Integration of Traffic Flow Management Decisions

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Abstract

The goal of traffic flow management in the national airspace system is to maintain efficient flow of air traffic without adversely impacting air traffic controllers' workload. It is shown in this paper that the air traffic service provider achieves this goal through a three-step process. In the first step, traffic flow management actions like Playbook and coded departure routes are used to reroute groups of aircraft flying in the same geographical neighborhood around flow-constrained areas. The rerouting process achieves the purpose of keeping traffic away from the flow-constrained areas but sometimes in the process creates congestion and bottlenecks in other regions of the airspace. To prevent this congestion, an additional layer of control is imposed on this traffic flow in the second step by temporal traffic decisions, such as miles-in-trail restrictions, which control the density of the flows along fixed paths. The aircraft comply with the miles-in-trail restriction by altering their speed, or by introducing a delay via flight path stretching or by airborne holding. In a third step, a few airborne aircraft may be locally rerouted around congested areas, while leaving other aircraft on their filed routes. The three-step hierarchical integration method is illustrated by an example that uses the West Watertown Playbook route along with a miles-in-trail restriction at Aberdeen VORTAC to reduce the demand on Sector 16 in Minneapolis Center. Aircraft that are already airborne are locally rerouted around Sector 16 to lower the traffic volume to within acceptable capacity limits. The results obtained from this example demonstrate that the hierarchical method is able to reduce the sector demand to within the capacity thresholds of the Sector.

Introduction

In the current national airspace system (NAS), a distributed, hierarchical process is used for traffic flow management (TFM). At the top level, the air traffic control system command center (ATCSCC) uses computer-based forecasting tools such as the Enhanced Traffic Management System (ETMS) to forecast traffic over a 3- to 24-hour time horizon [1]. Based on the expected weather conditions and demand in the sectors and airports, the ATCSCC specifies traffic management initiatives such as Playbook routes (PRs), ground-stops (GSs) and ground-delay programs (GDPs) [2]. Local adjustments to these initiatives are then proposed by the traffic management units (TMUs) in the air route traffic control centers (ARTCCs). These initiatives are realized in terms of miles-in-trail (MIT) or minutes-in-trail (MINIT) restrictions.

Traffic flow management is by definition a complex task. It relies on a distributed set of decision makers, each having somewhat disparate goals and information, to control a system characterized by high levels of uncertainty using imprecise procedures. The ATCSCC is interested in overall flow, the TMU at the ARTCC is interested in the local flow and the airline operations center (AOC) is interested in schedule adherence. Each party's decisions are complicated by the inherent uncertainty of the information used to forecast aircraft trajectories and the inability to model the differing objectives and reactions of the other decision makers in a dynamic situation. For example, the traffic forecast does not account for weather uncertainties, departure uncertainties, and potential airline responses. Traffic management initiatives such as Playbook routes, ground-stops, ground-delays and MIT restrictions are

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based on attempts at solving particular problems. For example, Playbook routes are used for circumventing severe weather, ground-stops and ground-delays are used for controlling demand at the airports, and MITs are employed for controlling workload in the sectors. The various TFM actions are imposed independently based on experience, and the interaction between different actions may not always be accounted for while making the decisions. The overall capacity of the NAS may be improved by developing methods to integrate and optimize the various traffic management initiatives such as Playbook routes, GS, GDP and MIT to result in a single cohesive plan that improves traffic throughput, reduces delay, reduces congestion, and provides flexibility to the aircraft operators.

A three-step hierarchical method is developed in this paper with the objective of integrating TFM decisions. In the first step, Playbook and coded departure routes are used for rerouting groups of aircraft around flow-constrained areas (FCAs). Regions of airspace that are impacted by weather, used for training or military operations, or congested due to large volume of traffic are classified as FCAs. Since the rerouting process alters the usual flow of traffic, regions of congestion sometimes are created along the Playbook route. Temporal flow controls such as miles-in-trail restrictions, ground stop and ground delay programs are used in the second step to control the timing of the aircraft on fixed paths. The combination of spatial rerouting with temporal miles-in-trail, ground stop and ground delay programs are useful in preventing bottlenecks at future time instants. In many cases, miles-in-trail or other temporal changes in the traffic flow may be inadequate. The third step of the hierarchical process is to reroute a few aircraft around the locally congested area.

