

Analysis of Increasing User Flow Management Responsibility using Shared Delay Information

Jeff Henderson* and Husni Idris†
Engility Corporation, Billerica, MA, 01821

Rafal Kicingier‡ and Jimmy Krozel§
Metron Aviation, Inc., Dulles, VA, 20166

In the National Airspace System traffic demand exceeds capacity of airspace resources during a number of conditions such as inclement weather. Currently, the traffic flow management function of maintaining demand below capacity is centralized within the air traffic service provider and users have limited opportunities to make flight changes through requests. To alleviate this limitation, this paper investigates shifting some of the traffic flow management responsibility to users when flights are sufficiently upstream of the congestion. A boundary at a threshold distance from congested sectors is introduced, outside of which users directly implement their preferences by assigning delay and switching their flights to alternate routes. The users make decisions using service provider generated delay feedback and flow plan that specifies alternative routes. Inside the boundary the service provider makes flight decisions without considering user preferences. This new allocation of responsibilities may not be feasible since allowing users to actively participate in traffic flow management with only delay feedback may not eliminate the congestion. Simulation experiments are conducted that vary the location of the boundary where responsibility is switched and the percentage of flights that are assigned delay by users, to analyze under which conditions the excess demand can be eliminated. Results indicate that delay feedback from the service provider is not sufficient to make independent user actions help in eliminating the congestion, and additional mechanisms are needed. Users benefited more when they disregarded the service provider delay feedback and did not assign delays to their flights.

Nomenclature

$\alpha_1, \alpha_2, \alpha_3, \alpha_4$	=	User route cost function coefficients
B_i	=	Indicator variable that equals 1 if flight i is projected to enter the congested sectors while crossing the responsibility boundary
$C_{i,k,t}$	=	Capacity of resource j during the time period t that route k is projected to demand resource j
CF_k	=	Cost function for route k
\overline{d}_{ground}	=	Mean ground delay obtained from the delay map
\overline{d}_j	=	Mean delay absorbed in sector j obtained from the delay map
D_a	=	Total ground and airborne delay required for sectors along the assigned route
D_k	=	Total ground and airborne delay required for sectors along alternative route k
E_i	=	Indicator variable that equals 1 if flight i enters a congested sector and contributes to demand exceeding capacity
ETA_a	=	Unimpeded estimated time of arrival to the destination for the assigned route
ETA_k	=	Unimpeded estimated time of arrival to the destination for alternative route k
h	=	Index of the last high priority flight in user priority ranked list of flights

* Senior Research Engineer, 300 Concord Road, Suite 400, AIAA Member

† Principal Research Engineer, 300 Concord Road, Suite 400, AIAA Member

‡ Senior Analyst, 45300 Catalina Court, Suite 101, AIAA Member

§ Senior Engineer, 45300 Catalina Court, Suite 101, AIAA Associate Fellow

$i_{j,k,t}$	=	Indicator variable for demand exceeding capacity for sector j along route k during time period t
I_k	=	Congestion for route k
$I_{AOCimpact,k}$	=	User route switch factor index representing additional cost to connecting flights for route k
$I_{fuel,k}$	=	User route switch factor for fuel burn cost index for route k
$I_{NASimpact,k}$	=	User route switch factor that measures the impact of this flight on congesting when using route k
$I_{sat,k}$	=	User route switch factor that measures customer satisfaction for route k
N	=	Number of flights that a user is responsible for
P	=	Percentage of flights that are considered high priority for the user and do not absorb delay
P_{ATSP}	=	Time parameter set by the air traffic service provider to minimize switching to an alternate route if the time savings is not sufficiently large
$q_{j,k,t}$	=	Demand of route k for resource j during time period t
$t_{departure}^*$	=	Controlled departure time from the origin airport
$t_{departure}$	=	Unimpeded estimated time of departure from the origin airport
t_{jentry}^*	=	Controlled entry time to sector j
t_{jentry}	=	Unimpeded entry time to sector j
t_{jexit}^*	=	Controlled exit time from sector j
t_{jexit}	=	Unimpeded exit time from sector j
U_k	=	Utility for route k

I. Introduction

TRAFFIC flow management is the air traffic management function that maintains demand below capacity for airspace resources, such as airports, sectors, routes, airspace fixes, and navigational aids. Congestion occurs when traffic demand exceeds resource capacity because of numerous events including convective weather, special use airspace activity, excessive traffic complexity, pass-back restrictions from other control facilities, or over-scheduling of demand by users. In the current National Airspace System the traffic flow management function is centralized and provided by the Federal Aviation Administration, who introduces flow initiatives to reestablish the demand-capacity balance. The Air Traffic Control System Command Center develops strategic initiatives over a planning horizon of 2 to 6 hours. The Traffic Management Units of the 20 Air Route Traffic Control Centers, or simply centers, develop tactical plans, consistent with command center initiatives, to manage the air traffic within their local airspace over a planning horizon of typically up to 2 hours.¹ The users of the airspace, mostly airlines, but including general and business aviation, are impacted by the traffic flow management restrictions included in these strategic and tactical plans, but their involvement in the decision-making process is limited.¹⁻⁷

TFM is a complex process with multiple decision-makers with conflicting interests and interdependent actions. Idris et al.^{1,4} described a number of inefficiencies in current operations including the lack of collaboration particularly in local situations. Local situations are contained within a single facility, such as a center. For example, the Air Traffic Service Provider lacks accurate demand information for developing a mitigation plan. Therefore, the service provider often acts conservatively. The service provider may at times respond reactively due to the uncertainty resulting in unpredictable and volatile traffic flow management actions. In addition, the service provider does not have adequate information about users' preferences and economic impacts for their flights, even though operational planning teleconferences are held every two hours between flow managers and users. As a result, imposed restrictions do not consider user preferences adequately, leading to numerous requests from users to traffic managers that are time consuming and usually not granted due to high traffic manager workload.⁴ On the other hand, users desire timely and certain options from the service provider to plan proactive changes according to the expected restrictions, which they do not always receive. The result is that users are passive rather than proactive in providing information and requesting preferences. Meanwhile traffic flow management decisions, as well as implementation of flow plans through modifying flight trajectories, are made by the service provider with limited information about impact on users and with limited airline participation.

Decentralization by involving users in the decision-making process to enable user preferences and increase capacity has been proposed.^{2,3,7} Most concepts for collaborative traffic flow management preserve the traffic flow management function centralized with the service provider and increase the users' input to select more efficient flow initiatives.^{6,7,10} For example, one⁶ concept allows users to send a prioritized list of alternative routing options, and the traffic managers, supported by decision support tools, incorporate the preferences in reroutes assigned to flights. An agent-based model¹⁰ for decision-making interactions in traffic flow management was used to conclude that the service provider cannot make the best decision without collaboration from airlines. However, if users make decisions independently, they cause excess congestion.

Idris et al.⁴ proposed a far term collaborative traffic flow management concept to address traffic flow management issues identified from extensive field observations¹ as well as the needs of increased demand under the Next Generation Air Transportation System.¹² This far term concept considers new collaboration schemes that advocate shifting, when possible, some of the traffic flow management responsibility to users both in selecting and in implementing flow plans. The service provider assumes a supervisory role, monitoring the system performance, and intervening if needed. The expected benefits are that proactive users' actions can reduce the need for service provider intervention and reduce service provider workload, thereby facilitating more efficient traffic flow management initiatives.

