User and Service Provider Collaboration on Flight Route and Delay under Uncertainty

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Collaboration between the service provider and users of the National Airspace System has so far been limited to strategic planning for mitigating flow constraints that have a wide impact. Benefits are expected if collaboration is extended to localized flow constraint situations. To demonstrate these benefits, a fast-time simulation of a local convective weather situation in Cleveland center was conducted to examine two types of user preferences: (1) user preferred routes among a set of alternative reroutes around the weather constraint, and (2) user preferred location to absorb delay along a route relative to the constraint. The effect of this collaboration was analyzed under a range of user and service provider behaviors, demand uncertainty, and over- or under- prediction of the capacity reduction caused by convective weather. The users increase their benefits by considering aggregate congestion impacts in addition to their own business objectives when generating their route preferences. More delay benefits are gained when the service provider considers the users' preference to absorb delay closer to the constraint, particularly when the magnitude of the capacity reduction is over-predicted.

Nomenclature

$\alpha_1,\alpha_2,\alpha_3,\alpha_4$	=	Airline route cost function coefficients
$Buffer_k$	=	Arrival time buffer for alternative route *k*
$c_{j,k,t}$	=	Capacity of sector *j* during the time period *t* that route *k* is projected to demand sector *j*
CF_k	=	Cost function for route *k*
C_R	=	Connecting rate at the destination airport
D_k	=	Total ground and airborne delay required for alternative route *k*
STA	=	Unimpeded scheduled time of arrival to the destination for the assigned route
ETA_k	=	Impeded estimated time of arrival to the destination for alternative route *k*
$Fuel_k$	=	Fuel burn 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 for the impact of using route *k* on airspace congestion
$I_{sat,k}$	=	User route switch factor that measures customer satisfaction for route *k*
$N_{j,k}$	=	Amount that demand exceed capacity for sector *j* if sector *j* is congested for route *k*
N_k	=	Number of congested sectors along route *k* (airline operation center criteria)
$q_{j,k,t}$	=	Demand of route *k* for sector *j* during time period *t*
S_k	=	Scaled delay for route *k*
U_k	=	Utility for route *k*

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I. Introduction

The traffic flow management function of developing initiatives to maintain demand below airspace capacity is currently centralized to the Federal Aviation Administration, the air traffic service provider for U.S. airspace. The users of the National Airspace System (NAS), which include commercial airlines, general aviation, and business aviation, are impacted by these initiatives, but their involvement in decision-making is limited. Collaborative decision-making seeks to improve traffic flow management initiatives by increasing data exchange and user involvement, particularly during ground delay programs and airspace flow programs, by allowing users to swap flight priorities.[1-5] However, collaborative decision-making has not been fully extended to local situations where users coordinate directly with a local traffic management unit.[6-12] As a result, benefits of collaboration in local situations are reduced since users do not always receive the desired, timely, and certain options from the air traffic service provider and user preferences and requests are not adequately considered due to high service provider workload.[6,9] The current practice for tactical local user requests is for users to send internet-based text messages to the tactical consumer advocate hotline at the service provider command center, which then coordinates with a local traffic management center.[6] However, the hotline messages are not always effective with one of the drawbacks being the latency of service provider response during periods of high service provider workload. Otherwise, the use of voice communication between airline operation centers and traffic management units is limited to cases when workload is permissibly low. The outcome is that the traffic flow management initiatives are restrictive and the airlines are passive rather than proactive in providing information and requesting preferences.

Previous work proposes increasing the involvement of users above the level of collaborative decision-making and to additionally include local traffic flow management situations to realize further benefit.[7,8,12,14] One concept allows users to send a prioritized list of alternative routing options, which the traffic managers incorporate in reroutes assigned to flights.[10] Idris et al.[9,10] proposed a concept that dynamically allocates some responsibility, both in selecting and in implementing traffic flow management plans, from the service provider to airline operation centers.[13,15] The concept proposes increasing user preferences to include flight ranking, route ranking, and a desired location to absorb delay. A previous study[18] analyzed the impacts of these preferences on user satisfaction and congestion in the absence of demand and capacity uncertainty.

User route ranking and location to absorb delay preferences are the focus of this paper, which is an extension of two previous studies that did not consider uncertainty or the range of behaviors considered in this paper[17-18]. The effect of considering these preferences was analyzed for a local severe convective weather constraint in Cleveland center, under a variety of user and service provider behaviors, demand uncertainty, and over- or under- prediction of the impact of the weather on capacity. The users and the service provider have differing objectives and a range of behaviors are considered. For the users, this range of behaviors is reflected in the generation of preferences and for the service provider this range of behaviors is reflected in the route switching, delay absorption, and preference evaluation behaviors. For route switching, the service provider considers the impacted aircraft in a first-come-first-served order for equity reasons and limits reroutes due to workload. In the absence of user route ranking preferences, the service provider identifies flights that may benefit from switching to an alternative route and implements this route switch by amending the flight plan route string. The service provider workload associated with the implementation of the route switch offers impedance to route switching that may result in reduced system efficiency. To address this inefficiency, a future environment is considered where the service provider defines available alternative routes and the users select the most desirable routes for each of their flights. Since some of the route switching workload is shifted to the users, there may be more switching of aircraft to shorter routes as compared to the case without route ranking preferences. To increase the chances of getting their preferences granted, the users may consider aggregate congestion impacts in addition to their business objectives when ranking alternative routes. The location to absorb delay preference specifies where users prefer delay to be absorbed relative to the constraint. The service provider may delay an aircraft upstream far from the congestion to manage workload, preserve flexibility, and prevent excessive congestion near the constraint. However, absorbing delay upstream is contrary to user objectives since the constraint may not occur or may have reduced severity causing delay to be unnecessarily absorbed. Also, by absorbing delay upstream, an aircraft may lose its place in the service provider first-come-first-served queue, causing it to be overtaken by another aircraft, and assigned additional delay. A user downstream location to absorb delay preference, where delay is preferred to be absorbed as close to the constraint as possible, is considered for the simulation experiments. A range of fast-time simulation scenarios based on a local Cleveland center convective weather constraint is used to evaluate both the route ranking and location to absorb delay preferences. The scenarios contain a range of demand and capacity uncertainties focusing on the case where the forecasted capacity is lower than the eventual simulated capacity.

This paper is organized as follows. First, Section II presents the user generation of route ranking preferences and the service provider evaluation of these preferences. The user location to absorb delay preference is then presented in Section III. The impacts of these preferences are evaluated using a fast-time simulation study of a local scenario in Section IV. The paper concludes in Section V.

II. User Route Ranking Preference

In local collaboration, the service provider sends the users a list of available alternative routes and the expected average delay at each sector along the route. For each flight, the users rank these routes using a user route utility function which is calculated based on service provider delay and sector count feedback. The users send a route ranking preference to the service provider and the service provider decides whether to grant the preference based on congestion in sectors along the route. The user behavior in generating the route ranking preference is first presented followed by the service provider acceptance criteria and an example. The example demonstrates the effect of user route ranking preferences under uncertainty and communication latency between the service provider and users.