The three-step hierarchical integration method was implemented in the Future ATM Concept Evaluation Tool (FACET) [2], which provides a computational test-bed for evaluating air traffic management concepts. The steps of the algorithm are illustrated by an example that uses the West Watertown Playbook route along with a miles-in-trail restriction at the Aberdeen VORTAC (ABR) to prevent the capacity of Sector 16 in Minneapolis Center (ZMP) from being exceeded. Aircraft that are already airborne are locally rerouted around Sector 16 to lower the traffic volume to within acceptable capacity limits. While performing the local reroute, the sectors surrounding Sector 16 are also monitored to ensure that their capacities are not exceeded.

The rest of the paper is organized as follows. The second section describes FACET. The third section describes the routing process using Playbook routes. This section also discusses the use of temporal controls such as MIT restrictions to control traffic congestion resulting from the routing process. The last step of the hierarchical technique, which uses local rerouting, is presented in the fourth section. Results discussed in the fifth section show that the integrated technique is able to keep aircraft out of the FCAs without overloading sectors. Finally, the paper is concluded in the sixth section.

Modeling Using FACET

The Future ATM Concepts Evaluation Tool (FACET) is an air traffic management decision support tool being developed at the NASA Ames Research Center. FACET provides an environment for modeling, developing and evaluating system-wide airspace operations over the United States prior to operational deployment. FACET can be broadly described in terms of three subsystems: 1) database, 2) algorithms and 3) graphical user interface (GUI) as follows.

The geometry database in FACET contains the structure of the airspace over the United States in terms of regions controlled by the 20 air route traffic control centers (ARTCCs). The horizontal boundaries of the ARTCCs and the horizontal and vertical boundaries of all low-altitude, high-altitude and super-high-altitude sectors within each ARTCC are included in the database. Victor airways and jet routes are represented in terms of the fixes (navigation aids and airway intersections) that define them. Position data for each fix is available within the database. The database also contains locations of over thirteen thousand U.S. airports.

The aircraft performance database in FACET contains performance models for 60 different aircraft types. It also contains an equivalence list that maps the 500+ aircraft types recognized by the Federal Aviation Administration (FAA) to these 60 performance models. The performance model for an aircraft is provided as airspeed and altitude-rate tables, derived from the calibrated airspeed (CAS) and Mach schedules, as a function of altitude during the climb and descent phases of flight. For cruise phase (zero altitude-rate), the airspeed is tabulated as a function of cruise altitudes and aircraft type.

The flight database is updated based on the schedule, flight plan, and track data, which are received from the ETMS every minute. The schedule data consist of the flight identification, estimated time of departure and actual departure time if the flight has already departed. The flight plan data include aircraft identification, type of aircraft and the route of flight. The track data consist of the aircraft identification and the position of aircraft specified in terms of latitude, longitude and altitude. An aircraft identification tag allows the schedule, flight plan and track data to be tied to the same aircraft within the database. As aircraft land, they are removed from the database.

The core of FACET is the algorithms that ingest data from the databases and provide the decision support data to be displayed on the GUI. Route parsing and trajectory prediction algorithms are the important ones in this category. The route parsing algorithm converts the flight plan provided by the flight database into a sequence of waypoints specified in terms of latitude-longitude pairs. The flight plan route is available from the flight database in terms of the names of fixes, fix-radial-distance (FRD) and coordinates of points along the route. The route parser uses the fix name to access position data from the geometry database. It is able to convert the FRD into a position because FRD is specified in terms of distance and bearing with respect to a named fix, whose position it knows via the geometry database.

FACET models 4D aircraft trajectories using spherical-earth kinematic equations. The trajectory prediction algorithm forecasts the future position of the aircraft along the planned route by propagating the equations of motion forward in time driven by the heading, airspeed and altitude-rate dynamics. These dynamics are a function of the climb, cruise and descent data obtained from the aircraft performance database. Initial conditions such as, the scheduled time of departure and track position for trajectory prediction are obtained from the flight database. For a detailed description of the trajectory modeling process, see [2]. The trajectory modeling capability provides FACET with the ability to forecast traffic within sectors and at fixes and airports being monitored, which makes decision support possible. Constraints such as reroutes, MIT restrictions at fixes and GDP at airports can be included in the trajectory prediction process to evaluate the impact of flow management initiatives.

The control and display of all information in FACET is achieved through a menu-driven GUI. FACET utilizes oblique stereographic projection for displaying airspace features and air traffic on the GUI. Figure 1 is a sample of the FACET GUI, which shows the boundaries of the Minneapolis and Chicago ARTCCs, their high-altitude sectors and the traffic.

