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Analysis of a Dynamic Multi-Track Airway Concept for Air Traffic Management

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July 2008

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Abstract

The Dynamic Multi-track Airways (DMA) Concept for Air Traffic Management (ATM) proposes a network of high-altitude airways constructed of multiple, closely spaced, parallel tracks designed to increase en-route capacity in high-demand airspace corridors. Segregated from non-airway operations, these multi-track airways establish high-priority traffic flow corridors along optimal routes between major terminal areas throughout the National Airspace System (NAS). Air traffic controllers transition aircraft equipped for DMA operations to DMA entry points, the aircraft use autonomous control of airspeed to fly the continuous-airspace airway and achieve an economic benefit, and controllers then transition the aircraft from the DMA exit to the terminal area. Aircraft authority within the DMA includes responsibility for spacing and/or separation from other DMA aircraft. The DMA controller is responsible for coordinating the entry and exit of traffic to and from the DMA and for traffic flow management (TFM), including adjusting DMA routing on a daily basis to account for predicted weather and wind patterns and re-routing DMAs in real time to accommodate unpredicted weather changes. However, the DMA controller is not responsible for monitoring the DMA for traffic separation. This report defines the mature state concept, explores its feasibility and performance, and identifies potential benefits. The report also discusses (a) an analysis of a single DMA, which was modeled within the NAS to assess capacity and determine the impact of a single DMA on regional sector loads and conflict potential; (b) a demand analysis, which was conducted to determine likely city-pair candidates for a nationwide DMA network and to determine the expected demand fraction; (c) two track configurations, which were modeled and analyzed for their operational characteristic; (d) software-prototype airborne capabilities developed for DMA operations research; (e) a feasibility analysis of key attributes in the concept design; (f) a near-term, transitional application of the DMA concept as a proving ground for new airborne technologies; and (g) conclusions. The analysis indicates that the operational feasibility of a national DMA network faces significant challenges, especially for interactions between DMAs and between DMA and non-DMA traffic. Provided these issues are resolved, sectors near DMAs could experience significant local capacity benefits.

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1.0 INTRODUCTION

1.1 Statement of the Problem

The National Airspace System (NAS) requires transformation to meet future demand, which Federal Aviation Administration (FAA) forecasts project will double or triple by the year 2025[1]. To facilitate this transformation, Congress passed and signed into law an act establishing the Joint Planning and Development Office (JPDO) for coordinating the research and development related to air transportation that will lead to a Next Generation Air Transportation System (NextGen). The JPDO is jointly managed by the FAA and NASA and is supported by staff from the departments of Commerce, Defense, and Homeland Security and private industry. One of the goals for NextGen is to enable a substantial increase in capacity to meet future demand for air travel while maintaining safety. Many concepts currently undergoing research and development focus on achieving this goal. This report contains a description and analysis of the DMA concept for ATM, which seeks to increase the capacity of the high-altitude airway system without increasing the workload of air traffic controllers to help meet increased en-route traffic demand. Corresponding increases in terminal arrival and airport capacity would also be necessary to absorb the increased en-route traffic. Thus, complementary concepts in these domains must be implemented to produce an increase in total system capacity. Such complementary concepts are not the subject of this report.

The current NAS is structured into en-route, terminal arrival, and terminal departure sectors. The DMA concept discussed in this report focuses only on en-route operations. The en-route system is structured into Air Route Traffic Control Centers (20 in the conterminous United States). Each ARTCC is subdivided into airspace sectors. Each sector is controlled by a radar controller, who is assisted by an associate data controller during peak traffic. The controller's job is to provide traffic separation and expedite traffic flow, tasks that become even more difficult in the presence of convective weather and traffic congestion. A principal factor limiting the number of aircraft that a sector can safely accommodate during peak hours is controller workload. The sector limit is typically 10 to 18 aircraft per sector, depending on the sector size and complexity. Adding to the workload is inter-sector coordination, where at each boundary the controller must hand-off responsibility for aircraft to the next controller. As shown in Figure 1, an aircraft traversing the current NAS crosses many sector boundaries, typically 25 to 30 for an east-coast to west-coast flight.

Today's structure for en-route navigation consists of a network of low- and high-altitude airways that generally define direct routing between ground-based navigation aids[1]. The airway structure is available to aircraft operators for flight planning and navigation and to air traffic controllers for maintaining structure within traffic flows to help minimize workload. Controllers use the airway structure extensively during periods of higher traffic volumes when direct routing produces unacceptable traffic management challenges. Current airways are typically single-track, bidirectional, and multi-layered

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[1] The impact of the FAA High Altitude Airspace Redesign Project, recently developed to provide fundamental changes in the navigation structure and operating methods to enable more flexible and efficient en-route operations in the high altitude airspace environment, was not included in the analyses that inform this report.

Figure 1. A typical flight from Newark to San Francisco crosses 25 airspace boundaries.

(1,000 feet separation between flow directions, e.g. Flight Level (FL) 320 westbound, FL330 eastbound, etc). The limitation of the single track forces aircraft to conform to a common operating speed at a given altitude, to operate at different (and potentially non-optimal) flight levels, or to be manually diverted around traffic by the air traffic controller. As traffic increases, restrictions at airspace boundaries significantly reduce the opportunity for one aircraft to overtake and pass another. The result is increased workload for the controller and decreased efficiency for the aircraft.

1.2 Concept Solution

The Dynamic Multi-track Airway (DMA) concept proposes a mechanism for increasing the capacity of en-route airspace without increasing controller workload. The DMA concept is based on a system of airways comprised of *multiple parallel tracks*, much like the interstate highway system, along which aircraft can safely maneuver while traversing otherwise congested airspace. See Figure 2. In the DMA Concept, aircraft will rely on emerging airborne surveillance technology to perform self-separation within the DMA. A single controller will monitor traffic flow for the entire DMA. Aircraft traveling in the DMA will not contribute to traffic in the individual sectors, thus reducing controller workload. In addition, the DMA will represent continuous airspace requiring controller hand-off only to enter and exit the DMA, which will further reduce controller workload. The "dynamic" aspect of the DMA concept derives from the need to conduct daily rerouting to determine a wind-optimal flight path and avoid regions of adverse weather.

The DMA concept combines aspects of two alternative concepts developed in related research: the Dual Airspace concept, developed by the Eurocontrol Experimental Center, calls for a multi-track approach and two independent control mechanisms; and the Dynamic Airspace Super Sectors concept, developed by George Mason University, calls for airborne self-separation. The DMA concept combines the multi-track approach of the
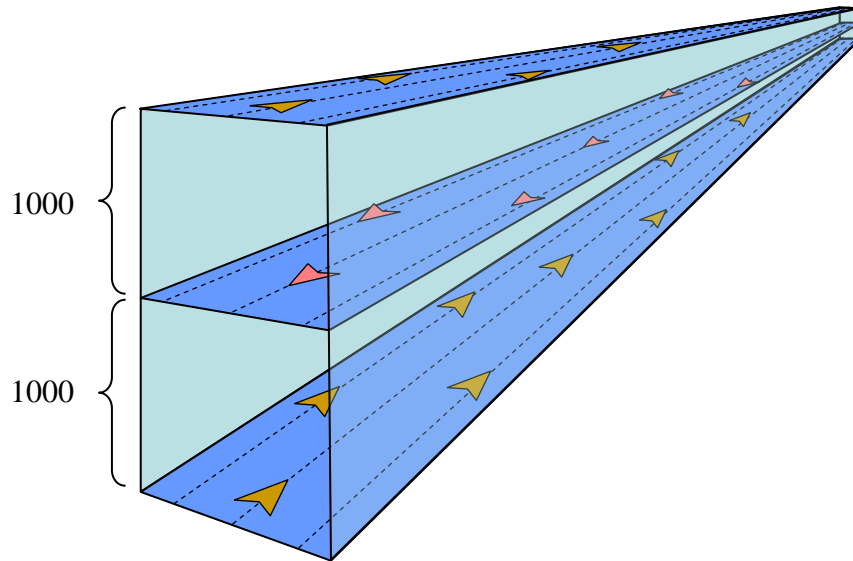
Figure 2. Notional representation of a Dynamic Multi-track Airway shown with multiple flight levels and bidirectional traffic flying on closely spaced, parallel tracks.

Dual Airspace concept with airborne self-separation called for in the Dynamic Airspace Super Sectors concept. The alternative concepts are discussed in the following sections.

1.2.1 Dual Airspace Concept

The Dual Airspace concept proposes two independent control mechanisms to share the airspace: (a) highways and (b) sectors [2].

(a) Highways. Few in total number, highways will accommodate dominant streams of long-haul cruising traffic that over-fly the core European airspace. Each highway "ribbon" will consist of multiple parallel lanes traffic lanes.

(b) Sectors. Sectors will accommodate the remaining flights with routes that do not align with the highways. Sectors will also accommodate shorter flights and aircraft transitioning between airports and highways.

Although not defined in detail, the Dual Airspace concept relies primarily on segregating traffic flows to offload sector controllers who are managing the highway traffic. And unlike the DMA concept, the Dual Airspace concept does not propose self-separation operations for aircraft.

An initial human-in-the-loop experiment examined a single sector penetrated by a highway and assessed the impact on the sector controller. Examiners found generally positive results: the operations were acceptable to controllers and the dual airspace operations safely increased sector capacity during high traffic density. The findings applied only to a single sector in isolation and there was no exchange of aircraft between the sector and the highway.

1.2.2 Dynamic Airspace Super Sectors Concept

The Dynamic Airspace Super-sectors concept proposes the separation of high-density traffic flows into elongated super sectors [3]. Each super-sector will receive optimal routing between city pairs and shift dynamically with changing weather (although the concept does not specify how this will be accomplished). Controllers external to the super-sector will treat each super-sector as a "ribbon" of 13-mile-wide, 2000-feet thick, special-use airspace and will be responsible for ensuring complete segregation of all sector traffic from the super-sector. The super-sector will contain a single centerline track that will provide faster aircraft with the option to pass slower aircraft laterally using self-separation authority. Although the Dynamic Airspace Super-sectors' concept does not call for a multi-track airway, its use of autonomous passing capability resembles that in the DMA concept.

George Mason University did not explore the Dynamic Airspace Super-sectors concept extensively for feasibility. However, researchers modeled the concept in several network configurations to determine potential impacts on controller workload and capacity. Results were mixed: complexity decreased in some sectors while workload increased overall. For aircraft traveling the super-sector, delay spikes near the entry/exit points were a concern, indicating that effective flow management would be non-trivial.

Researchers from George Mason University concluded from these results that the robustness and viability of the Dynamic Airspace Super-sectors concept and its ability to produce intended benefits depends on the resolution of key logistical and operational issues within the context of a complete ATM system.

1.3 Analysis Approach

The research approach is rooted in a multi-stage process in which multiple analyses are conducted across different dimensions characterizing the feasibility, viability, performance, and potential benefits of DMA operations. The results are intended to aid aviation decision-makers in determining whether further investment in DMA research and development is warranted.

The baseline operational context for the analysis discussed in this report derives from current operations in the NAS today augmented by new roles, responsibilities, required infrastructure, and enabling technologies for DMA, as described in <u>Chapter 2.0 Mature State DMA Concept Description</u>.

The DMA concept for ATM is consistent with the NextGen concept of "flow corridors" as defined by the JPDO and may be considered a part of the larger transformation of the air transportation system. However, the analysis discussed in this report assumes that the structure and procedures associated with the NAS today remain in place. It further assumes DMA implementation without the implementation of high altitude airspace redesign or other NextGen capabilities currently under consideration.

The multi-stage assessment of the DMA concept for ATM consists of the following activities and analyses:

Stage 1. **Concept Description.** The assessment begins with a high-level, mature-state description of the DMA operational concept that illustrates how DMA operations could work if widely implemented across the NAS. The description further identifies potential benefits to operators and service providers, lists roles and responsibilities of major players, summarizes anticipated equipage and infrastructure requirements, and identifies key design attributes involved in extending the DMAs from a single, isolated use to mature-state operations across the NAS. See Chapter 2.0 Mature State DMA Concept Description.

Stage 2. **Capacity Benefits and Demand Analysis.** This stage of the assessment focuses on two analyses:

    a. **Capacity Benefits Analysis.** Researchers examine the basic capacity-enhancing potential of the DMA concept and its relationship to air traffic demand. To assess first-order capacity effects, a single cross-country DMA is modeled in the context of current NAS sectors. The model is run at several demand levels to determine the impact on sector loading and potential conflict count. See Chapter 3.0 Capacity Benefits Analysis of a Single DMA.

    b. **Demand Analysis.** Researchers analyze current city-pair traffic demand to understand the likely physical layout of a DMA network within the NAS and to determine which population centers should be connected with DMAs to absorb the most traffic. The analysis makes the first-order assumption that these population centers will still be dominant in defining future demand for DMAs, even with growth in point-to-point traffic. See Chapter 4.0 Demand Analysis for the DMA Concept.

Stage 3. **Low-Fidelity Track Configuration Modeling and High-Fidelity Prototyping.** The next stage of the assessment examines options for aircraft self-separation for operations in a single DMA. The objective is to determine the feasibility and impact of different autonomous operations. The assessment consists of two parts: a low-fidelity modeling activity and a high-fidelity technology prototyping activity.

    a. **Track Configuration Modeling and Analysis.** The low-fidelity modeling activity examines speed-based and speed independent track configurations in a simplified, isolated DMA. The analysis examines fleet characteristics and basic traffic behavior as DMA loading increases. See Chapter 5.0 Track Configuration Modeling and Analysis.

    b. **Prototyping of DMA Spacing and Passing Capabilities.** The high-fidelity prototyping activity verifies the ability to develop airborne technologies needed to perform basic DMA operations. The analysis examines operations within a simplified, isolated DMA. See Chapter 6.0 Prototyping of DMA Spacing and Passing Capabilities.

Stage 4. **DMA Conceptual Analysis.** The next phase of the assessment focuses on a conceptual analysis of key design attributes that would affect the logistics of conducting DMA operations within the context of existing NAS operations—e.g.,

the placement of DMAs with respect to existing airways; altitude stratification and its impact on local sector traffic; procedures for handling DMA intersections and merges; and requirements and impacts of dynamically rerouting DMAs for weather. Researchers used the conceptual analysis to illustrate the feasibility of the DMA concept by identifying basic strengths and weaknesses of alternative designs. See Chapter 7.0 DMA Conceptual Analysis.

Stage 5. **Conceptual Analysis of DMA as a Transitional Step.** The final stage of the assessment sets aside the mature-state DMA concept and instead analyzes a limited, temporary implementation of DMAs as an interim step in a larger, more comprehensive transformation of the air transportation system, rather than an end in itself. The objective is to provide a safe environment as a proving ground in which to explore basic procedures, technologies, and potential benefits of corridor operations and, in particular, self-separation operations. The analysis explores DMA in the context of other segregation approaches as a means to segregate autonomous operations from non-autonomous operations. See Chapter 8.0 Conceptual Analysis of DMA as Proving Ground for New Airborne Capabilities.

2.0 MATURE STATE DMA CONCEPT DESCRIPTION

This chapter presents an overview of the mature-state DMA concept; discusses potential benefits to operators and service providers; identifies major participants and their respective roles and responsibilities; and specifies anticipated equipage and infrastructure requirements for implementing DMA operations in today's NAS. The specifications are sufficiently detailed for use in exploring basic concept feasibility.

The chapter concludes with a summary of key design attributes involved in extending the concept from a single, isolated DMA to mature-state DMA operations. (Note: these are the same design attributes selected for a conceptual analysis later in the story and are discussed in Chapter 7.0 DMA Conceptual Analysis. Design alternatives for each attribute are analyzed to assess concept feasibility and the impact on the potential benefits.)

2.1 Mature-state DMA Concept

The mature-state DMA concept for en-route operations proposes a network of high-altitude airways constructed of multiple, closely spaced, parallel tracks to increase en-route capacity in high-demand airspace corridors. Segregated from non-airway operations, these multi-track airways establish high-priority traffic flows along optimal routes between major terminal areas throughout the NAS. Air traffic controllers transition aircraft equipped for DMA operations to DMA entry points, the aircraft use autonomous control of airspeed to fly the continuous-airspace airway and achieve an economic benefit, and controllers then transition the aircraft from the DMA exit to the terminal area. Aircraft authority within the DMA includes responsibility for spacing and/or separation from other DMA aircraft. The DMA controller is responsible for coordinating the entry and exit of traffic to and from the DMA and for traffic flow management (TFM), including adjusting DMA routing on a daily basis to account for predicted weather and wind patterns and re-routing DMAs in real time to accommodate unpredicted weather changes. However, the DMA controller is not responsible for

monitoring the DMA for traffic separation.

2.2 Potential Benefits to Operators and Service Providers

Aircraft operators and service providers could benefit from DMA operations. This section explains how aircraft operators could maximize fuel efficiency, increase operational efficiency and minimize delays, and how ATC could increase workforce productivity.

Operators could maximize fuel efficiency. Aircraft operators who meet equipment requirements for DMA operations could access daily optimized routing between high-demand city pairs, which, as the most likely locations to establish DMAs, would receive priority status. Optimal routing and flight levels would of course translate into fuel savings. Depending on the design of the DMA system, other operators who do not meet equipment requirements could still fly between high-demand city pairs but would be relegated to less optimal routing and/or flight levels and be subject to greater schedule and/or in-flight delays.

Properly equipped aircraft could also eliminate a problematic operational constraint associated with single file airways in which faster aircraft must lag behind slower moving aircraft. This benefit would derive from DMA operational design, which calls for limited, autonomous operations which will allow aircraft to fly much closer to, or at, their best-economy airspeed (or any speed desired by the operator) throughout the DMA flight.

Aircraft operators could increase operational efficiency and minimize delays. DMA operations call for TFM based in part on highly scheduled flights, which would increase arrival time predictability and minimize delays.

ATC could increase productivity. Air traffic controllers (i.e., radar controllers) could significantly increase workforce productivity measured in total aircraft handled per unit-time, per controller, a benefit that derives from shifting responsibility for managing DMA aircraft away from the sector controller toward DMA controllers who would be responsible for managing traffic in highly traveled corridors with dominant traffic flows; e.g., through sectors with predominantly uni- or bi-directional traffic. Under the DMA concept, aircraft in dominant traffic flows would be managed with new procedures associated with DMA operations (discussed in Chapter 5.0 Track Configuration Modeling and Analysis and Chapter 6.0 Prototyping of DMA Spacing and Passing Capabilities), not by local sector controllers. The concept calls for DMAs to absorb increasing growth in traffic to meet demand in the most highly traveled corridors. Once relieved of managing traffic in the most highly traveled corridors, sector controllers can more readily manage non-corridor traffic in their sectors, thereby accommodating growth in non-corridor traffic. A dedicated DMA air traffic controller would manage traffic in each DMA. Other controllers would manage sectors penetrated by DMAs. DMA controllers and sector controllers would not exercise the same degree of tactical control.

A separate DMA controller designated to manage traffic flow throughout the length of a DMA will minimize tasks related to handing-off and receiving traffic across sector boundaries, thus reducing sector controller workload. The highly structured uni- or bi-directional design of DMAs could also allow the DMA controller to manage a larger number of aircraft within a DMA. In addition, limited DMA operational procedures for

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autonomous aircraft could reduce DMA controller workload.

Traffic flow managers could also reduce workload under DMA operations by benefitting from a characteristic of DMAs that would organize significant numbers of aircraft equipped with advanced 4-dimensional (4D) trajectory management capabilities into "bundles" or "tubes" that could be re-routed and managed as a group. Under the DMA concept, an entire group of properly equipped aircraft could be given a revised DMA track (via data link) as needed to avoid en-route convective weather systems, thus freeing the traffic flow manager from managing each aircraft individually. Aircraft equipped with 4D trajectory management capability would also be able to receive time-based, flow management clearances, which would provide an opportunity to replace miles-in-trail with schedule-based TFM.

2.3 Concept Roles and Responsibilities
The mature-state DMA concept for en-route operations proposes the following roles and responsibilities for service providers and operators.

2.3.1 Air Traffic Control System Command Center (ATCSCC) Controller

- Responsible for the DMA network structure and performance
- Establishes and disseminates the daily DMA route structure, accounting for user community preferences and predictions for traffic demand, wind patterns, weather hazards, airspace restrictions, and en-route congestion
- Performs strategic-level TFM for the DMA network
- Balances traffic loads between DMAs to minimize system delays and sector impacts
- Sets and adjusts DMA flow rates to match terminal-area capacity
- Determines when DMA re-routing will occur and defines non-conflicting re-routes for affected DMAs when necessary for weather hazards, airspace changes, or congestion
- Coordinates TFM and re-routing with individual DMA controllers

2.3.2 DMA Controller (New Position)

- Responsible for operations associated with an individual DMA
- Coordinates aircraft hand-offs to and from terminal area controllers
- Coordinates mid-DMA hand-offs to and from sector controllers
- Coordinates intersection and merge operations with other DMA controllers
- Coordinates DMA TFM and re-routing with ATCSCC
- Communicates DMA TFM constraints to aircraft (e.g. inter-aircraft spacing, intersection crossing times, Required Time of Arrival (RTA) at exit)
- Coordinates DMA re-routing with individual flight crews and sector controllers
- Monitors DMA performance (e.g. flow rate, local congestion, impact of perturbations) and exercises control by exception if DMA performance is expected to degrade

2.3.3 Sector Controller

- Responsible for sector traffic, but not DMA traffic that passes through the sector
- Coordinates mid-DMA hand-offs to and from DMA controllers for traffic entering or leaving the DMA in their sector
- Controls non-DMA sector traffic, giving right-of-way to DMA traffic

2.3.4 DMA Flight Crew

- Responsible for adhering to the track routing and assigned altitude, along-track separation once on the DMA, and between-track separation if changing tracks
- Remains at or greater than the minimum along-track separation from lead aircraft
- Achieves and maintains controller-assigned in-trail spacing, as may be required by DMA operational procedures[2]
- Maintains user-preferred airspeed within controller-assigned constraints for along-track separation and TFM, as may be required by DMA operational procedures[2]
- Follows track-changing procedure for assuring along- and between-track separation
- Coordinates with DMA controller for control-by-exception situations
- Coordinates with DMA controller during implementation of dynamic re-routes of DMA

2.3.5 Non-DMA Flight Crew

- No new roles or responsibilities

2.4 Anticipated Equipage and Infrastructure Requirements
This section identifies aircraft equipage and NAS infrastructure requirements associated with the mature-state DMA concept for en-route operations.

2.4.1 NAS Infrastructure

- Ground-to-air trajectory uplink infrastructure

2.4.2 Air Traffic Control System Command Center (ATCSCC)

- DMA network management automation system to provide support ranging from a manual planning capability to a fully automated capability addressing the following functions:
- Network planning (e.g. airspace routing, sector impacts, load balancing)
- Configuration planning (e.g. number of tracks, activation and deactivation times)

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[2] The possible requirement for these capabilities is discussed below as a concept design attribute.

- Entry/exit scheduling for TFM; coordinates with scheduling tools of entry/exit facilities
- Re-routing for weather; supports associated rescheduling for TFM
- DMA-relevant weather modeling and prediction
- DMA network structure dissemination to DMA and sector controllers

2.4.3 DMA Controller Position

- Individual DMA management automation system to provide support ranging from a manual planning capability to a fully automated capability addressing the following functions:
- Configuration management (e.g. number of tracks, nominal track speeds)
- Entry/exit facility coordination
- Scheduling for mid-DMA entry slots
- Intersection and merge scheduling for TFM
- Implementation of re-route defined by ATCSCC
- Trajectory and TFM constraints uplink, assumed to be Controller Pilot Data Link Communications (CPDLC) or an equivalent derivative capability
- Communication capability with every sector
- Surveillance of the whole DMA

2.4.4 Sector Controller Position

- Display of DMA position and status
- Communication with the DMA controller position
- Conflict management tool

2.4.5 DMA Aircraft

- Traffic surveillance using Automatic Dependent Surveillance Broadcast (ADS-B) in and out
- Area Navigation (RNAV) and Required Navigation Performance (RNP) capability that meets DMA requirements to ensure adequate procedural separation between parallel tracks
- Required time of arrival (RTA)-meeting capability if required for TFM within the DMA
- Airborne Separation Assistance System (ASAS) tools for spacing and/or passing maneuvers
- Control Pilot Data Link Communications (CPDLC) as the assumed mechanism for receiving uploaded DMA route definition

2.4.6 Non-DMA Aircraft

- No new requirements

2.5 Key Design Issues

This section identifies key design attributes associated with extending DMAs from single, isolated use to widespread deployment and mature-state operations across the NAS. This section also identifies important design alternatives that can affect the feasibility of DMA operations, the fundamental structure of DMAs, the performance of DMAs, potential costs to develop and operate DMAs, how easily DMAs can be integrated into the NAS, and how the aviation community will accept DMA operations.

For a conceptual analysis of the design alternatives, see <u>Chapter 7.0 DMA Conceptual Analysis</u>.

DMA Design Attributes	DMA Design Alternatives
1. Relationship of DMAs to existing airways	The placement of DMAs within the NAS could substantially affect non-DMA operations. Two alternative routings are considered: (a) airway collocated; and (b) airway independent.
2. Track configuration	The track configuration refers to the intended function of each DMA track and the rules and procedures governing track operations. Two alternatives are considered: (a) speed-based; and (b) speed-independent with passing.
3. Altitude stratification of DMAs	The flight levels at which DMA operations would be conducted may impact sector operations for non-DMA aircraft. Three possibilities are considered: (a) one or two; (b) four to six; and (c) all upper flight levels.
4. Separation between sector traffic and DMA traffic	DMAs segregate equipped aircraft from non-DMA sector traffic. Responsibility for separation between these traffic groups must be defined, and the choice may have implications on workload and general feasibility. Three alternatives are considered: (a) sector controller; (b) DMA controller; and (c) DMA flight crew.
5. Managing entry and exit at mid-DMA points	The procedures for joining and leaving the DMA at midway points along the DMA must be defined. Two alternatives are considered: (a) merging entry and diverging exit managed by the flight crew; and (b) direct entry and exit managed by controllers.
6. Interaction between DMA and terminal airspace	Major terminal airspace is likely to be a common destination for several DMAs arriving from different directions. The method for integrating these traffic flows may impact DMA design and operational procedures. Two methods are considered, both of which may be required: (a) pre-exit merging; and (b) post-exit traffic flow integration.
7. Intersecting DMAs	The intersection of DMAs (e.g. east-west with north-south) requires separation for the crossing streams. Three alternatives are considered: (a) procedural separation; (b) DMA controller is responsible for separation; and (c) DMA flight crew is responsible for separation.
8. Rerouting for convective weather and congestion	The DMA concept proposes to provide traffic flow managers with the ability to dynamically re-route high-volume streams of traffic as needed to address convective weather or traffic congestion. The concept must specify the method for accomplishing the re-route. Three alternatives are considered: (a) uplink aircraft-customized re-routed trajectories; (b) follow the leader; and (c) uplink a common re-routed reference track.

3.0 CAPACITY BENEFITS ANALYSIS OF A SINGLE DMA

This section describes the simulation tools used for the analysis, the demand modeling approach, the design of the simulated DMA, and the results of the study.

3.1 Simulation Tools

In order to determine the potential for DMAs to off-load traffic demand from conventional sectors and thereby reduce controller workload, a medium-fidelity simulation was conducted of a single DMA within the current and future Conterminous United States (CONUS) air traffic demand environment.

Two air transportation system simulation tools were used to perform this analysis: DMA Generator and AwSim.

3.1.1 DMA Generator

DMA Generator is a custom-designed code, written in C++, and has been developed for this research activity to define the specific DMA and to generate flight routes to and from the DMA. Using a demand data set as input, this code selects flights for the DMA, generates the new route that will use the DMA, and schedules each flight into the first available DMA entry time slot while maintaining required separation standards. It also computes basic statistics for analysis, including number of flights using each DMA track, DMA distances compared to distances by great circle routes and by Enhanced Traffic Management System (ETMS) recorded routes, additional flight time using the DMA, and time spent waiting for a DMA entry slot.

3.1.2 AwSim

AwSim is a commercial suite of tools to simulate, manipulate, and analyze trajectories. These tools were used for analyzing sector loading and traffic conflicts [4].

3.2 Future Demand Modeling Approach

The analysis of future air transportation system concepts requires the ability to predict future demand and transportation patterns. The FAA produces the *Terminal Area Forecast (TAF)*, the official forecast of aviation activity for active airports in the *National Plan of Integrated Airport Systems*. The TAF is based on an analysis of historical trends using projections provided by terminal area facilities that use FAA forecasting guidelines.

One of the demand sets considered for this study was developed by scaling up a baseline, current-day (1X) demand set using differential growth factors for different airports extrapolated from the TAF to provide the overall level of demand required [5]. Currently unpublished, the demand set was generated for the JPDO by the Sensis Corporation. The 2X and 3X demand levels produced by this approach represent the approximate multiple number of flights anticipated to occur. The baseline day of the JPDO demand set was Thursday, 19 February 2004, a moderate-demand, good-weather day (71st percentile traffic, 16th percentile instrument approach operations, and 10th percentile convective index). Based on Enhanced Traffic Management System (ETMS) data recorded for this

baseline day (including international flights), the 1X, 2X, and 3X demand levels were 57,093 flights, 112,421 flights, and 168,647 flights, respectively.

The second demand set considered for use in this study was the Transportation Systems Analysis Model (TSAM, developed by the Air Transportation Systems Laboratory at Virginia Tech University) [6]. TSAM improves on traditional transportation analysis models by first modeling all long distance travel (defined as one way distance greater than 100 miles) and then projecting traveler mode choice based on trip characteristics and traveler demographics. Since the demand model is based on passenger enplanements and not on flight numbers, alternate future scenarios can be investigated based on transporting the same number of passengers using a different aircraft fleet mix, new demand driven routes, or even entirely new means of transportation such as Very Light Jet (VLJ) air taxis. (Note that for this study, neither the JPDO nor TSAM demand set includes VLJ traffic.)

The TSAM demand projections based on ETMS recorded data for 19 February 2004 (again, including international flights) for 1X, 2X, and 3X passenger enplanements are 57,093 flights, 106,379 flights, and 142,227 flights, respectively. The corresponding flight multipliers for the latter two conditions are 1.86X and 2.49X, which are noticeably lower than the JPDO demand projections. The TSAM methodology introduces new direct routes between city pairs when demand warrants (saving connecting flights) and introduces larger aircraft (rather than more aircraft) once schedule frequency is sufficient to meet passenger needs. The JPDO methodology did not follow this approach. Thus, the TSAM methodology projects that 3X passenger demand can be satisfied by using 2.5X the current number of flights.

Researchers conducting this study selected the JPDO demand set as the more conservative basis for the capacity analysis and because it enables consistency with analyses of other NextGen concepts. The JPDO demand set used in this study includes the following data items:

- Aircraft identifier
- Aircraft type
- Departure airport
- Arrival airport
- Cruise altitude (based on ETMS recorded altitude)
- Cruise speed (based on ETMS recorded track positions)
- Waypoint list (based on ETMS recorded routes)
- Scheduled gate departure time

It should be noted that the demographics-based demand modeling approach of TSAM indicates that 3X flight demand is not likely to be reached until after 2045, based primarily on commercial transport traffic projections. TSAM projects that demand for VLJ air taxi services could add up to 20,000 flights per day by 2025. Even including the projections of VLJ demand, 3X number of flights will not be reached until beyond 2035, according to TSAM projections.

3.3 Design of the Modeled DMA

The current routes used by air traffic above FL300 populated at the 3X demand level are shown in Figure 3. These routes were recorded by ETMS for the 19 February 2004 data set. From the figure it is clear that there are many potential locations for DMAs following today's heavily traveled air routes. The DMA concept design is based on three main considerations: (1) geographic location of the DMA network within the NAS, including airway placement, entry points, exit points, and feeder routes; (2) track configuration, including number of tracks and the in-trail and lateral spacing of aircraft; and (3) altitude stratification.
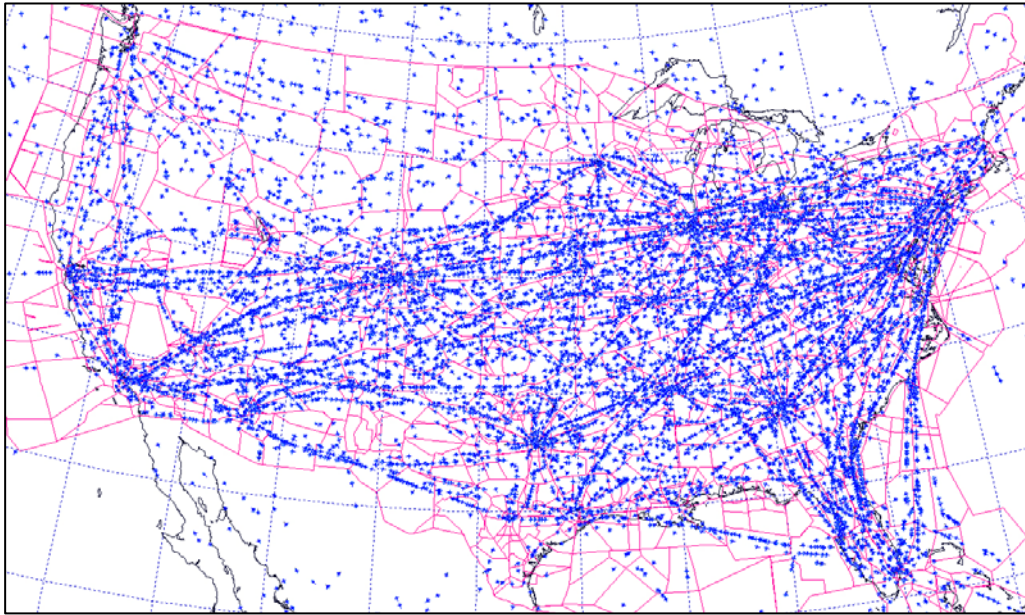
Figure 3. Flights above FL300 with 3X demand using ETMS recorded routes.