A. User Route Ranking Behavior

The user route cost function considers factors that are grouped into four indices as shown in Eq. (1) and used to specify a user route utility function. The utility function and the calculation of the component indices have been presented in a previous paper[18] and are included in Appendix I for the sake of completeness.

$$CF_k = \alpha_1 I_{fuel,k} + \alpha_2 I_{AOCimpact,k} + \alpha_3 I_{sat,k} + \alpha_4 I_{NASimpact,k} \quad (1)$$

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, and $I_{sat,k}$ is a customer satisfaction index. These first three indices represent user business objectives. The indices are functions of route travel time, delay along the route weighted by connecting passengers aboard the flight, and excess delay relative to the schedule respectively. The indices are estimated using the projected unimpeded route travel times and the service provider delay feedback, which contains an estimate of the projected average delay at each sector along the route. $I_{NASimpact,k}$ is an estimate of the impact of assigning a flight to this route on congestion in the NAS and is used to analyze the impact of users considering aggregate congestion impacts in their preferences. Congestion impacts are measured as the sector congestion along a route and are based on service provider feedback of projected sector counts at one minute (min) time intervals. The cost function is scaled so that the smallest value is the worst and the largest value the best according to Eq. (2).

$$U_k = \left(\frac{CF_k - CF_{WORST}}{CF_{BEST} - CF_{WORST}} \right) \quad (2)$$

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.

The coefficients α_1, α_2, α_3, and α_4 define users-specific behavior in terms of relative importance of the indices. However, the modeling approach has been to group the users by type into general aviation (GA), mainline legacy, low cost, and regional, then to specify coefficients for each group. The coefficient values are varied between users placing no weight on NAS impacts ($\alpha_4=0.0$) to a 50% weight on NAS impacts ($\alpha_4=0.5$) during the simulation experiments discussed in Table 1 in Section IV.

The service provider delay feedback information will not be as accurate as the delay information the service provider uses for two main reasons. First, due to latencies accumulated when the service provider generates the delay feedback, sends it to the users, and the users respond by sending the route ranking preference to the service provider this delay feedback may be out-of-date by several minutes. Second, the averaging of delays does not discriminate between higher and lower priority flights in the service provider first-come-first-served (FCFS) queue. Higher priority flights, according to the FCFS ranking, would receive lower delays than lower priority flights when the service provider is making delay decisions. However, this is not reflected in the service provider delay feedback since the delay feedback contains average delays. The aggregate sector count feedback suffers from similar issues.

To partially account for the lower quality information, the users send another piece of information with their highest ranked route: a delay threshold. This threshold is used by the service provider to decide when to switch a flight from the highest user ranked route due to excess delay accumulation along this route. This excess delay accumulation is not accurately known until the service provider makes the route decision so by including the threshold the effect of the inaccuracy of the service provider delay feedback is reduced. If the highest ranking route by the user received more delay than estimated from the service provider feedback then the service provider uses the threshold to consider another route that was not assigned as much delay so that the users are not negatively impacted by the quality of the service provider delay feedback information. The threshold is estimated by the users as the amount of delay that needs to be added to the highest ranked route to make its utility equivalent to the route utility for the second highest ranked route. The service provider uses this threshold as explained in the next subsection.

B. Service Provider Acceptance Criteria for User Route Ranking Preferences

The service provider assigns routes and delays to flights to maintain demand below capacity, specified as the maximum instantaneous sector count, for all constrained sectors. The service provider considers flights impacted by the constraint in a FCFS order based on the time of entry into a congested sector.[18] Impacted flights are projected to occupy a congested sector during the time that demand is projected to exceed capacity. The alternative routes for each flight are considered as follows.

The service provider is modeled to accept or reject user route ranking preferences on the basis of congestion, which is considered the primary service provider objective. The service provider starts evaluating user route ranking preferences by considering the highest ranked route. If the service provider is unable to find a feasible delay solution to maintain demand below capacity then this highest ranked route is rejected and the service provider considers the next highest ranked route. If a feasible delay solution can be found for several alternative routes then the user-provided delay threshold criterion is applied as follows. If the difference in travel time between the highest ranked route and any lower ranked route exceeds the threshold then the service provider switches the flight to the lower ranked route.

In the absence of a route ranking preference for a flight, the service provider makes decisions based on a route travel time savings threshold relative to the currently assigned route. The travel time savings must exceed the threshold for the service provider to switch a flight to an alternative route. The threshold is meant to represent the service provider workload impedance to excessive route switching. As an example, consider a flight with an expected travel time of 60 min along the currently assigned route and a service provider route travel time savings threshold of 10 min. If the travel time along an alternative route is 50 min or less, then the threshold of 10 min is exceeded and the service provider will make the switch. However, if the travel time along an alternative route is 55 min then the route switch would not be made because the 5 min saving is below the 10 min threshold.

C. Example: One Flight and Two Alternative Routes

The example shown in Fig. 1 will be used to demonstrate the user route ranking preferences in a local constraint situation involving a capacity prediction error. Consider a flight travelling from Los Angeles (LAX) to Newark (EWR) along route A when convective weather is forecasted to cause congestion in Cleveland center (ZOB) sector ZOB77. ZOB77 is along route A so the service provider switches the flight to route B, a less desirable route from the user perspective, to avoid the congestion. However, the forecasted convection does not occur and during the recovery the service provider does not switch the flight back to route A. There could be more than one reason for the service provider not to switch the flight to the shorter route but the reason considered in this example is workload. The service provider has obtained a solution that balances demand and capacity and any change will increase workload without reducing congestion. There may also be other constraints which require the attention of the service provider.

If the user sends a preference to the service provider to switch the flight back to route A and the preference is implemented by the service provider before the location where the routes diverge then the flight can be switched back to the original route A and user utility will increase. However, as the flight progresses along route B the benefits of switching back to route A are reduced since additional delay is absorbed.