FACET algorithms are implemented using the C programming language and the GUI is implemented using the Java programming language. The dual programming language architecture has resulted in efficient computation and platform independence.

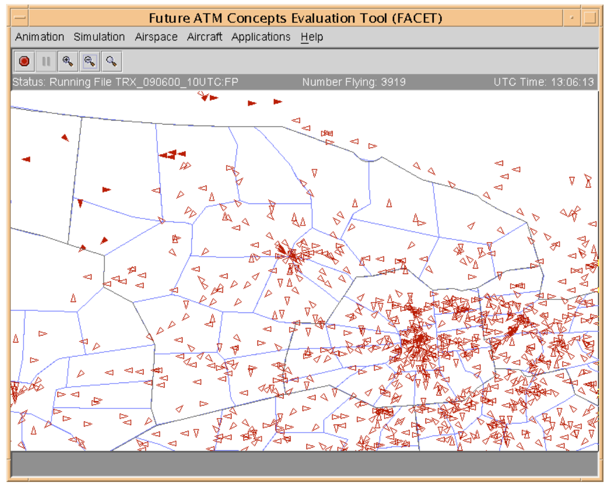

Figure 1. FACET display of traffic within the Minneapolis and Chicago ARTCCs.

Rerouting Traffic Flows Using Playbook Routes

The first step of the hierarchical method consists of selecting routes from the National Playbook to reroute aircraft around regions of severe weather.

The National Playbook is a compendium of standardized alternative routes intended to avoid specific regions of airspace that are commonly impacted by severe weather during certain times of the year, based on historically validated data. Playbook also contains alternative routes for circumventing closed airway segments, non-operational navaids, and airports that are impacted by weather or runway closures [4].

One of the planning templates, known as West Watertown, is provided in the Playbook for rerouting eastbound traffic through the Minneapolis ARTCC when a FCA blocks a large portion of airspace in the Midwest. Figure 2 shows the West Watertown Playbook on the FACET display. The large rectangular region in the southern portion of the Minneapolis

ARTCC in this figure marks a predicted severe weather region. The routes represented with a solid line in this figure represent alternative routes for aircraft originating on the West Coast and travelling to select East Coast destinations, such as BOS, LGA and IAD. An example of a flight that is impacted by the West Watertown route, is illustrated in Figure 3. As shown in the figure, United Flight 180 (UAL180) is scheduled to travel from Los Angeles International Airport (LAX) to Logan International Airport (BOS) on the following route:
LAX./.BCE.J100.EKR.CYS.J148.MCW.J16.BAE..FNT..BUF.J16.ALB.GDM2.BOS (dashed line). From this figure, it can be observed that this route passes directly through the severe weather region. After rerouting UAL180 according to the West Watertown route, the resulting flight plan is specified as: LAX./.BCE.J100.EKR.MBW.RAP.J158.ABR.J70.GEP.J106.GRB.J522.ASP.YEE.ART.ENE.SCUPP.SCUPP2.BOS (solid line). Observe from Figure 3 that the new route avoids the severe weather region entirely.

Visual examination of the West Watertown routes in Figure 2 shows that the routes from Helena (HLN), Sacramento (SAC) and Bryce Canyon (BCE) merge into a single route at ABR. These merges may cause bottlenecks due to traffic volume. This hypothesis was found to be true for the traffic through Sector 16 of the Minneapolis ARTCC, which was impacted by the West Watertown Playbook routes. Peak traffic counts through this sector are discussed in the Results Section. Figures 2 and 3 illustrate the first step of the hierarchical method, which is tailored towards the objective of redirecting traffic around flow-constrained regions.

In-Trail Restrictions to Reduce Traffic Flow Volume

By redirecting and merging the usual flows of traffic in a region to avoid a FCA, the Playbook-based rerouting process often causes congestion in those sectors through which traffic is diverted. In the current air traffic management system, historically validated MIT restrictions are routinely used to mitigate this sort of congestion. Application of these restrictions forms the second step of the technique. In the Results section, a traffic scenario is used to illustrate the effects of using the West Watertown route along with MIT restrictions to control the traffic volume to within acceptable limits.