3.3.1 Geographic Location

For modeling simplicity, the DMA network is limited to a single coast-to-coast routing for Eastbound and Westbound flights, linking the Newark (EWR)/Philadelphia (PHL) region with the San Francisco (SFO) and Los Angeles (LAX) regions, including intermediate entry/exit points near Pittsburgh (PIT)/Cleveland (CLE), Chicago (ORD), and Denver (DEN). Figure 4 shows the locations of the DMA entry/exit points with diamond symbols, and Figure 5 shows flights using the DMA. For this analysis, the flights using the DMA are still considered to be within the DMA during the fan in/out flight segments from the origin and destination airports. These DMA feeder segments were not explicitly modeled, but it is likely that a DMA design would need to accommodate at least part of the climb and descent phases of flight. Later analysis (discussed in Chapter 7.0 DMA Conceptual Analysis) indicates that transfer of separation responsibility during these transition phases might be logistically difficult. If feasible, this extension could take the form of a varying altitude DMA segment which would have an entry/exit point in terminal airspace serving one airport or more likely a group of airports. This would result in some aggregation of DMA fan in/out segments, compared to those visualized in Figure 5.

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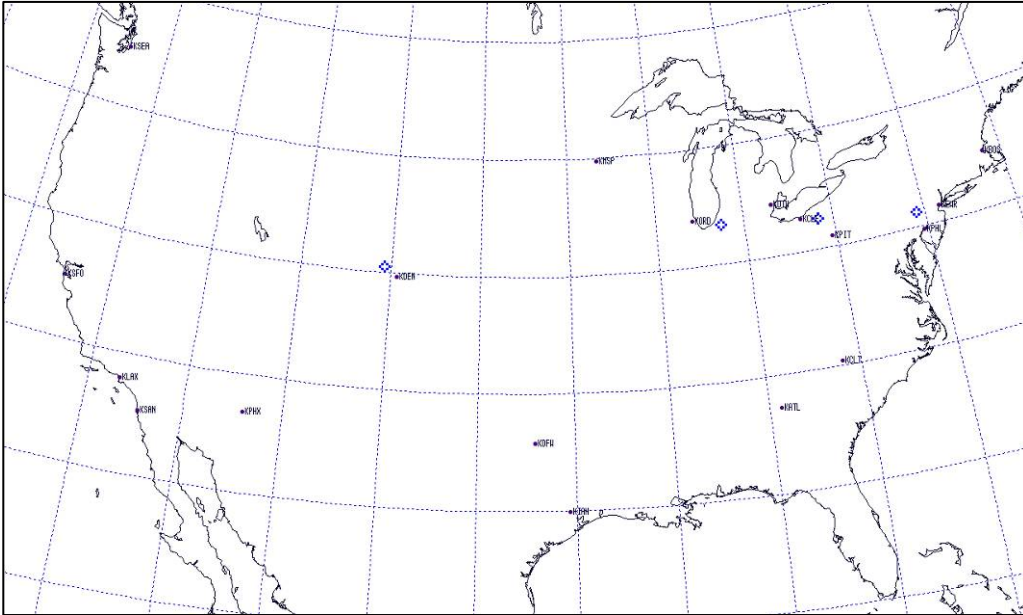
**Figure 4. Locations of DMA entry/exit points and some of the major airports
served by the simulated DMA.**
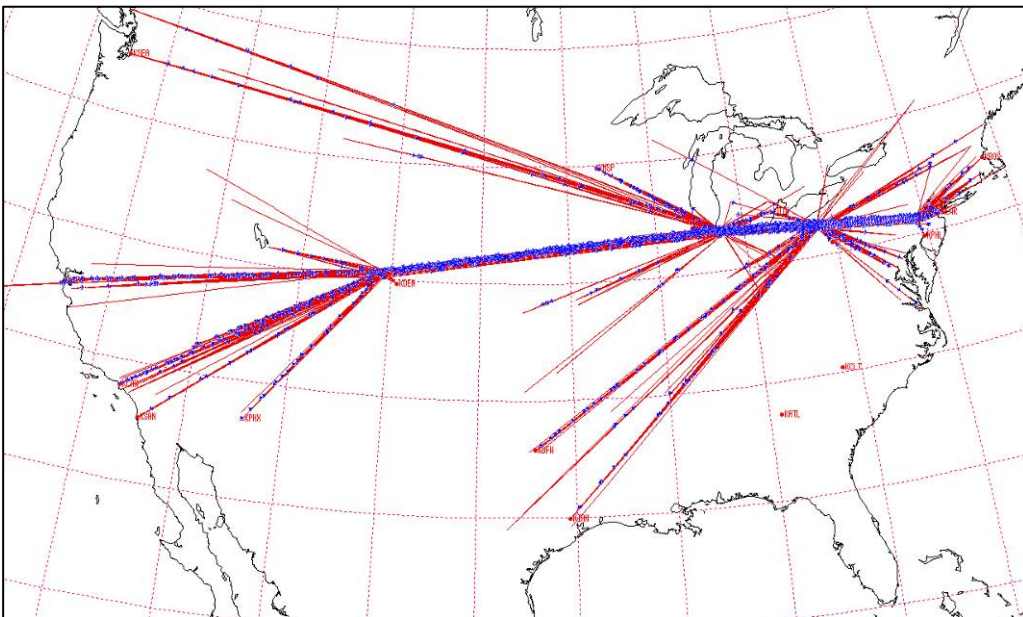
Figure 5. Flights using the simulated DMA.

3.3.2 Track Configuration

This analysis modeled only the speed-based tracks design, primarily because of the
simpler implementation in the simulation analysis tools. A subsequent analysis
(discussed in Chapter 5.0 Track Configuration Modeling and Analysis) considers speed-
based tracks and speed-independent tracks with passing.

In the speed-based tracks design, each parallel track is designated for a unique speed or Mach number, and aircraft are assigned to the track that best matches the operator's preferred speed. An analysis of the 19th February 2004 ETMS recorded data provides the range of cruise ground speeds currently being used by NAS traffic, as shown in Figure 6. The data show a major grouping of high speed jet traffic separated from other traffic. The lower speed traffic is generally shorter range and therefore not likely to be of interest for a DMA. The majority of jet traffic has a cruise ground speed in the range 400 to 500 nautical miles per hour (kts), so the DMA must accommodate this speed range. The selections of numbers of tracks, lateral track spacing, and in-trail minimum spacing are described in an upcoming section.
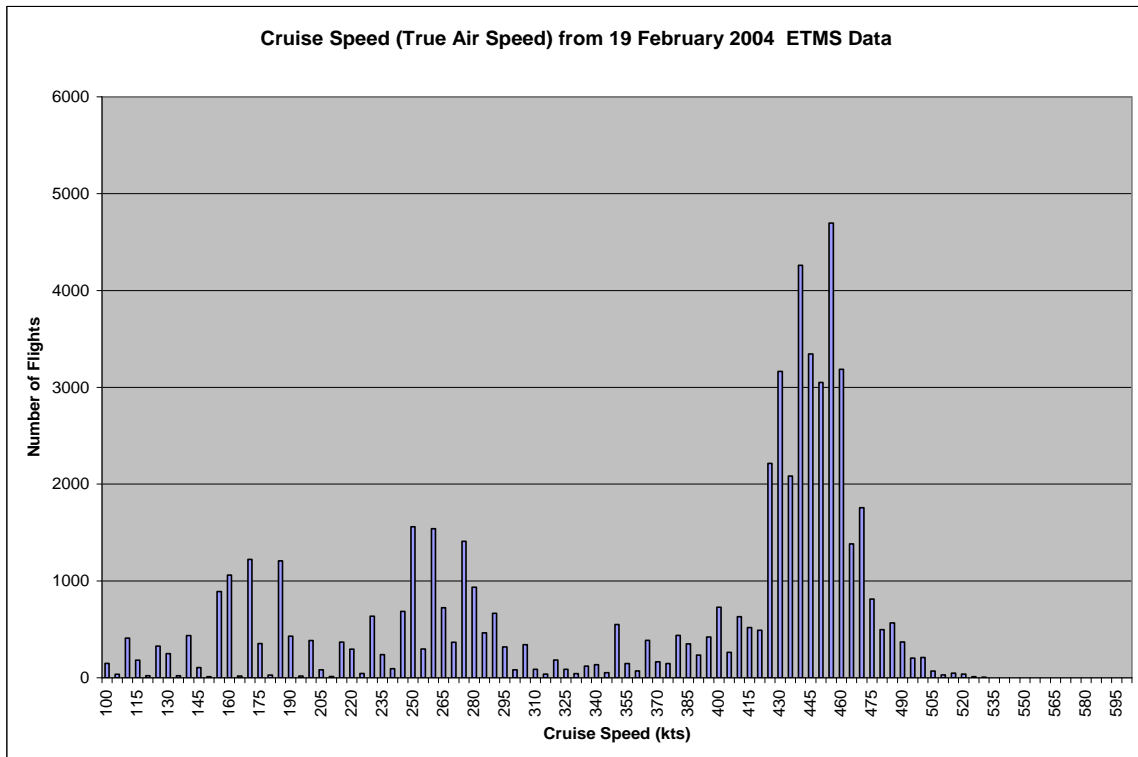
Figure 6. Cruise speed distribution of flights in the NAS.

3.3.3 Altitude Stratification

For the en-route sectors through which the DMA passes, reserving two flight levels for exclusive DMA operations can represent a substantial proportion of the usable airspace, typically 20-to-30 percent, reducing the volume of airspace available for the remaining air traffic. Therefore it was decided to minimize the number of altitudes used. Based on initial analysis of the traffic levels anticipated up to 3X current demand, a single flight level for Eastbound traffic and a different single flight level for Westbound traffic will provide sufficient capacity for the coast-to-coast DMA network of this analysis. Reserving two flight levels for the single DMA still represents a conservative modeling assumption because opposite direction traffic for a city pair usually has geographically separated routes for best winds. The current study did not model the effects of winds, and therefore the Eastbound and Westbound routes were collocated. If winds were

included, then separate DMAs for Eastbound and Westbound routes would be appropriate, and each could be operated with a single flight level, thereby reducing the impacted airspace.

Choosing the optimal altitudes for the DMA is quite a complex issue. See Figure 7 for the cruise altitude distribution of flights in the NAS. The cruise altitude range of jet aircraft is quite broad, ranging from about 27,000 ft to 40,000 ft. The DMA altitude needs to be near the maximum cruise altitude of the aircraft for fuel efficiency but must also allow aircraft to climb into and descend from the DMA at a reasonable vertical speed. It can typically take over 100 nautical miles (nmi) for jet aircraft to reach the upper flight levels. For this analysis, the altitude of the Westbound DMA is set to FL380, and the Eastbound DMA is set at FL390. These flight levels were chosen to place the DMA traffic above most of the sector traffic, which were assigned to lower flight levels. Segregating the DMA and non-DMA traffic by altitude minimizes the interactions in the simulation, which is preferable for this initial analysis. The chosen flight levels represent the extremes of what would be feasible, because aircraft at airports close to the DMA entry and exit points will be climbing or descending at excessive rates. In practice, the actual DMA flight levels would likely be chosen to account for the majority user preference. Lower altitudes are likely to be necessary for shorter DMAs, but for the purposes of this initial capacity analysis, the exact altitude of the DMA makes little difference. There are many other important design considerations which are also not modeled for this capacity analysis, such as design of the entry and exit airspace regions, interaction of DMA traffic with non-DMA traffic, and mechanisms for rerouting the DMA to avoid weather cells. These issues and more are conceptually analyzed in Chapter 7.0 DMA Conceptual Analysis.
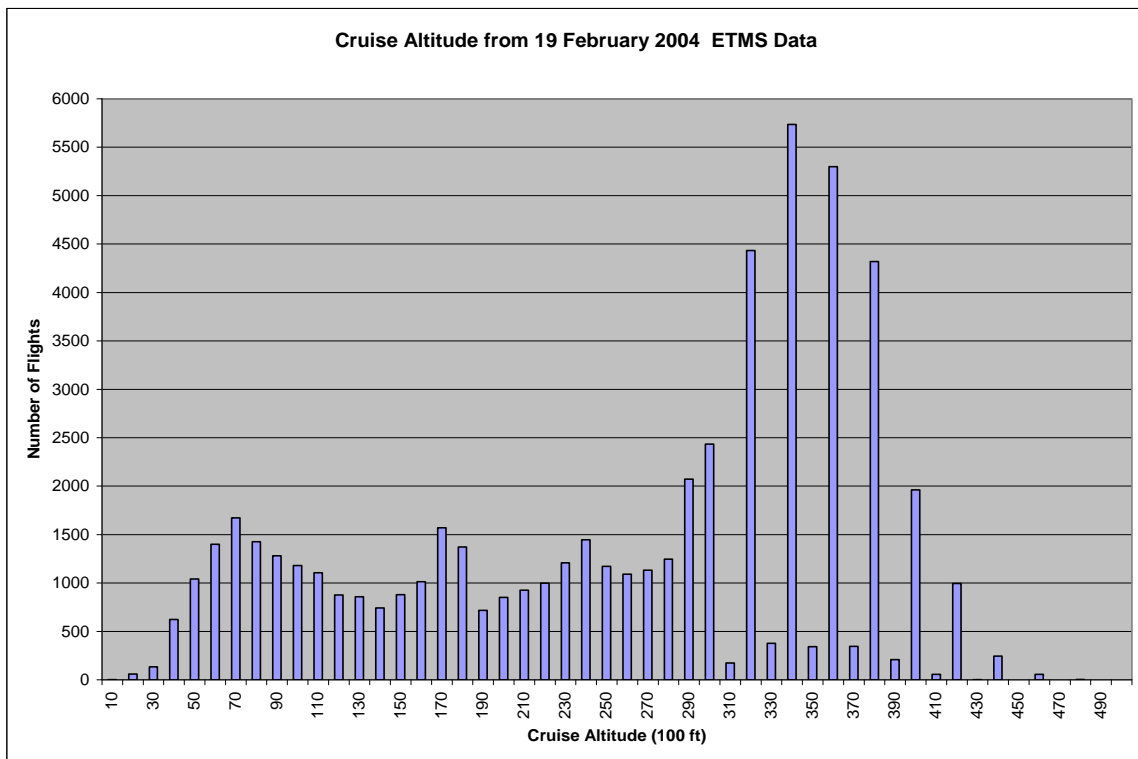
Figure 7. Cruise altitude distribution of flights in the NAS.

3.4 DMA Design Variations for Analysis

Based on the initial analysis of speed ranges and altitudes, several design variations were chosen for more detailed study. See Table 1. All variations used Westbound and Eastbound layers at FL 380 and FL 390, respectively, with the same number of tracks in each direction.

Table 1. DMA design variations implemented for the medium-fidelity analysis.

Parameter	Variation 1	Variation 2	Variation 3	Variation 4	Variation 5	Variation 6
Number of tracks	5	5	6	6	6	6
Assigned track speeds (true airspeed, kts)	492, 476, 460, 444, 428	480, 460, 450, 440, 420	470, 458, 452, 446, 440, 420	470, 458, 452, 446, 440, 420	470, 458, 452, 446, 440, 420	470, 458, 452, 446, 440, 420
Cruise speed range accepted into DMA (true airspeed, kts)	420 - 500	400 - 490	400 - 490	400 - 490	400 - 490	400 - 490
Lateral spacing between tracks (nmi)	5	5	4	4	4	4
Minimum in-trail spacing within tracks (nmi)	5	5	3	4	5	6
Theoretical maximum track capacity @ 460 kts (flights/hr, each direction)	460	460	920	690	552	460

3.5 Analysis of DMA Flight Efficiency

An efficient DMA design should preferably not cause undue entry delays for traffic loading onto the DMA. It should also not cause the DMA traffic to fly significantly further than the great circle distance between the origin and destination airports (i.e. the shortest route, ignoring wind, weather, and restricted airspace for this analysis). The total DMA route distance is the summation of (a) origin airport direct to DMA entry point, (b) great circle route along the DMA to the exit point, and (c) exit point direct to destination airport. This inefficiency can happen if aircraft must deviate excessively off course at either end of the flight in order to fly the DMA. In addition to comparing with the origin-to-destination great circle route, the distance flown by DMA aircraft can also be compared to actual distances flown by current-day traffic for the same airport pair, determined from recorded ETMS route data. To ensure that the total distance flown by DMA aircraft was reasonable compared to the origin-to-destination great circle distance, flights for this analysis were only accepted into the DMA that would deviate less than 6 percent or 100 nmi (whichever is less) from the great circle distance. These values are close to the average deviation of current air traffic from the great circle route observed from the ETMS recorded routes. Therefore, the goal of the DMA design in this analysis

was to make the total distance flown for DMA aircraft no worse, on average, than using current-day routes.

All design variations shown in Table 1 were evaluated for flight efficiency. For the efficiency analysis, the total distance flown by DMA aircraft was compared to both the great circle distance and the ETMS recorded route between the origin and destination airports. ETMS recorded routes are longer than great circle routes due to the non-direct structure of the airways and controller actions to resolve conflicts, and they also may deviate to take into account winds. Because this study did not include wind, the excess distance flown by the ETMS recorded traffic compared to the great circle route may be overstated since some of the deviation may have been intentional to provide more optimal wind routing on the recorded day. In the region studied, there did not appear to be any obvious deviations around special use airspace.

In addition to providing an efficient route of flight, a good DMA design should not require aircraft to deviate significantly from their optimal cruise speeds and altitudes. For this initial study, no attempt was made to optimize the altitude of the DMA, because, as discussed earlier, the DMA layers were fixed at FL380 and FL390. However, deviation from optimal cruise speeds is minimized by maintaining fairly narrow speed differences between tracks and by only accepting aircraft onto a DMA track if the ETMS recorded cruise speed is within the track acceptance range, as shown in Table 1. An assumption was made that the ETMS recorded cruise speed represented the operator's preferred speed for that aircraft, which may not have been true in every case. Detailed assessment of the economic impact of non-optimal cruise speeds and altitude is important, but would require further study using more accurate aircraft performance models that was beyond the scope of this effort.

Entry into the DMA was scheduled on a first-come, first-served basis; no attempt was made to prearrange gaps in the flow to allow additional flights to enter the DMA at downstream merge points. Improving the efficiency of the DMA would require a more advanced scheduling scheme than was possible in this initial study. As discussed in Chapter 7.0, TFM is one of the significant challenges and feasibility issues of the DMA concept.

All design variations were evaluated for efficiency using the 3X level of demand. The main criterion used in choosing an efficient design from among the design variations was the arrival time delay caused by differences in distance flown plus any DMA-entry wait time. This delay is implemented by holding aircraft on the ground, if necessary, until a DMA entry slot becomes available. This wait time could be absorbed in flight on the way to DMA entry, but the lowest cost option (for the airline) would be to hold prior to departure until an on-time entry into the DMA could be achieved.

It should be noted that the difference in arrival time is only the theoretical difference, assuming that the 3X demand could be accommodated in the current NAS with zero delay. The arrival time using the origin-to-destination great circle route is therefore the best case. The ETMS recorded routes from the JPDO demand sets do not include actual crossing times over route points, so the arrival times using the ETMS routes are based on constant cruise speed with zero delay. The arrival time difference is only intended to be a criterion used for choosing an efficient design. It is not meant to imply that flights using

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the DMA would arrive later than flights not using the DMA; even flights attempting to use the shorter great circle route would certainly be delayed by waiting to enter congested airspace with 3X demand. The expected situation is that, by design, flights using the DMA would have an unimpeded flight route and would arrive sooner than flights outside of the DMA. An arrival delay comparison between DMA and non-DMA traffic would require a more complete modeling of air traffic operations than was possible for this study.

3.5.1 Design Variation 1

Table 2 presents a comparison of arrival time difference (i.e. delay) and excess distance flown by DMA aircraft relative to the great circle routes and the current routes (as recorded by ETMS data) for the set of design variations. It is important to note, as stressed previously, that any measure of delay used here is not an actual delay prediction for a realistic NAS implementation of the DMA concept, but rather is a simulation representation used only to compare DMA designs. Actual delay for DMA flights is expected to be significantly less than for non-DMA flights, since DMA flights would experience no additional delay within the DMA, whereas non-DMA flights would be delayed due to airspace congestion. Off-loading the sectors of DMA flights would reduce airspace congestion, but at the 3X demand level the non-DMA flights would still experience substantial delay unless other measures such as airspace re-design and new technologies are put in place.

Table 2. DMA efficiency for 3X demand.

	Design variation	Average arrival time difference relative to great circle (s)	Average arrival time difference relative to ETMS (s)	Average additional distance relative to great circle (nmi)	Average additional distance relative to ETMS (nmi)	Daily number of flights in DMA
Average per flight	1	1301	1026	30	-2.9	-
	2	765	515	30	-2.5	-
	3	270	26	30	-2.3	-
	4	283	39	30	-2.3	-
	5	301	57	30	-2.3	-
	6	346	102	30	-2.3	-
Total	1	9,894,308	7,685,503	233,538	-22,539	7582
	2	5,884,073	3,959,746	236,503	-19,517	7695
	3	2,085,292	203,306	238,365	-18,014	7709
	4	2,187,936	305,950	238,365	-18,014	7709
	5	2,323,020	441,034	238,365	-18,014	7709
	6	2,673,946	791,960	238,365	-18,014	7709

The initial 5-track design was implemented such that the deviation from the assumed optimal cruise speed was within ± 8 kts. Initial analysis of this design indicated that the DMA capacity was sufficient for the EWR/PHL to ORD segment. However, extending

the DMA to SFO/LAX and adding an entry/exit point near CLE/PIT increased the traffic using the DMA from about 3000 flights to 7582 flights, reaching a point where the DMA capacity was not considered sufficient due to excessive wait time for DMA entry (1026 seconds relative to using current routes, as shown in Table 2). The actual wait time that would be acceptable is a subjective judgment. For the purposes of this study, an average wait time of less than 300 seconds was considered acceptable.

Peak demand through the DMA reaches about 280 flights per hour in each direction, well within the theoretical capacity of 460 flights per hour in each direction. However, the theoretical capacity assumes an even distribution of flights across all tracks spaced longitudinally at the separation minimum; it does not allow gaps for merging flights and cannot therefore be fully achieved in practice.

As shown in Table 2, the difference in arrival time between the unimpeded great circle routing (i.e. the ideal case) and the DMA routing was excessive at 1301 seconds per flight on average. The arrival time difference is due to additional distance flown and due to time spent on the ground waiting for a DMA entry slot. When compared to the ETMS recorded route, the average arrival time difference was 1026 seconds, still considered unacceptably large.

Also shown in Table 2 is the additional distance flown using the DMA in comparison to both the great circle route and the ETMS route. The extra distance was 30 nmi per flight on average compared to the great circle distance, but was actually slightly less than the average ETMS recorded route distance. This difference indicates that the arrival time difference is mainly an effect of the imposed departure delay to wait for a DMA entry slot, not additional flight time. This result confirms that the capacity of the DMA is not sufficient for the peak demand. Although additional capacity could be gained by adding flight levels, it was desired to explore other design variables for achieving the capacity.

3.5.2 Design Variation 2

In an attempt to improve performance, a new 5-track design variation was implemented using tracks with speeds closer to the most common cruise speed range of 450 kts to 460 kts. This design keeps ETMS recorded cruise speed within ± 5 kts and should result in more evenly distributed flights between tracks.

As shown in Table 2, design variation 2 was an improvement over design variation 1, but it still did not have sufficient capacity at 3X demand, as flights were again encountering excessive delay for entry into the DMA. For this reason the 5-track DMA capacity was deemed insufficient.

It should be noted that a design using five tracks (or fewer) would possibly have sufficient capacity for 2X demand and for less congested routes. (A specific analysis was not conducted at the lower demand level.) Also, a 5-track design with more than one altitude layer in each direction may have sufficient capacity for the 3X demand, but the disadvantage of fewer tracks remains, i.e., some aircraft not flying as close to optimal cruise speed. A possible solution could include varying the track speeds with altitude such that aircraft operators could select a track/altitude combination that best matches their desired performance.

3.5.3 Design Variations 3, 4, 5, 6

Design variations 3 to 6 were all 6-track DMAs with identical parameters except for the in-trail separation. The lateral spacing between tracks was reduced to 4 nmi to accommodate six tracks within the same airspace as the 5-track design. The 6-track design allowed the majority of traffic to maintain cruise speed within ± 3 kts of ETMS recorded cruise speed.

The data in Table 2 indicate that the difference in arrival time between the unimpeded great circle routing and the DMA routing is significantly lower with the 6-track design. With 6-mile in-trail separation (design variation 6), the average arrival time difference is 346 seconds per flight. For 3 nmi spacing (design variation 3) the average difference falls to 270 seconds. The capacity of design variation 6,460 flights per hour is equivalent to the 5-track design but imposes less delay because of more even distribution of flights between tracks.

Current separation standards allow for 5 nmi in-trail separation en-route, although actual in-trail separations are today more likely to be ~7 nmi or more to allow a buffer for speed differences between aircraft, navigation system errors, and position uncertainty due to radar tracking accuracy. Advances in navigation techniques, such as utilization of ADS-B for self-spacing and a capability to maintain accurate aircraft speed within the DMA should enable the in-trail spacing to be reduced to values closer to the wake-turbulence separation limit. Further research is needed to determine the minimum separation achievable. Future improvements in navigation and surveillance performance are expected to allow a reduction of the in-trail separation standard below the current standard of 5 nmi, provided that wake turbulence separation is also accounted for. In this analysis, 4 nmi spacing is assumed possible. Design variation 4 has sufficient capacity for the 3X demand (only 39 seconds delay relative to using current routes, as shown in Table 2) and therefore was selected as the preferred design variation for the remainder of the analysis.

3.5.4 Design Variation 4

Design variation 4 has a theoretical maximum capacity of 690 flights per hour in each direction. The total number of flights accepted into the DMA in 24 hours of simulation was 7709, yielding an average hourly flow of 160 flights in each direction which was well within the capacity and allowed accommodation of short term peaks in demand. The actual peak demand for the 3X traffic load was about 280 flights per hour in each direction. The arrival time difference compared to the unimpeded great circle route was 282 seconds per flight on average and, compared to the ETMS route, was only 39 seconds additional per flight on average. Each flight distance is on average an extra 30 nmi compared to the great circle distance, and using the DMA gives a slight reduction of 2.3 nmi compared to the ETMS route.

The arrival time differences compared to great circle and ETMS recorded routes for each flight accepted into the DMA are shown in Figure 8, sorted from left to right by decreasing amount of delay. As expected, delay relative to the unimpeded great circle route time is always greater than zero, assuming equivalent cruise speeds. Compared to the ETMS recorded route, a significant number of DMA flights arrive earlier (i.e. data
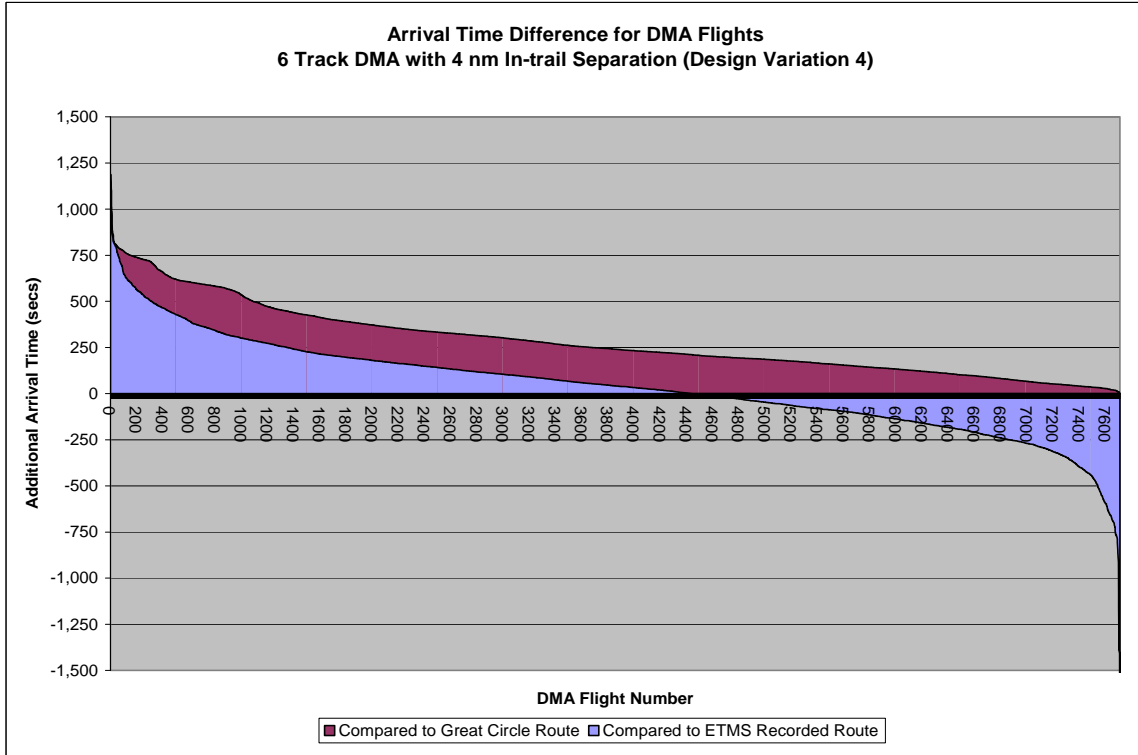
Figure 8. Arrival time difference for DMA flights.
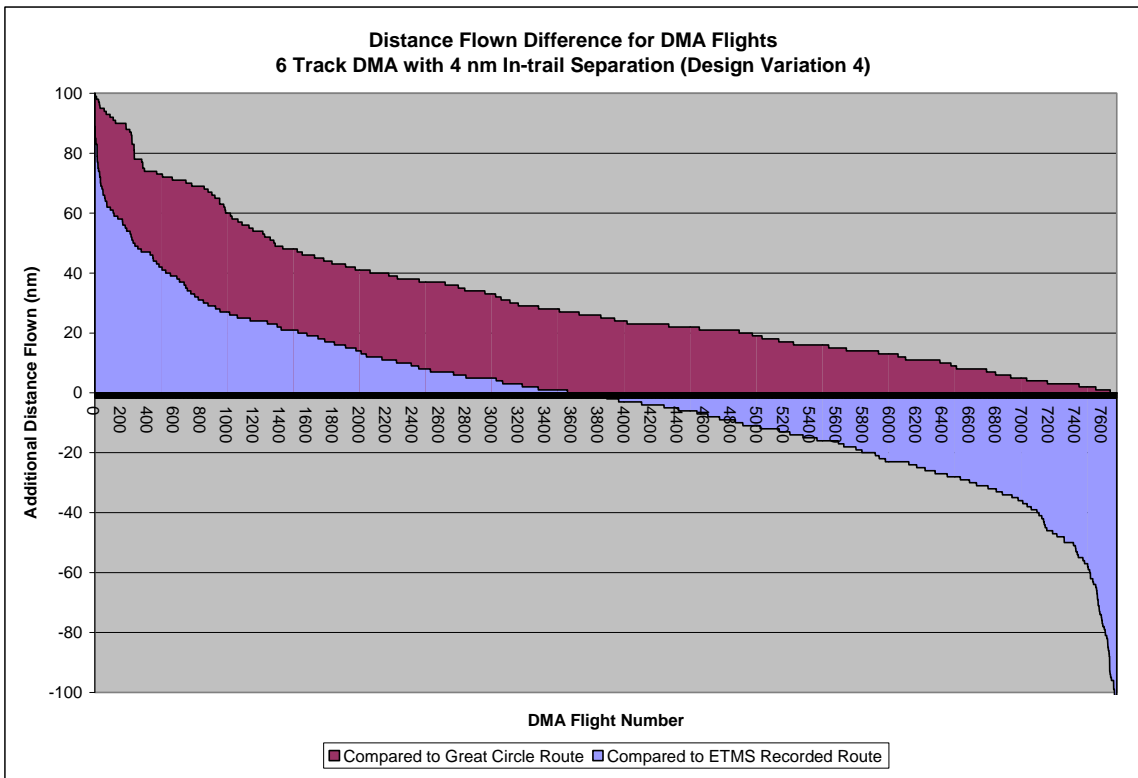
Figure 9. Distance flown difference for DMA flights.

below the horizontal axis). Very few flights (4 percent) arrive more than 500 seconds later compared to the ETMS recorded routes. A similar chart for distance flown is shown in Figure 9. The maximum additional distance of 100 nmi compared to the great circle route confirms this design criterion was achieved. Also, up to 100 nmi was saved relative to the ETMS recorded routes.