One of the potential effects of workload is the latency in evaluating the user route

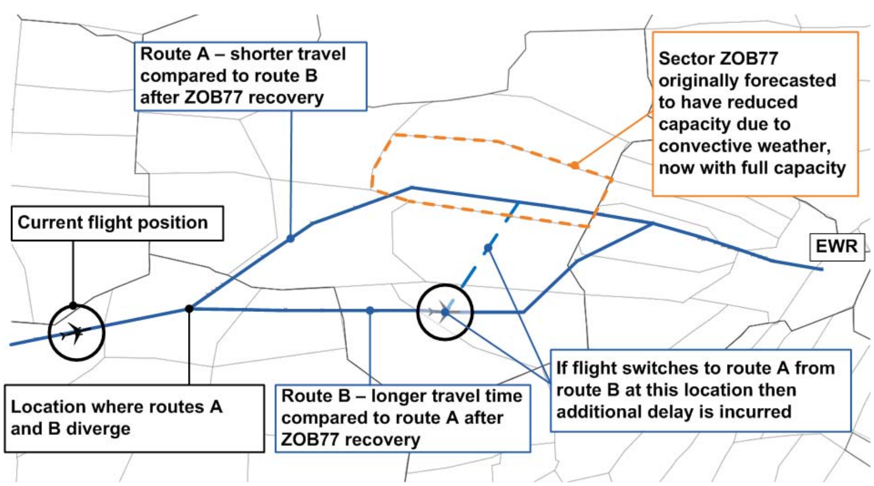

Figure 1. User route ranking preference example with two alternative routes for a flight.

ranking preference, which is considered in this example. The different times that the service provider evaluates the user route ranking preference are shown along the x-axis of Fig. 2, which contains the simulation results. At each of these times a comparison is made based on aircraft delay between the service provider accepting the user preference, the solid black line, or rejecting the user preference, the dashed grey line. The dashed grey line is constant at 12 min of aircraft delay which indicates that if the flight does not switch from route B then 12 min of delay is absorbed. If the flight does switch to route A then the delay must be less than 12 min for the user to benefit. If the service provider is not currently experiencing high workload and is able to implement the route ranking preference before 13:38 then the user benefits, otherwise an implementation later than 13:38 will produce at least 12 min of delay.13:38 corresponds to 33 min after the convective weather is no longer forecasted in ZOB77.

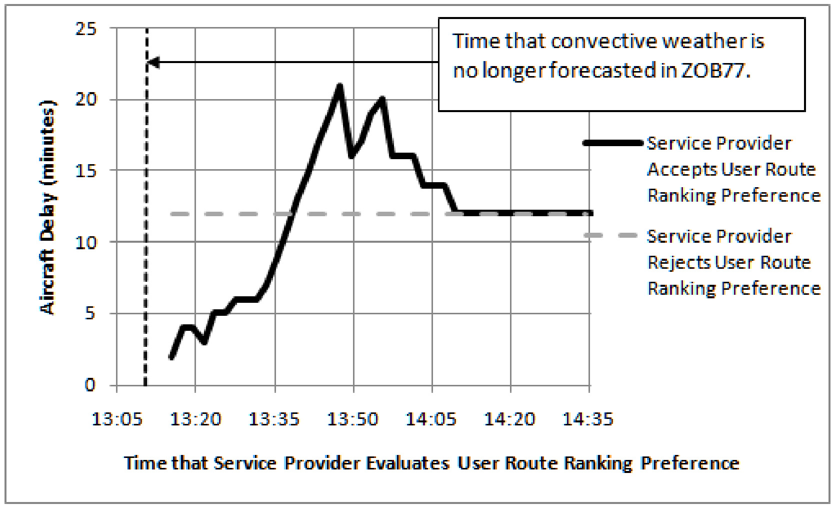

Figure 2. Aircraft delay as a function of the time that the service provider evaluates the user route ranking preference. Later times correspond to higher levels of service provider workload.

The oscillations in the solid black line in Fig. 2 are caused by trajectory selection logic of the fast-time simulator when switching the aircraft from route B to route A. The trajectory, when switching from route B to route A, is represented as a dashed line in Fig. 1. The heading and length of this dashed line will change as the flight progresses along route B impacting the aircraft travel time.

III. User Location to Absorb Delay Preference

A user location to absorb delay preference specifies where the users prefer to absorb delay for a flight relative to a congested region of airspace. As a simplification, two locations to absorb delay are considered: upstream and downstream. Upstream corresponds to absorbing delay as early as possible and as far from the congestion as possible. Downstream corresponds to absorbing delay as late as possible and as close to the congestion as possible. A previous paper[18], and the Appendix II of this paper, describes a mixed-integer programming model that calculates delay at sectors along a route according to upstream and downstream objectives. The differing user and service provider behavior are first presented followed by an example that shows the impact of the user location to absorb delay preference under capacity uncertainty.

A. User Location to Absorb Delay Behavior

Users are modeled to prefer a downstream location to absorb delay relative to the airspace congestion. A downstream location to absorb delay maintains the aircraft's place in the service provider FCFS queue and can prevent unnecessary delays since the decision to apply delay to a flight can be deferred until the congestion is more certain.

The user location to absorb delay preference is simplified since the characteristics of the flight are not considered when generating the preference. A more complex behavior could be considered where the user preference for higher priority flights would be more downstream while the user preference for lower priority flight would be more upstream. However, the extreme case of a downstream preference for all flights will be used in the experiments to demonstrate the effect of this preference.

B. Service Provider Acceptance Criteria for User Location to Absorb Delay Preferences

The service provider applies an implicit acceptance criterion in the mixed-integer programming model by attempting to accommodate the user downstream preference except in the cases where absorbing delay downstream would result in sector capacity being violated. In the absence of a user location to absorb delay preference the service provider implements an upstream location to absorb delay to allow the service provider more flexibility to reduce the congestion.

C. Example: Five Flights Demanding a Sector with Uncertain Capacity

The example shown in Fig. 3 is used to demonstrate the effect of a user preferred downstream location to absorb delay, as compared to a service provider upstream location to absorb delay, in the presence of uncertainty. In this example there are five flights demanding Cleveland sector ZOB59 with uncertain capacity. If the users do not send a location to absorb delay preference then the service provider will delay the flights upstream to prevent demand from exceeding capacity. In this example the upstream location is shown on the left in Fig. 3 just outside the boundary of Cleveland center. When flights are delayed upstream the delays will be absorbed earlier and if the forecasted congestion disappears then unnecessary delay has been incurred. If the users submit a location to absorb delay preference then the flights are delayed downstream closer to the congested sector. In this example the downstream location is shown as the sector to the left of ZOB59. The user may submit a downstream location to absorb delay in this instance if the user decides that the probability of the congestion impacting the user's flights is low.

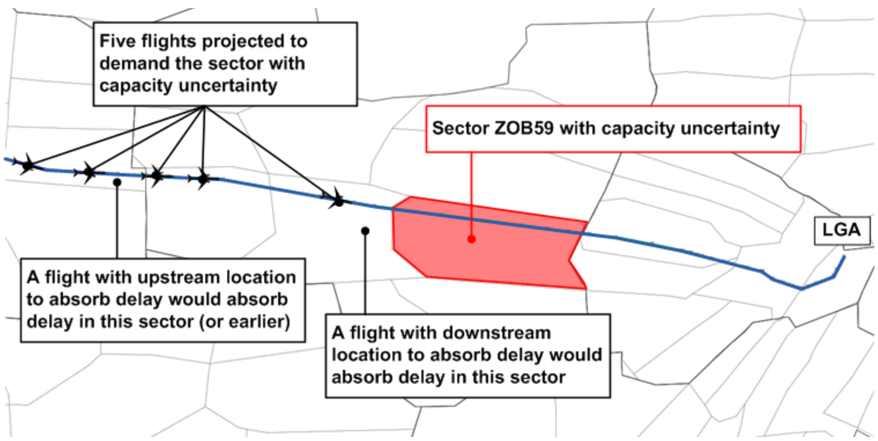

Figure 3. User location to absorb delay preference example with five flights demanding a sector with uncertain capacity.

