajectory generation, negotiation, and synchronization may be provided by third-party services [3][4]. In such a framework, flight operators may choose their preferred service provider, particularly for services that are not safety-critical. These TBO capabilities constitute examples of such services or packages of services that may be provided by government, users, or third-party providers. The integration of these services remains an important challenge, which is even more critical in such a federated environment.

In the following section, each of the phases of flight and the associated TBO solutions are described in more detail. The New York metroplex is used as an example to describe the integration of TFDM, TFMS, TBFM, and ATD capabilities, combined with airline operators’ prioritization inputs, to synchronize departure, arrival and en route scheduling. TFDM/ATD-2 and TBFM/ATD-1 provide tactical departure and arrival metering with sufficient access to close-in airports and in coordination with TFMS for airborne upstream flights, to ensure minimal impact on the airborne flow and sufficient delivery of traffic to capacity-constrained runways. TFMS tools strategically schedule arrival demand into TBFM that matches demand to the available capacity of the TBFM region. Coordinating the scheduling across TBFM, TFMS, and TFDM reduces the need for miles-in-trail and ground delay programs, better matches demand to capacity, can reduce airborne delays, and can distribute overall delay more equitably across long and short haul flights.

A. *Pre-flight*

An example scenario for Newark Liberty International Airport (EWR) illustrates how the TBFM, TFMS, and TFDM schedulers could be coordinated. EWR routinely sees a varied mix of short-haul and long-haul flights, with a load distribution across its three arrival gates that changes throughout the day. Scheduled demand is often at or near the airport's dual-runway Visual Flight Rules (VFR) capacity, so adverse winds or reduced visibility often reduce capacity well below demand. This imbalance is usually managed using MIT and TBFM metering controls, however close-in departures often take a disproportionate share of the TBFM-assigned delay since MIT pre-conditioning is often not precise enough to equitably reserve the capacity needed to fit these departures into the arrival stream [17][18]. This inequitable delay impact is often unnecessary and detrimental to the airport throughput when, for example, the overhead flow is saturated locally but has gaps over longer horizons, and the airport capacity is adequate to accommodate the airborne flights and close-in departures.

On a typical day, airports set AARs based on, among many other factors, flights that enter or depart within the TBFM planning horizon. If convective weather or other conditions result in persistent demand that exceeds capacity, AAR can also be set strategically in TFMS to meter the traffic demand into TBFM. In these situations, flights are assigned EDCTs by TFMS to control the rate of demand through departure ground delays. Coordinating TFMS and TBFM departure schedules, can improve demand distribution and management across all departures, and potentially for long-haul flights already en route. EDCTs produced by TFMS for flights that are still on the ground may be adjusted in response to airport capacity and demand predictions that are updated based on TBFM throughput. TFMS can reset the AAR based on those updated predictions. There are ongoing efforts to incorporate data-driving analytics and system uncertainty into such predictions [19].

In NASA's IDM concept [11], strategic planning of traffic flow rates and schedule is managed in TFMS in coordination with the rates and schedule set in the more tactical TBFM system (see Fig. 2). TFMS/TBFM integration utilizes a TFMS capability called Collaborative Trajectory Options Program (CTOP), which strategically sets traffic flow rates on a set of airspace bottlenecks by using multiple Flow Constrained Areas (FCAs). FCAs can be defined as lines or volumes that can be drawn across airspace bottlenecks and assign maximum capacity limits. In CTOP, an FCA is drawn around a flow constrained airspace and a capacity limit is associated with the FCA in order to meter the traffic flow through it. Using this capability, TFMS departure schedules are effectively synced to TBFM arrival schedules by collocating an FCA crossing point with the TBFM freeze horizon as shown in Fig. 2. The FCA rates are set in conjunction with the TBFM rates (as determined by TBFM inter-arrival spacing matrices) which freezes the aircraft sequence and schedule at the metering freeze horizon as they approach the destination airport. In this case, the AAR used by TBFM is also used to help predict capacity and resulting demand as the basis for setting the FCA capacity. Departures from airports outside the TBFM planning horizon (external flights) bound for the constrained airport are scheduled and routed using TFMS and CTOP based on projected FCA capacity at their expected time of arrival (ETA) at the FCA. This effectively syncs TFMS departure schedules to TBFM arrival schedules.