The wait time for DMA entry is shown in Figure 10. Nearly all flights (98 percent) waited for less than 200 seconds. The average wait time was 32 seconds, a reasonable delay for the benefits achievable. The wait times are quite small, but it might seem that the DMA capacity is more than sufficient to meet the demand and that the delays should be negligible. However, delays are present because the aircraft often arrive in clusters and are often not evenly distributed between tracks. The aircraft were simply scheduled into the DMA based on the original departure time and were allocated to the track with the speed closest to the assumed optimal cruise speed. The delay could likely be reduced further with a more optimal scheduling algorithm, which could be designed to introduce deliberate gaps into the flow and possibly move aircraft to a different speed track if the first choice track was busy.
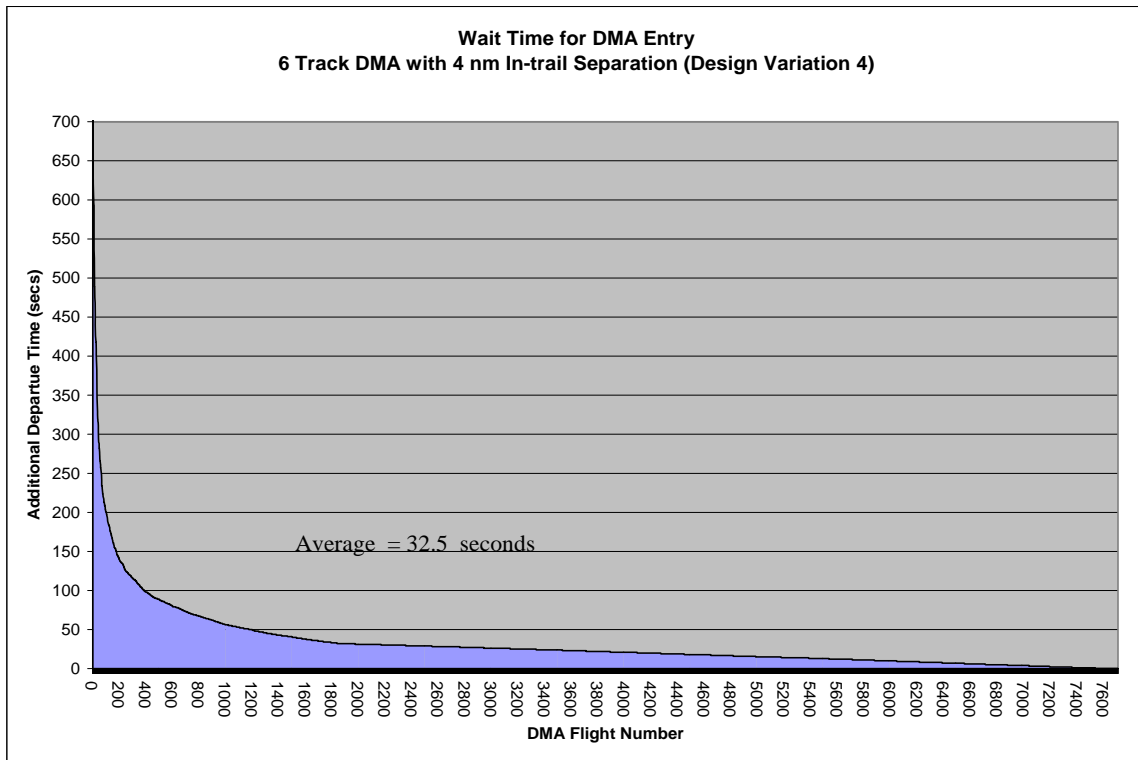
Figure 10. Wait time for DMA entry.

The average increase in arrival time compared to the great circle route is 283 seconds, as shown in Table 2. This result indicates that most of the arrival delay (calculated as 283 seconds total delay minus 32 seconds average wait time = 251 seconds) is due to the increased distance flown, not due to waiting for DMA entry slots, confirming that the DMA has sufficient capacity. (The average increased distance is 30 nmi, which is 235 seconds flying time at 460 kts nominal true airspeed.)

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3.6 Analysis of Sector Load

A further analysis was performed to assess the impact of the single coast-to-coast DMA on the traffic load of surrounding sectors. As discussed earlier in the concept description, a DMA operates as a separate sector such that its traffic need not be tracked or managed by the conventional sector controllers. The DMA is intended to be a mechanism for effectively removing traffic from the conventional sectors, at least as far as certain aspects of controller workload are concerned. Sector controllers would not need to perform handoffs for DMA aircraft passing through their airspace, nor would they need to manage their trajectories for separation. Other aspects of controller workload not addressed by the DMA concept or those newly generated because of the DMA concept, such as controller actions to segregate non-DMA traffic from the DMA, are not included in this analysis but may be significant.

This analysis first addresses the sector load distribution for current day traffic load, as simulated by the modeling tool. Simulations of the 2X and 3X demand levels are then analyzed for sector loading with and without the DMA. For the purposes of this study, the accuracy of actual loads is not specifically relevant, and values should be interpreted with caution due to simulation limitations described earlier. The key metric will be the comparison between sector loads with and without the impact of the DMA as demand levels are increased. Results of the sector load analysis are presented in Table 3 and Figure 11 through Figure 17.

Table 3. Sector load analysis summary.

Demand set	Total daily load in NAS (flights)	Total daily load in DMA	Mean total daily sector load, top 50 sectors	Mean instantaneous peak sector load, top 50 sectors	Total airspace boundary crossings saved for DMA flights	Mean airspace boundary crossings saved per DMA flight
19 Feb 2004 baseline	57,093	-	880	20	-	-
2X no DMA	112,421	-	1600	30	-	-
2X with DMA	112,421	4199	900	17	70,400	16.8
3X no DMA	168,647	-	2500	47	-	-
3X with DMA	168,647	7709	1250	25	125,000	16.2
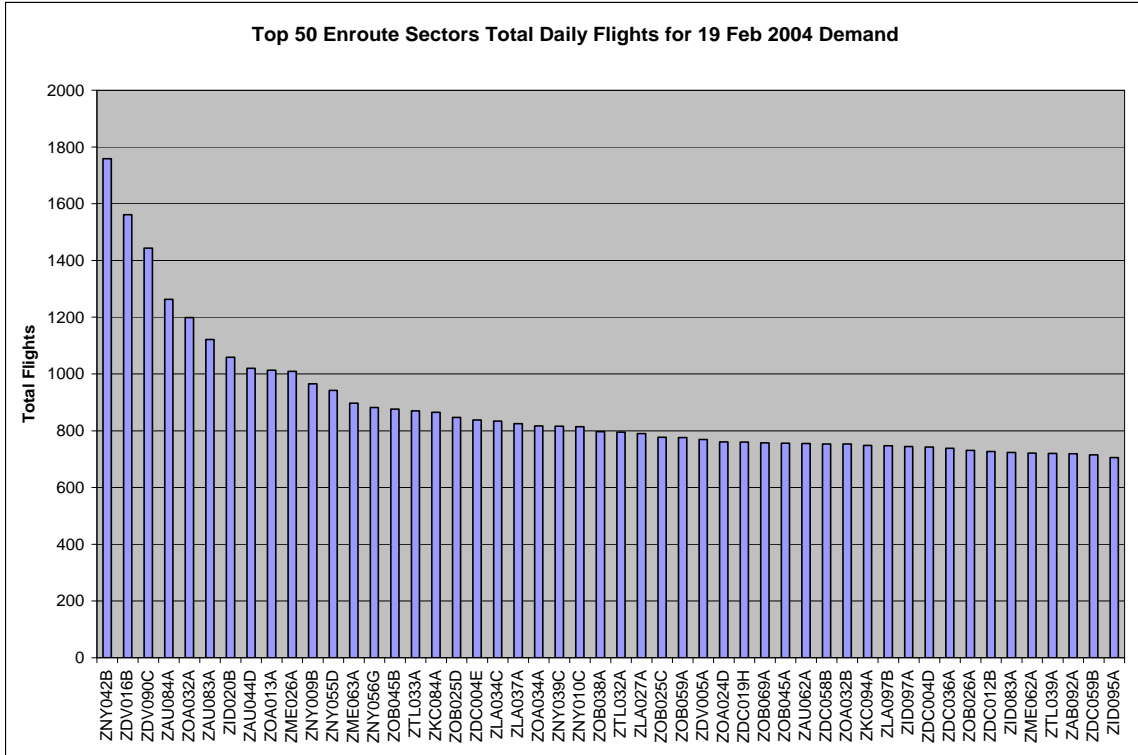
a) Total daily sector load.
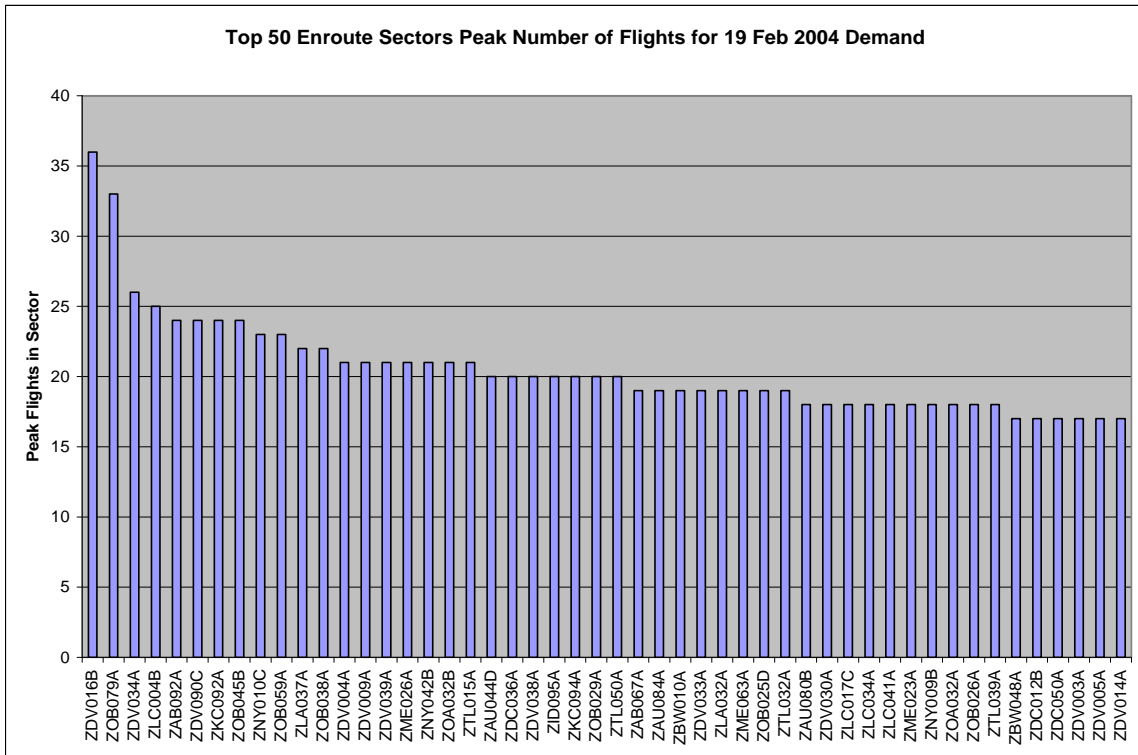
b) Peak instantaneous sector load.
Figure 11. Sector load for top 50 en-route sectors at 19 February 2004 demand.
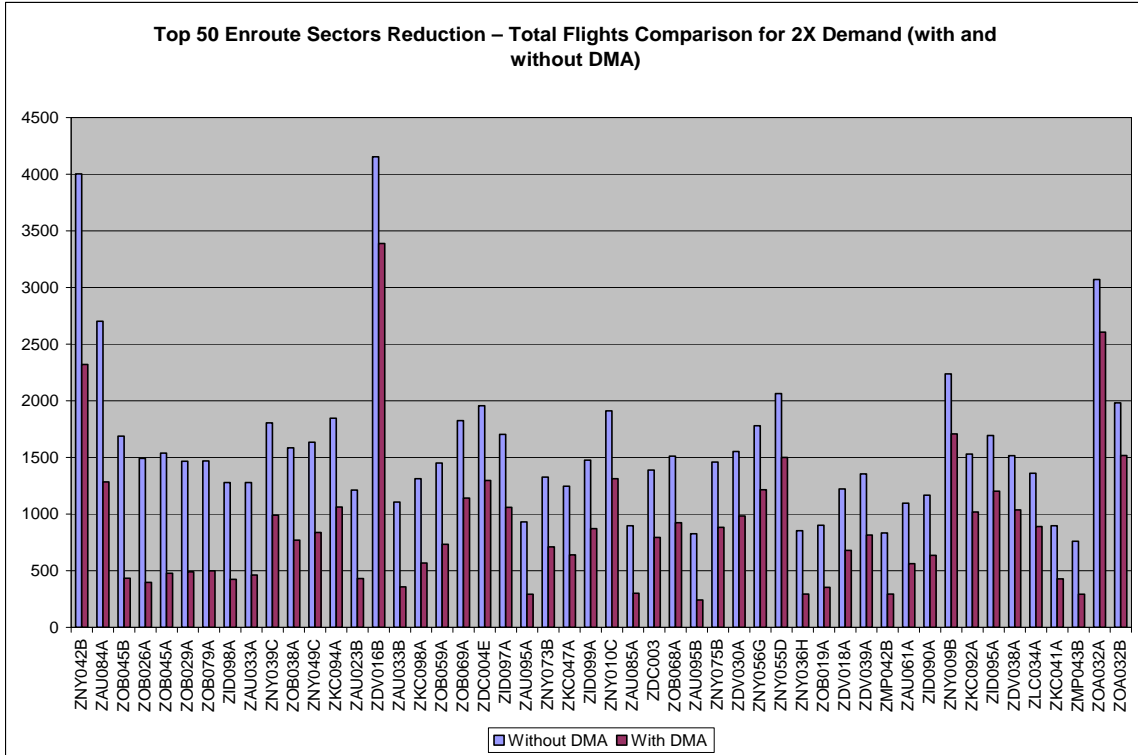
a) Total daily sector load comparison.
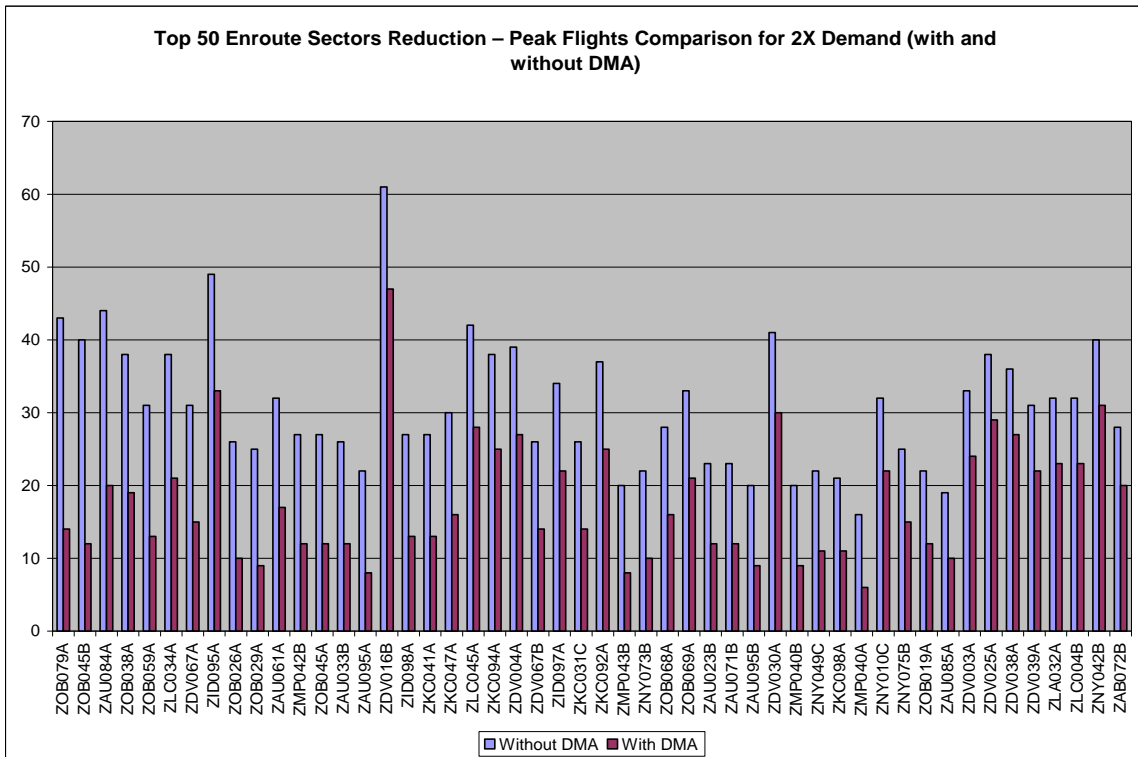
b) Peak instantaneous sector load comparison
Figure 12. Sector load for top 50 en-route sectors at 2X demand with and without DMA, sorted by magnitude of load reduction.

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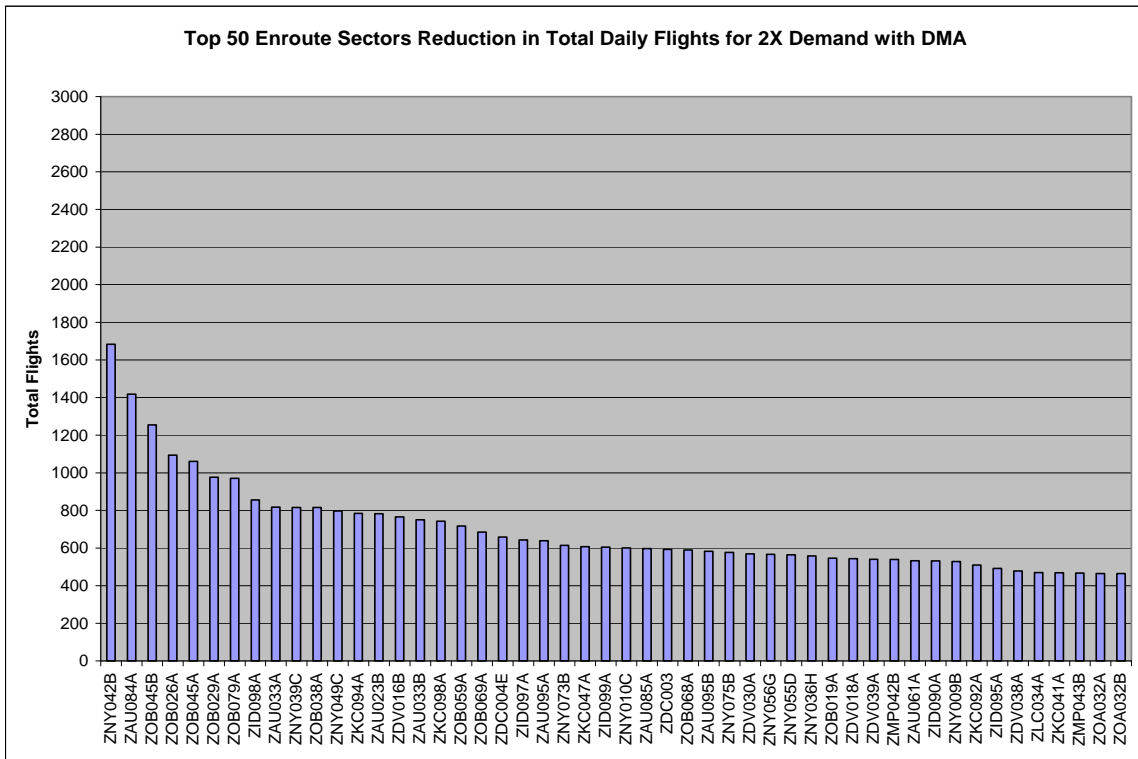
a) Total daily sector load reduction.
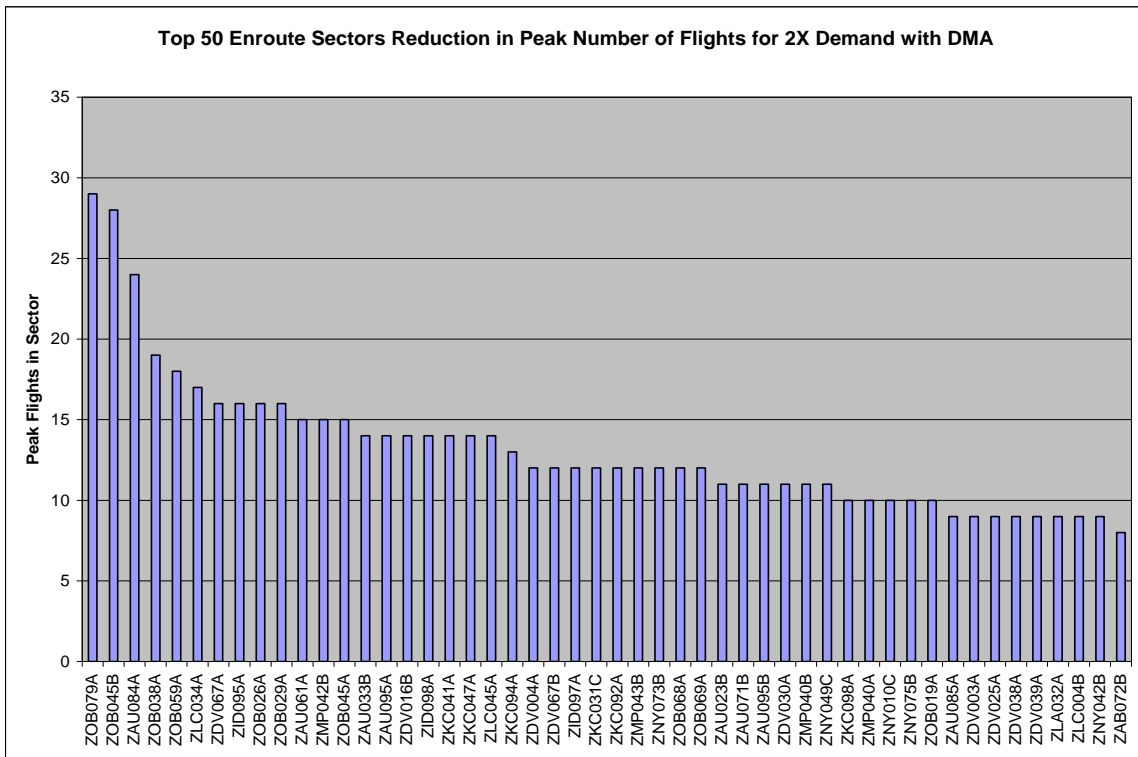
b) Peak instantaneous sector load reduction.
Figure 13. DMA-induced load reduction for top 50 en-route sectors at 2X demand.
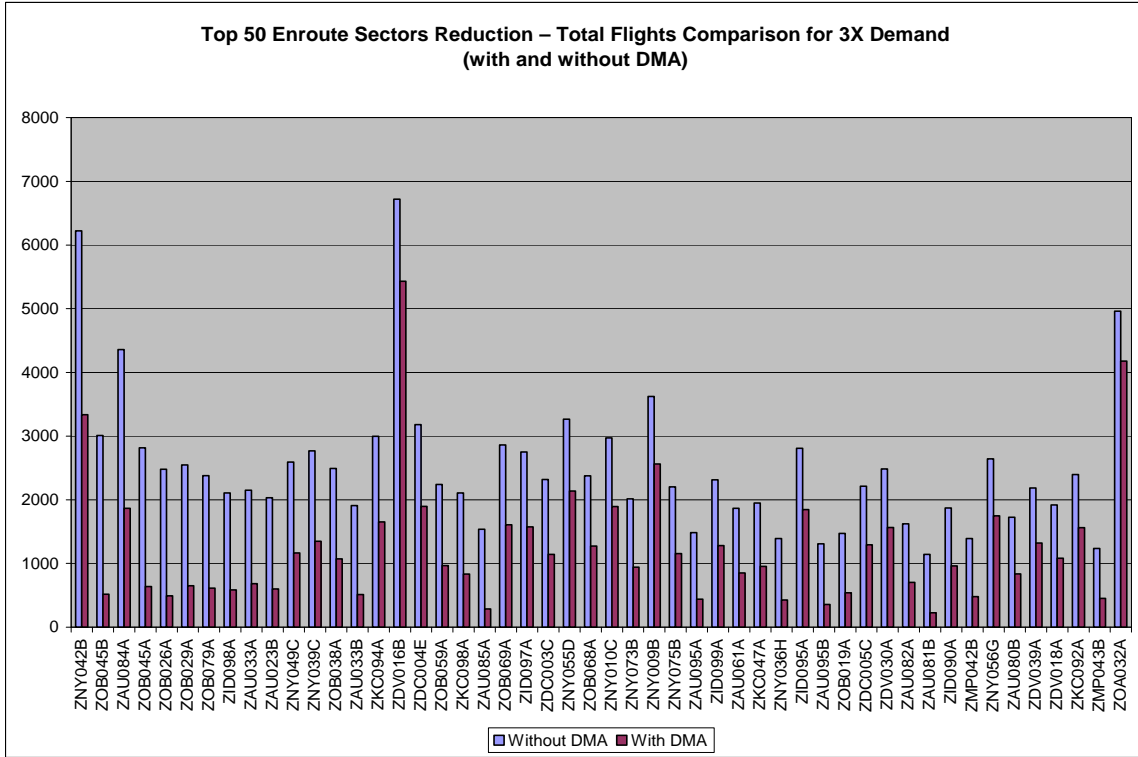
a) Total daily sector load comparison.
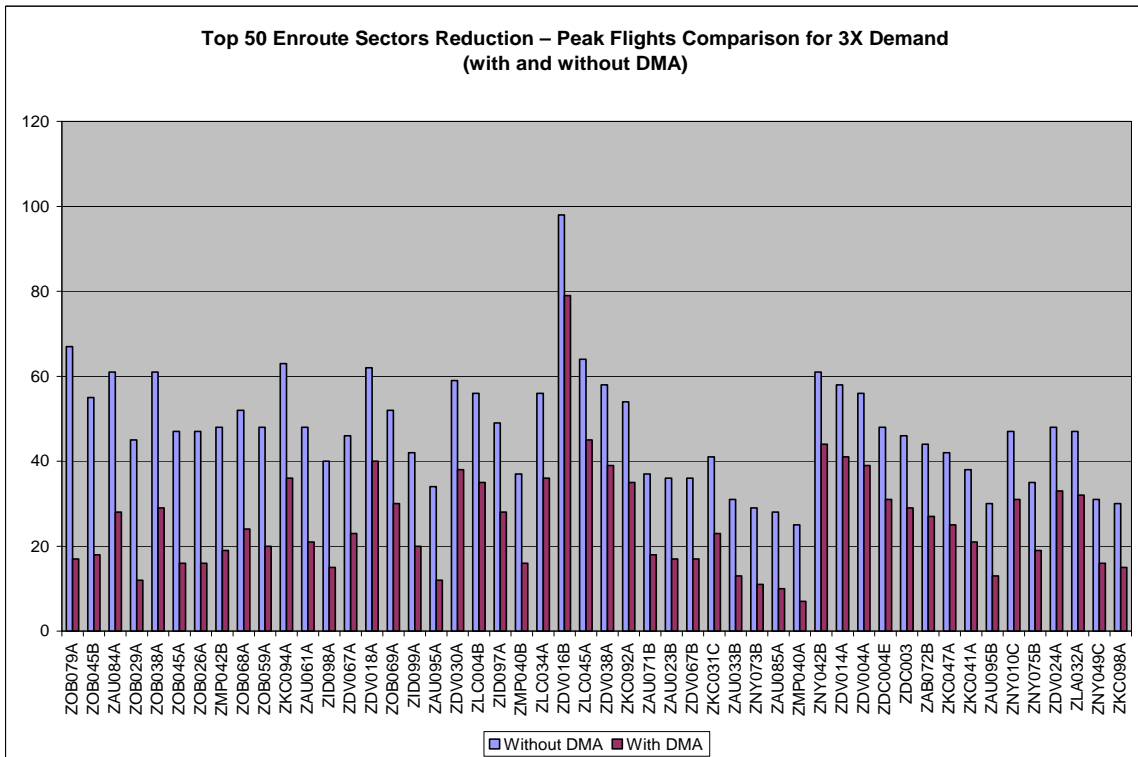
b) Peak instantaneous sector load comparison.
Figure 14. Sector load for top 50 en-route sectors at 3X demand with and without DMA, sorted by magnitude of load reduction.
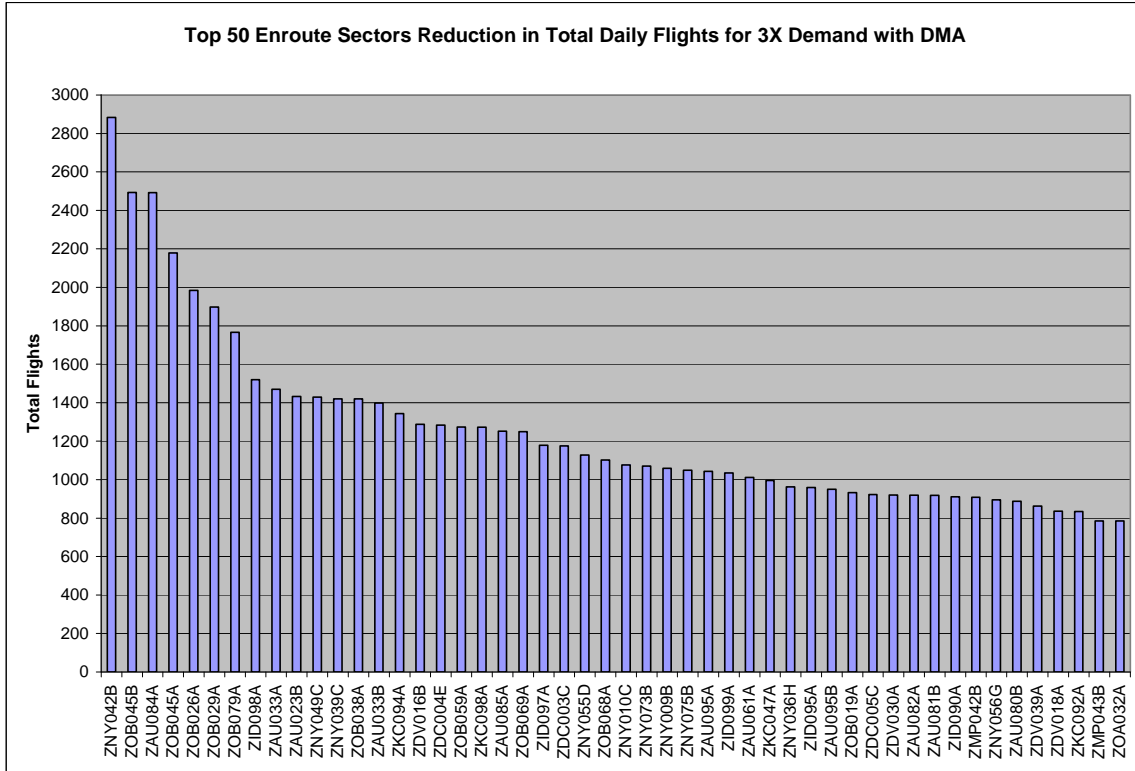
a) Total daily sector load reduction.
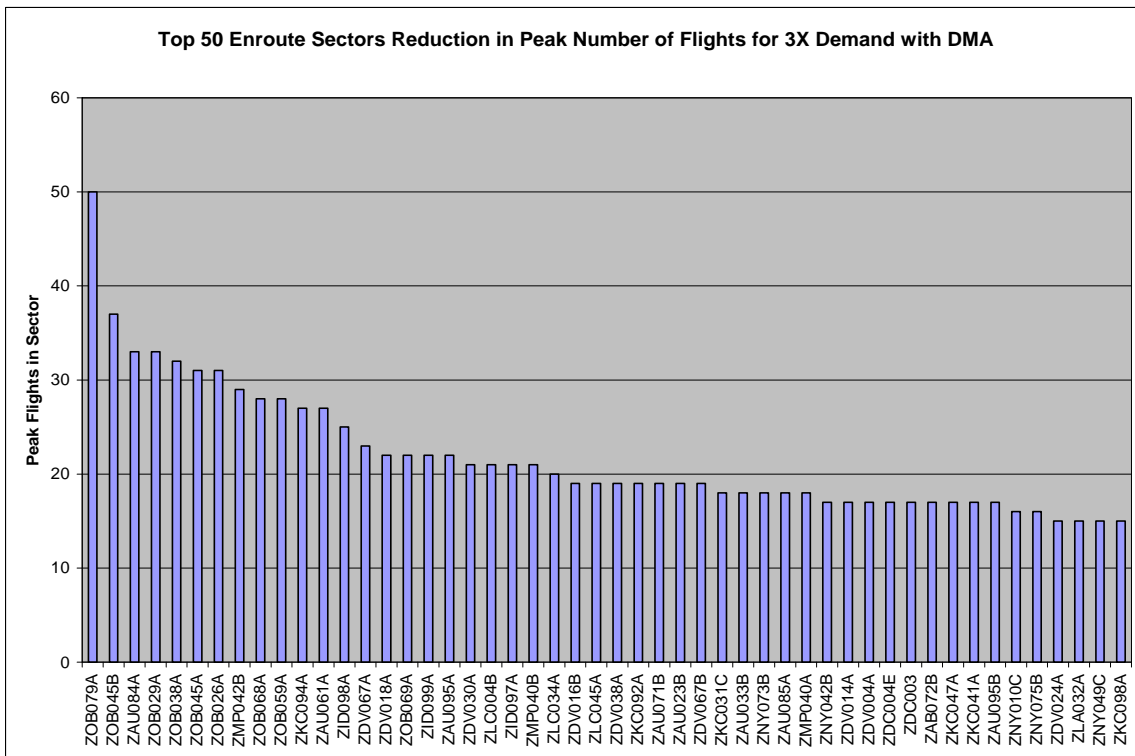
b) Peak instantaneous sector load reduction.
Figure 15. DMA-induced load reduction for top 50 en-route sectors at 3X demand.