The demand profile for ZOB59 considering these five flights is shown in Fig. 4. Time is along the x-axis while the demand (aircraft count) is along the y-axis. A solid black line indicates the demand from the five flights, which peaks at three. Dashed grey lines indicate the three forecasted capacities of one, two, and three slots. A forecast of one available capacity slot for these five flights is made between 22:00 and 22:20. Similarly, capacity forecasts of two and three available capacity slots are made between 22:20 to 22:40 and 22:40 to 23:00 respectively. The service provider assigns delays to flights based on the most recent forecasted available capacity.

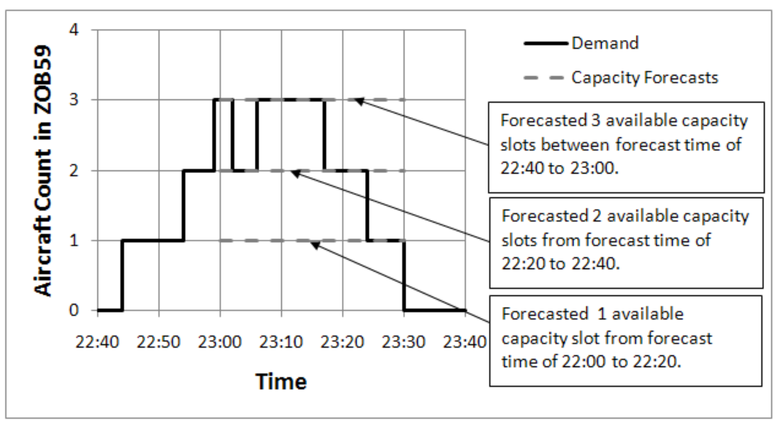

Figure 4. Sector ZOB59 demand and forecasted capacity profile for user location to absorb delay preference example.

The total aircraft delay assigned to the five flights is a function of the time that the service provider evaluates the user location to absorb delay preference as shown in Fig. 5 based on simulation results. A later evaluation of user preferences corresponds to the service provider experiencing workload that impedes consideration of user preferences which results in upstream delays. The plot is divided into three time periods of 22:00 to 22:20, 22:20 to 22:40, and 22:40 to 23:00 representing the three forecasts of one, two, and three available capacity slots for these five flights. The dashed grey horizontal line indicates that a total of 25 min of delay will be assigned to these five flights if the user downstream location to absorb delay preference is not implemented. The solid black line indicates that after 22:17 the aircraft start to absorb delay which cannot be reversed if the forecasted congestion does not occur. The corresponding user benefits also start to decrease after 22:17. By 22:40

the aircraft have already absorbed 25 min of delay so the updated forecast of three available capacity slots cannot be used to reduce the imposed delay.

IV. Results for User Preferences in a Cleveland Center Scenario

A local scenario in Cleveland center is considered to gain broader insights into the route ranking and location to absorb delay user preferences in a scenario with significant traffic. A range of capacity uncertainties is simulated ranging from capacity under-prediction, where the forecasted capacity is less than the eventual capacity, to capacity over-prediction, where the forecasted capacity is greater than the eventual capacity. Demand uncertainty is also introduced by reducing the prediction accuracy of wheels-off time from the service provider perspective. First, a description of the fast-time simulation environment is presented followed by the traffic demand and sector capacities used in the scenarios. Then, the route ranking user preference is considered in isolation under a range of service provider behaviors. The user preference for location to absorb delay is similarly evaluated in isolation under a range of capacity uncertainties from forecasted under-prediction to over-prediction of capacity. Finally, a combined case with both route ranking and location to absorb delay preferences is presented based on insights gained from studying the user preferences in isolation.

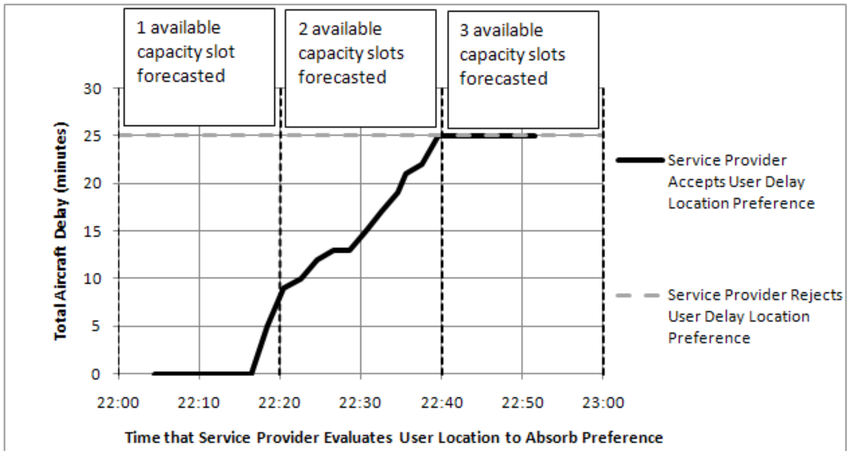

Figure 5. Total aircraft delay for the five impacted flights as a function of the time that the service provider evaluates the user location to absorb delay preference. A later time corresponds to the service provider objective of delaying flights upstream to maintain flexibility in resolving the congestion.

A. Simulation Parameters

A discrete event simulation environment was developed that models the users and the air traffic service provider as agents that collaborate through a messaging system. The simulation is time-stepped by fixed time increments of one minute duration. The platform leverages the capabilities of the Future ATM Concepts Evaluation Tool (FACET)[16] for modeling sectors and aircraft trajectories.

The service provider identifies constraints at 15 minute intervals (parameter 1 in Table 1) based on aircraft following their unimpeded trajectory. The service provider looks up to 45 minutes from the current time when identifying constraints (parameter 4 in Table 1). Based on the identified constraint, the service provider estimates the average delays that would reduce demand below capacity and mitigate the constraint based on service provider objectives then sends these average delays to the users at 5 minute intervals (parameter 2 in Table 1). The service provider identifies flights impacted by the constraint and sends a list of these flights and the alternative routes available to these flights. After receiving this information from the service provider the users make their route ranking decisions using this delay feedback information and send their route ranking and location to absorb delay preferences at 5 minute intervals (parameter 6 in Table 1) to the service provider. Even though the users send preferences at 5 minute intervals the service provider is modeled to evaluate these preferences at 15 minute intervals (parameter 3 in Table 1). It is expected that the service provider would be more responsive to user preferences in a future automated environment, however the 15 minute intervals are used for computational reasons. Latency in the service provider evaluation of user preferences is not varied during the experiments. Other timing schemes are also possible where the users react to the service provider and vice versa but are not considered. An example of an alternative timing scheme not considered is for the users to generate preferences at irregular time intervals and for the service provider to evaluate the preference upon receiving the preference from the users.