This paper studies the impact of increasing user responsibility in a local scenario. Congestion in the local scenario results from a reduction in en route sector capacities in a single center due to convective weather. A boundary is defined at a threshold distance from the congested sectors for the purpose of allocating responsibility for flight route and delay decisions to users, when flights are sufficiently upstream of the congestion. Outside the boundary users directly implement their preferences by making flight decisions regarding the assigned delay and route within limits set by the flow plan. The users make their decisions using service provider generated delay feedback. Inside the boundary the service provider takes over responsibility and makes flight decisions without consideration for user preferences. An analysis of incorporating user preferences in service provider decisions inside the boundary was presented in a previous paper¹¹. Three factors were considered during simulation experiments: the location of the boundary where responsibility is switched, the percentage of flights that the users assign delay to according to service provider delay feedback, and the level of user participation in the collaboration. The purpose of these experiments is to determine if demand is maintained below capacity under different degrees of user responsibility and adherence to the delay feedback and whether by increasing user responsibility the users are better able to implement their preferences.

The proposed increase in user responsibility may violate current Federal Aviation Administration rules and regulations. One current rule, which is being challenged by users, is that users cannot change a flight plan after 45 minutes prior to departure without approval. A second issue is that users cannot collaborate on flights more than 24 hours from scheduled departure. However there is no limitation on collaboration for flights less than 24 hours from departure and airborne flights. For this paper it is assumed that these two issues will not be limiting.

A description of the boundary that defines the allocation of traffic flow management responsibility is presented in Section II building on previous work.^{4,5,8} An overview of the algorithms that model service provider and user behavior when they have responsibility is described in Sections III and IV respectively. Section V presents the analysis scenario used to generate the simulation experiment results described in Section VI. Conclusions and suggested future work is discussed in Section VII.

II. Allocation of Traffic Flow Management Responsibility

This section describes the allocation of responsibility to the Air Traffic Service Provider (ATSP) and users to make route and delay decisions on a flight-by-flight basis. This allocation of responsibility is based on a subset of a collaborative traffic flow management (CTFM) concept that increases user responsibility in traffic flow management (TFM).^{4,5,8} For both the ATSP and the users the decisions are made under limits set in the flow plan including the available alternative routes and the rates along these routes.

A. Boundary to Allocate Responsibility

A boundary, called the responsibility boundary, is set for the purpose of allocating responsibility for flight route and delay decisions to the ATSP and the users. The responsibility boundary is set at a distance from congested sectors with demand projected to exceed capacity using a horizontal and a vertical distance threshold. An example of demand exceeding capacity for Cleveland center (ZOB) sectors is shown in Fig. 1 to illustrate the responsibility boundary. In Fig. 1 the responsibility boundary outlines a group of sectors that are inside the responsibility boundary while the sectors with demand projected to exceed capacity are shaded. Details of this congestion are presented with the results in Section VI.

The responsibility boundary is distance-based and aligned with sector edges beyond a threshold horizontal and vertical distance from the congested sectors. An alternative is to use a time-based boundary where the responsibility boundary is set based on the projected time to enter the sectors with projected congestion. These horizontal and vertical distance thresholds are used to vary the airspace that the ATSP and users have responsibility over in order to evaluate the impact on the ability to reduce demand below capacity and user objectives.

The algorithm to calculate the boundary begins with a list of sectors inside the boundary which is initialized to the list of congested sectors with demand projected to exceed capacity. A list of candidate sectors to be included

inside the boundary is generated by considering centers nearby the congested sectors. For each of the vertices of the candidate sectors a horizontal and vertical distance comparison is made with each of the vertices of the congested sectors as shown in Fig. 2. The horizontal distance between a candidate sector and a congested sector is shown on the top of Fig. 2 while the corresponding vertical distance is shown on the bottom of Fig. 2. If one vertex of a candidate sector is less than both the horizontal and vertical distance thresholds to a vertex of one of the congested sectors then the candidate sector is included in the list of sectors inside the boundary.

For flights that have not departed from the origin airport a comparison between the location of the origin airport and the vertices of the congested sectors is used to allocate responsibility. Flights at airports less than the horizontal and vertical distance thresholds from the congested sectors are included inside the responsibility boundary.

B. Identification of Flights with ATSP versus User Responsibility

The ATSP has responsibility for all flights within the boundary that are projected to enter the congested sectors during the times the sectors are projected to be congested. These flights are circled on the right-hand side of Fig. 1. The ATSP is also responsible for flights within the boundary that are not projected to enter the congested sectors but are projected to enter the congested sectors if the flight switches to an alternative route that is specified in the flow plan. The ATSP is also modeled to take responsibility for all flights outside the responsibility boundary that are operated by users that have the option to, but choose not to, take responsibility to assign delays and switch flights to alternate routes.

Users have the option to take responsibility for all of their own flights outside the boundary, shown on the left in Fig. 1. Also, the users have the option to take responsibility for a portion of flights that are inside the boundary and are no longer projected to enter the congested sectors and would not be projected to enter the congested sectors after switching to an available alternate route that is specified in the flow plan.

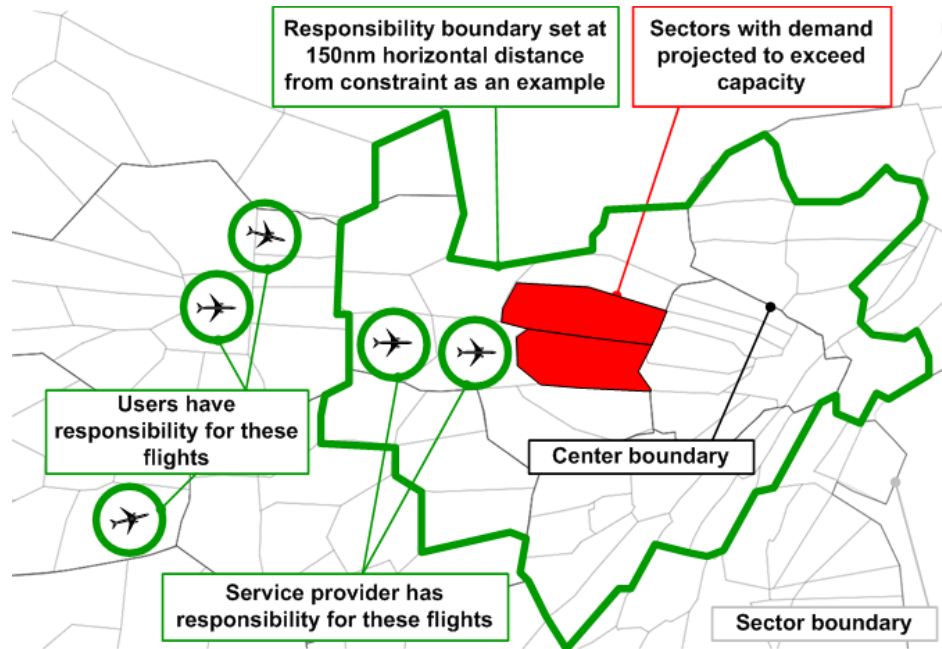


Figure 1. Responsibility boundary surrounding sectors in Cleveland center with demand projected to exceed capacity.