The example in Fig. 2 is the simplest operational scenario, for which the only constraint is the AAR, with a single TBFM freeze horizon, and no extended metering. A more complex

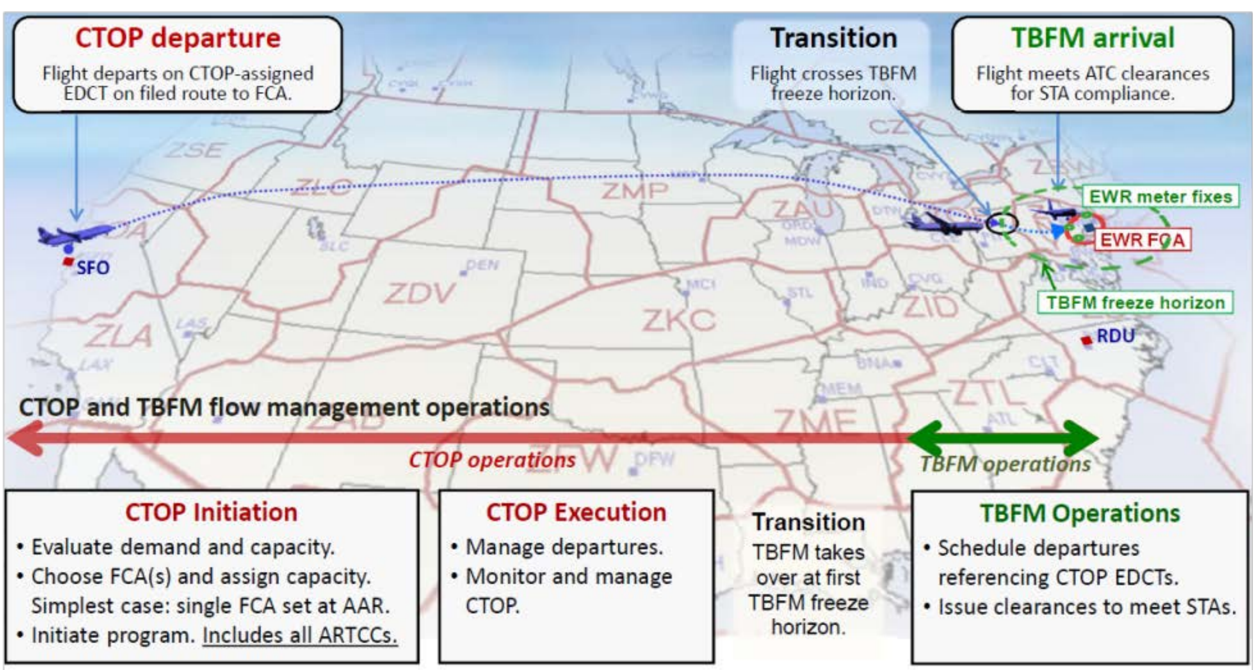

Fig. 2 IDM Concept: CTOP/TBFM Integration for Single FCA Scenario

CTOP/TBFM integration involves using multiple FCAs in CTOP and multiple TBFM freeze horizons for arrival and extended metering. One of the key capabilities in CTOP is to allow the airline operators during the pre-flight phase to submit a Trajectory Options Set (TOS), which consists of the initial flight plan, alternative user-preferred routes, and the trigger conditions in which the alternate routes are preferred over the initial flight plan. The decision to choose one route vs. another is rule-based, coordinated digitally, and done automatically by the CTOP automation.

The CTOP and TOS mechanisms provide a framework for moving traditional airspace operations towards a more user-centric / automated method for digital trajectory coordination, in which the airlines can generate their own trajectory solutions that better fit their business case and abide by any flow constraints that are broadcast by the service provider. However, TOS generation by the airlines without significant automation support has been challenging, and automated generation of TOS routes and other decision support tools would help to enable a wider adoption of TOS and CTOP. In the future, development of such tools may be better done by third-parties, who can then provide those services to many of the airlines.

B. *Departure*

As a flight gets closer to its departure time, close-in flights that depart within the TBFM free horizon (called "internal departures") are scheduled using TBFM to depart and merge into an available arrival slot using APREQ/CFR (Approval Request/Call For Release) procedures, which are often not well coordinated with TBFM, the overhead stream, and airport surface/departure scheduling operations. Therefore, TFDM/ATD-2 departure management is used to depart flights in accordance with their scheduled departure time and insert them into the overhead stream. Fig. 3 illustrates the environment in which ATD-2 operates. ATD-2 integrates TFDM airport surface management, TBFM departure scheduling, Integrated Departure Arrival Capability (IDAC), and collaborative decision making for all airports within a departure terminal area [7].