Three sets of user route utility coefficients are shown in Table 1 representing a range of user behavior from no consideration of NAS impacts by the users (parameter 7) to a high weight of NAS impacts (parameter 9). In the case that NAS impacts are considered the α_4 coefficient for the parameter $I_{NASimpact,k}$ is set to 0.5 for legacy, low-cost and regional airlines, and the α_4 coefficient is set to 0.0 when NAS impacts are not considered. These two sets of coefficients are used as experimental factors to test the effect of users considering NAS impacts.

The service provider route travel time savings threshold (parameter 5) is also varied as a factor to show a range of service provider behavior when the users are not sending a route ranking preference. A range of 0 to 30 min is considered for the threshold when the route ranking user preference is studied in isolation from the location to absorb delay user preference. For the location to absorb delay experiments and the combined route ranking and location to absorb delay experiments a value of 5 min is selected for the route travel time savings threshold which will be shown experimentally to be the best service provider behavior for this scenario.

Table 1. Simulation parameters.

	Agent	Parameter	Value	Description
1	Service provider	Constraint identification period	15 min	The interval that the service provider evaluates projected demand and capacity and identifies constrained sectors.
2	Service provider	Delay feedback period	5 min	The interval that the service provider sends delay feedback to the users.
3	Service provider	User preference evaluation period	15 min	The interval that the service provider evaluates user preferences.
4	Service provider	Projection time	45 min	The projected time in the future, measured from the current simulation time, that the service provider evaluates constraints.
5	Service provider	Route travel time savings threshold	varied 0 to 30 min	The route travel time savings threshold (the minimum time savings for the service provider to make a route switch in the absence of route preferences, is varied from 0 to 30 min).
6	Users	Send preferences	5 min	The users send route ranking and location to absorb delay preferences to the service provider at 5 min intervals.
7	Users	Route coefficients with no weight to NAS impacts	Legacy: α_1=0.65, α_2=0.2, α_3=0.15, α_4=0.0 Low-cost and regional: α_1=0.9, α_2=0.0, α_3=0.1, α_4=0.0 General aviation: α_1=0.0, α_2=0.0, α_3=1.0, α_4=0.0	
8	Users	Route coefficients with low weight to NAS impacts	Legacy: α_1=0.5, α_2=0.2, α_3=0.15, α_4=0.15 Low-cost and regional: α_1=0.8, α_2=0.0, α_3=0.1, α_4=0.1 General aviation: α_1=0.0, α_2=0.0, α_3=1.0, α_4=0.0	
9	Users	Route coefficients with high weight to NAS impacts	Legacy: α_1=0.15, α_2=0.2, α_3=0.15, α_4=0.5 Low-cost and regional: α_1=0.4, α_2=0.0, α_3=0.1, α_4=0.5 General aviation: α_1=0.0, α_2=0.0, α_3=1.0, α_4=0.0	

B. Scenario Demand and its Uncertainty

In the scenario, convective weather is forecasted to impact Cleveland center between 5-7 PM Eastern Daylight Time (EDT) on June 19, 2007. Aircraft Situation Display to Industry (ASDI) flight data were used in FACET to extract 1,576 flights 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). Of these 1,576 flights approximately 1,000 to 1,200 are projected to contribute to the congestion and are included in the simulated traffic management initiatives. The remaining flights are background traffic and more or less of these flights are included in a traffic management initiative depending on whether the constraint expands in time and space. The ASDI traffic data is from another day, May 6, 2004, to eliminate the effect of any traffic management initiatives that may have existed in the June 19, 2007 ASDI traffic data.

Demand uncertainty is considered in the scenario as the service provider inability to accurately predict wheels-off time. Generally, pre-departure uncertainty, and more specifically uncertainty in the wheels-off time, has the largest effect on demand predictions out of the sources of demand uncertainty.[19-21] For this reason, demand uncertainty for this scenario will focus on wheels-off time uncertainty with less attention placed on en route travel time uncertainty. Demand uncertainty due to altitude prediction, lack of coordination between local traffic control facilities, and cancellations are not considered. Across all experiments the level of demand is held constant, but there is uncertainty as to when this demand departs from the origin airport.

The departure error distributions are obtained using 28 days of historical flight departures between 2000 and 2005. Aircraft ASDI data was the source for the errors. This distribution is based on the error relative to the flight plan or flight amendment and not the published flight schedule which could be different from the flight plan. To simplify the modeling only the departure airport size is considered as a factor in the magnitude of the demand uncertainty even though other factors, such as if the user operates with a low cost business model, may have an effect. This demand uncertainty is applied in the simulation as follows. For flights that have a controlled departure time the flight cannot leave before the controlled departure time but may leave later due to uncertainty. For all other flights the departure time may be before or after the planned departure time.

C. En Route Capacity Reduction and its Uncertainty

The capacities of ZOB en route sectors are artificially reduced during 5-7 PM Eastern Daylight Time (EDT) in response to convective weather activity on July 19, 2007. These en route sectors, whose reduced capacities are shown in Table 2, have significant east-west flows between New York and Chicago airports. The focus is on uncertainty in the prediction of en route sector capacity and other airspace resources, such as airports, fixes, and routes, will not be included in the capacity uncertainty modeling. The model to translate weather to sector capacity used for the simulation experiments relates weather coverage to a reduction in sector capacity measured in terms of aircraft count.[22-24]

Table 2 shows the capacity reductions used in the experiments. The first column of Table 2 is the user preference grouping for the capacity scenarios. The first two groups are for the route ranking and location to absorb delay isolated cases while the last group corresponds to the experiments for the combined route ranking and location to absorb delay experiments. The two cases considered for route ranking are no recovery, where the eventual simulated capacity is substantially reduced by convective weather, and a full recovery case, where the forecasted constraint does not occur and full capacity is recovered. In both cases the forecast under predicts the capacity and the accuracy of the forecast improves over time. Five capacity cases are considered for the location to absorb delay preference experiments where each case corresponds to an over- or under-prediction of the eventual simulated capacity. For the combined preferences experiments, a partial recovery case in between the route ranking no recovery and full

Table 2. Scenarios for sector capacity during 5:00 PM to 7:00 PM EDT.