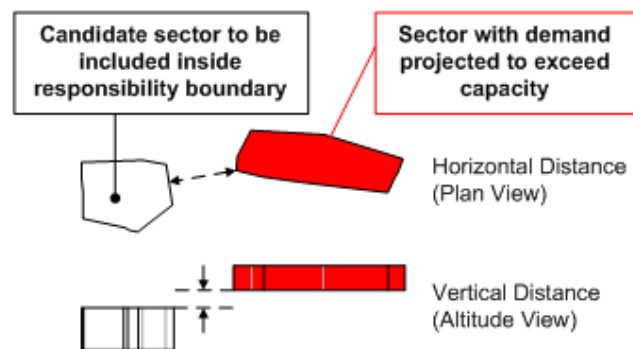


Figure 2. Horizontal and vertical distance between a sector with demand projected to exceed capacity and a candidate sector to be included within responsibility boundary. If both the horizontal and vertical distances are less than the thresholds then this sector is inside the boundary.

III. Flight Route and Delay Decisions when ATSP has Responsibility

A short description of the algorithms for the ATSP assignment of routes and delays to flights, without consideration for airline preferences, is included in this section. A more detailed description of ATSP algorithms for the assignment of delays and routes to flights incorporating user preferences is available in a previous paper.¹¹ User preferences are not considered to better isolate the impact of giving users more responsibility outside the responsibility boundary. The ATSP is modeled to always give highest priority to eliminating airspace congestion in terms of reducing demand below capacity. The inputs to the ATSP algorithm are first described followed by the ATSP algorithm for flight route and delay decisions.

A. Inputs from Other TFM Activities

It is assumed that other ATSP traffic TFM activities provide inputs for the ATSP flight route and delay decisions. One of these activities is the identification of all sectors with demand projected to exceed capacity, the determination of the start and end times capacity is exceeded, and a list of flights demanding the sectors during the times capacity is projected to be exceeded. Another input is a description of the responsibility boundary and the corresponding list of flights for which users have decision-making responsibility. Lastly, the ATSP switches a flight to an alternative route and assigns delay according to a flow plan, which is an input developed by the ATSP that specifies the alternative routes and the flow rates that are needed to reduce demand below capacity. The rates correspond to sector capacities in this paper.

B. Algorithm for Flight Route and Delay Decisions

The ATSP process to make flight route and delay decisions is incremental and on a flight-by-flight basis. To decide the order of flights first a priority ranked list of flights is generated. The ATSP congestion criteria ranks airborne flights higher than flights on the ground to prevent the release of too many flights into the airspace thus creating a condition where airborne demand can exceed capacity of sectors. Equity is a secondary criterion for ranking flights on a first-come-first-served (FCFS) basis measured at entry to the first sector with demand projected to exceed capacity along the flight trajectory.

Once the order of flights has been determined then the decision on whether to switch a flight to an alternate route is made based on congestion. Congestion is measured as the time-weighted amount that demand exceeds capacity as shown in Eqs. (1) and (2).

$$I_k = \sum_j \sum_t (q_{j,k,t} - c_{j,k,t}) i_{j,k,t} \quad (1)$$

$$i_{j,k,t} = \begin{cases} 1 & \text{if } q_{j,k,t} > c_{j,k,t} \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

where: I_k is the congestion, $q_{j,k,t}$ is the demand, $c_{j,k,t}$ is the capacity, and $i_{j,k,t}$ is an indicator for demand exceeding capacity all for route k demanding sector j during time period t .

If two alternate routes are equally congested then the ATSP route decision is based on travel time. For the travel time criteria, the ATSP switches a flight to an alternative route if the travel time difference between the currently assigned route and an alternative route exceeds a delay threshold parameter as shown in Eq. (3).

$$(ETA_a + D_a) - (ETA_k + D_k) > P_{ATSP} \quad (3)$$

where: ETA_a is unimpeded (without ground or airborne delay) arrival time to the destination for the assigned route, D_a is the total ground and airborne delay required to keep demand at or below capacity for sectors along the assigned route, and P_{ATSP} is a time parameter set by the ATSP to minimize switching to an alternate route if the time savings is not sufficiently large. ETA_k and D_k are defined similar to ETA_a and D_a for alternative route k . The purpose of the delay threshold parameter is to model a limit on ATSP workload.

A mixed-integer programming (MIP) model is used to calculate ground delays and airborne delays for a single flight so that demand remains below capacity.¹¹ The total delay calculated by the MIP model corresponds to D_a for the currently assigned route and D_k for alternative routes in Eq. (3). The MIP model is also used to implement a preference for the location to absorb delay relative to the congested sectors. The ATSP prefers to absorb delay upstream which is implemented as ground delay for flights on the ground and airborne delay in the current sector for flights that are airborne as shown in Fig. 3. If not all of the delay can be absorbed in the current sector, then a portion of the delay is incrementally moved downstream until demand is reduced below capacity. The ATSP prefers to absorb delay upstream to increase ground delay which prevents the release of too many flights into the airspace and also to prevent too much congestion near the constraint so that sufficient flexibility is available to maintain demand below sector capacity.

IV. Flight Route and Delay Decisions when Users have Responsibility

In order to assist users to make decisions that reduce demand below capacity the ATSP sends expected delay feedback to the users. The users use delay feedback when making decisions to switch a flight to an alternative route, assign ground delays, and assign delays at sectors along the route. In previous work users were always assumed to assign delays according to the ATSP delay feedback without modification.¹¹ However, this is a conservative approximation of user behavior since the delay feedback only contains ATSP objectives which are different from user objectives. User behavior is modified in this paper so that the users still use delay feedback when making route decisions but the users may choose not to assign ground or airborne delays for high priority flights. The inputs to the user flight route and delay decision algorithms are first described, including the ATSP delay feedback, followed by the algorithm.

A. Inputs from other TFM Activities

Similar to the ATSP it is assumed that other TFM activities provide inputs to the user route and delay decision algorithms. The inputs include: a list of congested sectors, the location of the responsibility boundary, a list of flights that each user has responsibility for, and the ATSP-generated flow plan specifying alternative routes and rates.

The users also receive ATSP delay feedback in the form of a delay map (see Fig. 4). The delay map specifies average ground delays at airports and average airborne delays in sectors based on reducing demand below capacity according to ATSP objectives such as absorbing delay upstream of the congested sectors. Generation of the delay map begins by ranking flights on a FCFS basis and assigning ground and airborne delays to flights to reduce demand below capacity without switching flights to alternate routes and assuming that the ATSP has responsibility for all flights (box 1 in Fig. 4). The delay observations are then categorized by the sector and unimpeded entry time to the sector (box 2 in Fig. 4). Sector delay observations are placed in 15 minute intervals (e.g. 10:30 to 10:45) which correspond to the unimpeded entry time to the sector (box 3 in Fig. 4). No flight-specific information is included with the delay observations. These delay observations are then sent to the users to aid in decision-making for routes and absorbed delays (box 4 in Fig. 4). The model

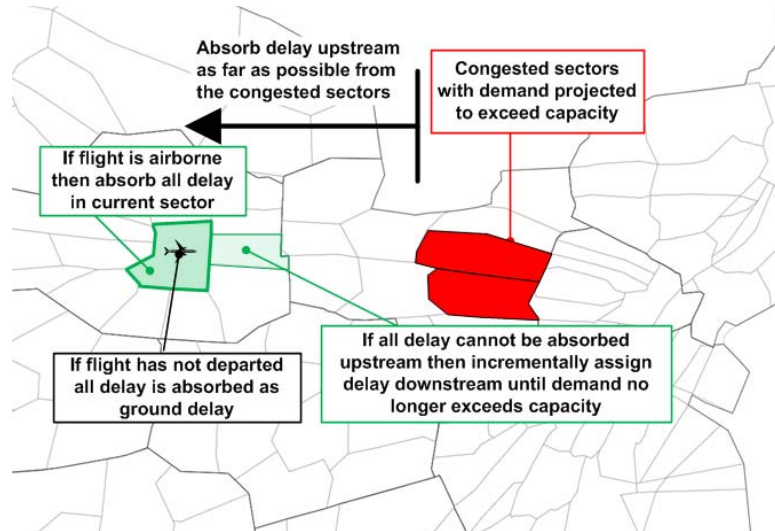


Figure 3. Upstream location to absorb delay far from the congested sectors with demand projected to exceed capacity.