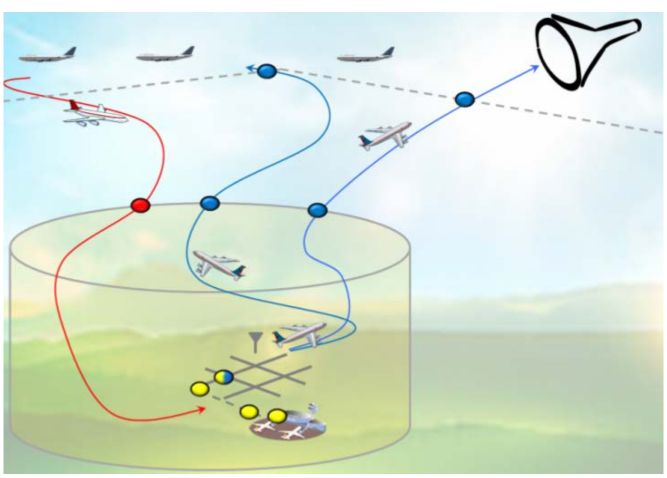

Fig. 3. ATD-2:Departure Scheduling Integrated with Arrivals

ATD-2 incorporates advanced trajectory-based surface modeling, scheduling, and metering capabilities, in conjunction with trajectory-based departure metering and digital data exchange. The resulting capability is expected to address most of the obstacles that prevent flights from departing at their assigned EDCT or CDT and allow the flight to also seamlessly merge into the overhead stream. Higher conformance to the assigned EDCT or CDT will provide greater demand predictability by helping operators and traffic management coordinators comply with scheduled departure times, avoid surges in arrival demand at the destination, and provide demand management necessary to increase the availability of arrival slots for flights coming from close-in airports.

TFMS collaborative decision-making capabilities currently allow operators to prioritize flights 45 minutes or more prior to pushback by EDCT swaps and substitutions. However, there is no way for flight priorities to be submitted and used by TBFM for scheduling departures 45 minutes or less prior to pushback. If TBFM and TFMS departure scheduling were incorporated together in a TFDM/ATD-2 departure scheduler, operators could use ATD-2's flight prioritization and substitution capabilities to prioritize departures originating from different airports based on their arrival flight priorities at their common destination airports that can be coordinated through TFMS. By integrating TBFM-like timelines from departure through arrival, operators could monitor the progress, sequence, and ETAs of all their flights and indicate how they want delays distributed among their flights, as well as request substitutions where available.

In the departure phase, the airline operators may submit alternative, user-preferred route options in response to weather or traffic conditions, similar to the pre-flight phase. They can submit TOS routes, which can be reviewed by the ANSPs and issued as new flight plans. All of the flight coordination and submission can be done digitally using Pre-departure Reroute (PDRR) and Tower Data Link System (TDLS) capabilities. Although the communication mechanism for delivering user-preferred routes exists, the ability for the airline operators to generate TOS that fits their business case again will need a significant automation support. Therefore, in the future, airline and/or third-party services that develop and distribute automated generation of TOS routes. along with decision support tools that provide relevant weather, traffic and airspace information would enable a wider use of TOS in the departure phase of flight.

C. *En Route*

Once an aircraft climbs out of the departure airspace and reaches a level flight, it enters the en route phase of flight until the flight approaches its destination airport. Although it prefers to fly unimpeded at its optimal altitude and speed during this phase, it can be rerouted when it encounters convective weather. One of the capabilities within the ATD-3 project, called Traffic Aware Strategic Aircrew Requests (TASAR), provides reroute capability around adverse weather on the flight deck. TASAR leverages flight management system and onboard weather radar, wind, and traffic data to identify wind-optimized routes and altitudes that save time and fuel [20].

From the ground-side, Multi-Flight Common Route (MFCR) within ATD-3 project provides a dynamically generated reroute capability around adverse weather [8]. MFCR advisories searches for a common trajectory that could benefit multiple flights and balances potential fuel/time savings with air traffic controller acceptability to achieve the best compromise reroute for a group of flights. MFCR capabilities are complementary to FAA's Advanced Flight-Specific Trajectories (AFST) which also provides a suite of weather avoidance reroute capabilities.