	Capacity Case	Sector(s)	Capacity at Prediction Horizon (min before constraint)			Simulated Capacity
			45 to 30	30 to 15	15 to 0	
Route Ranking	No Recovery	ZOB79/59	3	4	5	6
		ZOB77/57	2	3	4	5
		ZOB74	3	4	5	6
	Full Recovery	ZOB79/59	6	11	16	19
		ZOB77/57	5	9	13	16
		ZOB74	5	9	13	15
Location to Absorb Delay	100% Under Prediction	ZOB79/59	0	3	5	6
		ZOB77/57	0	2	4	5
		ZOB74	0	3	5	6
	50% Under Prediction	ZOB79/59	3	4	5	6
		ZOB77/57	2	3	4	5
		ZOB74	3	4	5	6
	Deterministic Capacity	ZOB79/59	6	6	6	6
		ZOB77/57	5	5	5	5
		ZOB74	6	6	6	6
	50% Over Prediction	ZOB79/59	9	8	7	6
		ZOB77/57	8	7	6	5
		ZOB74	9	8	7	6
	100% Over Prediction	ZOB79/59	12	9	7	6
		ZOB77/57	10	8	6	5
		ZOB74	12	9	7	6
Both Prefs	Partial Recovery	ZOB79/59	6	10	14	14
		ZOB77/57	5	9	13	13
		ZOB74	5	8	12	12

recovery cases is considered. Three prediction horizons are used by the service provider: 45 to 30, 30 to 15, and 15 to 0 min before the constraint is forecasted to occur. The predictions are binned into 15 min intervals so there are eight prediction groupings for the two hour capacity reduction between 5 and 7 PM EDT.

Convective weather on June 19, 2007 extends beyond the boundary of ZOB. However, only the weather in ZOB is considered to confine the scenario to a local problem. 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. The simulation will continue after capacity has recovered to enable analysis for user preferences sent during the recovery period.

D. Results for Route Ranking Preferences Only

For the route ranking experiments, the service provider behavior is varied by considering a range of route travel time savings thresholds (parameter 5 in Table 1) while the user behavior is varied by giving different weights to NAS impacts in their route utility function (parameters 7, 8, and 9 in Table 1). Two capacity scenarios are considered with the no recovery case presented first in Figs. 6 and 7. All of the results in this section, as presented in Figs. 6 to 8, are calculated using the mean value from 20 replications to account for uncertainty. Fig. 6 shows the service provider route travel time savings threshold on the x-axis and the mean delay per aircraft on the y-axis. The solid black line is for the case where no route ranking preferences are sent from the users to the service provider. In this case, as the threshold is reduced there is a corresponding delay savings until a 5 min threshold corresponding to 16.7 min of delay per aircraft, the optimal minimum delay solution for the service provider in this case. Reducing the threshold further to 0 has a small negative effect since the alternative routes have been saturated and there can be additional delay due to latency in route switching as discussed in Section II.

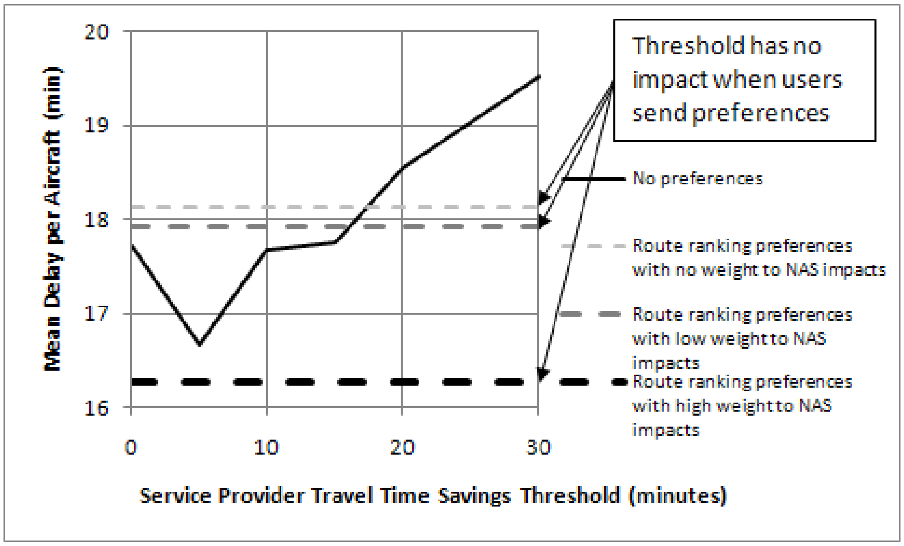

Figure 6. Mean delay per aircraft as a function of the service provider route travel time savings threshold for the no recovery route ranking capacity case. This threshold is only applicable when users do not send route ranking preferences to the service provider.

When users send route ranking preferences, shown as the three dashed horizontal lines in Fig. 6, the service provider route travel time savings threshold is not applicable and instead the range of user behavior is characterized by the weighting given to the NAS impacts factor in the route utility function. If users give greater weight to NAS impacts then delay can be reduced from approximately 18.1 min of delay per aircraft to approximately 16.3 min of delay per aircraft. The reduction is due to the users sending more flights away from the constraint to the alternative routes, which in this case have more certain capacity and result in lower delays. This implies that, if the constraint capacity does not recover, the users receive the minimum delay solution if they consider NAS impacts even though considering NAS impacts is contrary to user objectives of minimal delays.

Fig. 6 also shows that there are user and service provider behaviors that can result in the route ranking user preference decreasing delay as well as a range that can result in increased delay. The largest delay reduction, relative to the no preferences case, occurs when the users give a high weight to NAS impacts and the service provider has a high route travel time savings threshold. An increased delay result occurs if the users do not consider NAS impacts and the service provider uses a low route travel time savings threshold near 5 min.

A paired-t approach was used to test if the difference between two points on the curves is statistically significant using a 5% confidence interval.[25] Results of the test indicate that, for all service provider travel time savings thresholds, there is no statistically significant difference between the no preferences curve and the route ranking preferences curves corresponding to no weight or low weighting of NAS impacts. However, when high weight is given to NAS impacts there is a statistically significant difference from the no preferences case. The sample standard deviation of the mean delay per aircraft for the route ranking preferences with high weight to NAS impacts is approximately 0.8 min per aircraft and for all other data points in Fig. 6 the standard deviation is approximately 2.6 min per aircraft.

By using a low threshold, however, the service provider can experience high workload as shown in Fig. 7 using a total aircraft route switches metric. This metric is based on planned route switches and the aircraft may be planned to switch between the nominal route, through the constraint, and the alternative routes several times before a physical trajectory change occurs. The metric gives an idea of service provider workload since each of these planned route switches would require a corresponding route string amendment. For the service provider, the total aircraft route switches increases from approximately 225 to 575 when the threshold is decreased from 10 to 0 min respectively. The service provider may not wish to operate with lower thresholds since the workload may be unacceptably high with little delay benefit. On the other hand, when users send route ranking preferences the total route switches is increased to a range of approximately 625 to 725 switches with greater weights for NAS impacts corresponding to more route switches. When NAS impacts are considered there are more switches to alternative routes away from the congestion. The service provider was found to reject between 15 and 60 route ranking preferences on the basis of congestion which corresponds to a route ranking preference rejection rate of approximately 2% to 10%.