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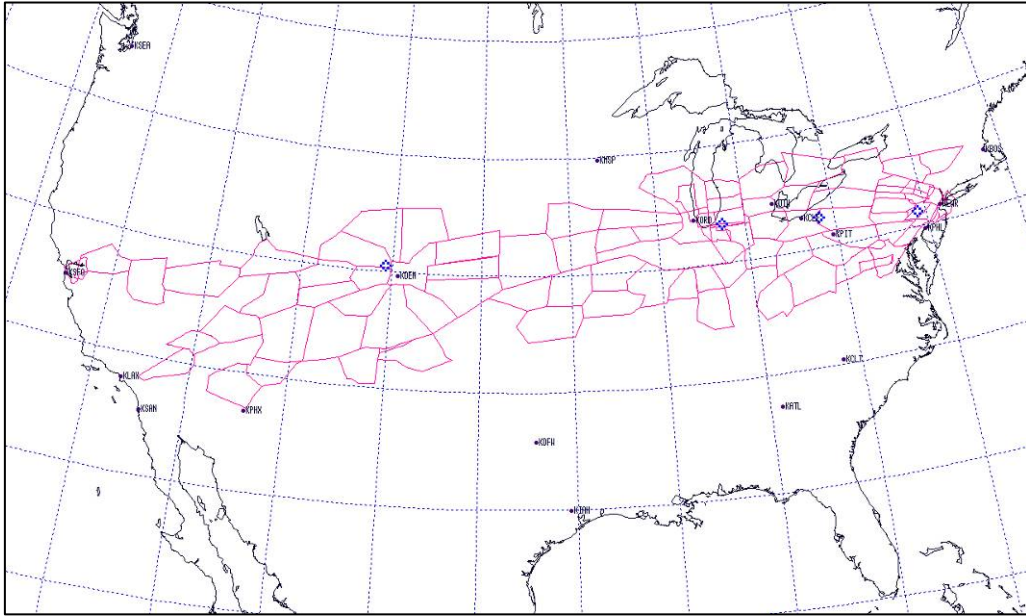
Figure 16. Top 100 sectors benefiting from load reduction with the modeled DMA.
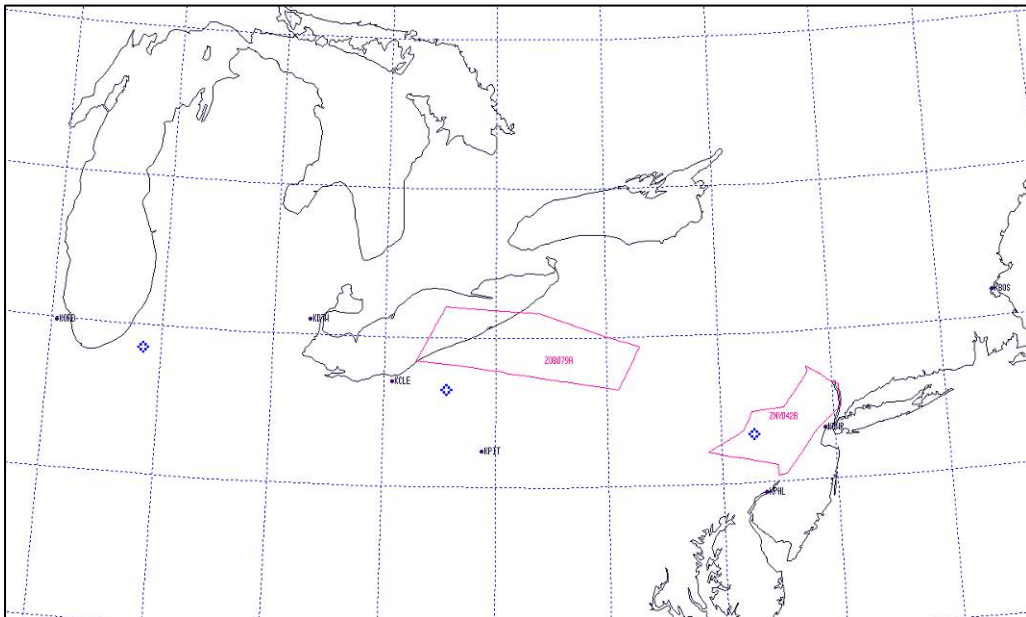
Figure 17. Locations of sectors with maximum total daily load reduction (ZNY042B) and peak load reduction (ZOB079A) with the modeled DMA.

3.6.1 19 February 2004 Sector Load

The 24-hour total and instantaneous peak sector loads for the simulation representation of the 19 February 2004 ETMS recorded demand are shown in Figure 11 for the top 50 busiest en-route sectors. For most sectors the peak demand in the simulation data is around or below 20 flights in a sector, which is in line with the typical capability in current operations to handle aircraft of around 18 per sector.

The sector with the highest peak load at 35 flights in the simulation was ZDV016B, which is a sector near Denver International Airport above FL310. This extremely high loading is an artifact of the simulation, which does not represent all of the procedures for inter-sector coordination. The demand set used to create the simulation includes only the cruise altitude data and does not include intermediate altitude data. The simulated aircraft are simply allowed to climb at a reasonable continuous rate to the cruise altitude. This profile may not reflect the true climb rate, nor may it reflect intermediate level-off altitudes imposed in real time by the controllers to prevent saturating the higher sectors. It is likely that aircraft departing from Denver would have been instructed by the controller to keep below the en-route sector ZDV016B as necessary to reduce the load.

3.6.2 2X Demand Sector Load

Sector loads for the 50 busiest en-route sectors at 2X demand are shown in Figure 12 with and without the impact of the DMA. Substantial reductions in both total daily sector load and instantaneous peak load are evident, indicating that many aircraft in these sectors met the qualifications for DMA flight including origins and destinations that were within 100 nmi or 6 percent flight distance of DMA entry/exit locations. The reductions in total and peak loads due to the DMA are shown in Figure 13. Total daily load reductions between approximately 500 and 1700 flights are indicated, and peak load reductions are generally greater than nine aircraft. As indicated in Table 3, the average total daily load reduction is 700 flights (1600 minus 900), and the average peak load reduction is 13 flights (30 minus 17). These data indicate that this single DMA, at 2X demand, reduced over half of the top 50 sectors to load levels that could potentially be manageable by a human controller (i.e. peak load of less than 20 aircraft). This finding ignores the additional DMA-related coordination tasks of sector controllers as indicated in the concept description, which are expected to add to workload. As shown in Table 3, there is a significant reduction in the number of airspace boundary crossings with the DMA concept. This will mean there are fewer handoffs for DMA operations, which should result in a workload reduction for both controllers and DMA pilots.

3.6.3 3X Demand Sector Load

Similar sector load and sector load reduction data are shown for the 3X demand level in Figure 14 and Figure 15. As before, substantial reductions in total daily sector load and instantaneous peak load are evident and even exceed the 2X reductions. The total daily sector load was reduced between approximately 800 and 2900 flights, with an average reduction of 1250 flights over a 24-hour period. The instantaneous peak sector load was reduced between approximately 15 and 50 flights, with an average reduction of 22 flights. These data confirm that the DMA had not reached capacity at 2X and was able to absorb quite a bit of the additional demand at 3X. One might conclude that adding

additional DMAs or additional tracks or altitudes to the single DMA would further absorb demand. However, these steps also add further complexity in controller coordination, TFM, separation assurance, and other areas, as discussed later in Chapter 7.0 DMA Conceptual Analysis. The aggregate impact of these factors on system capacity cannot be determined from the modeling performed here.

The locations of the 100 sectors showing the most benefit from the coast-to-coast DMA analyzed are shown in the Figure 16. Predictably, the sectors are located proximate to the modeled DMA. The locations of the sectors with maximum daily load reduction (ZNY042B) and maximum peak load reduction (ZOB079A) are shown in Figure 17. These sectors belong to the New York and Cleveland Air Route Traffic Control Centers respectively, indicating the benefit to the Northeast region of the NAS.

3.7 Analysis of Sector Conflict Potential

A significant component of a controller's tasking is the management of conflicts within the sector. The DMA concept has the potential to reduce this component by removing DMA aircraft from the controller's conflict management responsibility. An analysis was performed to estimate this effect.

The criterion used in this analysis to identify an en-route traffic conflict between non-DMA flights (i.e. flights remaining within sector control) was a separation of 5 nmi or less. Within the DMA, all flights were spaced at 4 nmi in-trail separation and were assumed to be adequately separated and to maintain this separation from other DMA traffic. In addition, in this simulation the DMA traffic was designed to not conflict with sector traffic during all phases of flight, because all non-DMA flights were assigned lower altitudes which do not conflict with the DMA. In practice, the sector controller would be responsible for ensuring the sector traffic remains clear of the DMA traffic. As discussed in Chapter 7.0, this requirement may pose a significant operational restriction on sector operations, depending on the location within the sector of the penetrating DMA. The analysis only considered the en-route phase of flight by modeling sectors with altitude ceilings at or above FL180.

The conflict counts reported here are the number of conflicts that would have occurred if no trajectory planning or resolution actions were taken by the controllers. In the simulation, the aircraft were simply propagated along the routes defined in the demand data sets with no corrective maneuvers and the resulting losses of separation were counted. The aircraft in the simulation were flown at a constant cruise speed matching the ETMS-recorded average speed during the cruise phase of flight. In addition, the demand data sets included only the cruise altitude and not any intermediate altitude data. The simulated routes therefore did not necessarily have the same altitude or time profile as the actual flights on which the data was based. For these reasons, the conflict counts from the simulation data should therefore be taken only as a measure of the *potential* for conflicts. The actual number of conflicts would have been far fewer because of the planning and resolution actions of the controllers. The metric of interest for this analysis is the *difference* between the numbers of *potential* conflicts with and without the DMA.

As traffic density increases, the number of potential conflicts would be expected to increase significantly. A simple conflict-scaling model can be developed and checked

against results from the simulation. For a unit volume of airspace containing *n* aircraft, there are *n-1* potential conflict pairs for each of the *n* aircraft, and the number of potential conflicts that could occur in that airspace is proportional to *n*(n-1)*. Therefore, the number of potential conflicts should approximately quadruple as the number of aircraft doubles in the same volume of airspace. Although this relationship is a simplification of the real situation, it serves as a useful check on results determined from simulation.

3.7.1 19 February 2004 Sector Conflict Counts

The total daily potential conflict count for the simulated 19 February 2004 ETMS demand using current ETMS recorded routes is shown in Figure 18 for the top 50 sectors (i.e. those sectors with the most recorded conflicts in the simulation). For most sectors, the number of potential conflicts was fewer than 100 per day, and the top 50 sectors averaged 80 per day. This rate equates to an average of about three or four potential conflicts per hour per sector, although more conflicts could occur at peak times. It provides a reference point in this simulation for reasonable controller workload for conflict management. Sector ZDV090C was found to have the largest number of potential conflicts. The data in Figure 11 indicate that this sector is one of the most heavily loaded sectors in the simulation, so it is reasonable to expect a large number of potential conflicts.
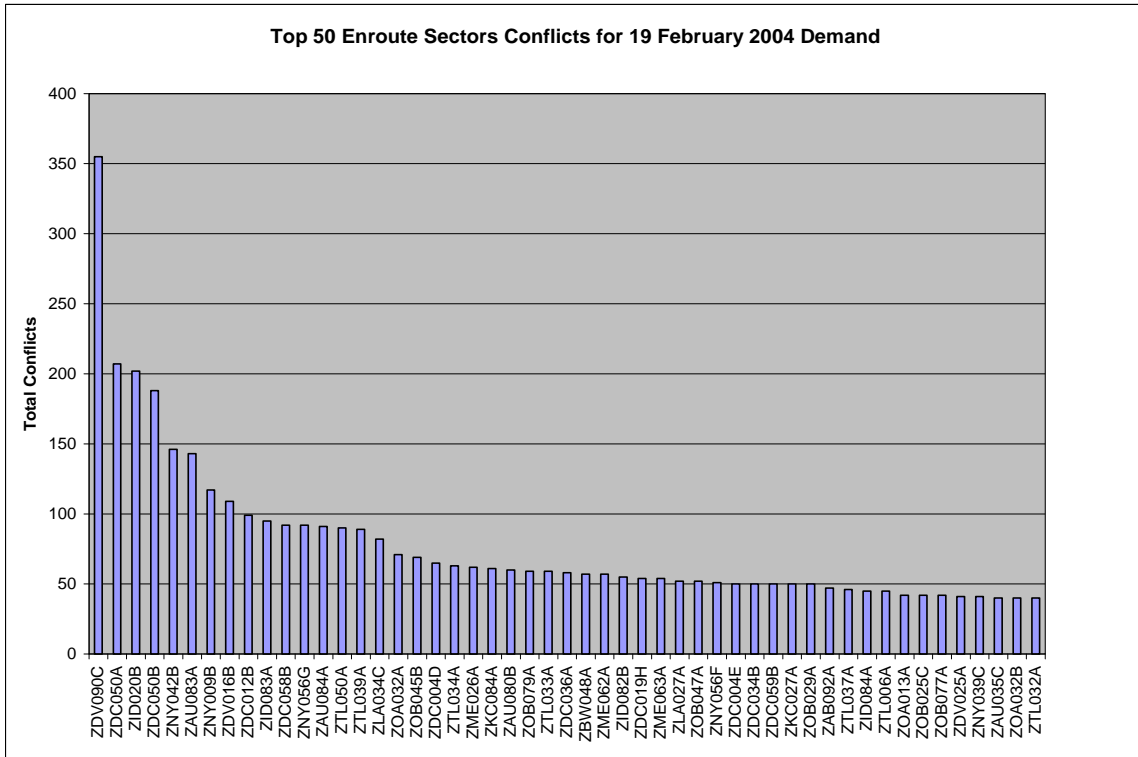
Figure 18. Potential conflicts for top 50 en-route sectors at 19 February 2004 demand.
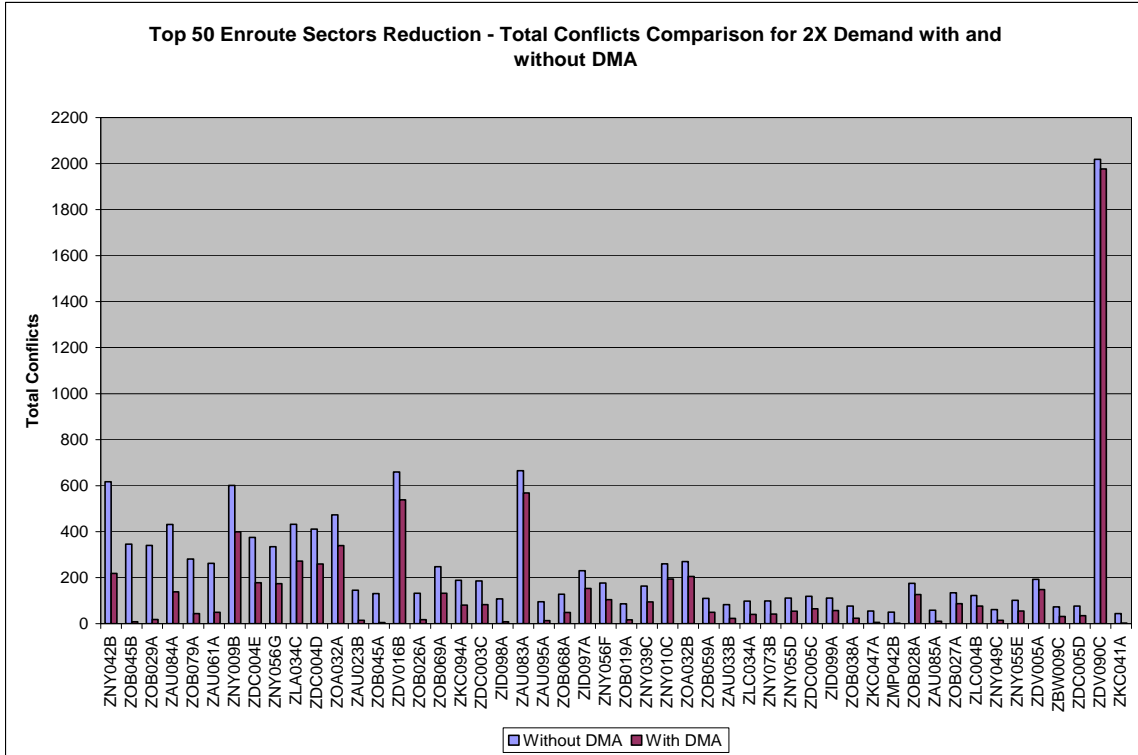
Figure 19. Potential conflicts for top 50 en-route sectors at 2X demand with and without DMA, sorted by magnitude of conflict count reduction.

3.7.2 2X Demand Sector Conflict Counts

The total daily potential conflicts for the 2X demand level with and without the DMA in the top 50 en-route sectors with most conflicts is shown in Figure 19. Tabular data showing average values for these sectors is presented in Table 4. The average conflict rate without the DMA was 450 conflicts per day, which was 5.6 times the average conflict rate of 80 for the 19 February 2004 demand. The average total daily number of flights in these sectors increased from 796 to 1919. Based on the simplified conflict-scaling model presented earlier, the theoretical ratio increase in the number of potential conflicts should be approximately equal to the square of the ratio increase in sector load, which is a factor of 5.8. This finding is in close agreement with the conflict scaling value of 5.6 obtained from the simulation data.

Table 4. Sector flight and conflict data.

Demand set	Total daily load in NAS (flights)	Mean daily sector load, top 50 sectors with most conflicts	Mean daily conflict count, top 50 sectors with most conflicts
19 Feb 2004	57,093	796	80
2X	112,421	1919	450
3X	168,647	3028	1133
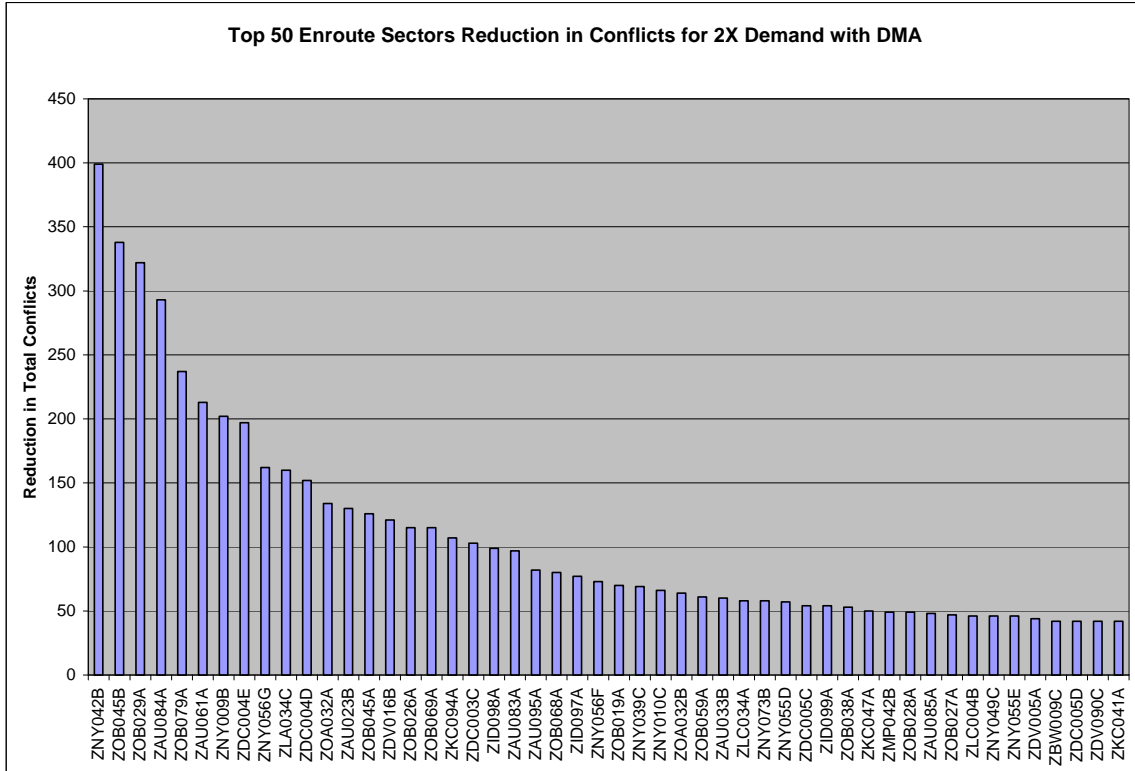
Figure 20. DMA-induced potential conflict reduction for top 50 en-route sectors at 2X demand.

The comparison data in Figure 19 and the corresponding conflict reduction data in Figure 20 show a significant reduction in potential conflicts between non-DMA flights with the addition of the DMA. (This assumes that DMA and non-DMA flights can be separated by altitude or other means without significant adverse impacts to the NAS or its users. As will be discussed in Chapter 7.0, accomplishing this segregation is a design challenge and a significant feasibility concern.) The simulation results showed that the average total number of potential conflicts in a sector was reduced by 109 conflicts (255 minus 146) in 24 hours with a maximum reduction of 399 for sector ZNY042B. This sector was also the sector with the maximum reduction in daily flights, as shown in Figure 12. The reduction in potential conflicts in these sectors is the result of removing the DMA traffic from the sector controller's responsibility.

3.7.3 3X Demand Sector Conflict Counts

Without the DMA, the average conflict rate at the 3X demand level was 1133 potential conflicts per day, as shown in Table 4. This rate is over 14.2 times the conflict rate of the simulated 19 February 2004 demand. The average total daily number of flights in the top 50 sectors increased from 796 to 3028. The theoretical ratio increase in the number of potential conflicts should be approximately equal to the square of the ratio increase in sector load, which is a factor of 14.5. Again, this finding is in close agreement with the conflict scaling value of 14.2 obtained from the simulation data.
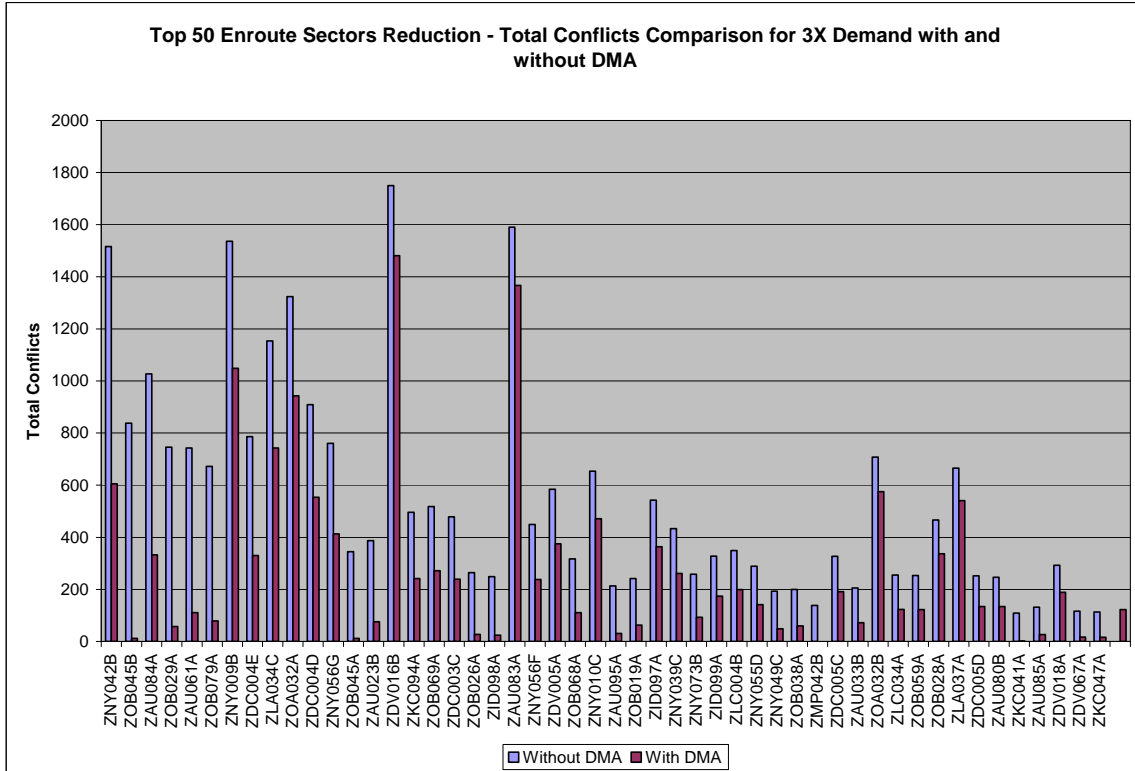
Figure 21. Potential conflicts for top 50 en-route sectors at 3X demand with and without DMA, sorted by magnitude of conflict count reduction.

Conflict comparison and conflict reduction data are shown for the 3X demand level in Figure 21 and Figure 22. Once again, including the DMA significantly reduced the potential conflicts recorded in the simulation. The average total number of potential conflicts per sector was reduced by 267 (548 minus 281) conflicts in 24 hours with a maximum reduction of 911 potential conflicts for sector ZNY042B, the sector with the maximum reduction in daily flights, as shown in Figure 15.

3.7.4 Sector Conflict Reduction as a Result of the DMA

This section relates the reduction in sector conflicts observed from simulation due to the inclusion of the DMA to the approximate theoretical reduction that should occur based on removing DMA traffic from the sector traffic count. The theoretical model purposefully ignores conflicts between DMA and non-DMA aircraft. Data for the analysis is presented in Table 5. This table shows conflict counts from the simulation with and without the DMA and calculated reduction factors and corrections, as described in the following analysis.

For the 3X demand case, the average total daily flights per sector are reduced by almost half (0.56) for the 50 sectors with the largest flight reduction. Therefore, the theoretical model would indicate, using the square of the sector load change, that these sectors should experience on average just over one quarter (0.31) as many conflicts in the same volume of airspace. In fact, the number of conflicts is reduced by only slightly less than half (0.51). The difference can be explained, as follows, by the reduction in airspace volume available to the remaining flights due to reserving flight levels for the DMA.

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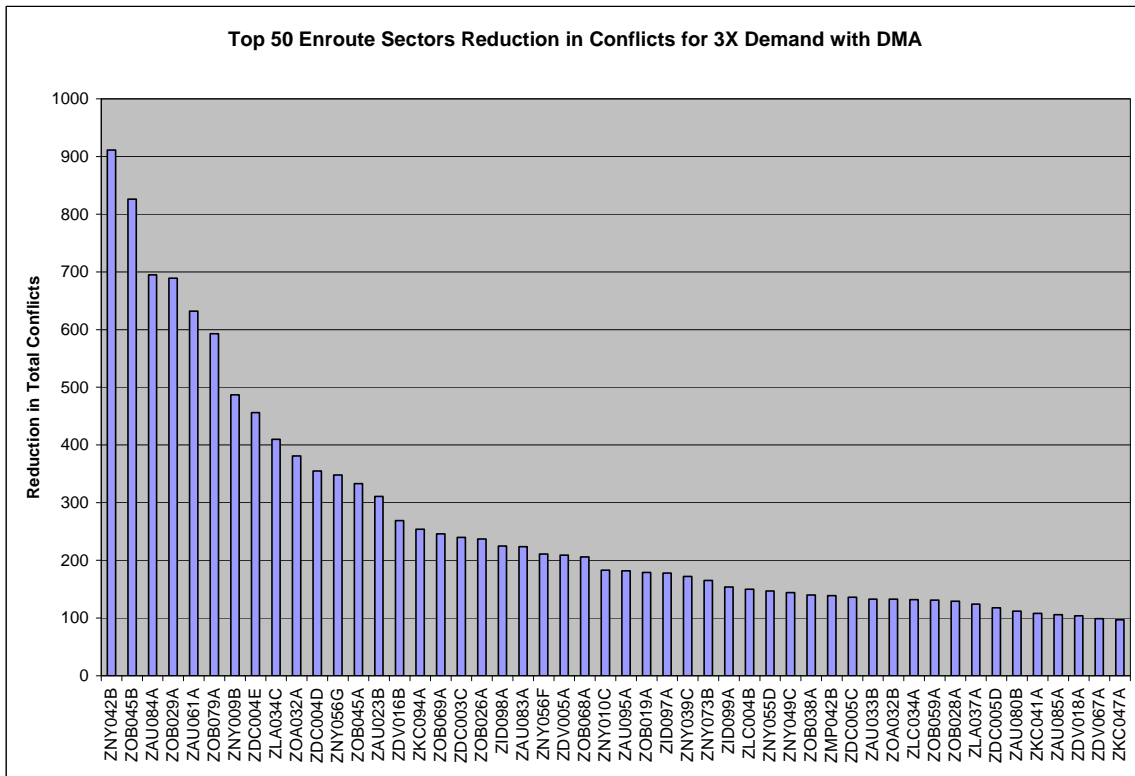
Figure 22. DMA-induced potential conflict reduction for top 50 en-route sectors at 3X demand.

It is helpful to first look at a single sector. The sector showing the maximum reduction in conflicts is ZNY042B, as indicated in Figure 22. This sector's altitude boundary is defined as all flight levels at and above FL290. Since most flights are at or below FL400, this airspace contains 12 flight levels. Reserving FL380 and FL 390 effectively reduces the volume of airspace available to non-DMA flights by 16.7 percent (two out of 12 flight levels), or an airspace volume factor of 0.83. To avoid conflicts with DMA traffic, sector traffic is restricted from the DMA flight levels throughout the sectors.

In the simulation of 3X demand, the daily total number of flights in ZNY042B was reduced from 6220 to 3336 with the addition of the DMA, a reduction factor of 0.54. The theoretical model predicts that conflicts would be reduced by the square of this factor, or only 0.29 as many conflicts. In fact the number of conflicts reduced from 1516 to 605, a reduction factor of 0.40. However the reduction in available flight levels means that the *sector density* (i.e. number of flights per unit available airspace volume) reduction can be calculated by dividing the flight count reduction of 0.54 by the airspace volume factor of 0.83; this equates to a sector density reduction factor of only 0.64. The theory would then predict the conflict reduction factor to be the square of this sector density reduction factor, or 0.41. This result is in good agreement with the value of 0.40 determined in the simulation.

Table 5. Sector conflict reduction analysis.

Parameter	3X Demand		2X Demand	
	Top sector	Top 50 sectors	Top sector	Top 50 sectors
Sector daily flight count w/o DMA, A	6220	2637	4004	1678
Sector daily flight count w/ DMA, B	3336	1478	2320	1055
Sector flight reduction factor, $C=B/A$	0.54	0.56	0.58	0.63
Theoretical conflict reduction factor, $D=C^2$	0.29	0.31	0.34	0.40
Sector conflicts w/o DMA, E	1516	548	617	255
Sector conflicts w/ DMA, F	605	281	218	146
Measured conflict reduction factor, $G=F/E$	0.40	0.51	0.35	0.57
Airspace volume reduction due to lost flight levels, H	0.83	0.75	0.83	0.75
Sector density correction factor, $I=C/H$	0.64	0.75	0.70	0.84
Corrected theoretical conflict reduction factor, $J=I^2$	0.41	0.56	0.48	0.70

Expanding the analysis to include the 50 sectors with the largest reductions in conflicts, the average reduction in available airspace caused by reserving two flight levels for the DMA is about 0.75, somewhat reduced from sector ZNY042B because many of these sectors have fewer than 12 flight levels. The average total daily number of flights was reduced by a factor of 0.56 with the addition of the DMA. The average number of conflicts was reduced by a factor of 0.51. Taking the 25 percent reduction in usable airspace volume into account, the sector density reduction factor is 0.75. According to the theoretical model, squaring this value provides the expected reduction factor for conflicts, or 0.56. This predicted value compares reasonably well with the measured average conflict reduction factor of 0.51.

Similar data and calculations for the 2X demand set are shown in Table 5. The agreement between the theoretical and measured conflict reduction factors is not as good as for the 3X demand set. For both the single sector (ZNY042B) and the top 50 sectors having reduced conflicts, the measured conflict reduction was greater than the theoretically predicted reduction. In the single sector case, a better agreement was achieved by ignoring the sector density correction factor, which may be an indication that the DMA simply removed traffic from the lower flight levels (and therefore conflicts) without compressing the remaining traffic into a smaller airspace. As shown in Figure 17, Sector ZNY042B is close to the airports serving the New York City area, where little high altitude traffic would be expected, a reinforcement of this potential explanation. For the top 50 sectors, the agreement with the density-corrected prediction is closer, and the remaining difference might be attributable to the influence of sector ZNY042B and similar sectors without much high altitude traffic. It must be emphasized that the theoretical relationship used here is simplistic and is only valid with random distribution of flights and higher flight densities.

3.8 Preliminary Conclusions from Capacity Benefits Analysis

The analysis showed that a DMA network has the potential to substantially ease sector

congestion, and thus could reduce a component of sector controller workload. This conclusion is drawn only from the DMA-induced reduction in sector traffic count and does not consider the workload of additional DMA-related tasks such as entry/exit coordination, traffic segregation, and handling dynamic rerouting of DMAs. The impact of these additional tasks, which add complexity to the controller's job and potentially more workload, are qualitatively assessed in Chapter 7.0 DMA Conceptual Analysis.

For the DMA analyzed at 3X demand, the average 24-hour total traffic load remaining under sector control was reduced by half for the top 50 sectors which benefit from the DMA. The average sector peak load is also reduced by nearly half to 25 aircraft. This level still exceeds the amount of traffic that can be handled by a controller using current day technology and procedures, but it only represents the impact of a single DMA, and additional DMAs may further reduce the peak load. The 24-hour average number of potential conflicts was also nearly halved at 3X demand.

For 2X demand, the average 24-hour total traffic load remaining under sector control was reduced by nearly half for the top 50 sectors that benefit from the DMA. The average sector peak load is reduced from 30 to 17 aircraft, which is still significant but within the range of sector levels controlled today. The potential for conflicts was again reduced nearly by half.