As an aircraft transitions from the en route to arrival phases of flight, the Dynamic Routes for Arrivals in Weather (DRAW) capability within the ATD-3 project provides trajectories to avoid adverse weather while also keeping it on time to its arrival schedule to the destination airport (see Fig. 4) [9]. DRAW is integrated with TBFM and serves two primary functions. First, it identifies defined weather avoidance routes that supply trajectory intent information necessary to support TBFM metering. Second, it is able to redistribute arrival demand to efficiently balance that demand across available arrival meter fixes. DRAW capabilities provide more opportunities to modify routes and sequences prior to flight crossing the TBFM meter fix freeze horizon in response to weather and traffic demand, thereby keeping aircraft on their trajectories in more adverse conditions.

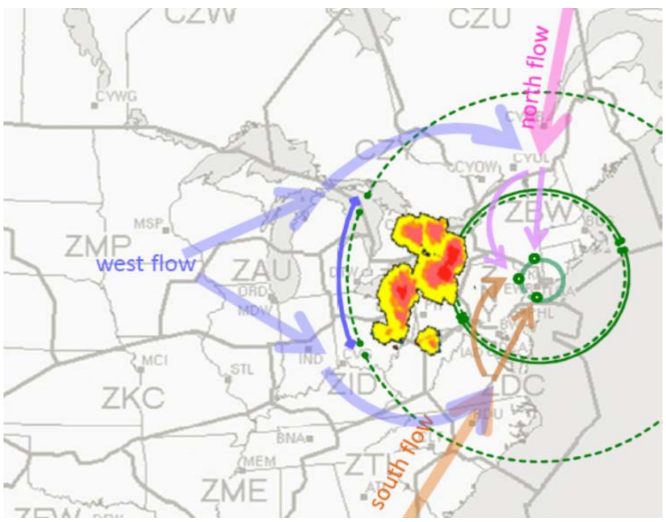

Fig. 4. DRAW Reroutes and Arrival Fix Balancing

During the en route and arrival phases, airline operators can provide user-preferred trajectory solutions using TOS, Airborne Reroute (ABRR), and airborne Data Comm capabilities, in a manner analogous to the one described in the departure phase. Similar to departure phase, the airline operators' ability to generate dynamic weather reroutes requires significant automation support that may be provided by the airlines or by third-party services.

D. Arrival

For the arrival phase of flight, the TBFM system allows multiple metering regions using extended metering (XM) and/or coupled scheduling (CS), in conjunction with existing arrival meter fix (MF) scheduling. Each of XM, CS, and MF has its own metering points and freeze horizon. These meter fixes and freeze horizons can be stacked and coupled to each other to provide rolling freeze horizons to the final TBFM metering point. A simple illustration of multiple TBFM regions for EWR is shown in Fig. 5. When a flight reaches a TBFM metering planning horizon, TBFM metering takes over based on the runway arrival rates, and controllers manage flights based on assigned TBFM scheduled time of arrivals (STAs). If TBFM extended metering is used, this transition would take place at the TBFM extended metering freeze horizon furthest away from the destination airport. Using extended metering in this manner provides relatively precise metering capability at longer distances. Opportunities for dynamic changes and application of preferences are maintained in between the successive TBFM horizons and are increased by making the horizons smaller and more numerous.