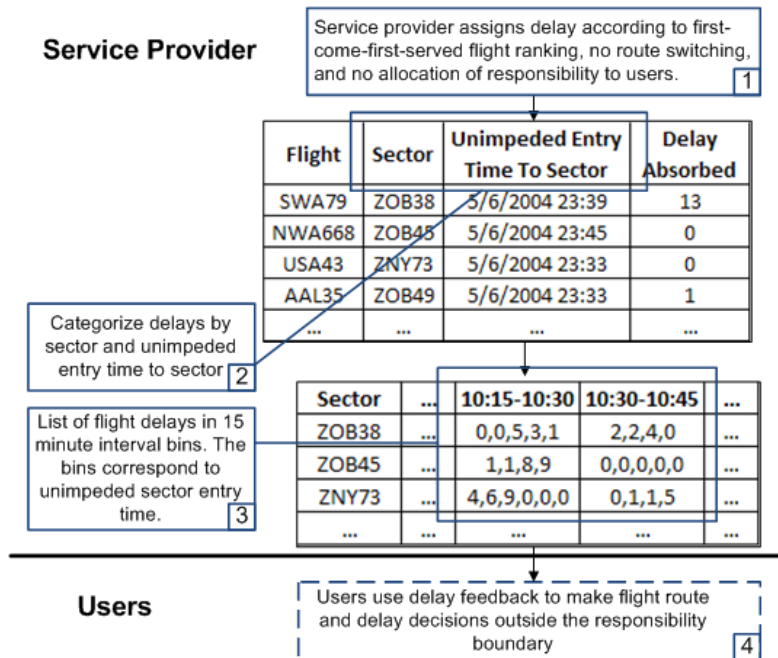


Figure 4. Generation of delay map.

assumes users make decisions based on mean delay.

B. Algorithm for Flight Route and Delay Decisions

The structure of the user decision algorithm is as follows. Users first consider switching a flight to an alternative route based on ATSP delay feedback. Then users decide if a flight is low or high priority. Low priority flights are assigned delays according to the mean delay from the delay map while high priority flights are not assigned delay at all. The percentage of flights that are high priority is an experimental parameter.

Users are modeled to always switch a flight to an alternate route with a higher utility. The route utility model initially considers 20 factors that users consider in their flight decision-making⁹. However, this list of factors is reduced based on data availability and likelihood of occurrence. The remaining factors are grouped into four indices as shown in Eq. (4) and used to specify a cost function.

$$CF_k = \alpha_1 I_{fuel,k} + \alpha_2 I_{AOCimpact,k} + \alpha_3 I_{sat,k} + \alpha_4 I_{NASimpact,k} \quad (4)$$

where: k represents a route, CF_k is the cost function, $I_{fuel,k}$ is a fuel burn cost index, $I_{AOCimpact,k}$ is an index representing additional cost to connecting flights, $I_{sat,k}$ is a customer satisfaction index, and $I_{NASimpact,k}$ is the impact of this flight on congestion in the NAS. Details of the factor index calculations are available in another paper.¹¹ The coefficients α_1 , α_2 , α_3 , and α_4 define users-specific behavior. However, the modeling approach has been to group the users by type including general aviation (GA), mainline legacy, low cost, and regional and specify coefficients for the group. To be consistent with utility theory the cost function is scaled so that the smallest value is the worst and the largest value the best according to Eq. (5).

$$U_k = \left(\frac{CF_k - CF_{WORST}}{CF_{BEST} - CF_{WORST}} \right) \quad (5)$$

where: U_k is the utility for route k , CF_{BEST} is the best (lowest) cost which should generally be zero, and CF_{WORST} is the worst (highest) cost for an alternative route.

Users generate a priority-ranked list of flights using a simplified criterion of number of passengers. Flights with more passengers are ranked higher in the priority-ranked list of flights. The number of passengers is derived based on available seats aboard the aircraft and historical airline load factors between city pairs. The load factors are calculated using the Bureau of Transportation Statistics DB1B database^{**}. In the priority-ranked list of flights the first flight is the highest ranked flight while the flight at index $N-1$ is the lowest ranked flight where N is the number of flights that the user is responsible for. The priority ranked list of flights is partitioned into high priority flights and low priority flights at the index shown in Eq. (6).

$$h = \text{round}(N * P) - 1 \quad (6)$$

where: h is the index of the last high priority flight, P is the percentage of flights that are considered high priority for the user and do not absorb delay, and round is a function to round to the nearest integer. All flights at an index $\leq h$ in the priority ranked list of flights are considered high priority by the airline and are not assigned delay. High priority flights depart at the planned departure time and fly unimpeded to the boundary where responsibility shifts to the ATSP. Assigning delay to low priority flights reduces airspace congestion which is an objective of the ATSP.

For low priority flights that have not departed the departure time is pushed back by the mean ground delay from the delay map as shown in Eq. (7). The controlled entry time to each sector is then calculated as the sum of the unimpeded entry time to the sector and the sum of the ground delay (if the flight has not departed) and the airborne delay at all sectors along the flight trajectory preceding this sector as shown in Eq. (8). The controlled exit time is calculated as the difference between the unimpeded entry and exit times from the sector and the delay absorbed in the sector as shown in Eq. (9).

$$t_{departure}^* = t_{departure} + \overline{d_{ground}} \quad (7)$$

$$t_j^{entry*} = t_j^{entry} + \overline{d_{ground}} + \sum_{m=0}^{j-1} \overline{d_m} \quad (8)$$

$$t_j^{exit*} = t_j^{exit} + (t_j^{exit} - t_j^{entry}) + \overline{d_j} \quad (9)$$

where: $t_{departure}^*$ is the controlled departure time from the origin airport, $t_{departure}$ is the unimpeded estimated time of departure from the origin airport, $\overline{d_{ground}}$ is the mean ground delay obtained from the delay map, t_j^{entry*} is the controlled entry time to sector j , t_j^{entry} is the unimpeded entry time to sector j , $\overline{d_j}$ is the mean delay absorbed in

^{**} http://www.transtats.bts.gov/Tables.asp?DB_ID=125

sector j obtained from the delay map, t_j^{exit*} is controlled exit time from sector j , and t_j^{exit} is the unimpeded exit time from sector j . The mean delay for a sector is similarly defined when sector index m replaces sector index j in Eq. (8).