This single-DMA analysis indicates it may be possible to reduce delays for those users who choose to make use of DMAs and to reduce a component of controller workload for some peak sectors provided that substantial feasibility issues identified in Chapter 7.0 are resolved. This workload reduction may allow twice the demand to be accommodated in sectors near the DMA than would be possible without the DMA. The analysis indicates that use of DMAs alone would not enable controllers at current staffing levels using current control mechanisms to handle three times the current en-route traffic load, but it would provide a significant contribution towards that goal.

4.0 DEMAND ANALYSIS FOR THE DMA CONCEPT

The demand analysis presented in this section explored candidate DMA routes based on current-day traffic demand. The analysis made the first-order assumption that current population centers will still be dominant in defining future demand for DMAs, even with growth in point-to-point traffic. The objective was to determine the demand fraction that DMAs would be expected to handle. If demand fractions are significant, an increase in controller productivity could result. This assumes the ratio of traffic to controllers increases significantly for traffic within the DMAs and that other significant design issues discussed in Chapter 7.0 are resolved. Because intersecting DMAs are of particular concern, the analysis also investigated the number of likely DMA intersections.

4.1 City-Pair Analysis

The analysis made use of Official Airline Guide (OAG) data for 2004. City pairs were ranked by frequency of operations over the year. The data indicated 5166 unique airport-airport combinations, where at least one airport was in the CONUS. For routes more than 30 statute miles in length, the 25 highest-density routes are shown in Figure 23. The straight-line routes shown in the figure are illustrative only, and are not representative of
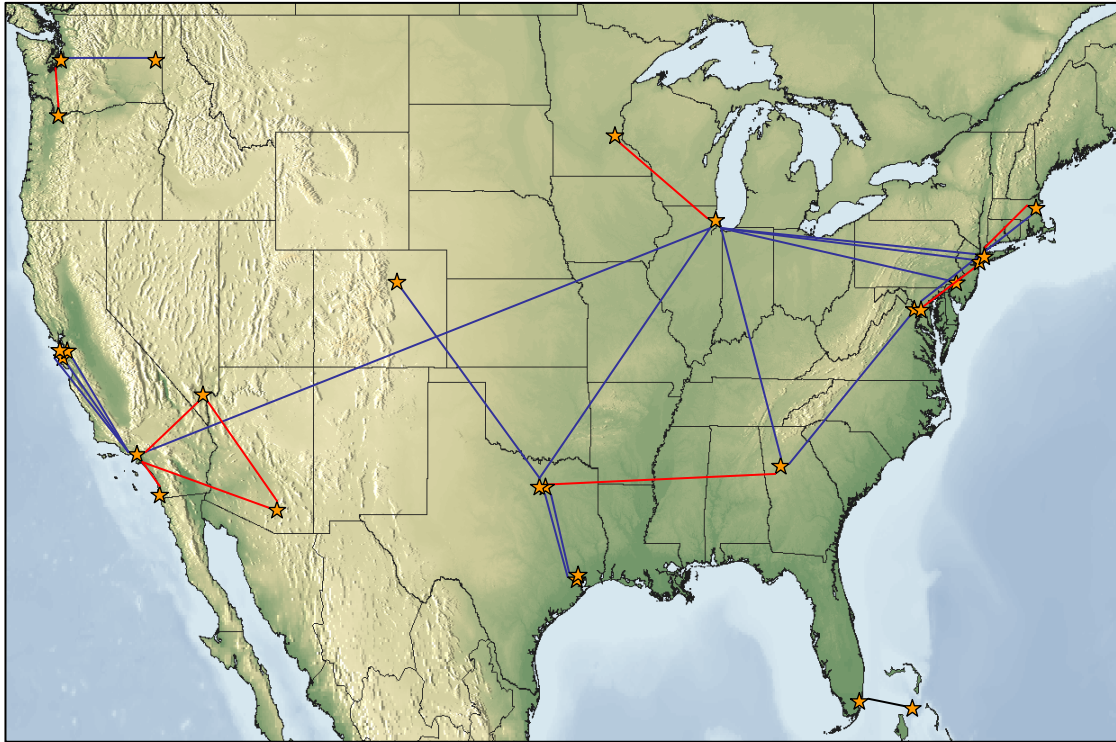
Figure 23. The 25 highest-density CONUS-linked city pairs over 50 miles apart based on 2004 OAG data. The top 10 routes are shown in red.

actual flight paths. Note that because the routes are based on current data, they implicitly reflect the hub and spoke system. A system based solely on traveler origin-destination demand would be different. The figure shows the potential for some intersecting routes. Fifty-three percent of all operations occurred between cities that were separated by less than 500 miles, and thirty-four percent of all operations occurred between cities separated by less than 300 miles. Because of the extra measures that must be taken to enable traffic to enter and exit DMAs, short distance DMAs equivalent to only a few sectors in length may not be effective in offloading controller workload and increasing sector capacity. For a very low number of operations, implementing DMA routes may also provide no capacity benefit. Therefore, a window of unique city pairs can be defined for which DMA operations may prove feasible and viable, as shown in Figure 24. In the figure, the window is defined as all routes having a distance greater than 500 miles and operations greater than 1000 for the year.

The analysis also investigated sensitivity of results to city pair distance. Two cases were examined. In the first case, city pairs separated by less than 500 miles were considered unviable as DMA candidates and were therefore eliminated from the analysis. In the second case, the viability criterion was lowered to 300 miles. In both cases, for the city pairs considered as viable DMA candidates, the top 25 pairs by operations density were identified for analysis.

Table 6 lists the top 25 DMA candidate routes for the 500 mile criteria, and Table 7 lists the top 25 DMA candidate routes for the 300 mile criteria. Each table indicates the fraction of demand that may be served by the top 25 direct city-pair routes as well as the

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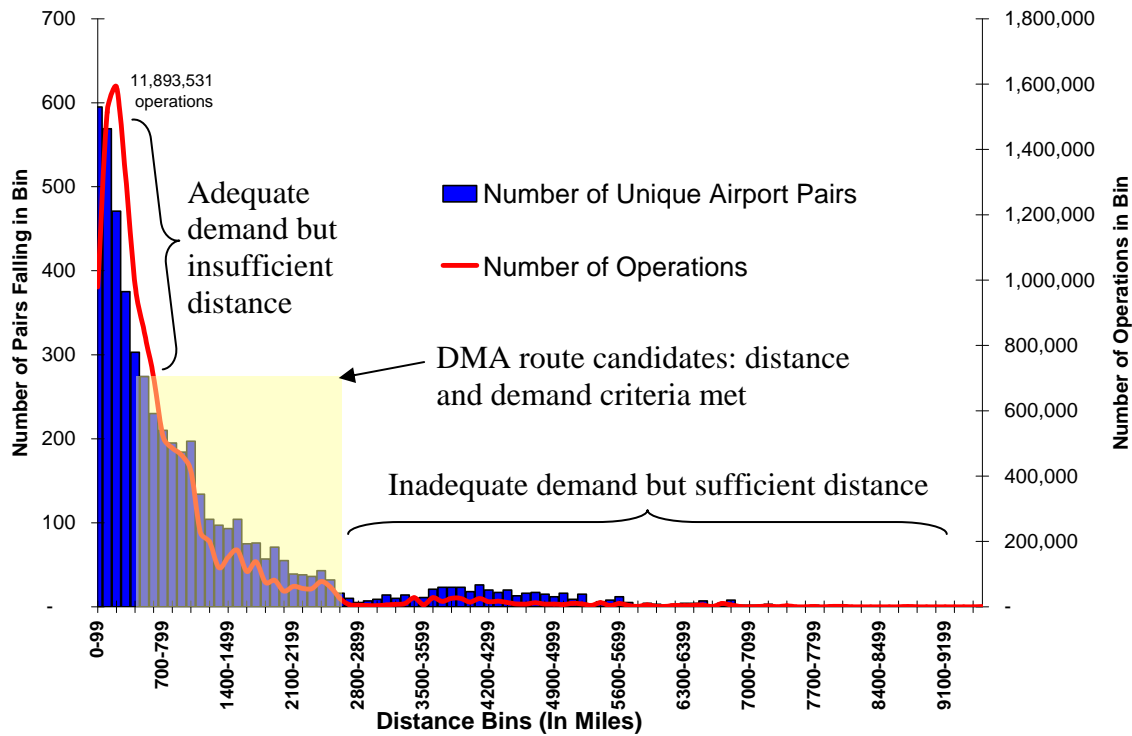
Figure 24. Unique city-pair operations and distances.

number of operations in 2004, based on OAG information. For the 500 mile criterion, the 10 highest-density routes were less than 500 miles and were, therefore, excluded from DMA consideration. For the 300 mile criterion, the 9 highest-density routes were excluded for the same reason.

For the 500 mile criterion, the 25 DMA candidate routes may serve approximately 3.65 percent of the total demand based on number of operations, and 3.93 percent of total demand based on available seat miles (ASM). For the 300 mile criterion, the 25 DMA candidates may serve approximately 4.05 percent based on number of operations, and 3.35 percent based on ASM. These levels do not indicate a significant demand for DMAs instituted between city pairs.

4.2 Regional Pooling Analysis

To explore the potential of increasing DMA benefit by having a single DMA serve several airports, the analysis was repeated based on pooled demand between geographic regions. Within the CONUS, 13 primary regions were defined, each with two to seven primary airports within a 60 mile radius of a designated center airport. Table 8 shows the regions and the airports they contain. The top 25 DMA candidate routes using the regional pooling approach and the 500 mile minimum distance criterion are shown in Table 9. Note that in some cases, pooled routes serve one origin or destination airport, denoted by use of the airport 3-letter identifier. Seven of the 10 highest density routes between regional pools did not meet the minimum distance criterion and were not included.

Table 6. Top 25 DMA candidate direct city-pair routes having a minimum city pair distance of 500 miles, based on 2004 OAG data.

Airport Pair		Annual Number of Operations	Route Density Rank	Percent of NAS Flights	Distance (smi)	Total Two-Way ASM	Percent of NAS ASM
ATL	DFW	23561	11	0.20%	715	2,360,817,745	0.18%
LGA	ORD	22578	14	0.19%	731	2,133,389,143	0.16%
ATL	IAD	21693	16	0.18%	533	1,103,688,430	0.08%
LAX	ORD	20591	19	0.17%	1739	5,832,110,385	0.45%
ORD	PHL	19195	24	0.16%	675	1,611,343,125	0.12%
DFW	ORD	18720	26	0.16%	800	1,869,532,800	0.14%
EWR	ORD	18646	27	0.16%	715	1,619,696,650	0.12%
DEN	DFW	18593	28	0.16%	660	1,419,566,940	0.11%
ATL	ORD	18114	30	0.15%	605	1,298,497,585	0.10%
ATL	PHL	17690	32	0.15%	665	1,506,098,650	0.12%
JFK	LAX	17600	33	0.15%	2464	7,317,335,872	0.56%
ATL	EWR	17307	36	0.15%	745	1,676,930,185	0.13%
ATL	LGA	17199	37	0.14%	759	2,067,840,093	0.16%
PHX	SLC	16224	40	0.14%	507	791,815,362	0.06%
BOS	ORD	16137	41	0.14%	863	1,846,458,403	0.14%
ATL	BWI	16099	43	0.14%	575	1,278,434,875	0.10%
DCA	ORD	15943	44	0.13%	610	1,180,524,460	0.09%
DEN	LAX	15888	45	0.13%	847	1,963,432,394	0.15%
DFW	PHX	15283	48	0.13%	882	1,654,261,560	0.13%
DEN	ORD	14855	52	0.12%	898	2,267,214,724	0.17%
ANC	SEA	14698	56	0.12%	1443	2,825,643,639	0.22%
IAD	ORD	14414	58	0.12%	587	871,270,012	0.07%
ATL	DCA	14350	59	0.12%	546	1,005,843,384	0.08%
DEN	PHX	14205	60	0.12%	589	1,131,964,938	0.09%
DFW	LAX	14091	61	0.12%	1246	2,644,505,416	0.20%
Total		**433674**		**3.65%**		**51,278,216,770**	**3.93%**
					NAS Total	**1,304,725,629,593**	

Table 7. Top 25 DMA candidate direct city-pair routes, having a minimum city pair distance of 300 miles, based on 2004 OAG data.

Airport Pair		Annual Number of Operations	Route Density Rank	Percent of NAS Flights	Distance (smi)	Total Two-Way ASM	Percent of NAS ASM
MSP	ORD	24330	10	0.20%	334	893,955,008	0.07%
ATL	DFW	23561	11	0.20%	715	2,360,817,745	0.18%
LAX	PHX	22975	12	0.19%	367	970,711,697	0.07%
LGA	ORD	22578	14	0.19%	731	2,133,389,143	0.16%
ATL	IAD	21693	16	0.18%	533	1,103,688,430	0.08%
BOS	DCA	20952	17	0.18%	398	747,514,048	0.06%
LAX	SJC	20714	18	0.17%	308	567,443,492	0.04%
LAX	ORD	20591	19	0.17%	1739	5,832,110,385	0.45%
LAX	SFO	19777	21	0.17%	338	819,288,678	0.06%
LAX	OAK	19662	22	0.17%	337	803,649,629	0.06%
ORD	PHL	19195	24	0.16%	675	1,611,343,125	0.12%
DFW	ORD	18720	26	0.16%	800	1,869,532,800	0.14%
EWR	ORD	18646	27	0.16%	715	1,619,696,650	0.12%
DEN	DFW	18593	28	0.16%	660	1,419,566,940	0.11%
ATL	ORD	18114	30	0.15%	605	1,298,497,585	0.10%
ATL	PHL	17690	32	0.15%	665	1,506,098,650	0.12%
JFK	LAX	17600	33	0.15%	2464	7,317,335,872	0.56%
ATL	MCO	17506	34	0.15%	403	1,278,751,240	0.10%
PHX	SAN	17489	35	0.15%	302	680,703,470	0.05%
ATL	EWR	17307	36	0.15%	745	1,676,930,185	0.13%
ATL	LGA	17199	37	0.14%	759	2,067,840,093	0.16%
PHX	SLC	16224	40	0.14%	507	791,815,362	0.06%
BOS	ORD	16137	41	0.14%	863	1,846,458,403	0.14%
ATL	BWI	16099	43	0.14%	575	1,278,434,875	0.10%
DCA	ORD	15943	44	0.13%	610	1,180,524,460	0.09%
Total		479295		4.05%		43,676,097,965	3.35%
					NAS Total	1,304,725,629,593	

The data in Table 9 indicate that 25 candidate DMA routes using the pooling approach would serve 7.15 percent of the anticipated operations demand and 9.09 percent of the ASM demand. Table 10 corresponds to the top 25 pooled candidate routes using the 300 mile minimum distance criterion. These DMA routes would serve 11.32 percent of the anticipated operations demand and 8.64 percent of the ASM demand. The results indicate that regional pooling would increase the demand for DMA routes by a factor of 2 to 3, and about 10 percent of total NAS demand would therefore be served by DMAs. The ASM demand is reduced when the 300 mile criterion is used, probably due to a lower number of passengers per operation for routes of shorter distance.

Note that this analysis may somewhat underestimate the potential demand for DMA operations by limiting the DMA use to flights originating from within the defined regions. Flights coming from longer distances that overfly the region would be able to

join the DMA at this point and therefore add to the demand. Also, this analysis does not consider the level of difficulty in implementing the routes. For example, the 300 mile minimum distance criterion may result in more DMA routes that do not intersect than would be possible with the 500 mile criterion. If this is found to be true, then the analysis assumption that an equal number of top routes would be implemented for each case would not be correct. A more sophisticated analysis would need to be performed to determine accurate estimates of demand for DMA operations. For each potential DMA route, such an analysis should consider user incentives for its use, air traffic management efficiencies gained, and predictions of future demand that include changes in demographics.

Table 8. Regions used in regional pooling demand analysis.

Pool Name	Center Airport	Airports
SanFranPool	SJC	MOD MRY OAK SFO SJC
DetroitPool	FNT	DET DTW LAN MBS FNT
DallasPool	DFW	DAL DFW
BostonPool	BOS	EWB ORH PVC MHT PVD BOS
HoustonPool	IAH	EFD HOU IAH
TampaPool	TPE	PIE SRQ TPE
ChicagoPool	ORD	CGX MDW ORD
DCPool	IAD	DCA BWI HGR IAD
LosAngPool	LAX	BUR LGB ONT OXR SNA LAX
FortLaudPool	FLL	MIA PBI FLL
PhilaPool	PHL	PHL ACY TTN
DaytonaPool	DAB	DAB MCO SFB
NewYorkPool	HPN	HVN EWR ISP JFK LGA SWF HPN

Nevertheless, the demand analysis is useful for indicating overall trends. Figure 25 shows the cumulative demand met by implementation of DMAs for the 500-mile criterion and 300-mile criterion, represented in Figure 25-a and 25-b, respectively. The figures illustrate the efficiency of regional pooling over the city-pair method. The analysis indicates that implementation of nine DMAs would absorb half as much demand achieved with 25 DMAs.

Figure 26 depicts the top 25 routes based on regional pooling of demand for both the 500 and 300 mile minimum criteria. By excluding many of the shorter high-demand city-pair routes shown in Figure 23 and by using regional pooling, the number of potential DMA intersections increases. As will be discussed in more detail later, DMA intersections present significant challenges, and they must be addressed if the top 25 routes are to be implemented. Fewer routes or less efficient routes may reduce or resolve the issue, but at the cost of a reduced benefit potential. For instance, the top 10 routes, shown in red in Figure 26, involve only one intersection (i.e. Los Angeles to New York and Washington DC to Chicago). The figure also indicates several opportunities for combining DMAs that nearly overlap (e.g. Atlanta-Washington DC and Atlanta-New York).

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Table 9. Top 25 DMA candidate routes having a minimum city pair distance of 500 miles, based on regional pooling of city pairs.

Airport / Regional Pool Pair		Annual Number of Operations	Route Density Rank	Percent of NAS Flights	Distance (smi)	Total Two-Way ASM	Percent of NAS ASM
NewYork	Chicago	69299	4	0.58%	731	5,951,975,716	0.46%
Miami	NewYork	65447	6	0.55%	1093	11,894,343,144	0.91%
ATL	WashDC	52142	9	0.44%	533	3,387,966,689	0.26%
WashDC	Chicago	46921	11	0.39%	610	3,582,680,034	0.27%
ATL	NewYork	44994	12	0.38%	759	4,389,799,054	0.34%
Miami	ATL	36299	14	0.31%	596	3,545,010,236	0.27%
NewYork	LosAngls	35100	17	0.30%	2464	14,126,818,293	1.08%
Dallas	LosAngls	33817	18	0.28%	1217	5,677,930,417	0.44%
Chicago	LosAngls	33419	19	0.28%	1739	9,427,880,274	0.72%
Chicago	Boston	32346	21	0.27%	845	3,779,866,450	0.29%
SEA	SanFran	30158	25	0.25%	672	2,775,589,876	0.21%
Miami	WashDC	29946	26	0.25%	920	3,731,159,998	0.29%
Chicago	SanFran	29908	27	0.25%	1840	8,953,861,084	0.69%
NewYork	Daytona	29442	28	0.25%	949	4,671,628,829	0.36%
DEN	LosAngls	28326	31	0.24%	847	3,288,977,108	0.25%
Chicago	ATL	27573	33	0.23%	605	2,031,088,195	0.16%
NewYork	Detroit	27532	34	0.23%	500	1,404,506,094	0.11%
LosAngls	SEA	27408	35	0.23%	979	3,604,432,520	0.28%
NewYork	CVG	26194	37	0.22%	554	1,136,003,346	0.09%
PHX	SanFran	25317	43	0.21%	618	2,140,030,843	0.16%
Chicago	Dallas	25243	44	0.21%	795	2,674,832,025	0.21%
SanFran	NewYork	24231	46	0.20%	2575	10,341,281,553	0.79%
SanFran	PDX	23607	47	0.20%	550	1,625,819,223	0.12%
Philly	Chicago	23598	48	0.20%	675	2,093,089,563	0.16%
ATL	Dallas	23561	49	0.20%	715	2,360,817,745	0.18%
Total		**851828**		**7.15%**		**118,597,388,309**	**9.09%**
					NAS Total	**1,304,725,629,593**	

Table 10. Top 25 DMA candidate routes having a minimum city pair distance of 300 miles, based on regional pooling of city pairs.

| Airport / Regional Pool Pair		Annual Number of Operations	Route Density Rank	Percent of NAS Flights	Distance (smi)	Total Two-Way ASM	Percent of NAS ASM
LosAngls	SanFran	136487	1	1.58%	341	5,119,449,207	0.39%
WashDC	Boston	78885	3	0.74%	398	2,766,428,831	0.21%
NewYork	Chicago	69299	4	0.84%	731	5,951,975,716	0.46%
Miami	NewYork	65447	6	0.62%	1093	11,894,343,144	0.91%
LosAngls	PHX	58472	7	0.60%	336	2,493,318,632	0.19%
ATL	WashDC	52142	9	0.33%	533	3,387,966,689	0.26%
WashDC	Chicago	46921	11	0.58%	610	3,582,680,034	0.27%
ATL	NewYork	44994	12	0.40%	759	4,389,799,054	0.34%
Miami	ATL	36299	14	0.28%	596	3,545,010,236	0.27%
NewYork	LosAngls	35100	17	0.33%	2464	14,126,818,293	1.08%
Dallas	LosAngls	33817	18	0.38%	1217	5,677,930,417	0.44%
Chicago	LosAngls	33419	19	0.44%	1739	9,427,880,274	0.72%
Chicago	MSP	33197	20	0.44%	334	1,370,824,976	0.11%
Chicago	Boston	32346	21	0.47%	845	3,779,866,450	0.29%
SMF	LosAngls	31454	22	0.35%	359	1,489,935,476	0.11%
SAN	SanFran	30963	24	0.36%	416	1,599,612,640	0.12%
SEA	SanFran	30158	25	0.30%	672	2,775,589,876	0.21%
Miami	WashDC	29946	26	0.28%	920	3,731,159,998	0.29%
Chicago	SanFran	29908	27	0.38%	1840	8,953,861,084	0.69%
NewYork	Daytona	29442	28	0.24%	949	4,671,628,829	0.36%
SanFran	LAS	29327	30	0.28%	405	1,632,419,490	0.13%
DEN	LosAngls	28326	31	0.37%	847	3,288,977,108	0.25%
Chicago	ATL	27573	33	0.27%	605	2,031,088,195	0.16%
NewYork	Detroit	27532	34	0.24%	500	1,404,506,094	0.11%
LosAngls	SEA	27408	35	0.22%	979	3,604,432,520	0.28%
Total		1078862		11.32%		112,697,503,263	8.64%
					NAS Total	1,304,725,629,593	
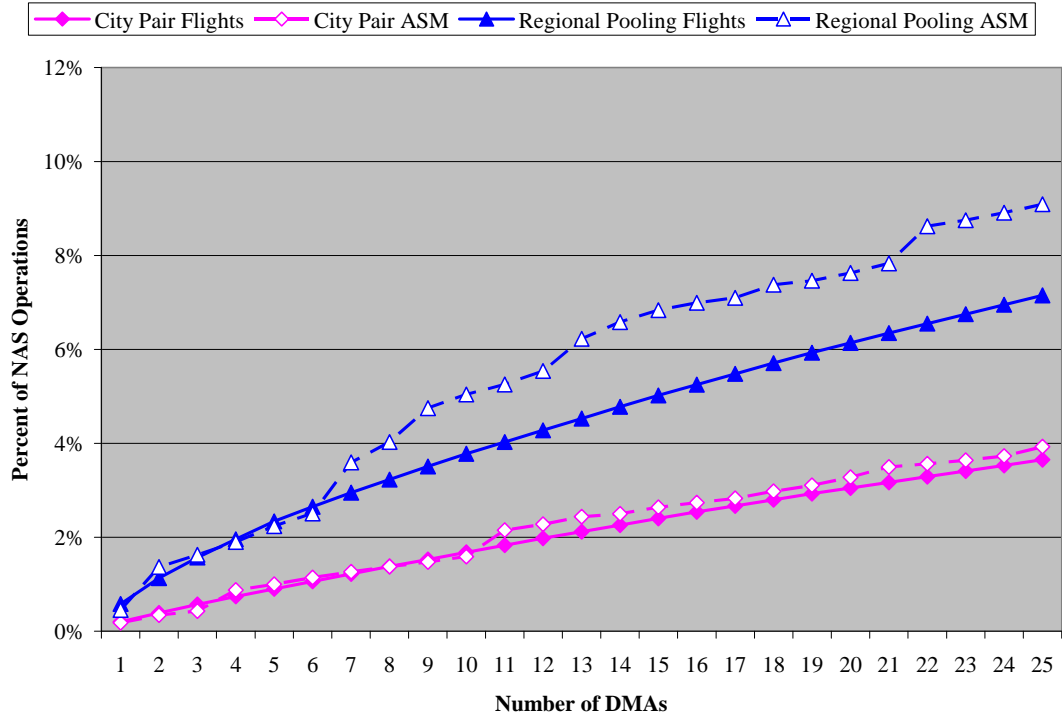
(a) 500 mile minimum distance criterion
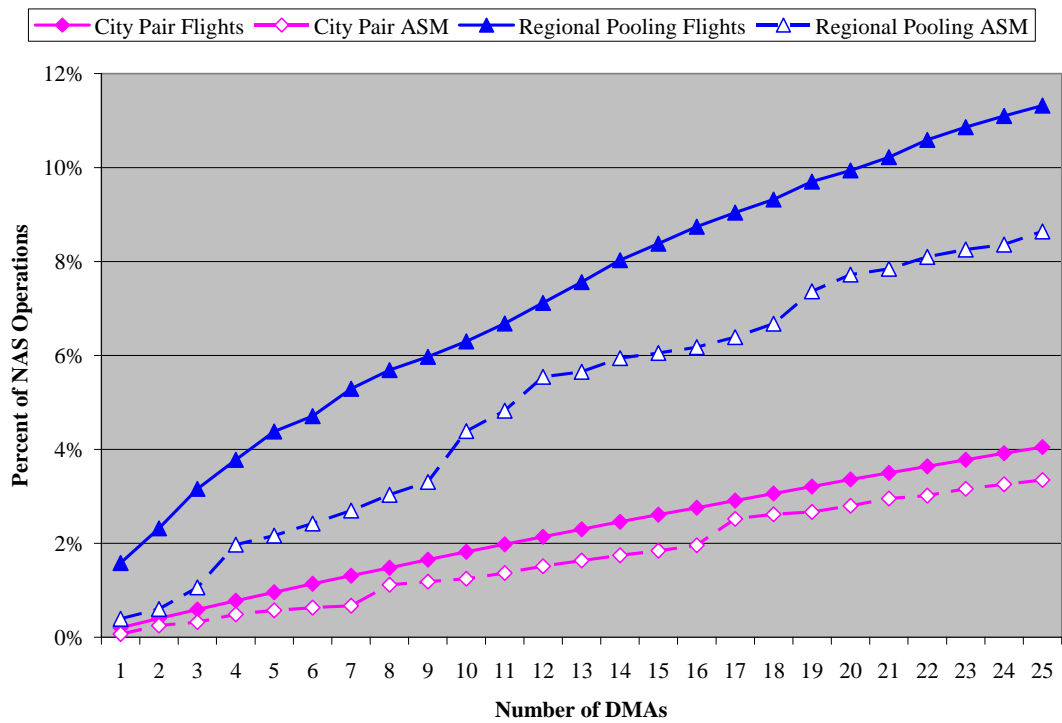
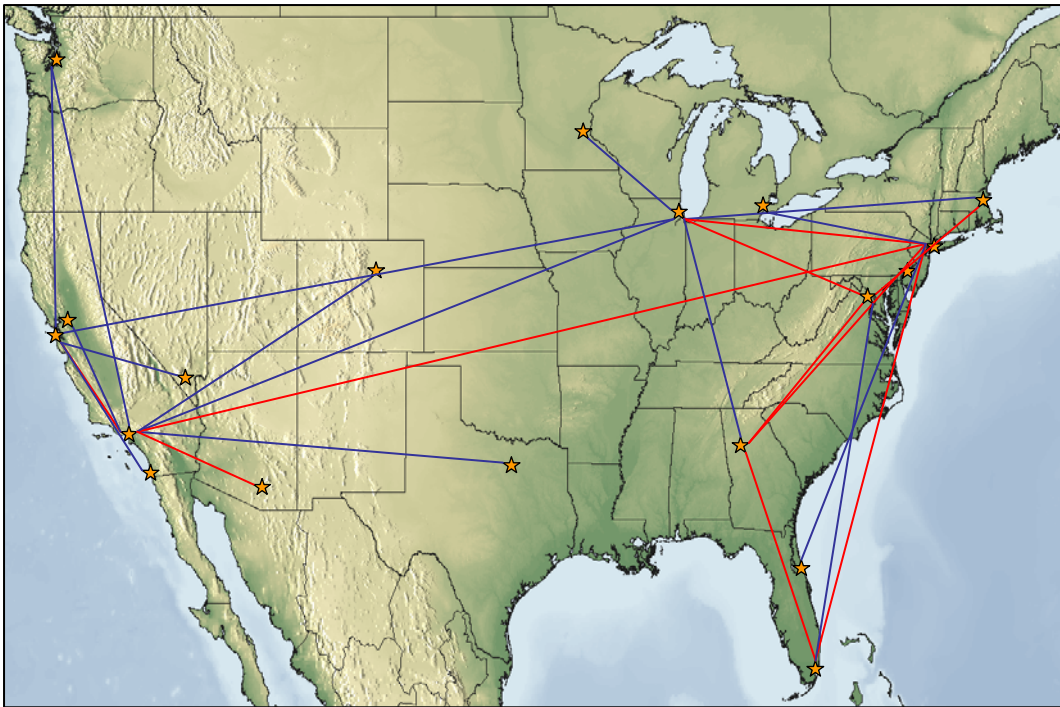**(b) 300 mile minimum distance criterion**

Figure 25. Cumulative demand met by implementation of DMAs using city-pair and regional pooling methods.
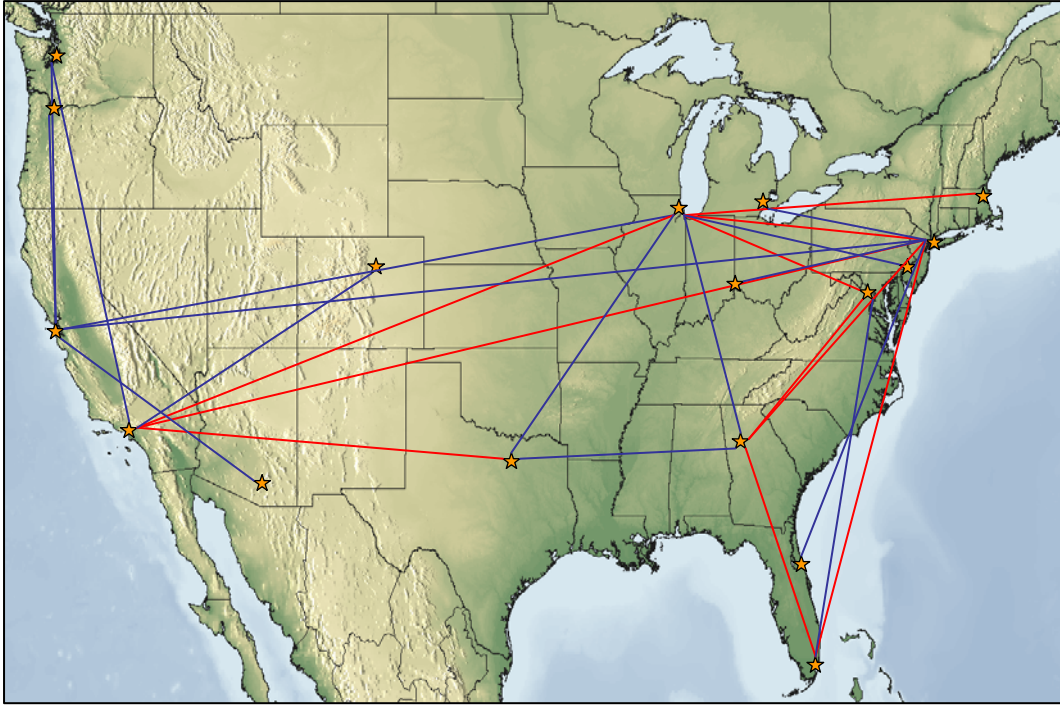
(a) 500 mile minimum distance criterion.

(b) 300 mile minimum distance criterion.

Figure 26. Top 25 candidate DMA routes based on regional pooling of city pairs. Top 10 routes, shown in red, involve only one intersection.

4.3 Preliminary Conclusions from Demand Analysis

The results indicate that, based on 2004 demand and current hub-and-spoke operations, implementation of DMA routes will have a relatively small impact on the total number of NAS operations. If DMA's are implemented between the top 25 candidate city pairs, about 4 percent of the total NAS operations would be served by these routes. If routes are pooled into regions, an additional improvement in the fraction of operations served by the DMA routes of roughly 5 percent may be possible. About half the benefits achieved from implementing 25 routes is achieved by implementing the first 9 routes. These results are not strongly impacted by changing the minimum distance for viable DMA routes from 500 miles to 300 miles, assuming an equal number of routes are implemented in each case. These estimates may change if the nature of demand significantly changes from 2004, for example if population demographics change or if traffic patterns favor more point-to-point operations over hub and spoke operations. If feasibility and benefits issues can be resolved for DMA routes under 500 miles in length, the overall positive impacts of implementing DMA routes may increase slightly depending on other factors such as the number of DMA routes that can be implemented practically.