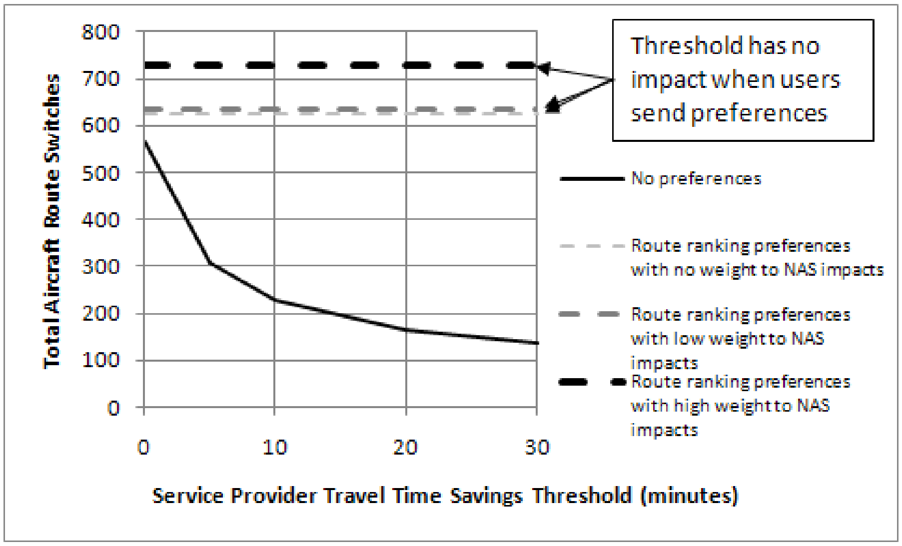

Figure 7. Total aircraft route switches as a function of the service provider route travel time savings threshold for the no recovery route ranking capacity case. This threshold is only applicable when users do not send route ranking preferences to the service provider.

The full recovery capacity case is also considered as shown in Fig. 8 similar to Fig. 6 for the no recovery capacity case. The delays are lower when the users give more weight to NAS impacts in the route utility function starting from an average of approximately 14.0 min of delay per aircraft when users give no weight to NAS impacts, down to approximately 13.4 min of delay per aircraft when users give high weight to NAS impacts during their route ranking decisions. However, the range of user and service

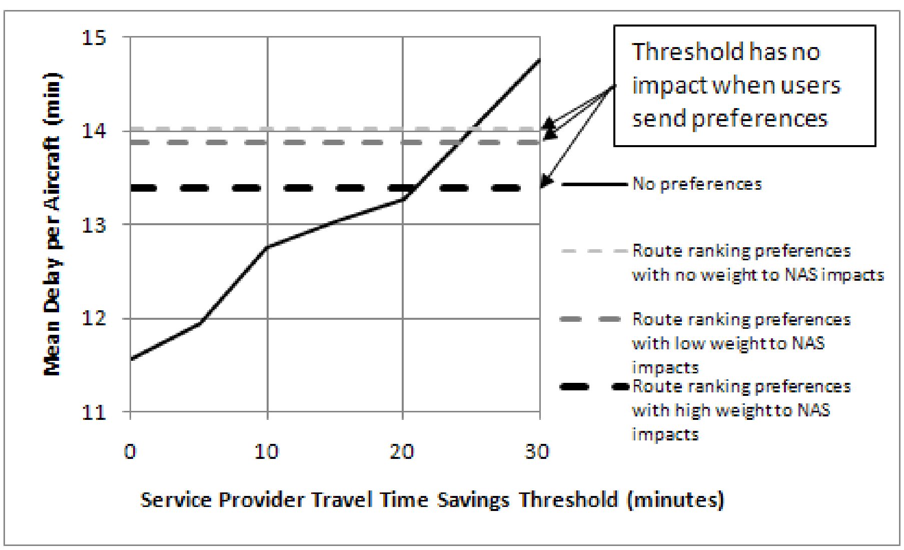

Figure 8. Mean delay per aircraft as a function of the service provider route travel time savings threshold for the full recovery route ranking capacity case. This threshold is only applicable when users do not send route ranking preferences to the service provider.

provider behaviors where the route ranking preference has benefit has reduced to the case where the service provider route travel time savings threshold exceeds 25 min and the users place high weight on NAS impacts during their route decisions. If users weight NAS impacts high in their route decision making this results in lower delays compared to the no weight case. The reason is that the no weight case corresponds to more flights through the projected constraint, causing the service provider to delay flights upstream which does not occur for the high weight for NAS impacts case since the users send flights to alternative routes which are less congested. The users' route ranking preferences result in higher delays relative to the no preferences case since the users are basing their congestion decisions on out-of-date congestion information making the users less responsive to the opening up of available capacity along the nominal routes through the constraint.

The difference between the three curves for route ranking preferences with no, low, and high weights to NAS impacts and the no preferences case are statistically significant. The standard deviations for no preferences at 0 to 30 minute travel time savings thresholds are approximately 0.8 min per aircraft which is lower than for the no recovery case which was approximately 2.6 min per aircraft.

Overall, for both the no recovery and full recovery capacity cases the users are benefiting from considering NAS impacts when generating route ranking preferences. The benefits of the user route ranking preference relative to the no preferences case is impacted by the congestion forecast accuracy indicating that the quality of information provided to the users impacts the benefit of the route ranking preference.

E. Results for Location to Absorb Delay Preferences Only

For the location to absorb delay preferences the user and service provider behavior is held constant and a range of demand and capacity uncertainties is considered as shown in Table 2. This range of capacity over- and under-prediction magnitudes are shown along the x-axis of Fig. 9 with a value of 0 corresponding to a deterministic capacity case since there are no capacity prediction errors. The mean value, out of 20 replications, is presented in Figs. 9 and 10 similar to the isolated route ranking preference results. All along the range of these capacity predictions when the users send a location to absorb delay preference, shown as a solid grey line, there is a reduction of 0.5 to 1.5 min of delay per aircraft relative to the no preferences case, shown as a solid black line. For both solid lines there is demand uncertainty in the experiment. As a comparison, the two data points with circular markers represent the case with deterministic demand and capacity which can be compared to 0 along the x-axis corresponding to deterministic capacity with demand uncertainty. The difference between the no preferences and location to absorb delay preferences cases without demand uncertainty is approximately 1.4 min per aircraft which is approximately equal to the difference of 1.5 min per aircraft for the solid lines representing cases with demand uncertainty. Regardless of the magnitude there is a statistically significant delay reduction when the users send a location to absorb delay preference, across a range of demand and capacity uncertainties, relative to the no preferences case.