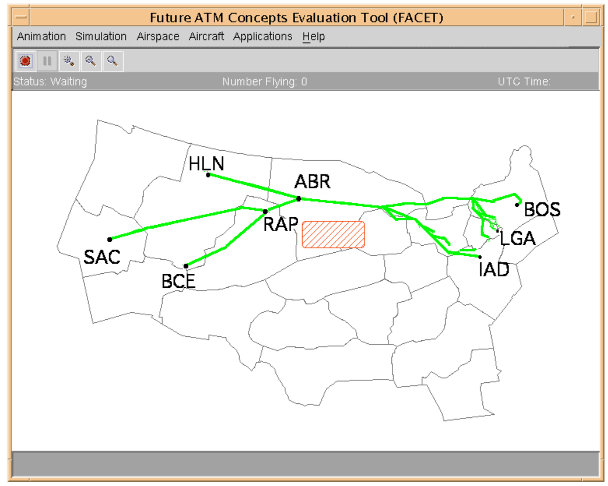

Figure 2. West Watertown routes on FACET display. A potential region of severe weather is represented by the shaded red polygon.

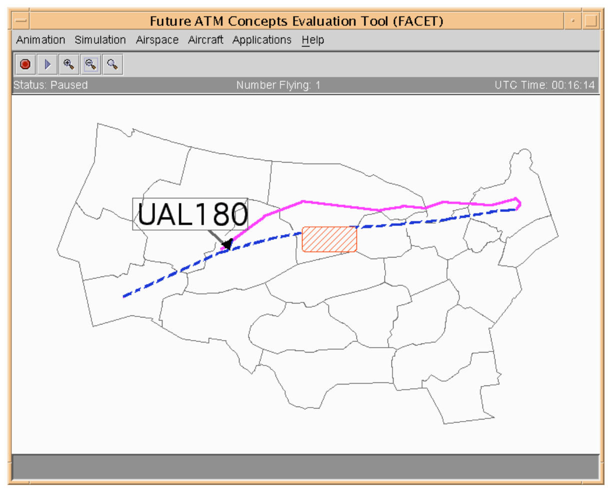

Figure 3. Nominal (dashed blue line) and Playbook route (solid magenta line) for UAL180.

Local Rerouting to Reduce Traffic Flow Volume

To control en-route congestion, traffic management initiatives such as reroutes, ground delay programs and miles-in-trail (MIT) restrictions can be used. Of these initiatives, only MIT restrictions and rerouting can be used to prevent congestion for airborne traffic. Since an MIT restriction is applied to an entire stream of aircraft, it lacks the precision that is needed for minor adjustments. A local rerouting procedure that allows a few aircraft to circumvent the congested areas is much more desirable, because it builds on the previous solution and obviates the need for a more severe MIT restriction.

This section provides an overview of an algorithm that is implemented in FACET to reroute aircraft locally around flow-constrained areas. Within the context of this paper, a flow-constrained area is defined to be a sector whose capacity is exceeded. Sector capacity is defined in terms of the peak traffic through the sector in a 15-minute time interval [1]. FACET is used to forecast traffic counts in the sectors, assuming that the Playbook routes and MIT restrictions are in place. Sectors whose capacities are predicted to be exceeded are identified as flow-constrained areas. All aircraft whose planned routes pass through these regions are flagged as candidates for local rerouting and added to a queue. The position of each aircraft in the queue is determined by the sector entry time. Aircraft are released from the queue in a first-in-first-out order. Those aircraft that are predicted to cause the sector capacity to be exceeded and have not been previously impacted by a Playbook reroute or a MIT restriction are locally rerouted. All other aircraft fly along their nominal routes. This is but one of many possible ways to select aircraft for rerouting. The algorithm will be refined in the future to select aircraft for rerouting in a more fair and equitable manner. A considerable body of work exists within the Collaborative Decision Making (CDM) community, which examines the equitability of selecting aircraft impacted by TFM restrictions [5].

The local rerouting algorithm used in this study is designed to minimize the number of auxiliary waypoints (or bends in a piece-wise linear trajectory) required to avoid the FCA. The details of the local rerouting algorithm are provided in Appendix A. The flexibility of this algorithm lies in the fact that there are an infinite number of lateral routes can be constructed for avoiding the polygon defining the FCA. This fact makes it possible to use alternative routes that prevent sector capacity thresholds from being exceeded. For example, if the sector on one side of the FCA is capacity-limited, the route from the opposite side may be usable. Also, as sector capacities are reached, the FCA is expanded to include the impacted sectors and routes are constructed to circumvent these newly expanded FCAs.