V. Analysis Scenario

For this scenario, the capacities of ZOB sectors are artificially reduced in response to convective weather activity on July 19, 2007. These sectors, whose capacities are reduced during 5-7 PM Eastern Daylight Time (EDT) as shown in Table 1, have significant east-west flows between New York and Chicago airports. The reduction in en route sector capacities result in demand exceeding sector capacities a total of 1,953 aircraft-minutes based on aircraft following their nominal trajectories and without a TFM initiative in place. The total is the product of the number of aircraft above the capacity of the sector and the duration of time when capacity is exceeded.

Convective weather on June 19, 2007 extends beyond the boundary of ZOB as shown in Fig. 5, however only the weather in ZOB is considered in the scenario. Normally a weather system of this magnitude would require coordination between the Air Traffic Control System Command Center and several Air Route Traffic Control Centers. Coordination on a national scale is not considered.

A discrete event simulation was used to model the ATSP and users as agents that collaborate through a messaging system to maintain demand below capacity. The simulation is time-stepped by one-minute time increments. The platform leverages the capabilities of the Future ATM Concepts Evaluation Tool (FACET)¹⁴ for modeling sectors and aircraft trajectories.

The simulation uses the parameters described in Table 2. The user route preference coefficients were selected assuming that fuel burn (α_1) is the most important factor for all airlines. Legacy airlines using hub-and-spoke networks consider the impact of delays on connecting passengers (α_2) while low-cost and small airlines that operate mostly point-to-point services do not consider this factor. Customer satisfaction (α_3) is considered by all airlines but is given relatively less weight by legacy and low-cost carriers. NAS impacts (α_4) is not emphasized for all airline types, but relatively more for legacy and low-cost carriers that operate at more congested airports and in more congested airspace and hence need to consider to get their preferences granted. GA operations through the congested sectors are mainly due to business jets so customer satisfaction is the only consideration for these flights. The route preference coefficients sum to one.

Aircraft Situation Display to Industry (ASDI) flight data from May 6, 2004 were used in FACET to extract 5,422 flights that are projected to enter the congested sectors, other ZOB sectors, Chicago center (ZAU) sectors, or New York center (ZNY) sectors during the time demand is projected to exceed capacity (5:00 PM to 7:00 PM EDT). During the simulations a total of 2,334 to 2,658 flights were projected to contribute to the congestion even though a flight may not incur any delay. The airspace where demand exceeds sector capacity, listed in Table 1, may enlarge in time and space thus capturing more flights than originally projected. This is the reason why the number of flights projected to contribute to the congestion is not the same for different simulation experiments corresponding to different

Table 1. Artificial reduction in sector capacity during 5:00 PM to 7:00 PM EDT on June 19, 2007.

Sector	MAP Value	Reduced Capacity
ZOB79	19	6
ZOB77	16	5
ZOB74	16	6
ZOB59	16	6
ZOB57	16	5

Table 2. Parameters in CTFM simulations.

Agent	Parameter	Value	Description
ATSP	Detect demand exceeding capacity interval	15 minutes	The interval at which the ATSP evaluates if demand exceeds capacity. If demand is projected to exceed capacity then the process to generate a TFM plan is initiated.
ATSP	Projection time	120 minutes	The projected time in the future measured from the current simulation time that the ATSP estimates demand and capacity for a sector.
ATSP	Route switch threshold	10 minutes	The P_{ATSP} parameter.
Users	Route preferences coefficients	Legacy airlines: $\alpha_1=0.5, \alpha_2=0.2, \alpha_3=0.15, \alpha_4=0.15$ Low-cost airlines: $\alpha_1=0.8, \alpha_2=0.0, \alpha_3=0.1, \alpha_4=0.1$ Small airlines: $\alpha_1=0.8, \alpha_2=0.0, \alpha_3=0.2, \alpha_4=0.0$ General aviation: $\alpha_1=0.0, \alpha_2=0.0, \alpha_3=1.0, \alpha_4=0.0$	

factor combinations listed in Section VI. The remaining flights are background traffic that were never projected to enter a congested sector during a time when the sector was congested.

VI. Analysis Results

The location of the responsibility boundary, the percentage of flights that are assigned delay by airspace users, and the level of user participation are the three factors varied during the simulation experiments. Six factor levels are considered for the location of the responsibility boundary factor as described in Table 3. For the first factor level only the five congested sectors are inside the responsibility boundary while the other five factor levels move the responsibility boundary incrementally further from the congested sectors in the horizontal direction. All altitude levels within the horizontal distance threshold, including airports, are inside the responsibility boundary for all factor levels except the first factor level. The last factor level includes the entire NAS, however only 126 sectors are monitored. Aircraft are only able to absorb delay in these 126 monitored sectors and at airports within two hours of the congested sectors. The two hours is specified using the projection time parameter in Table 2.

The factor for the percentage of flights that are assigned delay modifies the users' incorporation of ATSP delay feedback in their decisions. By incorporating ATSP delay feedback the users can help reduce the level of airspace congestion. Five factor levels are considered corresponding to the percentage of flights that absorb delay: 0%, 25%, 50%, 75%, and 100%.

Other than the results presented in subsection D all results are presented based on 100% of users taking responsibility for making flight decisions. Subsection D presents the factor levels for user participation and the impact of the level of user participation on remaining congestion and equity. Five other metrics are discussed including the remaining congestion to check if demand is maintained below capacity (subsection A), the percentage of the congestion solved by airspace users (subsection B), aircraft delay (subsection C), and user benefits including route switching and passenger delay (subsection E).

A. Remaining Congestion

By giving users more responsibility to make flight route and delay decisions it is possible that the ATSP is no longer able to reduce demand below capacity. A metric of unsolved congestion quantifies the amount of the congestion that remains. The metric is calculated by comparing the observed (not predicted) demand and capacity for each sector at each one-minute time interval in the simulation and if the observed demand exceeds capacity then the metric is increased by the difference between the observed demand and capacity for the sector multiplied by the time interval of one minute. Larger values of this metric

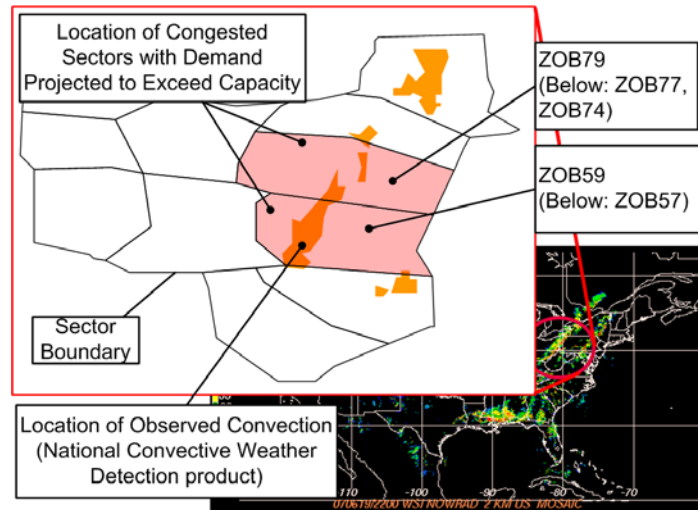


Figure 5. Congested sectors in Cleveland center due to severe weather on June 19, 2007.

Table 3. Factor levels for the location of the responsibility boundary.