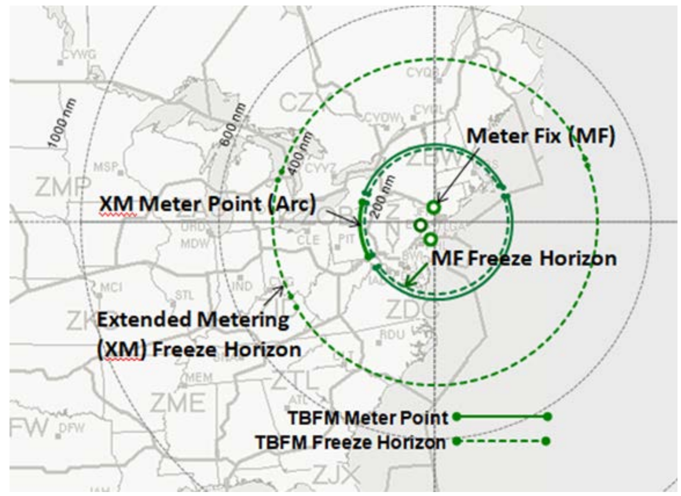

Fig. 5. Simple Illustration of TBFM Extended and Arrival Metering

In today's operations, TBFM schedule conformance ends once the aircraft enters the Terminal airspace. However, Terminal Sequencing and Spacing (TSAS) capability within ATD-1 project provides the controllers with the ability to manage aircraft on their assigned trajectories and STAs all the way to the runway threshold [10]. TSAS generates a time-based schedule and 4-dimensional trajectories to the runway threshold that de-conflict arrival aircraft from each other at merge points within the Terminal airspace. TSAS then creates "slot markers" that continually displays the desired target positions of the aircraft as they traverse through the Terminal airspace, so that the air traffic controllers can use the slot markers as visual targets to adjust aircraft speeds in order to keep aircraft on their STAs. TSAS integrates seamlessly with existing TBFM schedule, thereby creating integrated TBO solutions from the TBFM freeze horizon to the runway.Integration of TBFM scheduling and TSAS capability has the potential to address some of the metroplex inefficiencies, especially in the New York region. It enables the simultaneous use of scarce metroplex airspace by competing flows when beneficial. Alternating slot assignments between two airports would allow airspace sectors that are currently delegated to one airport only to be shared. For example, utilizing TBFM and TSAS, JFK and LGA arrivals could be scheduled to share lower altitude approach routes in the highlighted red airspace in Fig. 1. LGA arrivals in this case could approach runway 4 while JFK arrivals can approach runway 13L. Similarly, scheduling and de-confliction can allow TEB and LGA arrivals to share the airspace highlighted in blue in Fig. 1 and allow flights to avoid extended travel along loops or long level segments, and significantly improve efficiency.

IV. Need for Integrated TBO for Increasingly Diverse Air Traffic Operations

High demand for access to the airspace from new entrants with diverse missions (e.g., Urban Air Mobility (UAM), Uncrewed Aerial Systems (UAS) activities, Space launch/re-entry) will require traditional users of the NAS, such as commercial passenger and cargo airlines, business jets, and general aviation to accommodate the newcomers. The NAS will also need to accommodate a wider range of vehicle performance characteristics than in current operations, from supersonic flight [21] at the high end of the speed spectrum of current operations (e.g., Mach 1.4-1.6), to slow aircraft such as High Altitude Low Endurance (HALE) and Vertical Takeoff and Landing (VTOL) and UAS drones at the low end of the spectrum. The increased number of VTOL flights particularly supporting UAM operations [1][22] will operate mostly in the low-altitude Class G airspace, many operations close to the major airports. An increase in cruise-efficient short takeoff and landing (CESTOL) flights [23], particularly to support thin-haul operations connecting less served areas to major airports [24][25], increase the demand for short runways at major airports and the underutilized runways at secondary airports.

While initial concepts may segregate the new operations from traditional traffic, in the farther term these flights may operate in the same airspace and along the same flows as traditional traffic. Some missions such as space launches may require handling through static or dynamic reservation of airspace or other tailored solutions that may be disruptive to other nominal operations. Other new operations may be possible to integrate into the traditional traffic more seamlessly. The interaction between vehicles with wide disparity in performance, maneuverability and risk will require special consideration of the safety envelopes around them.

In addition, the expectation is that on-demand access, while existing today from general aviation and air taxi, will increase dramatically due to UAM and UAS operations, and will exhibit varying degrees of uncertainty in scheduling and nature of operations. Also, they may need more flexibility to change their plans more tactically than traditional operators. In order to effectively share busy airspace among a wide variety of missions, better planning and intent sharing will be required. In the future, high levels of connectivity and information sharing, automation and autonomy, and smart machine-based operations are expected to enable such accommodations.

The variation in vehicle performance and equipage capabilities will pose many challenges to predicting trajectories with accuracy. Additional tools and methods will be needed to provide better predictions, to accurately communicate these trajectories, to synchronize the trajectories so that all interested parties have the same information and expectations, and to ensure conformance to trajectories and flexibility to make changes in trajectories when needed.

For the traditional operations to be able to operate in this airspace, diverse vehicle performance, better trajectory prediction, better automatic data exchange, and better planning and intent sharing are needed. This will require advanced TBO capabilities to keep aircraft on their intended trajectories and share them automatically with others. The integration of TBO concepts in this paper provides a framework as to how it can be accomplished.

V. Conclusion

This paper describes a framework for combining and advancing those NASA efforts to improve arrival and departure demand management by integrating select NASA TBO capabilities with the TFMS, TBFM, and the TFDM tools. to support surface, departure and arrival metering, as well as dynamic reroutes for weather avoidance. The paper also describes a mechanism of integrating operator priorities and preferences into service-oriented operations.

Taken together, integrated TBO solutions provide a solid foundation for future NAS transformations in order to handle highly diverse operations that are envisioned. Effective integration of TBO capabilities in traditional operations opens up the airspace to be shared with future diverse sets of vehicles and missions that has potential to transform the NAS in the 21st century.

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