A sample route generated from the local rerouting algorithm is shown in Figure 4. A portion of the nominal route for AAL197, flying from Boston to San Francisco is shown as a dashed line in this figure. The rerouted path suggested by the algorithm to avoid Sector 16 of Minneapolis ARTCC is shown via a solid line.

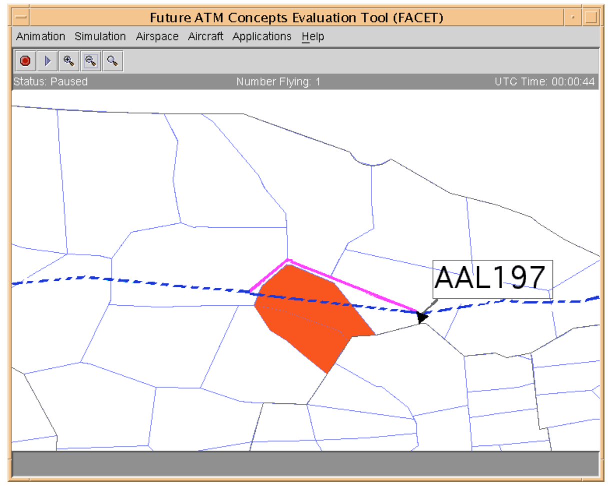

Figure 4. AAL197 is routed around the congested Sector 16 in the Minneapolis ARTCC.

Results

To evaluate the potential of integrating the various traffic management initiatives using the three-step hierarchical method, discussed in this paper, real air traffic data for a 24-hour period were collected using the ETMS system. The data were recorded on September 6th, 2000. The origin, destination and flight plans (including amendments) of the individual flights were used along with other data (aircraft performance and airspace structure) in FACET to forecast the traffic demand. The traffic data were then used to compute the peak traffic through the sectors in five-minute intervals.

Figure 5 shows the peak traffic through Sectors 16 and 17 of the Minneapolis ARTCC (ZMP) for the nominal scenario, e.g. without rerouting or metering restrictions. In Figure 5, the row labeled "Cap" contains the monitor alert parameter (MAP) value for each of the sectors [1]. Observe that the traffic demand values are below the MAP value except in the time-bin 00:10 for Sector 16. The highlighted demand value of 19 aircraft for the time-bin 00:10 indicates that the sector capacity of 18 aircraft will be exceed if the entry times or routes of inbound airborne aircraft and those that are currently on the ground but scheduled to arrive in the future are not altered.

Table 1 shows the peak traffic counts for the nominal traffic condition together with those obtained with Playbook rerouting, metering and local rerouting. The first column of Table 1 shows the time intervals. Column [A] lists the peak traffic counts through Sector 16 of the Minneapolis ARTCC for the nominal case. The "+" sign appended to the traffic count indicates the time segments for which FACET projects that sector capacity will be exceeded: the "-" sign indicates the time intervals for which FACET projects that traffic demand will be below the sector capacity. Letter *A* is appended to indicate that the airborne aircraft alone will exceed the capacity (i.e., a ground stop or ground delay program will not solve the problem). The letter *G* indicates that the combined volume of currently airborne flights and proposed departures will exceed the capacity (i.e., a ground stop or ground delay program could ameliorate the problem).

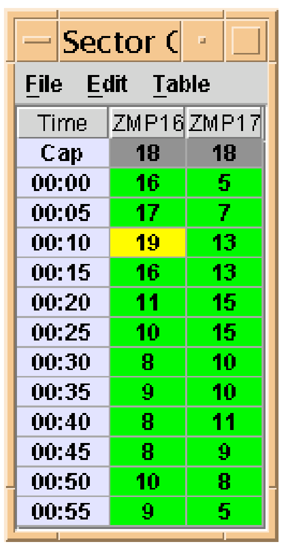

Figure 5. FACET display of peak traffic counts in Sectors 16 and 17 of the Minneapolis ARTCC.

The impact of rerouting traffic using West Watertown is summarized in column [B] of Table 1. Observe by comparing columns [A] and [B] that the rerouting increases the demand, such that the MAP value is exceeded in two additional time periods.

Column [C] summarizes the results when MIT restrictions are imposed. By applying a 20 MIT restriction at ABR for eastbound traffic, FACET forecasts that sector overload will be reduced significantly.