Factor Level	Horizontal Distance of Responsibility Boundary from Congested Sectors	Vertical Distance of Responsibility Boundary from Congested Sectors	Count of Sectors Inside Boundary
1	0 nm (only congested sectors are inside responsibility boundary)	0 ft (only congested sectors are inside the responsibility boundary)	5
2	1 nm (Sectors adjacent to congested sectors are inside the responsibility boundary)	All altitude levels, all sectors and all airports are inside boundary (i.e. 99,999 ft)	19
3	50 nm		27
4	100 nm		48
5	300 nm		103
6	Extending to all monitored sectors		126

indicate that less of the congestion has been solved. This metric considers both the sectors that were congested and other sectors that have become congested because of ATSP and user TFM actions.

Results for the remaining congestion metric are shown in Fig. 6 with each of the curves corresponding to the percentage of flights that are assigned delay by the users. Increasing line thickness of the curves corresponds to an increasing percentage of the flights that are assigned delay by users. The levels of the responsibility boundary are shown on the x-axis and the remaining congestion is shown on the y-axis. Results indicate that congestion is reduced as the responsibility boundary is moved further from the congested sectors since moving the responsibility boundary further from the congestion provides the ATSP increased opportunity to adjust for user actions. The congestion drops quickly until the responsibility boundary is set at 50 nm and is generally flat beyond 50 nm. Generally, as expected, higher remaining congestion occurs with a lower percentage of flights that are assigned delay. For example, if only the congested sectors are inside the responsibility boundary (0 nm horizontal and 0 ft vertical distance thresholds) the remaining congestion is 1,284 aircraft minutes if 0% of the flights are assigned delay by airspace users which is reduced to 406 aircraft minutes if 100% of the flights are assigned delay. The congestion remains until the ATSP has responsibility for all flights, which indicates that the delay feedback alone is not sufficient to make user action help eliminate the congestion.

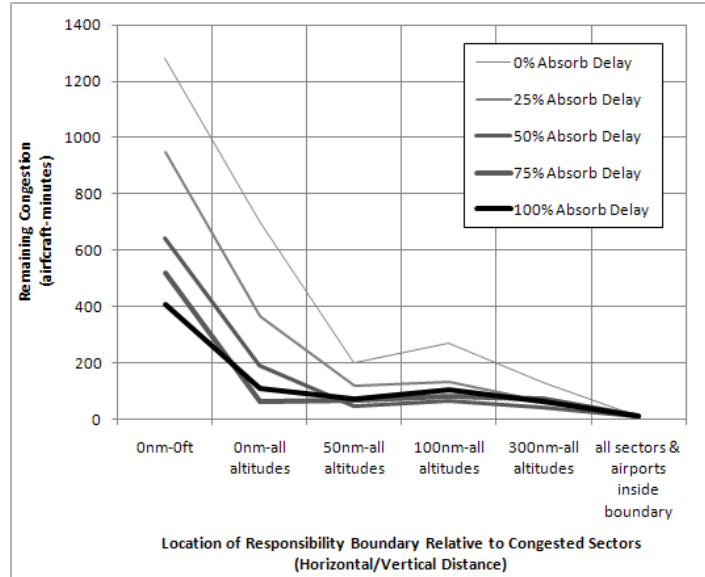


Figure 6. Remaining congestion after ATSP and airspace user TFM actions.

B. Congestion Solved by Airspace Users

By making decisions to switch routes and assign delay to their flights airspace users are able to solve a portion of the projected congestion. By solving a portion of the projected congestion airspace users reduce workload for the ATSP and potentially eliminate the need for ATSP intervention. A metric that quantifies the users solving a portion of the congestion is shown in Eq. (10) based on the ratio of the projected congestion after user actions outside the responsibility boundary to the projected congestion before user actions.

$$\% \text{ solved} = 100\% - \frac{\sum_{i=1}^{\# \text{ flights}} (E_i t_i B_i)}{\sum_{i=1}^{\# \text{ flights}} (E_i t_i)} (100\%) \quad (10)$$

where E_i is 1 if flight i enters a congested sector and contributes to demand exceeding capacity and 0 otherwise, t_i is the projected amount of time flight i will spend in a congested sector, and B_i is 1 if flight i is projected to enter the congested sectors while crossing the responsibility boundary and 0 otherwise.

A plot of congestion solved by airspace users is shown in Fig. 7 with the levels of the location of the responsibility factor on the x-axis and the percentage of the congestion solved by airspace users on the y-axis. Results indicate that when users assign delay to a larger percentage of their flights according to the delay map a larger percentage of congestion can be solved by users. For example, if only the congested sectors are inside the responsibility boundary (0 nm horizontal and 0 ft vertical distance thresholds) and the users assign delay to 100% of their flights then 76% of the congestion can be solved by the users compared to users solving only 4% of the congestion when assigning delay to 0% of their flights. The solving of 4% of the congestion corresponds to users switching flights to alternative routes to avoid the anticipated delays to be assigned by the ATSP. The percentage of the congestion that is solved by users drops as the location of the responsibility boundary is shifted further from the sectors with projected congestion. With the responsibility boundary set at 300 nm in the horizontal direction and users assigning delay to 100% of their flights the percentage of the congestion solved by users drops down to 12%.

If the ATSP is responsible for all flights then the users solve 0% of the congestion since the users are not implementing any of their decisions.

C. Aircraft Delay

Total aircraft delay results are presented in Fig. 8 with the location of the responsibility boundary along the x-axis and the total delay along the y-axis. Similar to the other plots increasing line thickness corresponds to an increasing percentage of the flights that are assigned delay by users. The total aircraft delay has components of ground delay, which is generally in the range of 85% to 95% of the total, and airborne delay, which is generally in the range of 5% to 15% of the total. The components are not shown to emphasize the trend for total aircraft delay. The trends are different for the cases where 25% or fewer of the flights are assigned delay by users and the cases where 50% or more of the flights are assigned delay by users. These two cases are differentiated using a dashed horizontal line in Fig. 8 indicating the aircraft delay when the ATSP has responsibility for all flights.

The trend is as follows if 25% or fewer of the flights are assigned delay by users. If the responsibility boundary is located at 50 nm or less from the congested sectors then there is a reduction in aircraft delay relative to the when the ATSP has responsibility for all flights. As the responsibility boundary shifts further from the congested sectors to 100 nm and 300 nm and the ATSP has responsibility for more flights a higher amount of delay relative to the dashed line is observed.

For cases where 50% or more of the flights are assigned delay by users the aircraft delay trend is mostly flat as the location of the responsibility boundary is moved further from the congested sectors. There is no delay benefit over the case where the ATSP has responsibility for all flights which is shown as the dashed line in Fig. 8.