5.0 TRACK CONFIGURATION MODELING AND ANALYSIS

The next area of analysis addresses the options for aircraft self-separation within the DMA. The objective is to determine the feasibility and impact of different autonomous procedures. The analysis is in two parts, a low-fidelity modeling activity presented in this chapter and a high-fidelity technology prototyping activity presented in Chapter 6.0 Prototyping of DMA Spacing and Passing Capabilities. The low-fidelity modeling activity is conducted to illuminate basic traffic behavior and characteristics as DMA loading is increased. The high-fidelity prototyping activity is intended to verify the ability to develop the needed airborne technologies to perform the basic DMA procedures. These activities are focused only on operations within a single DMA. Interactions with other DMAs, other traffic, and other factors such as dynamic rerouting are addressed in the conceptual analysis later in the report.

The DMA concept for ATM calls for aircraft to fly on prescribed tracks and exercise the responsibility for longitudinal separation, thereby reducing controller workload and increasing their productivity. This limited autonomous operation is also intended to benefit the operators, by enabling aircraft to fly more consistently at their optimal cruise speed than in current-day operations. Two design options have been considered for the track configuration to provide this improvement in flight efficiency: speed-based tracks (Figure 27) and speed-independent tracks with passing (Figure 28). To quantify these benefits, identify possible trade-offs, and gain insight into the characteristics of aircraft operations within a DMA, low-fidelity modeling in MatLab® of a simplified, isolated DMA was undertaken. Both speed-based and speed-independent track configurations were modeled. The modeling did not consider TFM constraints, winds, weather, DMA intersections or merges, or most complexities of DMA operations. These factors are discussed in Chapter 7.0 DMA Conceptual Analysis.
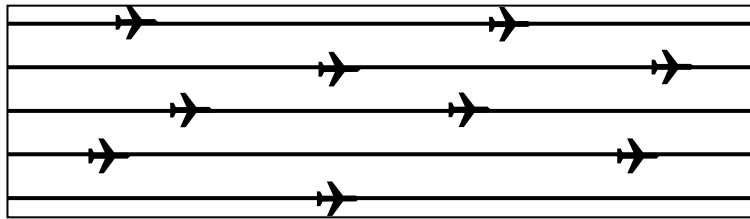
Figure 27. Speed-based track configuration. Each track is designated with a nominal Mach number.
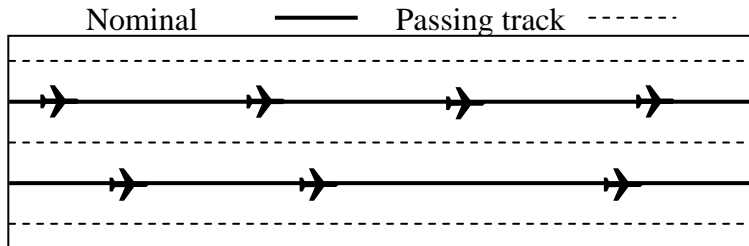
Figure 28. Speed-independent track configuration with nominal and passing tracks.

5.1 Aircraft Fleet Characteristics Modeling

The model uses a representative set of aircraft types that are commonly encountered at a major hub airport [7] but augmented with a few faster and slower aircraft types to ensure that the modeled fleet had a wide spread in cruise Mach numbers. All these aircraft types were assumed to be equally common within the DMA. The operations were assumed to occur at a single flight level, FL350, and the aircraft were assumed to have the appropriate weight for this flight level. Typical speed characteristics of these aircraft types at FL350, shown in Figure 29, were obtained from a desktop air traffic simulator [8] that uses the Base of Aircraft Data models [9]. The optimum Mach numbers for each type are indicated by the circular symbols, while the upper and lower Mach limits are marked by triangular symbols. Since the analysis focused on the cruise phase of flight, the practical lower Mach limit was assumed to be operationally limited to 1.5 times the stall Mach number. These adjusted lower Mach limits are indicated by the square symbols for each aircraft type. Thus, each aircraft type had the effective Mach range depicted by the solid line in Figure 29.

5.2 Speed-based Track Configuration Analysis

In the speed-based configuration, aircraft are assumed to be loaded onto the track closest to their desired cruise Mach numbers, within acceptable safety margins. Within each speed-based track, aircraft must maintain sufficient spacing relative to the aircraft ahead of them at all times and fly the track-specific Mach number for the entire length of the track. Therefore, for safety, all aircraft on a track would fly at a constant Mach that could be slightly sub-optimal for any given aircraft's operation. The degree to which aircraft would be required to fly at a sub-optimal cruise speeds may limit benefits achievable from a speed-based configuration and therefore is used as a surrogate metric for its attractiveness to users.
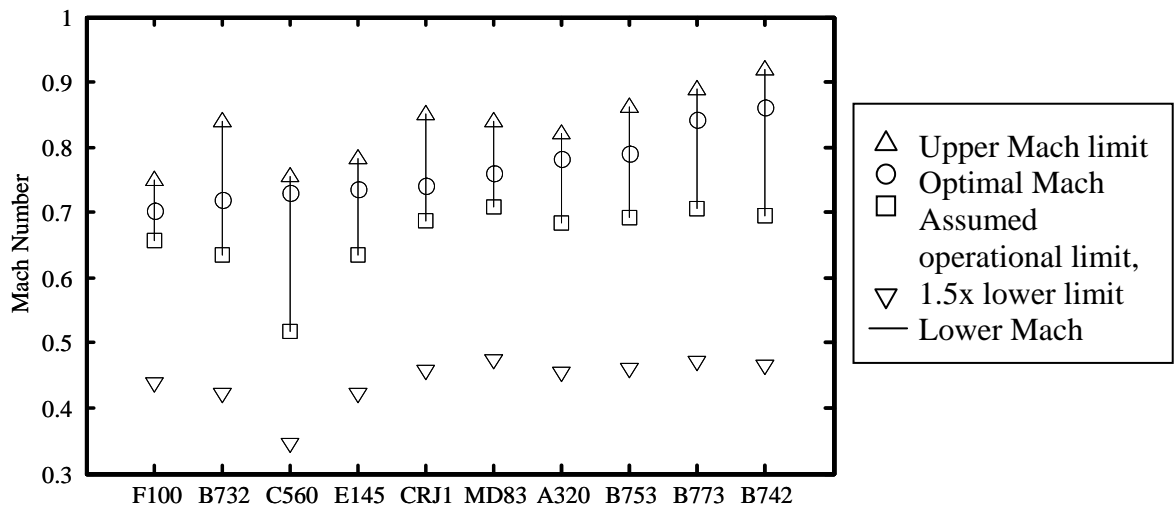
Figure 29. Operational Mach ranges for representative aircraft types in cruise flight at Flight Level 350.

The speed-based configuration was modeled with two, three, four, five, and six parallel tracks. Mach number assignments for each track were determined based on the randomly developed demand for the DMA at initialization. It was assumed in actual operations that the Mach number assignments would be optimized based on the actual fleet mix expected to use the DMA. Depicted in Figure 30 are the results of modeling the speed-based design. The figure shows deviations from optimal Mach, for a fleet composed of the above aircraft types, as a function of the number of tracks in the DMA. The data indicate that the degree of sub-optimality is related to the number of tracks in the DMA. A greater selection of tracks translates into flying closer to one's optimal speed.

If track loading is low, it is conceivable that aircraft within a track could fly their optimal Mach numbers until such time that they closed in on the minimum spacing requirement from aircraft in front. At that point, aircraft would have to slow-down to match the speed of its lead aircraft, and eventually all aircraft on the track would be flying at the speed of the slowest leader of the track. These effects were not included in this initial modeling exercise.

5.3 Speed-independent Track and Passing Analysis

In the alternative configuration, speed-independent tracks, aircraft are loaded onto a few (probably two) nominal tracks, but are permitted to shift over to a passing track in order to overtake slower-moving aircraft (see Figure 28). This passing option permits aircraft to remain at their individual optimum speeds for much of the length of the DMA, including the portion during passing maneuvers. Deviations from optimum speeds would be required only when the passing lane was unavailable for use or when constrained by TFM requirements. It is therefore to be expected that this concept would be characterized by dynamic changes to the sequence of aircraft on the track system.
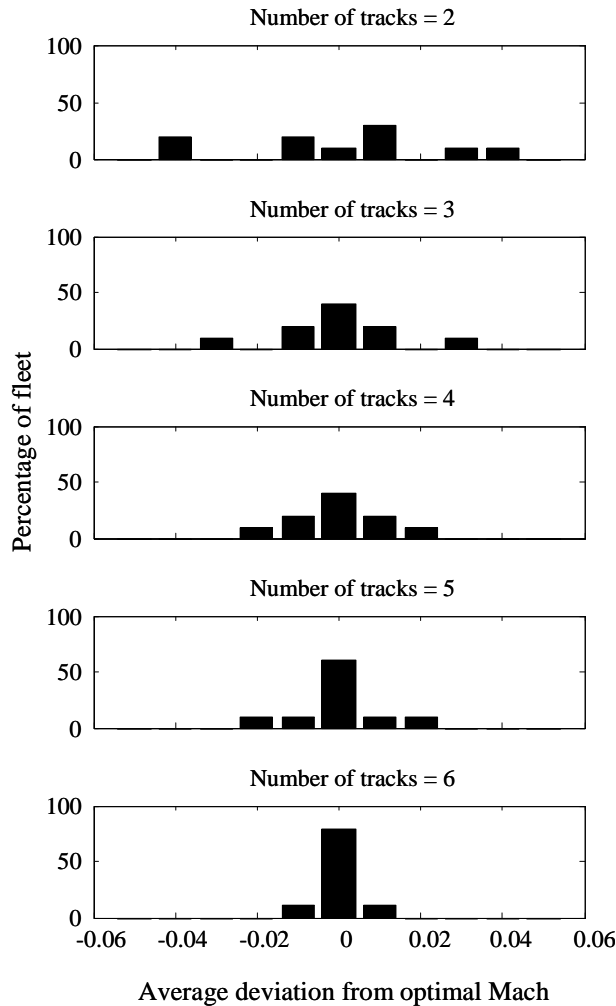
Figure 30. Reduction in Mach deviation with increasing number of tracks.

5.3.1 Duration of Passing Maneuver

The small differences in the optimal cruise speeds of the aircraft types depicted in Figure 29 suggest that passing maneuvers may often be a slow drawn-out process that can span large distances. Presented in Figure 31 is the time taken for a faster airplane to pass a slower airplane as a function of the Mach differential, with the passing maneuver assumed to take the fast airplane from 5 nmi behind to 5 nmi ahead of the slow airplane (i.e. a bare-minimum passing maneuver with no buffers, based on the current separation standard). It is immediately evident that with Mach differences less than about 0.05, more than 20 minutes are required to complete the passing maneuver. In a similar vein, the distances covered in the course of the passing maneuver as a function of the cruise Mach numbers of the two airplanes are presented in Figure 32, indicating that substantial ground distances would be covered in the course of even a bare-minimum passing maneuver. It is expected that additional longitudinal separation buffers would be desired to provide the DMA controller with room for "control by exception" tasks, and these buffers would further increase the duration and distance required to complete a passing maneuver.
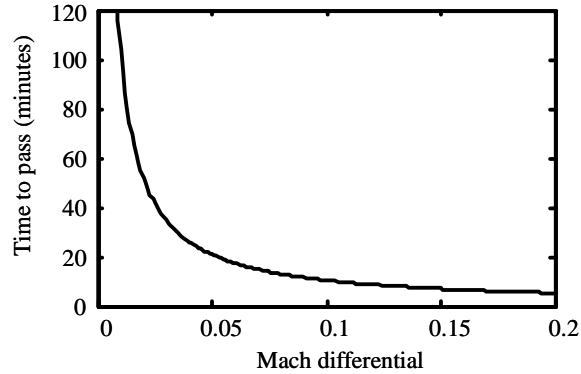
Figure 31. Time required to pass from 5 nmi behind to 5 nmi ahead.
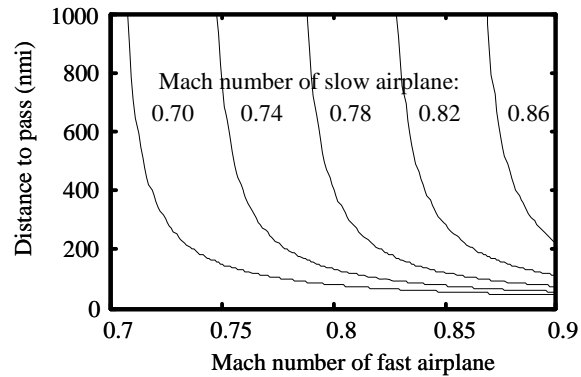
Figure 32. Distance required to pass from 5 nmi behind to 5 nmi ahead.

These data have implications for the minimum lengths of DMAs that would be required to attain the benefits of the speed-independent configuration, since incomplete passing maneuvers could challenge the orderly termination of a DMA at a terminal area. Likewise, these data also suggest a possible challenge in using passing lanes if DMA intersections are spaced close together, since maintaining separation from crossing traffic may be easier if aircraft were not in the process of passing when crossing the intersection. Finally, these data suggest that loading aircraft randomly on each nominal track (with no regard to their optimal speeds) may actually be better than sorting airplanes onto the nominal tracks based on their optimal speeds (i.e. fast and slow lanes), since the passing times and distances would be considerably longer in the latter case. Presorting to maximize speed differential may provide reduced passing times and distances than random loading. However, more passing may create more bottlenecks that may in turn reduce the benefits of passing.

5.3.2 Availability of Passing Opportunities

If aircraft stay on the passing track for prolonged periods, other aircraft that desire to pass may be denied access to the passing track. In such situations, the aircraft that desires to pass may need to slow down to the speed of its lead aircraft until the passing track becomes available. These flight crew decisions may require support from onboard

automation that can monitor the traffic, predict these constrained situations, and advise the crew whether passing is an option. A simple, exploratory prototype of this automation tool has been modeled in MatLab®. The tool is given access to traffic state data (position and velocity but no intent such as a planned passing maneuver) and uses that data to assess whether a passing maneuver could be initiated. Once its aircraft is established on the passing track, the tool analyzes the acceptability of shifting back to the nominal track. In either case, if changing tracks is not immediately possible, the tool ensures that the aircraft slows down to maintain required separation behind the lead aircraft and then resumes the optimal speed when it is acceptable to do so.

For this portion of the analysis, one nominal lane and one dedicated passing lane were modeled. Aircraft were required to maintain at least 10 nmi longitudinal separation within a track (i.e. minimum separation plus a 5 nmi buffer). Capacity is defined here such that 100 percent capacity equates to aircraft spaced 10 nmi apart. The operations of this prototype are summarized in Figure 33. A group of aircraft is initialized with approximately 20 nmi inter-aircraft spacing (i.e. 50 percent capacity). The initial sequence number for each aircraft is shown. The aircraft relative positions are then tracked over a period of 60 minutes as they apply the passing procedures.
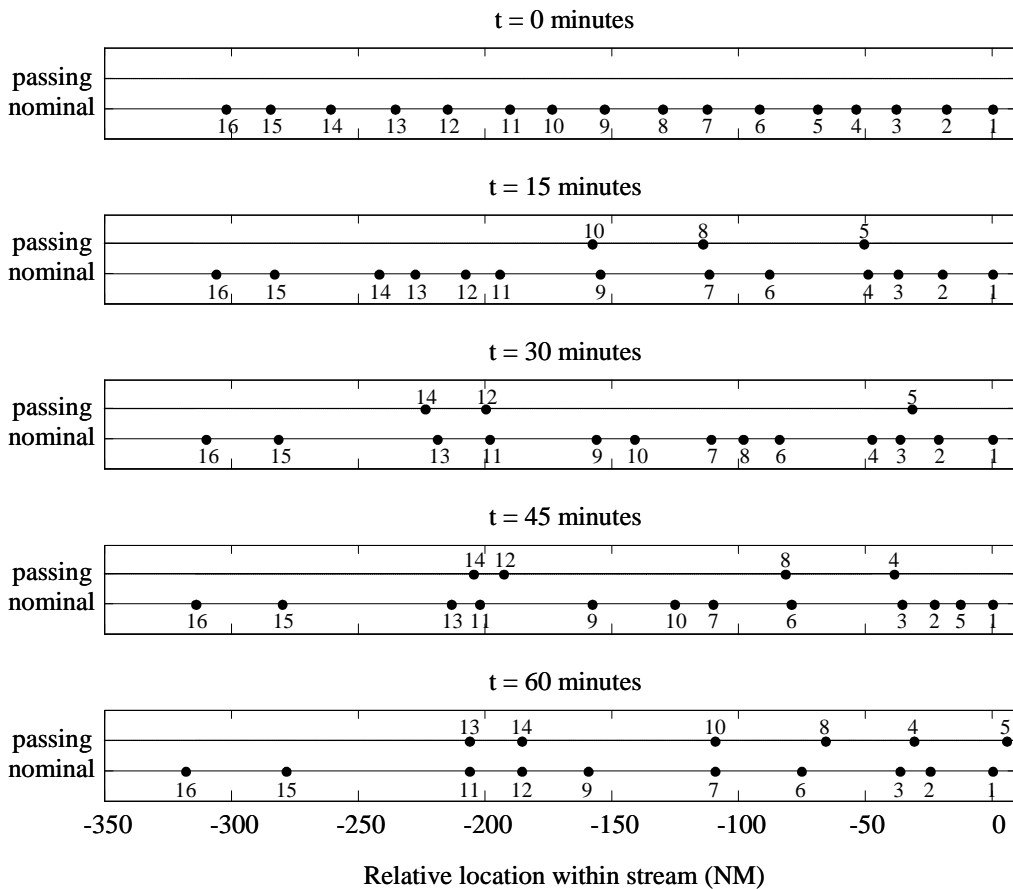
Figure 33. Visualization of DMA passing concept in action for average track loading of one aircraft every 20 nmi (i.e. 50 percent capacity).

Aircraft in this scenario were generally able to maintain optimal speed throughout their transits of the DMA. One can see this by visual inspection of Figure 33, which shows several of the faster aircraft (e.g. aircraft 5, 8, and 10) successfully conducting multiple passing maneuvers. However, the track loading in this scenario is high enough that bottlenecks are being created, resulting in speed deviations as aircraft get "stuck" behind slower aircraft for longer stretches of time (such as aircraft 14 waiting for aircraft 12 to clear the passing lane). The data in Figure 34 charts the time-averaged deviations from optimal speed for a group of aircraft as the track loading is increased (that is, aircraft are packed closer together on the nominal track). The data show that as track loading increases, speed deviations are increased. This trend is captured in Figure 34. For designs that use one passing lane for each nominal lane, track loadings exceeding 50 percent capacity may impart an unacceptably high penalty on aircraft flight efficiency due to the inability for many of the aircraft to conduct passing maneuvers to maintain
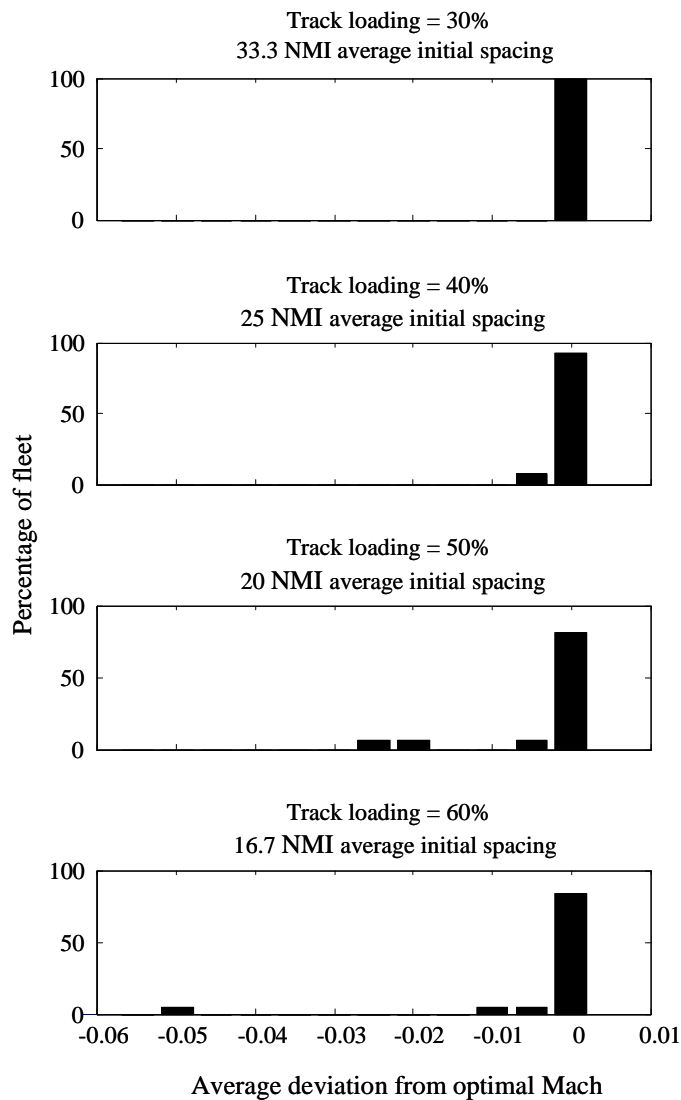
Figure 34. Growth in Mach deviation with increased
track loading for the passing tracks concept.

60

optimal speed. Adding an additional passing lane would ease the bottlenecks by providing more track capacity for passing.

Track loadings above 60 percent could not be evaluated with the simple prototype tool because some aircraft were unable to slow down sufficiently to maintain required separation. A more sophisticated tool would be able to determine complete passing maneuvers (including both departure from and return to the nominal track) using intent information for traffic aircraft. This more capable tool, which may enable operations at higher track loadings, was prototyped and is discussed in the next section.

5.4 Preliminary Conclusions from Track Configuration Analysis

From these initial characterizations of the two proposed track configurations, it appears that at lower track-loadings, the speed-independent configuration may out-perform the speed-based design. At about 40 percent track loading, for example, the speed-independent configuration achieves Mach deviations of less than 0.01 Figure 34), while even the 6-track speed-based version imposes about 0.01 Mach deviations on some airplanes (Figure 30). However, the speed-based configuration generally allows aircraft to be packed more closely together than the speed-independent configuration. Indeed, since aircraft on each track would be of comparable speeds, aircraft could presumably be packed as closely as the minimum spacing requirement (with allowances for crossing traffic and intersections, not modeled in this analysis). At that high a track loading, the speed-independent configuration would permit no passing at all, and aircraft would likely be held at non-optimal speeds for extended durations provided that the speed margins available to each airplane in the DMA permit spacing operations.

Another distinction between these two types of operations is that the speed-based configuration is completely insensitive to the uninterrupted length of the DMA, while the speed-independent configuration may require at least 200 nmi uninterrupted DMA length between intersections to ensure orderly flow at the intersection. Given its independence from considerations of DMA length, and relatively higher inherent capacity, the speed-based configuration appears better suited for high-traffic corridors and for shorter DMAs. A more detailed estimation of these trade-offs would need to assess the sensitivity of flight efficiency to different magnitudes of Mach deviations. The actual track-loadings likely within a DMA at 1x, 2x and 3x capacity (based on current-day city-pair traffic volumes) and the frequency of different aircraft types in the DMA would also need to be carefully modeled for these higher-fidelity trade-off studies.

6.0 PROTOTYPING OF DMA SPACING AND PASSING CAPABILITIES

To determine the feasibility of technologically enabling the airborne role in DMA operations and to support possible future piloted simulations, a software prototype of the airborne spacing and passing capabilities required for self-separation from other DMA traffic was developed. The software prototype was built not from scratch, but from existing platforms systems developed for advanced airborne spacing and separation applications. The systems used for this development were the Advanced Terminal Area Approach Spacing (ATAAS) system [10] for the in-trail spacing capability and the

Autonomous Operations Planner (AOP) system [11] for the passing capability. Designed for human-in-the-loop simulation and flight research, the ATAAS and AOP enable varying degrees of autonomous control by aircraft in an ATM environment. The level of fidelity of these systems is such that they could be integrated into a high-fidelity flight simulator or into flight research aircraft. ATAAS has been integrated in both of these environments. AOP and a derivative of ATAAS are both implemented in the medium-fidelity Airspace and Traffic Operations Simulation (ATOS) [12] hosted in the Langley Air Traffic Operations Laboratory (ATOL).

6.1 Prototype Spacing Capability for Speed-Based Tracks

The ATAAS system provides speed commands to the pilot for achieving and maintaining a precise time or distance spacing behind a lead aircraft on a common path. The central ATAAS algorithm was originally developed for application in the challenging domain of terminal approaches to maximize throughput to a runway. It was therefore straightforward to apply the algorithm here to the simpler spacing function of managing a stable in-trail interval along a level DMA track. The algorithm records a time history of position data from the lead aircraft, received through ADS-B data link. This history is compared with current ownship position to determine whether an increase or decrease in speed is required to establish and maintain the target spacing interval, which would either be the minimum standard or a custom interval assigned by the DMA controller. This approach to the speed-based track operation is preferred over flying the track-assigned Mach number (e.g. fly Mach 0.80 on a "Mach 0.80 track") because it eliminates the effect of sensor discrepancies between aircraft and enables automatic coordination in the event the lead aircraft must adjust speed (e.g. slow down for turbulence penetration). Distance separation monitoring prevents inadvertent penetration of the in-trail separation standard, and speed protections ensure that the aircraft remains within a safe speed range.

The basic procedure for using this capability is as follows. The DMA controller assigns the aircraft to a DMA track that best matches the desired cruise speed of the aircraft and ensures acceptable initial spacing behind the preceding aircraft. The controller issues to the trailing aircraft the identity of the lead aircraft and the spacing interval assignment. The pilot of the trailing aircraft transfers this information to the ATAAS spacing algorithm; in the prototype simulation, this entry is accomplished through the Multifunction Control & Display Unit. Notional versions of the pilot's flight and navigation displays for a typical spacing scenario are shown in Figure 35. Five DMA tracks are shown, and the ownship is positioned on the far left track. The flight crew has selected the aircraft in the front for spacing, as indicated by the green border around that aircraft, and has entered an assigned spacing interval (not shown). The ownship currently has excess spacing with the lead aircraft symbol and may need to accelerate to close the gap (as indicated by the symbol just above the ownship symbol). Once enough time history data has been recorded on the lead aircraft, ATAAS indicates that a Pair-Dependent Speed (PDS) command is available. The PDS speed command is shown on the Primary Flight Display, indicating the recommended faster speed (i.e. 275 kts) to achieve the specified spacing. The pilot has the option of coupling the speed command directly to the autothrottle or manually adjusting speed to match the guidance and monitoring it periodically for changes. This spacing algorithm and procedures for application in approach spacing have been extensively tested and verified in piloted and batch simulations, and in flight [13, 14].
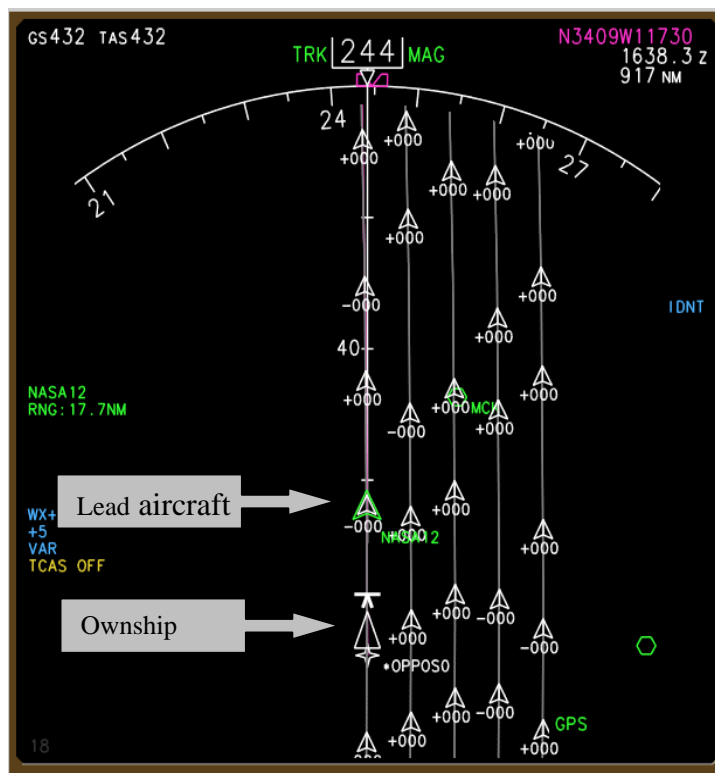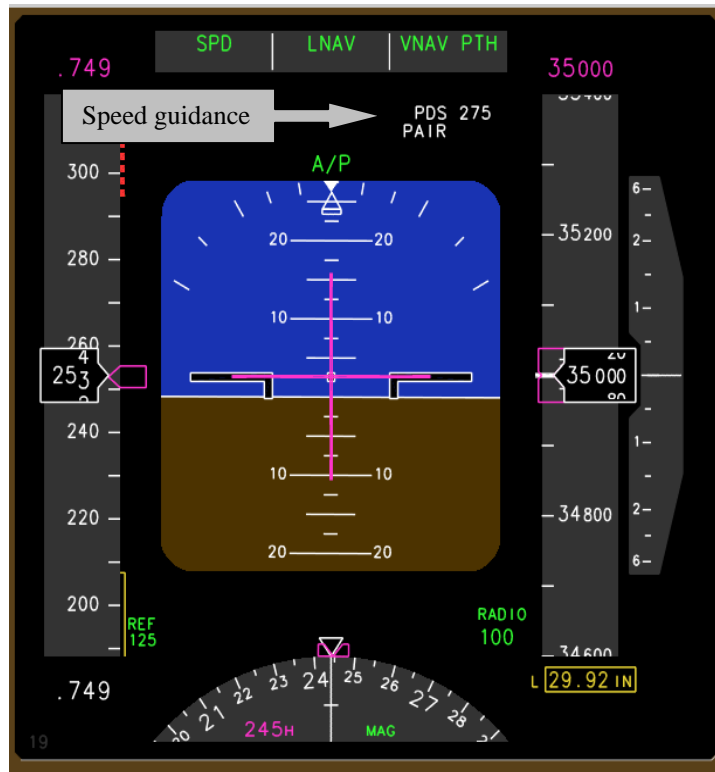
Figure 35. Flight deck displays showing prototype speed guidance and symbology for DMA spacing.

6.2 Prototype Passing Capability for Speed-Independent Tracks

The DMA passing capability requires a prediction that an aircraft will overtake its lead aircraft on the same track. It also requires a track-switching maneuver to be designed that transfers the ownship temporarily onto a passing track and later back to a nominal track. This passing maneuver must be accomplished without losing separation with any DMA traffic, including those that may be currently performing their own passing maneuver. The AOP system was originally designed to perform these kinds of functions without being restricted to an airway system. AOP monitors ownship and traffic trajectories, detects traffic separation conflicts of any geometry (i.e. not just track-based overtakes), and computes new lateral or vertical trajectories to resolve the conflicts. In the DMA implementation of AOP, the conflict detection function was modified to filter out any traffic not on the DMA. This is in accordance with the concept definition, which says the sector controllers must give right-of-way to DMA traffic when controlling non-DMA traffic.

The principal function of AOP modified to support DMA operations is the strategic conflict resolution function. This function employs a genetic algorithm approach to generate candidate resolution trajectories that are free from all conflicts, meet any specified trajectory constraints, and are optimized using a fitness approach [15]. When operated in an open-airspace environment, the solution space for trajectory generation is normally unconstrained, which provides the most flexibility for generating viable solutions to conflict problems. To support the more restrictive multi-track environment, a pattern-based version of the genetic algorithm was developed which limits solutions to specific families of patterns [15]. A pattern fixes certain characteristics but allows parameters within those characteristics to be searched and selected.

The pattern applicable to the DMA is illustrated in Figure 36. This example shows a five-track system consisting of two nominal tracks and three passing tracks. AOP is capable of working with a DMA of any configuration defined by a single reference route, the number of tracks, and the lateral offset (distance left or right) of each track from the reference route. The resolution pattern consists of the following geometric characteristics: (1) the maneuver leg of the current track on which the passing maneuver will be initiated, (2) the passing track to be used, (3) the return track, which could be any nominal track, (4) the maneuver start distance, or the delay before initiating the pass, and (5) the offset length, or the distance spent on the passing track. In the current implementation, the turn-out and turn-back angle was set to a constant 45 degrees, because no discernable advantage was found to making it flexible.

AOP analyzes permutations of these five geometric characteristics to find passing maneuvers that maintain separation from all traffic throughout and beyond the maneuver. The passing maneuver terminates when it reaches the final nominal track (the return track). AOP presents a resolution route only if it predicts that there will be no loss of separation on that route, from the present position (prior to the passing maneuver) to a point T minutes past the end of the maneuver, where T is the ordinary look-ahead time for conflict detection (typically 10 minutes). Therefore AOP searches for conflicting traffic not only on the nominal tracks but also the passing tracks. In the example shown in Figure 36, the entire DMA has a turn point midway through the passing maneuver. Also, the return track is different from the original track. The AOP implementation supports this level of complexity.