To reduce the predicted congestion occurring in the 00:10 minute time bin after applying the MIT restriction, the local rerouting algorithm described previously in the fourth section of this paper is used to reroute two additional aircraft. The result of this local reroute can be seen in column [D] of Table 1. Although rerouting of a single aircraft was advised by FACET, two aircraft were rerouted simply to demonstrate the use of the local rerouting algorithm. The results in the table are shown as time histories in Figure 6.

Table 1. Peak traffic counts using the hierarchical method. [A] Baseline calculations, [B] Playbook Reroute, [C] Playbook+MIT, [D] Playbook+MIT+Local Reroute

Time	[A]	[B]	[C]	[D]
00:00	16-	17-	16-	16-
00:05	17-	19 +A	16-	16-
00:10	19+G	20 +G	18+G	16-
00:15	16-	18 +G	16-	14-
00:20	11-	11-	11-	9-
00:25	10-	10-	10-	11-
00:30	8-	11-	11-	11-
00:35	9-	14-	15-	15-
00:40	8-	13-	13-	13-
00:45	8-	14-	11-	11-
00:50	10-	14-	16-	16-
00:55	9-	12-	13-	13-

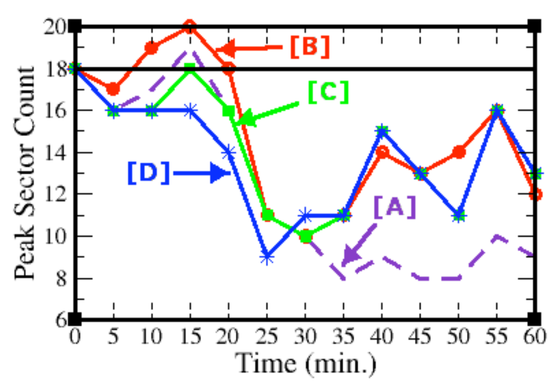

Figure 6. Peak traffic counts in Sector 16 of the Minneapolis ARTCC. [A] Nominal Counts, [B] Playbook Reroute, [C] Playbook + MIT, [D] Playbook + MIT+Local Reroute.

The airborne delays resulting from each of the steps of the three-step hierarchical method are summarized in Table 2. The number of impacted aircraft, total airborne delays (sum total of individual delays for all impacted aircraft) and average airborne delays associated with each of these TFM initiatives is listed in columns 2 through 4. The first step of using Playbook routes impacts the most number of aircraft and has the largest contribution to the delays. The second step of imposing MIT impacts fewer aircraft and a smaller amount of delay. The final step of local rerouting impacts very few aircraft.

For the scenario described in this section, the local rerouting did not cause the traffic demand on the adjacent sectors to exceed the MAP value. If on the other hand, the second step of the hierarchical method, MIT restrictions, had been skipped, then the local rerouting algorithm would have moved too many aircraft into neighboring sectors. To illustrate this point, the peak traffic through Sectors 16 and 17 of the Minneapolis ARTCC are presented in Figure 7. Figure 7a contains the peak counts with the three-step hierarchical method implemented to reduce traffic in Sector 16, and Fig. 7b demonstrates the impact of omitting the second step of the hierarchical method. As can be seen Figure 7, the local rerouting algorithm was able to reduce the congestion in Sector 16 in both cases, but the omission of the MIT restrictions resulted in congestion in a neighboring sector.

In the future, efficient optimization procedures (for example, see: Reference 6) will be used for real-time decisions of TFM constraints required for reducing en-route congestion.

Table 2. Total number of impacted aircraft, total airborne delays and average airborne delays associated with the following TFM restrictions: [1] Playbook Reroute, [2] 20 MIT at ABR and [3] Local Reroute around Sector 16.

	Impacted Aircraft Count	Total Delay (min)	Average Delay (min)
[1]	48	1448	30.16
[2]	18	48.47	2.69
[3]	4	8.0	2.0

Time	ZMP16	ZMP17
Cap	18	18
00:00	16	5
00:05	16	7
00:10	16	13
00:15	14	13
00:20	9	16
00:25	11	16
00:30	11	12
00:35	15	10
00:40	13	10
00:45	11	8
00:50	16	7
00:55	13	4

(a)

Time	ZMP16	ZMP17
Cap	18	18
00:00	16	5
00:05	16	7
00:10	14	15
00:15	10	18
00:20	7	21
00:25	9	18
00:30	11	14
00:35	14	11
00:40	13	10
00:45	14	8
00:50	16	7
00:55	12	5

(b)

Figure 7. Impact of local rerouting on Sector 16 and 17 with MIT restrictions (left table) and without MIT restrictions (right table).