D. Level of User Participation

For the results in the previous subsections it is assumed that all airlines and all GA flights are taking responsibility for flight route and delay decisions outside the responsibility boundary. For users who are not taking responsibility the ATSP makes flight decisions for their flights outside the responsibility boundary. In this

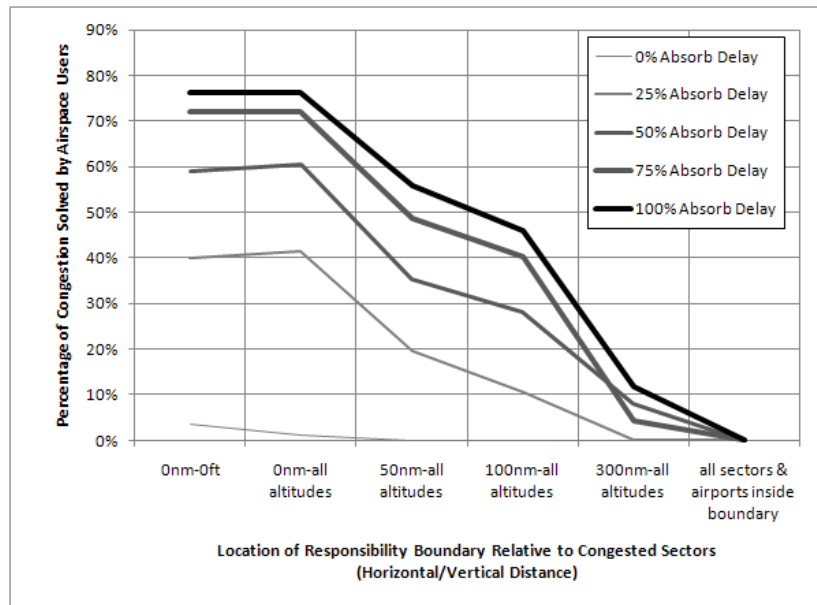


Figure 7. Percentage of projected congestion solved by airspace users.

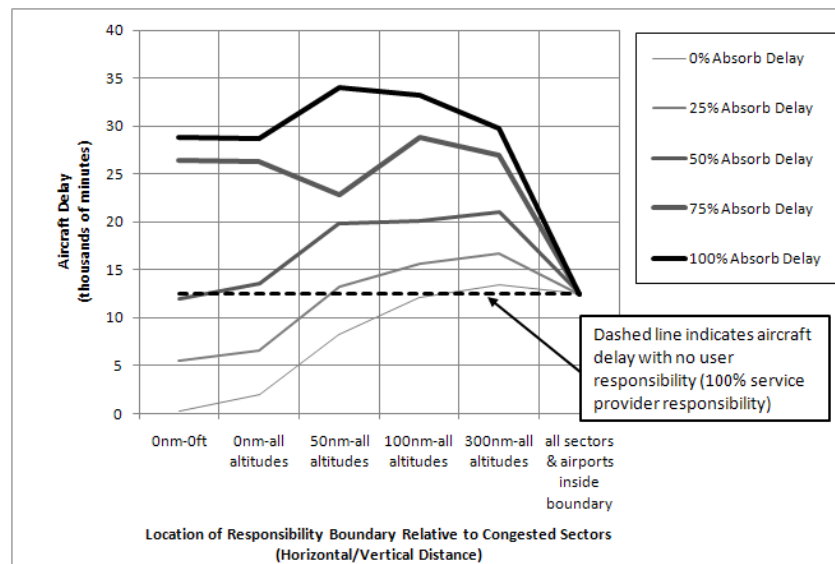


Figure 8. Aircraft delay.

subsection the level of participation by airspace users is varied to measure its impact on the remaining congestion and equity.

Users are placed into three categories for the purpose of developing the factor levels: GA users, airlines with five or more flights projected to enter the congested sectors, and all other airlines. The factor levels for user participation are:

- Level 1: 100% of users (includes GA)
- Level 2: 100% of airlines with 5 or more flights projected to enter the congested sectors (excludes GA)
- Level 3: 50% of airlines with 5 or more flights projected to enter the congested sectors (excludes GA)
- Level 4: 30% of airlines with 5 or more flights projected to enter the congested sectors (excludes GA)

In selecting the participating airlines it is assumed that airlines with more flights projected to enter the congested sectors are more likely to participate. So, for example, for factor level 4 each airline of the 30% of airlines that are participating operate more flights projected to enter the congested sectors as compared to the 70% of airlines that are not participating. Since these 30% of airlines operate many of the flights, factor levels 3 and 4 were selected with a relatively low percentage of airlines that participate to create a significant difference from factor level 2 in terms of the number of flights that are participating.

The impact of the four levels of user participation on remaining congestion is shown in Fig. 9 and is based on users assigning delay for 0% of flights, which can be considered the most restrictive condition from the perspective of the ATSP. The location of the responsibility boundary is shown on the x-axis with the remaining congestion on the y-axis. The curves correspond to the different levels of user participation with a solid line used for 100% of users participating and dashed lines used for fewer than 100% of users participating. The trends of the curves are similar to the remaining congestion plot shown in Fig. 6. However, with fewer users participating the ATSP has more flexibility to eliminate the congestion and the magnitude of the remaining congestion is reduced as the user participation level is reduced. For example, if only the congested sectors are inside the responsibility boundary and GA users are not participating then the remaining congestion is reduced to 500 aircraft-minutes when compared to the case where GA users are participating. Also, if less than 100% of airlines participate then demand can be maintained below capacity if the responsibility boundary is located at 50 nm or further from the congested sectors, which is not the case if 100% of users participate.

If a portion of the users do not participate then there may be inequity between users that take responsibility for

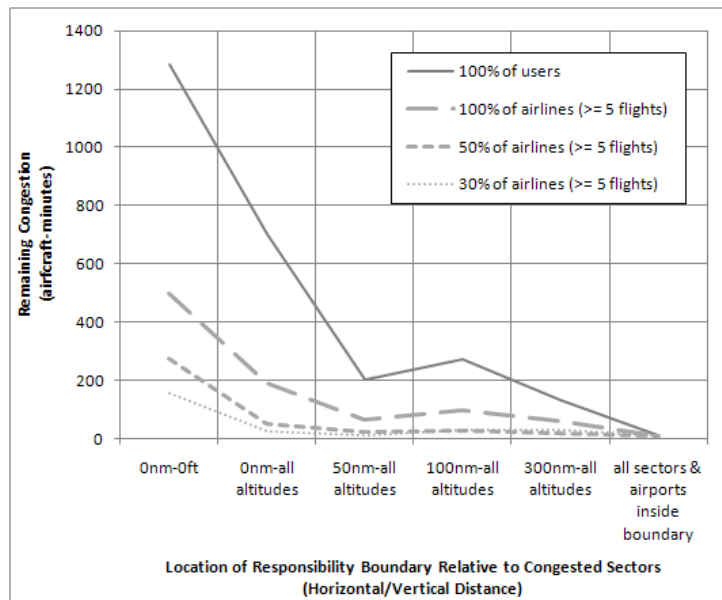


Figure 9. Impact of level of user participation on remaining congestion. All results based on users assigning delay to 0% of their flights.

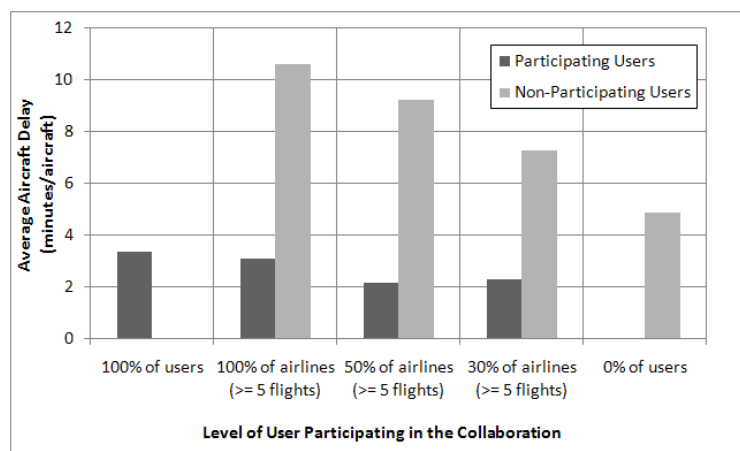


Figure 10. Impact of level of user participation on equity between participating and non-participating users expressed as average aircraft delay when the responsibility boundary is located at 50 nm from the congested sectors.

their flights and users that do not take responsibility for their flights. The metric used to quantify the potential inequality is the average delay per aircraft for participating and non-participating users as shown in Fig. 10. The results in Fig. 10 correspond to the location boundary at 50 nm from the congested sectors. Along the x-axis is the level of user participation with an additional data point corresponding to the ATSP having responsibility for all flights. The most equitable solution occurs when either 0% or 100% of users are participating since the average delay is the same within the participating and non-participating categories. The inequalities occur when a portion of the users are not participating. For example, when all the airlines but no GA users participate, the airlines absorb an average of 3.1 minutes of delay per aircraft compared to 10.6 minutes of delay per aircraft for the GA users not participating.