The fitness function used for optimizing the maneuver can be designed to consider almost any criteria. In the current implementation, two criteria are used. First, AOP favors maneuvers that pass on an outside passing track over those that use an internal track. The use of internal passing tracks are discouraged because of the increased likelihood that aircraft from other nominal tracks might simultaneously try to use the same passing track, which might require additional coordination procedures or information exchange. Second, AOP minimizes the length of the offset length, that is, the time spent on the passing track. The passing track is intended for temporary use, and routes that minimize its use are considered preferred solutions.
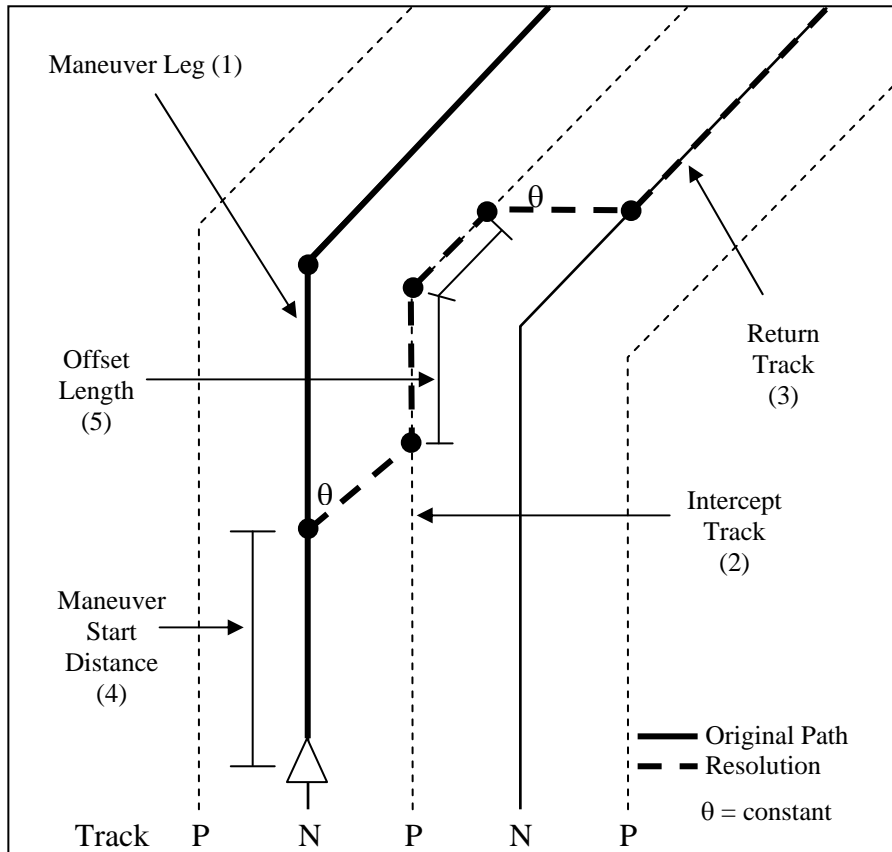
**Figure 36. Pattern-based conflict resolution capability implemented in
AOP for the DMA passing maneuver. Tracks are designated
"nominal" (N) and "passing" (P). Note that the maneuver can end on
any nominal track.**

A sequence of screen shots showing notional displays from the prototype implementation of the passing capability is shown in Figure 37. A five-track configuration is shown, similar to the illustration in Figure 36, and the ownship is located on the left-hand nominal track (second track from left). The entire DMA includes a routing around an upcoming region of convective weather, indicated by the polygon. In the sequence, a traffic conflict is detected by AOP and a passing maneuver is generated and executed. This maneuver has the ownship pass the overtaken aircraft on the center track and then
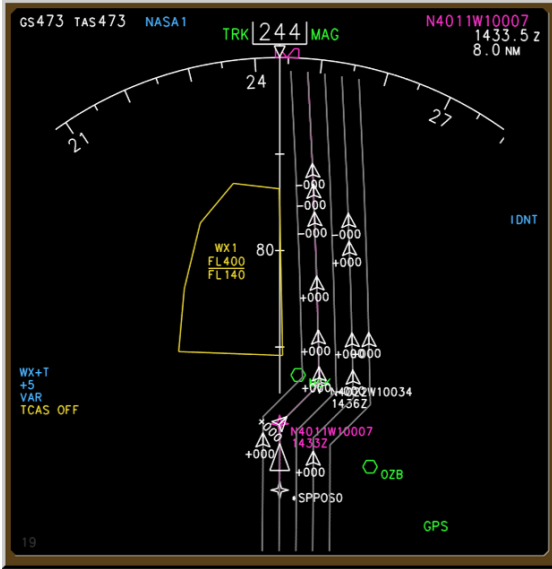
(a) Ownship is the large triangle located on second track from left.
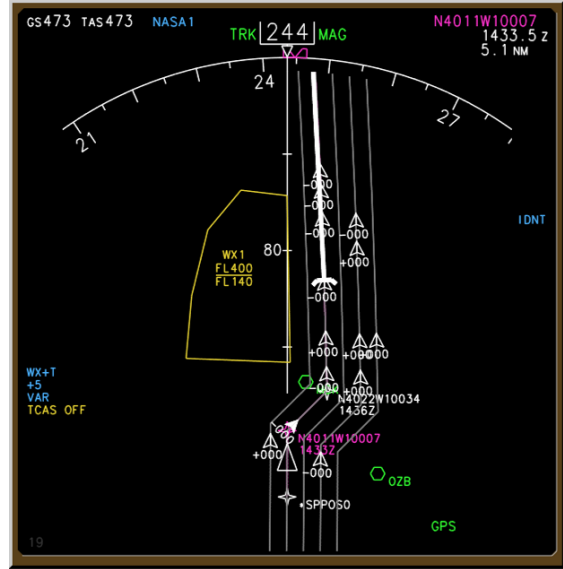
(b) Overtake conflict is indicated with lead aircraft (solid). Bottom of white bar indicates first loss of
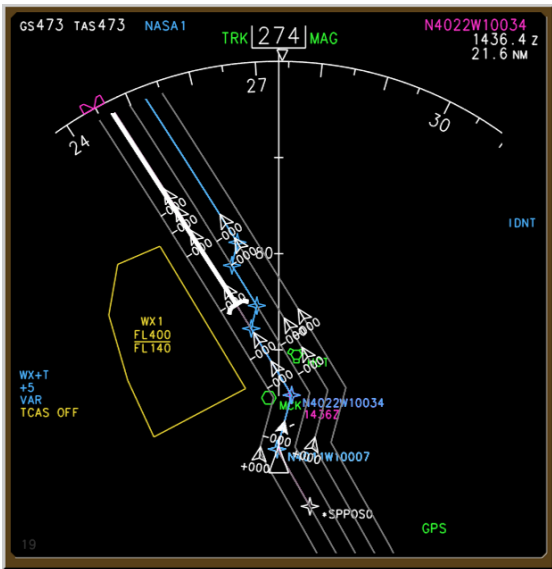
(c) Passing maneuver proposed by AOP is shown in blue. Distance traveled on passing track is
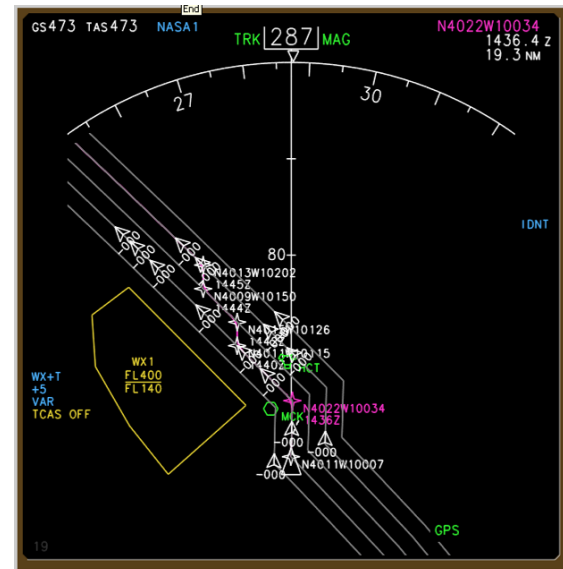
(d) New active route (magenta) includes the passing maneuver, terminating on passing track is

Figure 37. Sequence showing the detection and resolution of a DMA overtake conflict using a passing maneuver generated by AOP. The five-track DMA is shown with a course adjustment around an area of convective weather (polygon).

eventually switch to the other nominal track. AOP determined that the preferred passing maneuver on the left outside track is blocked by another aircraft. Flight crew procedures include requesting a resolution maneuver from the automation system, evaluating its acceptability, and executing the modified route. Detection of the conflict, calculation of the optimal resolution maneuver, and broadcast communication of the new route are all performed by automation. This AOP capability for detecting and resolving conflicts has been extensively tested and verified in piloted and batch simulations for application in the broader domain of full airborne separation environments [16].

6.3 Preliminary Conclusions from Prototyping of DMA Spacing and Passing Capabilities

The high-fidelity prototyping activity was intended to verify the ability to develop the needed airborne technologies to perform the basic DMA procedures. The engineering models were developed that successfully verified these capabilities at the algorithmic level for nominal spacing and passing maneuvers. In addition, the ability to handle the basic interactions with avionics data, flight crew displays and controls, and periodic broadcast surveillance data was verified. These research prototypes are of sufficient readiness for human-in-the-loop testing of basic procedures and scenarios. They illuminated no significant feasibility issues in the development of these airborne capabilities for the DMA concept.

7.0 DMA CONCEPTUAL ANALYSIS

The previous sections of the report defined the DMA concept, analyzed the capacity benefits and city-pair demand, and assessed the characteristics of different track configurations and the airborne technology to operate in them. This section addresses the feasibility of mature-state DMA operations in the NAS by conceptually analyzing eight key concept design attributes that would affect the logistics of conducting DMA operations within the context of existing NAS operations. These attributes were introduced early in the concept description. They include such considerations as where to place DMAs with respect to existing airways, the altitude stratification and its impact on local sector traffic, how to handle DMA intersections and merges, and the requirements and impacts of dynamically rerouting DMAs for weather.

A conceptual analysis of each design attribute is presented below. The analyses include an evaluation of alternative designs to identify the basic strengths and weaknesses of the alternative designs, thereby shedding light on the overall feasibility of the DMA concept. This section does not perform a detailed design of the DMA concept, nor select between the various alternatives. Rather, it is intended to raise critical design issues, discuss the pros and cons of alternative approaches, and identify whether a natural design emerges from the review of these issues. Although it is beyond the scope of this paper to make definitive conclusions on concept feasibility, the results of the conceptual analysis are expected to illuminate the level of complexity involved in designing a viable DMA operational network.

7.1 Relationship to the Existing Airway Structure

The DMA network is envisioned as a mechanism for increasing the capacity of high-demand traffic corridors. For best effectiveness, DMAs would be positioned, activated, and discontinued according to the ebb and flow of traffic demand, both geographically and temporally. The placement relative to the existing airway structure must consider the effect on the impacted sector controller's use of airways for non-DMA traffic and the implications for non-airway traffic management. In addition, the impact of weather on routing must also be considered. Predicted wind and weather patterns are used by dispatchers in optimizing daily flight plans. Significant changes in these patterns from day to day can completely change the location of the high-demand corridors, making a fixed, route-limited multi-track airway system unlikely to be considered useful or cost-effective by the user community. Two design options for a versatile and agile DMA network structure are considered: (1) collocate DMAs with the current airway system, but redefine daily and/or hourly which routings through the airway network will be designated as DMAs; or (2) establish DMAs independent of the current airway system on wind-optimized or great-circle routing.

7.1.1 Airway-collocated Routing

Collocating DMAs with the existing airway structure may be the best choice if near-term implementation is desired, since this structure is currently matured and accepted. It is also consistent with many other well-established factors, such as airspace sectorization, ATC inter-facility procedures, terrain clearance, navigation and communication signal coverage, and air/ground databases. Approximate wind-optimized routing that accommodates weather systems can be achieved as it is today by designating as DMAs the best path along the airway structure. The demand placed on the remaining non-DMA airways would be reduced, and therefore they could remain as single-track operations. Using the existing airway structure also simplifies the communication of daily DMA route decisions, since the airway system is codified and universally known by dispatchers, pilots, and aircraft navigation systems. An example of airway–collocated DMA routing is shown in Figure 38. This DMA routing would support either Eastbound or Westbound flights, depending on the prevailing wind pattern. Flights in the opposite direction would desire a different routing to minimize the effects of headwinds. This factor may reduce the number of flight levels needed for DMA operations, but would also increase the number of DMAs needed to support a given city pair, provided that sufficient traffic demand exists in each direction warranting the DMA.
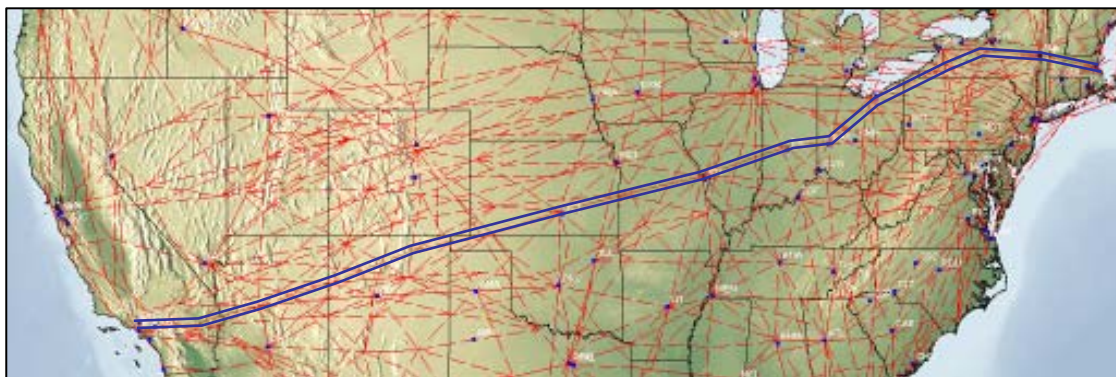
Figure 38. DMA collocated with current airway structure.
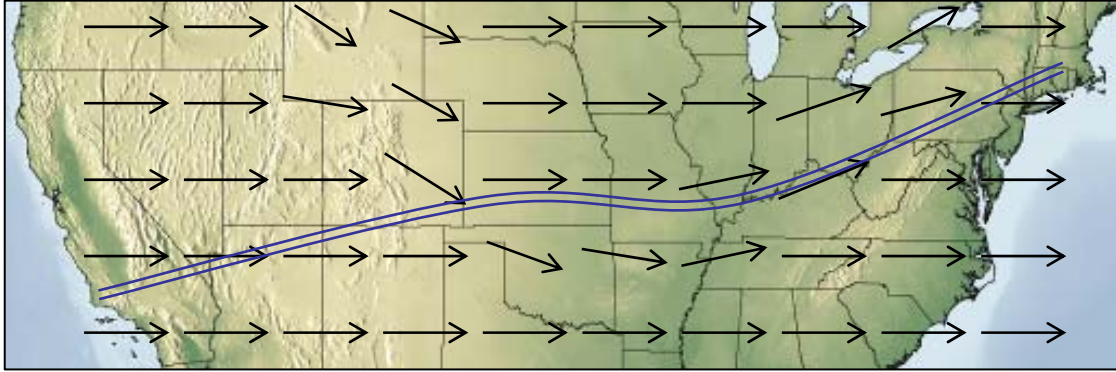
Figure 39. Wind-optimized DMA independent of airway structure.

7.1.2 Airway-independent Routing

The second design option, shown in Figure 39, is more consistent with true route optimization, because it is decoupled from the rigidity of the current airway structure. However, it may only provide a marginal benefit above the first design option, considering that the current airway structure already provides a reasonable number of options for efficient long-distance routing. True route optimization would also have to be sacrificed to stay clear of restricted airspace, which the airway route structure already does. From the viewpoint of sector controllers, the acceptability of airway-independent routing of DMAs would depend on the traffic density of the DMAs passing through their sectors. If DMA traffic density is heavy or highly concentrated, it would represent a significant impediment to non-DMA traffic flows in the sector. In addition, this impediment shifts location daily as the prevailing winds change. Because of these factors, keeping the DMA aligned with the existing airway structure may be preferred. If DMA traffic density is light or highly diffused by altitude, then sector controllers may be better able to manage interactions on a per-conflict basis away from the normal airways. Confirmation would require human-in-the-loop simulation with realistic city-pairs, crossing traffic, and winds.

7.2 Track Configuration

To generate the incentive necessary to attract users to the DMA network, this concept must enable participating aircraft to fly at or near their preferred airspeed for the full length of the DMA even at times of high demand for DMA services. It is expected that demand for DMA services would rise and fall in the course of the day, leading to variable loading on the track system. While low loading may imply very sparse traffic on the tracks, it is essential to analyze DMA operations assuming high demand and local clustering of traffic such as may occur during a heavy departure rush at the originating airport.

Two design options for track configuration, in which limited autonomous airborne authority is exercised, provide the foundation for this user incentive: (1) speed-based tracks and (2) speed-independent tracks accompanied by adjacent passing tracks. The traffic behavior of these two configurations was analyzed as a function of traffic load earlier in the report. In addition, the aircraft capabilities needed to enable these operations were prototyped and discussed. A third design option, a variant of the speed-

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independent tracks design that permits aircraft to remain permanently on the passing tracks was excluded from further analysis because its operational characteristics and performance were considered likely to be bounded by the first two design options. In addition to the design analysis that follows, track configuration was modeled numerically and analyzed for its operational characteristics. Results of this activity are presented in Section 5.0 Track Configuration Modeling and Analysis.

7.2.1 Speed-based Tracks

The multi-track system could be implemented in such a way that each track is designated with a unique nominal airspeed (or more likely, Mach number) that the aircraft will maintain. This design requires a sufficient number of tracks to cover the optimal speeds of the participating fleet while minimizing the deviation of any given aircraft from its own optimal speed. An example of this configuration with five speed-based tracks is shown in Figure 27. The DMA fleet make-up would be a key factor in whether this design option is viable, in that a fleet with a wide speed range (e.g. Mach 0.71 to Mach 0.91) might require many more tracks than one with a narrow speed range (e.g. Mach 0.80 to Mach 0.84). In the latter case, for example, five tracks could be designated Mach 0.80, 0.81, 0.82, 0.83, and 0.84, thus providing each aircraft with the opportunity to fly and maintain within 0.005 Mach of its optimal speed. In the former case, five tracks with evenly spaced Mach number designations of Mach 0.71, 0.76, 0.81, 0.86, and 0.91, could cause aircraft to fly up to an undesirable 0.025 Mach from its optimal speed, and probably more since aircraft at high altitude typically have little speed margin above optimal speed. This negative effect of the wide speed range could be mitigated by (a) tailoring the track speeds to the most common aircraft types in the participating fleet, (b) increasing the total number of tracks, or (c) reducing the total speed range accommodated by the DMA, and therefore the fleet diversity supported by the DMA concept. The speed-based track configuration was used in the analysis of DMA capacity benefits presented earlier. Also presented earlier was an analysis based on low-fidelity modeling to assess the impact on maintaining desired cruise speed as a function of the number of speed-based tracks. Both analyses indicated a 6-track system may be required for a single-altitude DMA. Distributing the 6-track system over multiple flight levels would potentially provide operators with more flexibility in trading optimal speed and optimal flight level.

Flight operations within speed-based DMA tracks would be similar to today's airway operations. Laterally and vertically, all aircraft would follow the assigned DMA track and flight level. Longitudinally, flight speeds are primarily based on the designated track speed but could include an additional autonomous capability in speed management to maintain stability during perturbations. A lead aircraft, i.e., one without a same-track aircraft in front within a reasonable distance, nominally flies the designated Mach number for that track. A following aircraft could simply command the same indicated Mach number, and this would be acceptable under undisturbed conditions. However, to enhance robustness, the proposed limited autonomous capability calls for the in-trail aircraft to dynamically maintain a controller-assigned spacing behind the aircraft in front of it. This spacing could be measured in either distance or time. The result is essentially a train of aircraft. Airborne precision spacing capability has been the subject of research for application in terminal arrival flows[13]. This in-trail spacing capability enables speed changes by the lead aircraft to self-propagate to following aircraft without requiring

explicit communications. A lead aircraft might slow, for example, to penetration speed when encountering unexpected clear-air turbulence. Using this airborne precision spacing capability, all following aircraft automatically slow in turn, without each requiring a specific instruction to do so. The spacing capability could also enable a stream of aircraft to remain in-trail and properly spaced behind a re-routed lead aircraft, which may be one mechanism for a controller to implement DMA re-routes. Such an application was evaluated in flight trials by NASA at Chicago O'Hare Airport [14]. Using in-trail spacing to build large gaps would also benefit the DMA controller by providing a simple mechanism for ensuring a slot exists for a future aircraft anticipated to join the DMA. In this case, the controller would assign a double-wide spacing interval in the stream, which would later be filled by a new aircraft.

7.2.2 Speed-independent Tracks with Passing

An alternative DMA structure that may provide more optimal speed management for participating aircraft is to establish one or more speed-independent tracks for nominal flight and one or more additional tracks designated for temporary passing maneuvers in overtake situations. The simplest version of this structure, one nominal track and one passing track, would provide the speed optimization opportunity but little capacity increase for the track system. This structure is similar to the concept proposed in [3]. For a notable capacity increase, more than one nominal track and one or more passing tracks would be required. For example, two nominal tracks could be accompanied by a single shared passing track between them and/or additional external passing tracks. Figure 28 illustrates a 5-track example. In this design, flight crews would use conflict detection automation to determine whether it is currently overtaking another aircraft on its track, determine whether a passing track is available for use, and autonomously execute the passing maneuver.

Airborne conflict detection and resolution has been the subject of much research in non-airway airspace [15-19]. This same capability can be applied within the structure of multi-track airways to allow aircraft to maintain optimal airspeed to the extent that passing opportunities exist. Alternatively, if the passing track is clear, an autonomous passing maneuver may be implemented to maintain the desired speed. When passing is temporarily not an option because a shared passing track is occupied, the faster aircraft may be required to slow to the lead aircraft's speed until the opportunity to pass appears. Changing speed to generate a passing opportunity is a normal procedure on automobile highways, but would not likely be the preferred option in flight because the user benefit of DMAs is linked to maintaining efficient speed/altitude profile.

Fleet composition may also be an important determinant of the usefulness of a shared passing track. Given that aircraft in high-altitude cruise have limited Mach envelopes, the time and distance covered in the course of a passing maneuver can be considerable, rendering a shared passing lane unavailable for extended durations. This factor was shown in Figure 31 and Figure 32 and discussed in the earlier analysis of track configuration using low-fidelity modeling.

Determining the best initial design of a speed-independent track system is primarily an issue of designing for safety. Two nominal tracks plus a single shared inboard passing track raises issues of coordinated use of the passing track. For autonomous passing

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maneuvers, each aircraft on either track intending to pass must first be able to determine whether an aircraft on the parallel nominal track intends to use the passing track at the same time. Alternatively, two nominal tracks plus two independent, outboard passing tracks require much less coordination or inferring of intent, and therefore will likely be found to be safer or less costly to implement. Including the inboard passing track in addition to the external tracks may sufficiently increase operational flexibility such that its inclusion is warranted, provided it is not the first choice for passing. Implementing more than two nominal tracks in this design might be feasible but also brings additional challenges in that aircraft on inboard tracks would be constrained from any lateral deviations should the need arise (e.g. emergency diversion). Of course, additional tracks also widen the DMA, taking up more airspace from the sector controllers.

7.3 Altitude Stratification of DMAs

An important design issue is the selection of flight levels for the DMAs. Cruise flight level is an important consideration for operational flight efficiency, and any operational concept that depends on the incentive of user benefits must consider it. The optimum flight level varies between aircraft based on performance and aircraft weight, and varies with time for long flights as fuel is burned. It also varies based on direction of flight relative to the prevailing winds, as well as the magnitude of winds. Safety and passenger comfort also frequently play a role, resulting in flight crews seeking altitudes with low turbulence often at the expense of fuel efficiency. In considering the altitude stratification of DMAs, three alternatives are assessed, as shown in Figure 40: (1) one or two flight levels; (2) four to six flight levels; and (3) all 10 to 11 commonly used upper flight levels (i.e. FL300 to FL390).

7.3.1 One or Two Flight Levels

Whether to use one or two flight levels depends upon the predominant traffic flow and the winds. If the DMA is located in a predominantly uni-directional flow, then only one DMA flight level is required corresponding with the flow direction. Uni-directional flows along airways are typically the norm, as aircraft seek to avoid extended flight in significant headwinds. If the flow is bi-directional, then one flight level for each direction would be provided. The former case of uni-directional flow will be used here for discussion.

Of the three alternatives presented here, this may be the only one consistent with collocating DMAs with existing airways. To implement this design alternative would likely involve designating either the most optimal flight level (e.g. best winds) or the most requested flight level for DMA operations. Aircraft must be properly equipped and capable of DMA procedures in order to have access to the DMA flight level. Aircraft at other altitudes will continue to use conventional airway procedures and ATC control. This design alternative could result in a concentration of co-altitude DMA aircraft, which, if placed along the existing route structure, will provide an operational impediment to sector controllers wishing to climb or descend non-DMA aircraft through that flight level. However, the airway would be minimally obstructive to crossing traffic, as many other flight levels would be available under the sector controller's domain. This design alternative may be detrimental to most users for whom the selected DMA flight level is sub-optimal. For long-distance DMAs, the adverse impact increases, because most cross-

	Two FL Design	Six FL Design	All FL Design	
Single-track ——————— Multi-track ≡≡≡≡≡≡≡≡≡				
FL390	————	≡≡≡≡≡≡≡	≡≡≡≡≡≡≡	FL390
FL380	————	≡≡≡≡≡≡≡	≡≡≡≡≡≡≡	FL380
FL370	————	————	≡≡≡≡≡≡≡	FL370
FL360	————	————	≡≡≡≡≡≡≡	FL360
FL350	≡≡≡≡≡≡≡	≡≡≡≡≡≡≡	≡≡≡≡≡≡≡	FL350
FL340	≡≡≡≡≡≡≡	≡≡≡≡≡≡≡	≡≡≡≡≡≡≡	FL340
FL330	————	————	≡≡≡≡≡≡≡	FL330
FL320	————	————	≡≡≡≡≡≡≡	FL320
FL310	————	≡≡≡≡≡≡≡	≡≡≡≡≡≡≡	FL310
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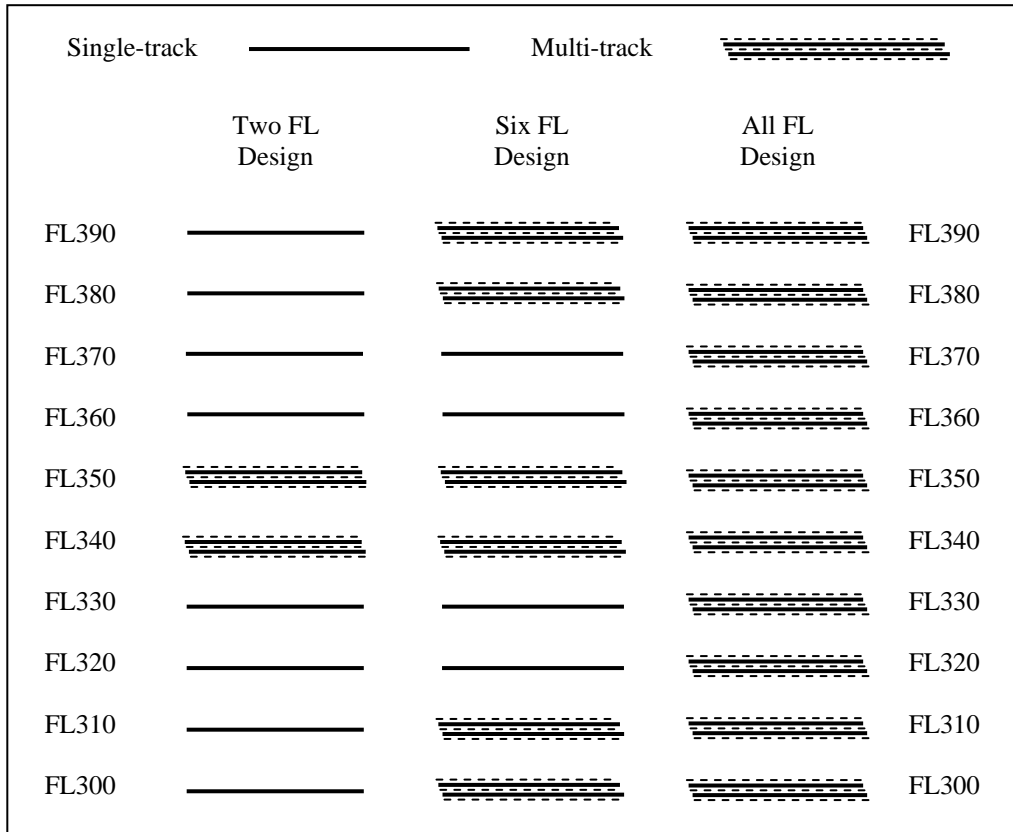
Figure 40. Three alternatives for designating DMA flight levels.

country flights would prefer to climb several times as fuel is burned and the aircraft becomes lighter. Further analysis would be required to determine whether a single flight level would satisfy enough users to warrant this restricted application of DMAs.

7.3.2 Four -to- six Flight Levels

Opening more flight levels to DMA operations improves the user business case in that more aircraft will be able to operate closer to their optimal altitudes, adjusting as needed during the flight. However, the sector controller's use of this airway could effectively be eliminated, given the relatively few flight levels remaining under the controller's domain. Therefore, this alternative would probably require placement of the DMA apart from the current airway structure.

7.3.3 All Commonly Used Upper Flight Levels

The third alternative would again require either relocating the DMA apart from existing airways or converting the airway to exclusive DMA use above a certain flight level. This alternative may provide the best option for the equipped users and for the sector controllers. It enables users to fly at their optimal cruise altitudes regardless of aircraft type, weight, or direction of flight (within the rules of Reduced Vertical Separation Minimums and cardinal altitudes). It enables sector controllers to more easily manage crossing traffic. This benefit occurs because opening up more flight levels to DMA traffic reduces the crowding on any individual DMA flight level. The DMA itself

becomes more "porous", in that more natural gaps form to be used by sector controllers for crossing traffic.

7.4 Separation Between Sector Traffic and DMA Traffic

As mentioned earlier, DMA aircraft operate autonomously within the DMA, but the only active degrees of freedom are speed and track selection. Nominally, no flexibility exists for lateral or vertical changes other than track-change or flight-level-change clearances coordinated through the DMA controller. Since non-DMA aircraft are not authorized to use the DMA, DMA aircraft are procedurally segregated from all non-DMA traffic with the exception of aircraft crossing the DMA. As shown in Figure 41, crossing traffic will be a regular issue for sector controllers. Three design options exist for providing traffic separation in this situation: (1) assign responsibility to the DMA controller; (2) assign responsibility to the DMA aircraft flight crew; and (3) assign responsibility to the sector controller.
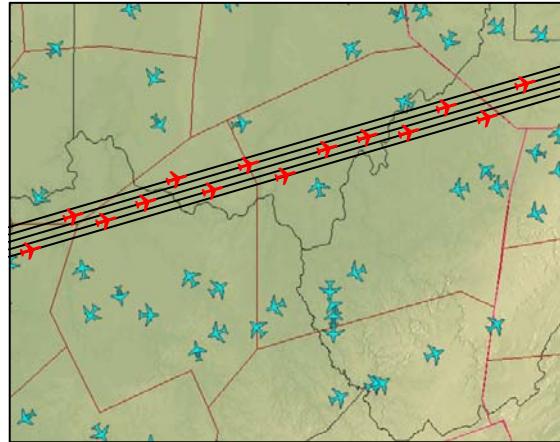
Figure 41. Sector traffic in the vicinity of a DMA, including many that would need to cross the DMA. Blue aircraft are current-day traffic (screen shot from Flight Explorer®). Red aircraft on the DMA were added to illustrate the interaction.

7.4.1 DMA Controller is Responsible for Separation

This option negates a key objective of the DMA concept, which is to increase controller productivity. Giving this new control position the task of coordinating DMA crossings in all sectors along the length of the DMA would require significant tactical workload by the DMA controller. The DMA controller position is already significantly tasked with activities such as DMA flow management, coordination with ATCSCC, coordination with other DMA controllers, coordination with sector controllers for non-crossing issues, and coordination with flight crews for DMA entry, exit, and flow control. This existing workload disqualifies the design option of adding the large task of tactical conflict management for crossing traffic. A possible exception where this option is reconsidered will be discussed later for the specific situation of intersecting DMAs.

7.4.2 DMA Flight Crew is Responsible for Separation

This option could potentially be a viable solution, but its feasibility is significantly limited by the procedural requirement for DMA aircraft to remain on the structured multi-track system and by the equipage of non-DMA aircraft for surveillance. DMA aircraft limited to only speed and/or track changes would have insufficient maneuvering degrees of freedom to ensure successful resolution of all conflicts with crossing traffic. In current operations, when controllers resolve conflicts, they make extensive use of vectoring and altitude changes. In related research, NASA defined and studied an operational concept in which maneuvering flexibility is given to the equipped aircraft to resolve conflicts with ground-controlled aircraft [16]. This maneuvering flexibility is

similar to that used by controllers today to resolve conflicts, including lateral and vertical deviations from the current trajectory. If applied to the DMA concept, DMA aircraft would require the authority to deviate from the track structure as needed for conflict resolutions. While this would create a viable solution to the problem, it would be contrary to the structured nature of the traffic flow. Within the bounds of the multi-track structure, this alternative is not considered feasible.