Conclusions

A three-step hierarchical method, based on current operations, was presented to integrate the traffic flow management initiatives for avoiding regions of severe weather and preventing congestion in the sectors. The method consists of using Playbook routes to avoid severe weather regions and then using a combination of miles-in-trail restrictions and local rerouting to control demand in the sectors. To evaluate the potential of this method, a realistic traffic simulation driven by actual air traffic data was used with the West Watertown route structure from the National Playbook to circumvent a region of severe weather located in the southern portion of the Minneapolis ARTCC. It was shown that the traffic following West Watertown caused the capacity of Sector 16 of the Minneapolis Center to be exceeded. Miles-in-trail restrictions were used to reduce the traffic volume. Excess airborne traffic was then rerouted around Sector 16 using the local rerouting algorithm described in the paper. The results obtained for this scenario demonstrates that the hierarchical method is able to reduce the demand to be within the capacity thresholds of the congested regions of the airspace.

Appendix A

The rerouting algorithm is designed to minimize the number of piece-wise linear route segments needed to circumvent the FCA. This procedure is equivalent to minimizing the number of inflection points (or corners) in the rerouted trajectory that avoids the FCA. For the polygon that defines the FCA, there are an infinite number of routes that can be constructed on either side of the polygon partitioned by the straight-line connecting the origin to the destination, shown in Figure 8.

The algorithmic details of the rerouting method are as follows. As an example, consider the FCA shown in Figure 8. Its vertices P1 through P8 define the outer boundary of the polygon. The origin of the rerouting segment is Po and the destination is Pf. As the first step, the intersections of the straight line joining the origin, Po, to the destination, Pf, with the line segments connecting the vertices of the polygon are determined. Observe in Figure 8 that the intersection points are Q1 and Q2, which are obtained via intersection with P1-P8 and P5-P6 edge-segments. The closest and farthest intersection points with respect to the origin point (P0) are found. In this example, Q1 is the closest intersection point and Q2 is the farthest intersection point with respect to the origin Po. The midpoint between these two extreme is found, which in this case is Qm. Distances from the midpoint (Qm) to the vertices on the two sides of the polygon about the origin-destination axis are obtained. The vertices on the upper side are P1 through P5 and the ones on the lower side are P6 through P8. The largest distances (from Qm to the FCA vertices) on both the top and bottom sides are determined and the smallest of these is chosen as the radial distance for drawing an arc centered about the midpoint. For the example in Figure 8, the radial distance is Lr, which is the distance between Qm and P6. Next, a normal to the straight-line connecting the origin to the destination, Po-Pf, or Q1-Q2, is constructed from the midpoint, Qm, in the direction of selected side. The intersection point of the arc and the normal, Ra, is found. The reroute path is determined as segments connecting the origin to the destination via the inflection point, Ra.

If the path from the origin, Po, to the inflection point, Ra, is found to intersect the FCA, then more than one inflection point is required to avoid the FCA. For example, if the line segment Po-Ra intersected the FCA then the route construction procedure would be repeated with the inflection point, Ra, as the intermediate destination point. Once a new inflection point is evaluated, it is treated as the new point of origin. The algorithm proceeds with the new origin and final destination, Pf. The complete route is obtained recursively, in the forward and backward direction, until a clear route from the true origin, Po, to the final destination, Pf, is found. This route synthesis procedure generates routes that have a minimum number of inflection points. For the example shown, there is a single point of inflection, Ra.

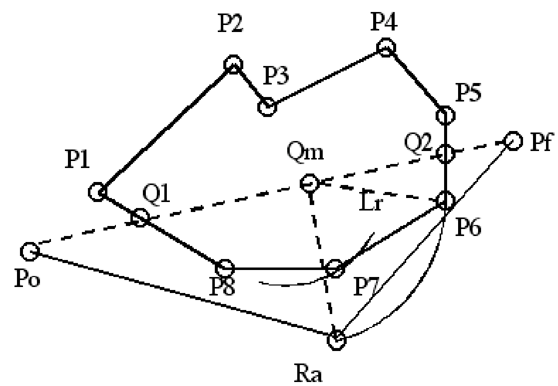

Figure 8. Local rerouting around an FCA.

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