E. User Benefits

A measure of user benefit is the count of flights that are assigned their preferred route by users. For the modeled user and ATSP behavior if the ATSP is responsible for all flights then no flights will be assigned their preferred route by users. However, if the users are given responsibility to make route decisions for their flights in this scenario the count of user initiated route changes is in the range of 750-950 flights that are assigned their preferred route.

Another user benefit metric is passenger delay. By giving higher priority to larger aircraft with more passengers the delay per passenger should be reduced if user preferences are being met. Passenger delays follow the trend of total aircraft delay that is shown in Fig. 8. Numerical results are not presented, however, because the results are similar indicating that the users are meeting their preference of lower passenger delays.

VII. Conclusions and Future Work

Increasing user responsibility in directly implementing flight delays and switching flights to alternative routes, using only delay feedback from the service provider, has mixed benefits from the service provider perspective. By allocating some of the responsibility to users, the users are able to solve some of the congestion problem, in terms of reducing demand below capacity. However, allowing the users to solve some of the congestion problem results in a condition whereby the service provider cannot solve the remaining portion of the congestion problem, except with sufficiently low user participation and taking over responsibility sufficiently far from the congestion.

Users benefit from the increased responsibility, especially if the users disregard the service provider delay feedback and assign delays to a small percentage of their flights. Users experience reduced aircraft and passenger delays if they do not assign delays to all of their flights. However, the user aircraft and passenger delay benefits are at the expense of not helping reduce demand below capacity.

Even with users incorporating shared service provider delay feedback and assigning delay to their flights the congestion problem is not completely solved, indicating that solely providing service provider delay feedback is not sufficient to make user actions helpful in maintaining demand below sector capacity. Another mechanism is required for the users to help solve the congestion problem, which potentially involves coordination among users such that their actions are complementary in terms of reducing demand. This coordination does not violate current rules as long as the coordination is for airborne flights or flights close to departure. Also, this revised mechanism should include incentives to solve the congestion since users may benefit from disregarding TFM plans by not assigning delays to their flights.

Acknowledgments

This research was funded by NASA under contract NNA07BB35C. The authors would like to thank Kapil Sheth of NASA Ames, Jose Garcia-Chico, Sharon Woods, Brendan Lefebvre, Robert Vivona, David Karr, Tarek El-Wakil of Engility Corporation and Danyi Wang, Jason Burke, and Jason Pepper of Metron Aviation Inc. for contributions to algorithm and software development.

References

¹Idris, H., Evans, A., Vivona, R., Krozel, J., and Bilimoria, K., "Field Observations of Interactions between Traffic Flow Management and Airline Operations," *AIAA 6th Aviation Technology, Integration and Operations \ Conference*, AIAA Paper No. 2006-7721, Wichita, KS, Sept., 2006.

²NASA, "Concept Definition for Distributed Air/Ground Traffic Management v1.0," Milestone Report, Advanced Air Transportation Technologies (AATT) Project, NASA Ames, Moffett Field, CA, 1999.

³Green, S. M., Bilimoria, K. D., and Ballin, M. G., "Distributed Air/Ground Traffic Management for En Route Flight Operations." *Air Traffic Control Quarterly*, Vol. 9, No. 4, 2001, pp. 259-285.

⁴Idris, H., Vivona, R., Penny, S., Krozel, J., and Bilimoria, K., “Operational Concept for Collaborative Traffic Flow Management based on Field Observations,” *AIAA 5th Aviation Technology, Integration and Operations \ Conference*, Paper No. 2005-7434, Arlington, VA, Sept., 2005.

⁵Idris, H., Vivona, R., Evans, A., Evans, S., Garcia-Chico, J. L., Krozel, J., Penny, S., Doble N., and Clover S. “Collaboration for Mitigating Local Traffic Flow Management (TFM) Constraints due to Weather, Special use Airspace (SUA), and Complexity – Operational Concept Description,” L-3 Communications, Metron Aviation, Technical Report Prepared for NASA Ames Research Center, 2007.

⁶Klopfenstein, M. W., Wilmouth, G., Smith, P. J., Spencer, A., Mintzer, M. J., and Sud, V., “Congestion Management via Interactive Dynamic Flight Lists and Customer Submitted Multiple Routing Options,” *AIAA 5th Aviation, Technology, Integration, and Operations Conference*, Paper No. 2005-7436, Arlington, VA, Sept., 2005.

⁷Ball, M. O., Chen, C.-Y., Hoffman, R., and Vossen, T., “Collaborative Decision Making in Air Traffic Management: Current and Future Research Directions,” *New Concepts and Methods in Air Traffic Management*, edited by Bianco, L., Dell’Olmo, P., and Odoni, A. R., Springer-Verlag, Germany, 2001.

⁸Garcia-Chico, J.L., Idris, H., Krozel, J., and Sheth, K., “Task Analysis for Feasibility Assessment of a Collaborative Traffic Flow Management Concept”, *AIAA 6th Aviation, Technology, Integration, and Operations Conference*, Paper No. 2009-8909, Anchorage, AK, Sept., 2008.

⁹Idris, H., Evans, A., Krozel, J., Doble, N., Eckhause, J., and Hemm, R., “Benefit Mechanisms of Enhanced Collaboration in Tactical Traffic Flow Management”, *AIAA Aircraft Technology, Integration, and Operations Conference*. Wichita, KA, Sept., 2006.

¹⁰Wojcik, L. “Three principles of Decision-Making Interactions in Traffic Flow Management Operations,” *4th FAA/Eurocontrol Air Traffic Management R&D Seminar*, Santa Fe, NM, Dec., 2001.

¹¹Henderson, J., Idris, H., Kicinger, R., Krozel, J., Wang, D., and Sheth, K.S., “Airline and Service Provider Collaborative Algorithms for Flight Route and Delay Decisions” *AIAA Guidance, Navigation, and Control Conference*. Chicago, IL, 2009.

¹²Joint Planning and Development Office, "Next Generation Air Transportation System: Integrated National Plan," Washington, DC, 2004.

¹³Sridhar, B., Sheth, K., and Grabbe, S., “Airspace Complexity and its Application in Air Traffic Management,” *2nd FAA/Eurocontrol Air Traffic Management R&D Seminar*, Orlando, FL, Dec., 1998.

¹⁴Bilimoria, K. D., Sridhar, B., Chatterji, G., Sheth, K. S., and Grabbe, S., “FACET: Future ATM Concepts Evaluation Tool,” *Air Traffic Control Quarterly*, Vol. 9, No. 1, 2001, pp. 1–20.