7.4.3 Sector Controller is Responsible for Separation

This option is not optimal, because it will impose an additional burden on the sector controller to ensure DMA traffic receive right-of-way in all crossing conflict situations. In some situations, it might not even be a feasible solution. The feasibility would depend on the number of conflicts, the degrees of freedom available to the controller for solving them, and the controller's existing workload. For sectors with a significant amount of either DMA traffic or crossing traffic, the challenge for the controller could become significant. With control over only the crossing traffic, the controller would need to identify gaps in the DMA traffic flow and properly time the crossings. Depending on the altitude stratification of the DMA, this may include issuing frequent altitude change clearances. Handling several of these situations at a time would challenge the controller even further. Furthermore, the presence of weather would reduce the controller's maneuvering flexibility. To determine the actual limits of feasibility would require extensive human-in-the-loop simulation. However, since the other two design alternatives were shown to have greater feasibility issues, this design is assumed in the remainder of the conceptual analysis.

7.5 Managing Entry and Exit at Mid-DMA Points

An additional interaction between DMA controllers and sector controllers is for sector traffic that operates out of smaller airports that will be joining or emerging from the DMA, as shown in Figure 42. Such occurrences could be frequent if DMA usage is not restricted to origin and destination airports near the DMA end points. The task then falls to the sector controller to coordinate with the DMA controller for aircraft joining or emerging from the DMA. Two alternatives are considered.
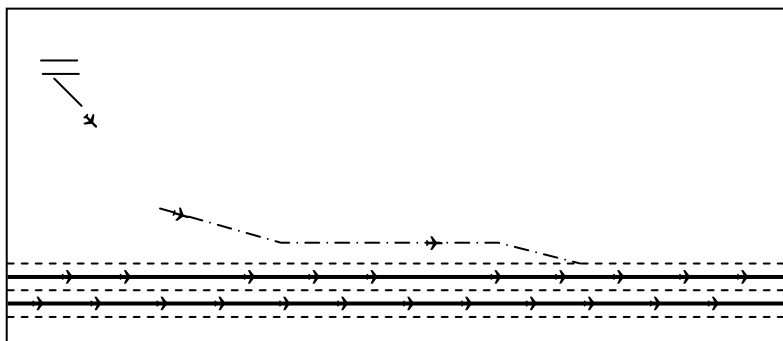
Figure 42. Aircraft entering a DMA from an airport mid-way along the DMA.

7.5.1 Merging Entry /Diverging Exit Managed by the Flight Crew

A merging track, analogous to a highway acceleration lane, could be implemented in which the sector controller delivers the aircraft to the merging track, which is parallel to the DMA. Once on the merging track, the flight crew times the entry into the next visible slot in the DMA traffic flow. The obvious concern with this approach is the situation where no slot becomes available within a suitable time window. Each time this occurs, the sector controller – or the next downstream sector controller – must be ready to re-engage and take back control of the aircraft. Controller workload considerations will probably preclude this option.

7.5.2 Direct Entry / Exit Managed by Controllers

An alternative approach is to time each entry with a prearranged slot in the DMA flow. This approach has significant implications for the TFM role of the DMA controller, because the ability to prearrange slots becomes more complex with each additional entry point along the DMA. The creation of timed slots at various mid-DMA entry points require plenty of advanced notice and careful upstream planning. This approach has precedence in a similar function performed in current operations. Departing aircraft are held on the ground until a release time, coordinated to allow integration of that aircraft into overhead traffic flows, is reached. In the DMA concept, the coordination will be more challenging and the constraints tighter. The difficulty arises because the sector controller cannot alter the DMA flow and the DMA controller may need to use gaps for other purposes, such as to help manage the intersection of two DMAs (discussed in an upcoming section). Sophisticated scheduling automation tools for planning and prearranging slots in the DMA traffic flow would be required to enable this design approach.

7.6 Interaction Between DMA and Terminal Airspace

Since DMAs are likely to be placed in high-demand traffic corridors, DMA primary entrances and exits will likely be located in the vicinity of complex terminal airspace. DMA loading might, therefore, involve merging a primary traffic stream from a major airport with several secondary traffic streams from airports in neighboring airspace. Funneling aircraft to the DMA would be the task of either the sector controller or the DMA controller, depending on the required workload. The task would be to direct aircraft to their assigned track (through vectors and/or feeder airways) and to provide adequate spacing such that the flight crews can assume responsibility for longitudinal separation upon entering the DMA. Timing the transfer of responsibility to the flight crew, i.e. the point at which DMA procedures such as autonomous passing are permissible, must consider how altitude separation from crossing traffic will be provided. Delaying the transfer until after the aircraft is stabilized at cruise altitude would enable procedural altitude separation to be initiated simultaneously, thereby relieving the sector controller of all control tasks for DMA aircraft at one time.

At the destination-end of the DMA, authorization for airborne DMA procedures (e.g. passing) may need to be terminated prior to the top-of-descent point so that controllers can provide altitude separation and spacing management during descent. Again, whether control is transferred to the DMA controller or to the local sector controller will be

dependent on workload. If more than one DMA is feeding into a complex terminal airspace, then coordination of these arriving DMA traffic flows may provide a significant TFM challenge, and the resulting flow constraints could feed back to the origins of the DMAs. This scenario of multiple DMA arrival flows is illustrated in Figure 43. Two approaches to coordinating the multiple traffic streams are discussed.
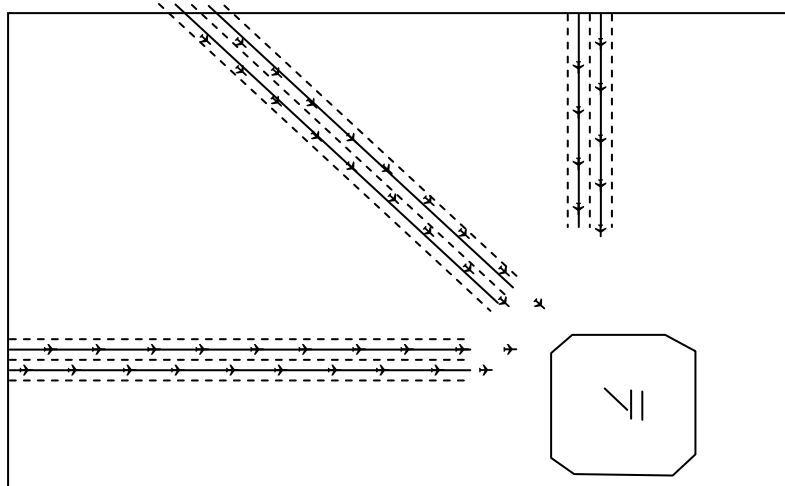
Figure 43. Multiple DMAs interacting at the terminal airspace.

7.6.1 Pre-exit Merging

One coordination approach is for the DMAs to be merged into a single DMA prior to the exit. To accomplish this, slots in both traffic streams must be created in advance of the merge point to enable the traffic streams to be joined or "zippered" together. Current day operations of "miles in trail" (MIT) use a similar technique. For instance, in order merge two traffic streams to create a single traffic stream with 10 MIT spacing, the streams prior to the merge point must each have 20 MIT spacing. In the DMA concept, creating these slots would be a primary TFM function of the DMA controller. Since DMA aircraft exercise the longitudinal degree of freedom within the DMA, slot generation would need to be translated into operational constraints for each aircraft. These may include either an RTA at the merge point or an aircraft-pair relative spacing target to be achieved through airborne surveillance and speed adjustments.

7.6.2 Post-exit Traffic Flow Integration

An additional approach for coordinating multiple DMA traffic streams entering a terminal area would be to terminate DMA procedures before the traffic flow integration. The integration therefore becomes the task of the sector controllers receiving these streams using normal ATC procedures. In this case, care must be taken in the loading of DMAs not to exceed the terminal area capacity. Unchecked, DMA capacity may far exceed terminal airspace capacity, even if exiting aircraft disperse to different airports. Multiple DMAs compound the problem. Extensive TFM load-scheduling of the DMAs will likely play a central role in preventing terminal area saturation and delays that back up into the DMAs. Absorbing newly developed terminal-area delays within existing DMA streams would require the communication of new constraints to all DMA aircraft,

such as maximum permissible speed or increased inter-aircraft spacing. Such constraints may conflict with the user business case for DMA participation built around speed flexibility.

7.7 Intersecting DMAs

As more DMAs are instituted in the NAS, the number of DMA intersections (i.e. where two DMAs cross paths) will increase. As shown in Figure 44, DMA intersections present an operational challenge in that separation must be provided for aircraft at the intersection point. Design options for separating intersecting DMA traffic streams include (1) procedural separation through physical track interweaving; (2) separation provided by the DMA controller; and (3) separation provided by the DMA flight crews.
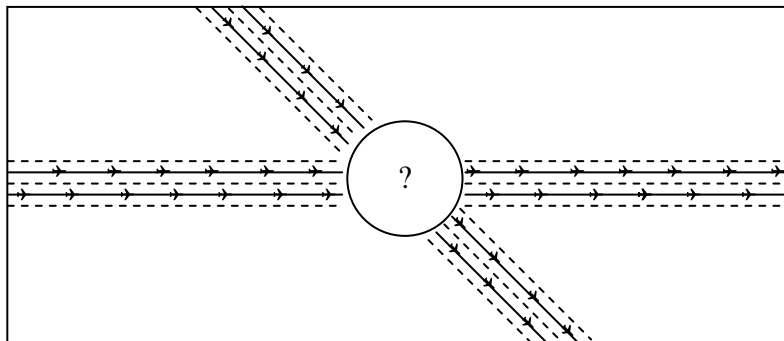
Figure 44. Intersecting DMAs pose a challenge for traffic separation.

7.7.1 Procedural Separation Between Intersecting DMAs

The procedural separation approach is independent of specific aircraft conflicts. As long as all aircraft follow the established published procedure, separation of all traffic is assured. In the case of intersecting DMAs, procedural separation must be implemented through vertical interweaving of tracks such that no two tracks intersect in three-dimensional space. To achieve 1000 ft vertical separation between crossing tracks using procedural separation would require 2000 ft vertical separation within each DMA, an inefficient restriction unlikely to be economical to the user community. The alternative is to reduce the vertical separation standard at DMA intersections to 500 ft. Even if that were possible, the aircraft procedure of repeatedly climbing and descending at intersection locations would likely not be accepted by pilots as reliably safe or economical.

An alternate approach to procedural separation would be to ensure that crossing DMAs always use different flight levels. With this option, it becomes necessary to restrict the number of flight levels used for each DMA (see earlier discussion on altitude stratification of DMAs). Even with this restriction, the intersection airspace would be effectively unavailable to the sector controller and thereby contribute to controller productivity losses.

7.7.2 DMA Controller is Responsible for Separation Between DMAs

Assigning separation responsibility to the DMA controller yields two further alternatives: (a) give the controller authority to vector aircraft as needed to resolve conflicts; and (b) provide separation through intersection crossing-time control.

(a) Authority to vector. The first alternative is akin to transferring control completely back to the DMA controller, because all degrees of maneuvering freedom may be needed by the controller to resolve intersection conflicts. This would require all passing operations to have been completed prior to the transfer point, an infeasible requirement given that passing maneuvers could span great distances (discussed earlier and shown in Figure 32) while intersections may occur frequently. The DMA controller's lateral degree of freedom would also be reduced by the presence of the parallel tracks. In addition, actions of the two DMA controllers (one for each DMA) would require frequent coordination. Simple workload issues preclude this alternative from consideration.

(b) Intersection crossing-time control. The second alternative involves using a time management technique to control aircraft crossing the intersection such that conflicts are prevented. Performing this technique for a single crossing is conceivable, although the same limitation described above applies, i.e. requiring all passing maneuvers to be completed prior to the intersection. Scheduling multiple intersection crossing times for a given aircraft as it proceeds along the DMA could be very difficult to achieve within the limited speed range of the aircraft, particularly at high altitude. Even only a few scheduled crossing times would likely negate the principal user benefit of autonomous speed management.

7.7.3 Flight Crew Is Responsible for Separation Between DMAs

A third design option for managing separation at DMA intersections is to make it an airborne responsibility to be met by flight crews supported with airborne conflict management tools. This approach resolves the human workload issue, because each crossing conflict would have the dedicated attention of two flight crews, rather than the attention of two DMA controllers divided across the coordination of multiple crossings and other DMA tasks. As mentioned earlier, resolving these conflicts would require the authority for the flight crews to maneuver laterally, which effectively balloons the DMA-impacted airspace near all intersections – a potential impact on the sector controller. Depending on the DMA intersection angle, and the potential for DMA aircraft to be solving multiple conflicts, the size of impacted airspace could be significant. Also as mentioned earlier, lateral maneuvering to solve conflicts would be constrained by the presence of parallel tracks, and this constraint could be crucial depending on whether the preferred maneuver is to cross in front of or behind the other aircraft. Airborne responsibility for crossing conflicts would require coordination between the aircraft, but it could be as simple as following a common set of right-of-way rules.

Although this third design option is the most feasible of the options considered here, it remains highly constrained given the requirement of DMA traffic to be procedurally segregated from sector traffic by remaining strictly on the prescribed airway. Removing this constraint and tasking the equipped aircraft to separate from all traffic – both equipped and non-equipped – improves feasibility in that traffic flows will naturally

spread apart to increase flexibility, thereby restoring the essential degrees of freedom for conflict management in both lateral and vertical dimensions.

7.8 Rerouting DMAs for Convective Weather and Congestion

Each day, DMA routing would be established based on the winds and weather patterns expected throughout the day. Considering the dynamic and unpredictable nature of weather systems and the frequent need to re-plan traffic streams accordingly, procedures for re-routing active DMAs must be available. Figure 45 illustrates an example situation where the DMA would need to be rerouted due to convective weather. The DMA concept is intended to enable and facilitate the re-routing of large streams of aircraft by promoting a real-time shared awareness of the DMA route structure by all DMA users. As weather patterns develop during the day, the ATCSCC determines whether one or more DMAs must be re-routed to accommodate the developments. New routing is then generated using automation tool support, and the reroute plan is communicated to the DMA controllers and the impacted sector controllers. A determination is also made regarding which DMA aircraft are to use the new routing and which aircraft have progressed far enough along the DMAs to use the original routing (because the weather system developments will not impact their flight). The new routing and any additional instructions for switching to the new routing must be communicated by the DMA controller to the appropriate aircraft crew. Three options are considered: (1) uplink a customized track trajectory to each aircraft; (2) redirect lead aircraft and instruct following aircraft to use autonomous in-trail spacing to follow; and (3) uplink a single, revised reference track to all affected aircraft (e.g. the revised DMA centerline).
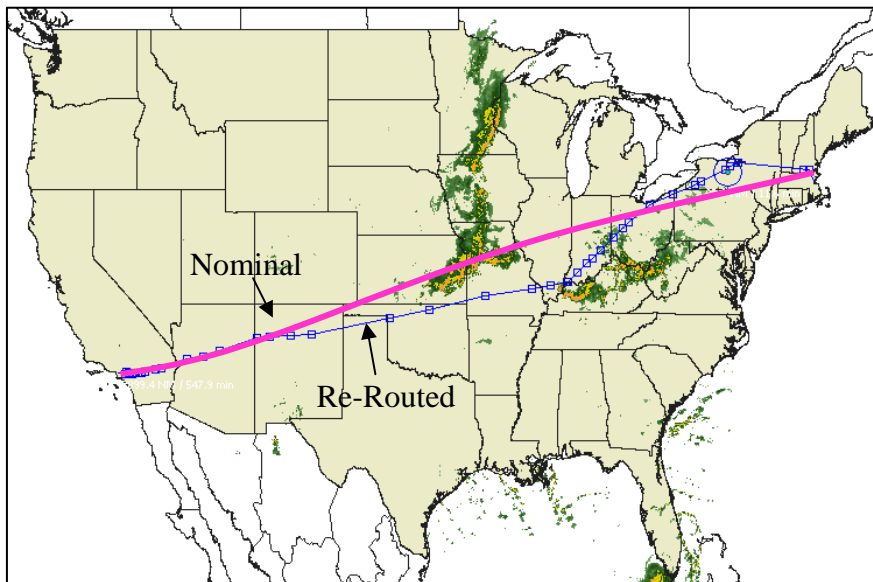

Figure 45. Re-routing DMAs to accommodate weather deviations from the forecast will be commonplace.

7.8.1 Uplink Aircraft-Customized Re-routed Trajectories

The most direct approach is to send each aircraft via data link a new flight plan that contains the entire re-routed track, that is, the subset of the multi-track airway on which they are flying. The flight plan is automatically loaded into the Flight Management System (FMS) as a "mod" route and then executed by the flight crew. Because the route is customized for each aircraft, this method avoids any misinterpretation of what trajectory is to be flown.

This approach has several liabilities. Of significant concern for this design option is the assurance of message receipt by all aircraft and the assurance and timing of execution. A mismatch of execution and/or timing could prove hazardous for DMA aircraft in close proximity. The problem could be compounded if a flight crew rejects their reroute because of a safety concern. For the ground side, the automation system that generates the reroutes will need to be sophisticated enough to manage the circumstances of each individual aircraft, taking into account its present position, its performance limitations, and the FMS data link peculiarities specific to its aircraft type. The ground automation will also need to specify the reroutes with enough precision to ensure that the revised tracks will not inadvertently converge, cross, or violate separation requirements. For the airborne side, this option requires equipage for complete trajectory uplink and FMS auto-load for all participating aircraft. Because only customized routes are received, it limits airborne knowledge of the other track locations within the DMA. For speed-based tracks, this issue may be negligible, since track changes might not be permitted in the concept. For speed-independent tracks with passing, it would be critical to know the location of all tracks. The ground system could uplink all tracks to all aircraft, but data link bandwidth may limit this option.

7.8.2 Follow the Leader

An alternative approach to re-routing DMA traffic streams uses airborne surveillance and in-trail spacing capabilities to create a dependent train of aircraft. In this approach, the DMA controller identifies a lead aircraft in each track for re-routing and either uplinks a new routing or provides vectors, depending on the weather situation. The next aircraft in the track receives instructions to precisely follow the lead aircraft's position history and to maintain a specified spacing behind the lead (e.g. the current spacing prior to the re-route). The remaining aircraft in each track are given similar instructions to space behind the aircraft preceding them.

This approach has less dependence on trajectory-upload data link than the first option and therefore can support operators without this capability. It also supports tactical vectoring of the stream by the DMA controller, although the need for such tactical flexibility has not been determined. This approach also has liabilities. It would likely not be suitable for the speed-independent track configuration because of incompatibility with passing maneuvers. Aircraft navigation relative to position history trails rather than geographically fixed airway segments may be less accurate and therefore not preserve strict track spacing, leading to a potential degradation in safety. Also, this procedure would likely be suitable only for a few aircraft at a time, since weather system passage

may soon shut off the route defined by the lead aircraft's position history.

7.8.3 Uplink a Common Re-routed Reference Track

A third approach is for the ground system to specify a new reference track from which all other tracks can be derived onboard each aircraft using a predefined rule set. For example, the rule set might state that the reference track is the DMA centerline track, and all other tracks are offset by a given number of nautical miles and remain parallel to the reference track. A reference time for the new track system to become effective would also be required to ensure execution coordination among the aircraft.

This approach has several advantages. The rule set would ensure that all DMA aircraft will have a consistent definition of all tracks, and that the tracks will not converge or cross inadvertently. This approach also simplifies the ground automation system, in that re-routing can be performed for the aggregate DMA fleet rather than for each individual aircraft. The data link implementation may be far simpler because actual trajectories are not being constructed, customized, sent, and auto-loaded. In fact, it may be possible to codify the reference track using existing waypoint and airway names, which already exist in navigation systems, thereby potentially reducing the uplink to a text message. These simplifications on the ground and airborne sides could reduce cost relative to the first approach discussed above, although some FMS auto-load capability may still be necessary to receive routing from the onboard automation system that derives the new track from the rule set and the reference trajectory.

7.9 Preliminary Conclusions from Concept Attribute Analysis

From the preceding discussion of the eight concept attributes and the various alternatives that were considered, few clear winners were evident and therefore no principal design of the DMA concept emerges from this analysis. This result is a significant liability, and it presents a critical challenge to the feasibility of developing a DMA concept that is both viable and provides the intended benefits. In general, the complications prohibiting an obvious design arise because a DMA does not operate in isolation, but rather must interact with the remaining air traffic environment in the domestic NAS. Factors such as local-sector crossing traffic, aircraft joining at non-hub entry points, multiple DMAs exiting at terminal areas, and DMA intersections add layers of complexity that must be managed either tactically by controllers and/or pilots in the field or strategically through extensive TFM planning and scheduling of the DMA traffic streams. The complexity is magnified further when considering that dynamic rerouting of DMAs for weather avoidance changes the DMA interactions with the air traffic environment in unpredictable ways. This analysis has shown that an operational concept that accounts for these interdependent factors within the context of current operations is elusive.

Most of the analyzed attributes typically involved a trade-off between user benefits and controller tasking, where user benefits were judged according to the ability for participating aircraft to fly the most efficient routing, the most optimal flight level, and the most unimpeded user-preferred cruise speed without delay to the destination. Many of the alternatives either imposed route, altitude, or flow restrictions that would erode user benefits or involved controller tasking solutions that would reduce controller productivity. Alternatives that gave responsibility to DMA flight crews to manage some

of the interactions described above were considered feasible were it not for the maneuvering restriction of remaining on the DMA track system.

8.0 CONCEPTUAL ANALYSIS OF DMA OPERATIONS AS PROVING GROUND FOR NEW AIRBORNE CAPABILITIES

The previous sections of this report illustrated the complexities and challenges associated with implementing DMAs to increase en-route capacity. This section examines an alternative to system-wide implementation and instead how DMAs might alternatively serve a purpose different from increasing capacity. The new purpose would be to provide a safe, benefits-producing, operational setting as a proving ground in which to evaluate emerging airborne capabilities relevant to future ATM concepts in which the growing consensus holds that aircraft will play a more active role.

However, the precise nature and scope of aircraft's new role has not been established. A common vision of the extent to which ATM functions should be distributed to aircraft must be developed. However, a consistent impediment to developing a common vision is the lack of an operational record on ATM-related capabilities of aircraft. This operational record is needed to validate the value to ATM, the benefits to users, and the safety of operations. As a transitional concept, the DMA may provide an ideal environment to begin establishing this operational record.

Accordingly, this section moves away from the mature-state concept to discuss the benefits of a more limited, near-term, and temporary application of DMA operations. Here, DMAs are evaluated as an interim step in a larger transformation process for ATM, not as an end in itself. Implementation of a few isolated DMAs would avoid many of challenges associated with system-wide implementation discussed earlier in this report. A safe demonstration of the DMA passing maneuver and other select new autonomous airborne capabilities in an operational setting could inspire and accelerate the development of other advanced air/ground ATM applications for NextGen.

8.1 Segregation of Autonomous Aircraft Operations

This section discusses two alternative methods to the DMA concept's segregation of autonomous aircraft operations: regional segregation and altitude segregation. Each method is then compared to the DMA concept (airway segregation) as environments for conducting exploratory evaluations and gaining experience with autonomous aircraft operations.

8.1.1 Regional Segregation

Regional segregation refers to establishing a geographically bounded, three-dimensional region in which autonomous operations may presumably be conducted safely. These regions are typically described as special-use airspace in which only properly equipped aircraft are permitted to operate. They would be located in low traffic density environments away from mainstream traffic demand. The perceptions that traffic density would be sufficiently low and that normal ATC operations would not be affected by this type of segregation suggest that this type of operation is a viable option.

However, two critical issues inhibit effective evaluation of autonomous airborne operations using regional segregation.

The first issue is the inability for effective ground monitoring of operations and retaking of control should problems arise during the evaluation. To a controller, the set of trajectories produced by autonomous maneuvering in segregated airspace would appear to be random and unstructured, which greatly complicates the controller's task of intervening for safety as these new operations are explored. Safely removing an aircraft from the segregated region would be difficult to execute without extensive coordination or taking control of all aircraft.

The second issue is that regional segregation could eliminate the user benefits of autonomous operations if the region itself is located away from high traffic demand. In addition, the bounded geometry offers little possibility for efficiency gains unless implemented over a geographically large area at low-demand times of the day. Therefore, the user community is unlikely to participate in a regionally segregated operational evaluation with revenue aircraft.

8.1.2 Altitude Segregation

Altitude segregation refers to establishing a flight level above which autonomous aircraft operations are permitted. Typically, this threshold is proposed to be very high—e.g., FL400, to ensure traffic density and impact on ATC are low. This approach addresses the second issue of user benefit, because users would be able to self-optimize routing within their established city-pair network of revenue flights, thus gaining benefit while participating in the evaluation. Of course, participation would be limited to aircraft capable of flight at these high altitudes, which may limit the diversity of operators. The problems of ATC monitoring and intervention, however, still exist in altitude segregation, since aircraft trajectories will still be unstructured. The ATC role in operations for which they cannot easily monitor and intervene may inhibit altitude segregation from providing a suitable first venue for exploring autonomous aircraft operations.

8.1.3 Airway Segregation

Using a limited version of the DMA concept to provide airway segregation may provide what the other two segregation approaches lack: the business case for user participation and a benign environment for safety monitoring and intervention by ATC. Segregation is provided by restricting autonomous aircraft operations to the designated airways and limiting the autonomous authority of the flight crew to only spacing and passing control. This single degree of freedom is both valuable to the users and easily monitored and recovered by the controllers. Using established airways at commonly-used flight levels helps provide the business case (provided that desirable airways are selected). For aircraft already intending to use this routing, the flight evaluation provides an opportunity to improve schedule performance and/or reduce operational cost by using airspeed flexibility. ATC concerns regarding monitoring and intervention are also addressed because operations are confined to the airway, and relative velocities of aircraft in overtake situations along an airway are low. Monitoring can be easily performed (or perhaps automated) in this single dimension, and intervention may be as simple and fast as vectoring one aircraft off the airway.

8.2 DMA Design Considerations

To effectively use DMAs for segregating and evaluating autonomous aircraft capabilities, it would be prudent to limit the complexity of the DMA design. For example, the evaluation should incorporate only a small number of geographically separated airways that do not intersect, merge, or otherwise interact. It should be possible to continue normal use of the airway by non-participating aircraft during the flight evaluation. However, non-participating aircraft may still be required to broadcast surveillance data. Alternatively they could be restricted to flight levels at which multi-track operations are not being conducted.

The track structure itself could be simplified variations of either the speed-based tracks or the speed-independent tracks with passing. The speed-based design could be limited to even just two tracks and still provide benefit by separating the traffic into slower and faster aircraft streams. This approach would enable evaluation of the in-trail airborne spacing capability, perhaps the simplest and most benign of all autonomous aircraft capabilities. The speed-independent design could start with a total of two tracks – one for nominal operations and one for passing. This approach again provides benefits to participating operators and can be easily monitored. To limit duration and distance of passing events, passing might be restricted to overtakes of larger speed differential.

An initial flight evaluation using DMA procedures to explore autonomous aircraft capabilities might best be performed using the existing airway system or in an existing multi-track-based environment such as the North Atlantic Oceanic Track System. In addition to these environments being currently codified, well-understood navigation standards, changes to inter-facility agreements would be minimized and perhaps may only have to address passing-in-progress while crossing facility boundaries. This issue arises primarily at Center and Flight Information Region boundaries and can possibly be avoided by confining the DMA passing procedures within a single Center, or as mentioned, by operating in the oceanic environment within a single Flight Information Region.

9.0 SUMMARY AND CONCLUSIONS

An ATM operational concept of dynamic multi-track airways, postulated as a potential means to increase NAS en-route capacity, was explored for feasibility, performance, and benefits. DMA operations would enable properly equipped aircraft to operate autonomously on a high-capacity, multi-track airway structure designed for minimal monitoring and intervention by controllers. Potential benefits to air traffic controllers may include a decrease in tasking associated with DMA aircraft, thereby increasing overall productivity and availability to manage non-DMA traffic. Traffic flow managers may benefit from the DMA traffic structure and procedures that facilitate large-scale re-routing of traffic flows for weather events. Potential benefits to the operators include optimal routing, priority handling, and speed restriction elimination.

A capacity benefits analysis showed that a DMA network has the potential to substantially ease sector congestion. This conclusion was drawn only from the DMA-induced reduction in sector traffic count and did not consider the additional DMA-related duties for the sector controller such as entry/exit coordination and traffic segregation. The use of DMAs may allow two times the demand to be accommodated in sectors near

the DMA than would be possible without the DMA, provided that substantial feasibility issues identified in the report are resolved.

A demand analysis based on 2004 demand and current hub-and-spoke operations indicated that the implementation of the top 25 candidate DMA routes would serve about 10 percent of NAS operations. This assumes use of regional pooling rather than operating DMAs directly between major airports, which would be only about half as effective. About half the benefits achieved from implementing the top 25 DMAs is achieved by implementing the first nine DMAs. These results are not strongly impacted by changing the minimum distance for viable DMA routes from 500 miles to 300 miles, assuming an equal number of routes are implemented in each case. These estimates may change if the nature of demand significantly changes from 2004, for example if population demographics change or if traffic patterns favor more point-to-point operations over hub and spoke operations.

The feasibility and impact of different autonomous procedures were explored through low-fidelity modeling and high-fidelity technology prototyping. The analyses of speed-independent and speed-based track configurations suggest that the speed-independent track configuration may be best utilized in longer, uninterrupted DMA systems, while the speed-based track configuration generally allows greater capacity increases. At lower track-loadings, both designs appear to provide comparably small deviations from optimal speeds for operators. The high-fidelity prototyping of the airborne spacing and passing capabilities relevant to DMA operations verified that operational implementation of these capabilities for this application is technically achievable. Extensive human-in-the-loop and batch evaluations of these capabilities for this particular application would be required to ensure all feasibility issues are resolved and performance is understood. The research prototype capabilities are suitable to support part-task testing.

A conceptual analysis across eight key concept design attributes indicated that implementation of a NAS-wide DMA concept, integrated with current-day operations, involves a significant degree of complexity such that feasibility of the DMA concept has not been established. The complexity is caused not so much by operations within the DMA, such as autonomous passing, but by interactions between DMA traffic flows and with external influences. Examples include intersecting DMA traffic flows, non-DMA sector operations, and flow interactions with terminal airspace. The role of the DMA controller, a new position in this concept, would be both extensive and intensive, given the tasks of coordinating between DMA aircraft, sector controllers, other DMA controllers, and ATCSCC traffic flow managers. The most feasible role would be that of the DMA aircraft flight crew. Their responsibilities are relatively contained and their degrees of freedom well defined. The automation system needed to support their operation would not be difficult to develop, and in fact a research prototype of the basic spacing and passing functions was developed and described in this report. Although no attempt was made to prototype the ground automation system, it will likely be prohibitively complex and costly to develop. The complexity centers on the challenges of integrated TFM that considers terminal arrival flow rates, interactions between intersecting and merging DMAs, and dynamic re-routing for weather.

A limited, transitional application of the DMA concept was briefly assessed in which the DMA supplies a flight evaluation proving ground to explore limited autonomous aircraft

operations. The DMA was found to provide a unique "airway segregation" environment, with better characteristics for safety monitoring and for attracting operational users than either regional or altitude segregation.

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GLOSSARY

4D	four dimensional
ADS-B	Automatic Dependent Surveillance Broadcast
AOP	Autonomous Operations Planner
ASAS	Airborne Separation Assistance System
ASM	available seat mile
ATAAS	Advanced Terminal Area Approach Spacing
ATCSCC	Air Traffic Control System Command Center
ATM	air traffic management
ATOL	Air Traffic Operations Lab
ATOS	Airspace and Traffic Operations Simulation
CLE	Cleveland Hopkins International Airport
CONUS	conterminous United States
CPDLC	control pilot data link communications
DEN	Denver International Airport
DMA	Dynamic Multi-track Airways
ETMS	Enhanced Traffic Management System
EWR	Newark Liberty International Airport
FAA	Federal Aviation Administration
FL	flight level
FMS	flight management system
ft	feet
hr	hour
JPDO	Joint Planning and Development Office
kts	nautical miles per hour
LAX	Los Angeles International Airport
MIT	miles in trail
NAS	National Airspace System
nmi	nautical miles
OAG	Official Airline Guide
ORD	Chicago O'Hare International Airport
ownship	In training and simulation technology, ownship is a vehicle or platform being simulated (e.g., aircraft). In this report, ownship refers to the point of view of the subject aircraft.
PDS	pair-dependent speed
PIT	Pittsburgh International Airport
PHL	Philadelphia International Airport
RNAV	Area Navigation
RNP	Required Navigation Performance
RTA	required time of arrival
s	seconds
SFO	San Francisco International Airport
smi	statute miles
TAF	Terminal Area Forecast
TFM	Traffic flow management
TSAM	Transportation Systems Analysis Model
VLJ	very light jet

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14. ABSTRACT

The Dynamic Multi-track Airways (DMA) Concept proposes a network of high-altitude airways constructed of multiple, closely spaced, parallel tracks designed to increase en-route capacity in high-demand airspace corridors. Aircraft authority within the DMA includes spacing and/or separation from other DMA aircraft. The DMA controller coordinates entry and exit, adjusts routing to account for predicted weather and wind patterns, and re-routes DMAs to accommodate unpredicted weather changes. This report defines the concept, explores its feasibility and performance, and identifies potential benefits. The report also discusses (a) modeling of a single DMA to assess capacity and impact on regional sectors; (b) a demand analysis to determine likely city-pair candidates and expected demand fraction for a nationwide DMA network; (c) analysis of two track configurations for their operational characteristics; (d) software-prototype airborne DMA capabilities; (e) a feasibility analysis of key attributes in the concept design; and (f) a near-term, transitional application of the DMA concept as a proving ground for new airborne technologies. The analysis indicates that the operational feasibility of a national DMA network faces significant challenges, especially for interactions between DMAs and between DMA and non-DMA traffic. Provided these issues are resolved, sectors near DMAs could experience significant local capacity benefits.

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