However, this delay reduction is at the expense of solving the congestion problem to reduce demand below capacity when the capacity is over-predicted, as shown in Fig. 10 in the range of positive x-axis values. The imbalance metric shown on the y-axis in Fig. 10 is a product of the amount that demand exceeds capacity multiplied by the time duration when capacity is exceeded. The remaining congestion is due to a limitation of the simulation algorithms since the service provider would likely take an action to reduce the imbalance by assigning higher delays. If the higher delays are assigned

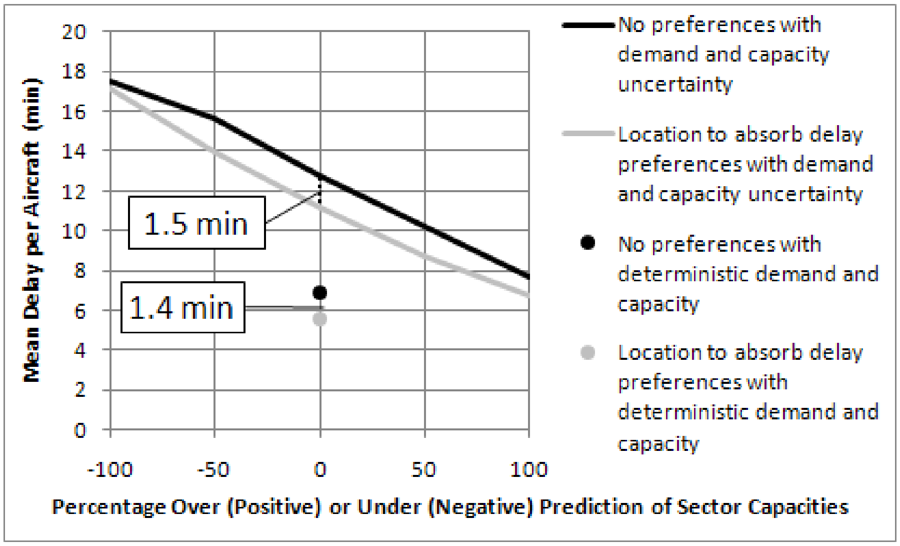

Figure 9. Mean delay per aircraft as a function sector capacity over- or under-prediction for the location to absorb delay experiments.

then the no preferences upstream case may result in lower delays relative to the user preferred downstream case since the upstream case preserves flexibility and a wider range of solutions is available. Therefore, a limited finding can be made, by considering Figs 9. and 10 simultaneously, where the location to absorb delay user preference is observed to create a benefit for the under prediction of sector capacity and deterministic cases since delay reduction was observed relative to the no preferences case and no demand to capacity imbalance remains.

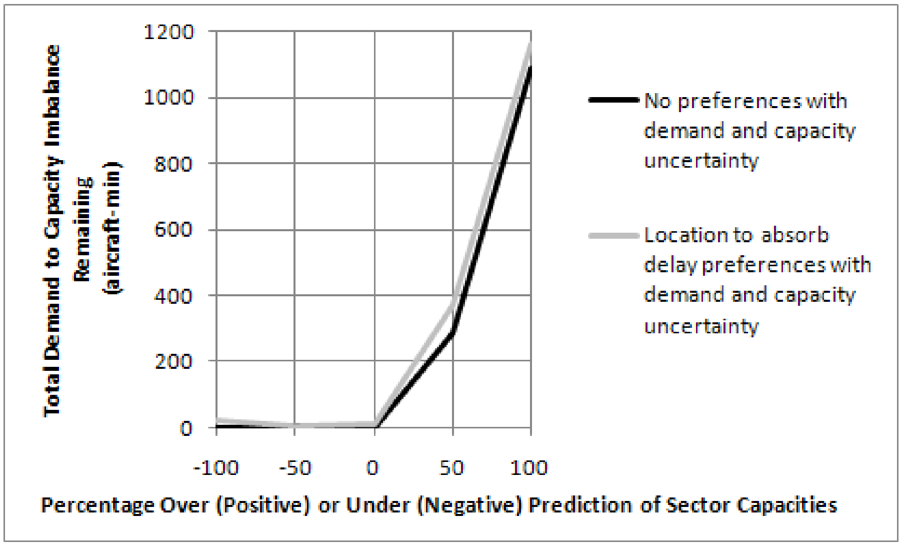

Figure 10. Total demand to capacity imbalance remaining as a function sector capacity over- or under-prediction for the location to absorb delay experiments.

F. Results for Combined Consideration of Route Ranking and Location to Absorb Delay User Preferences

To compare the route ranking and location to absorb delay preferences a combined case is now considered. When considering route ranking, the user and service provider behaviors that result in the minimum delay are selected for the combined case. The service provider applies a 5 min route travel time savings threshold in the absence of user route ranking preferences while users place a high weight on NAS impacts when generating their route ranking preferences. When capacity is under-predicted there is a benefit for the location to absorb delay user preference without remaining demand to capacity imbalance so a partial capacity recovery case, which corresponds to capacity under prediction, is selected for the combined case shown in Fig. 11. Along the x-axis of Fig. 11 are different combinations of user preferences starting with the case that users do not send any preferences (left column) followed by the isolated route ranking only (second column from left) and location to absorb delay only (third column from left) preferences as considered earlier. Finally, a case where users send both route ranking and location to absorb delay preferences is considered (right column) to demonstrate interaction effects between the two preferences.

When users send route ranking preferences the delay of approximately 14.2 min per aircraft exceeds the no preferences case where total aircraft delay is approximately 12.0 min per aircraft. This difference between the route ranking preference and no preference cases of approximately 2.2 min per aircraft is greater than the full recovery case of a 1.4 min per aircraft increase in delay. This result is consistent with the finding that the effect of the route ranking preference depends upon the accuracy of the capacity prediction and the corresponding quality of the

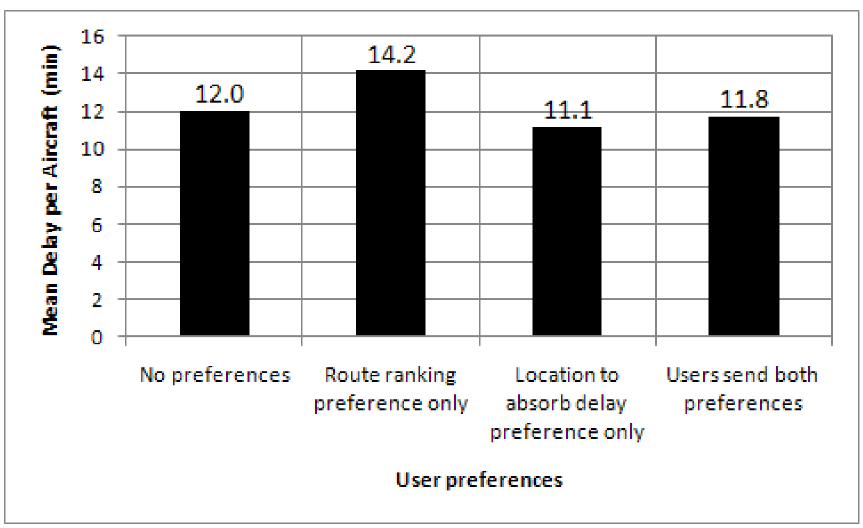

Figure 11. Comparison of mean delay per aircraft under combinations of route ranking and location to absorb delay user preferences.

aggregate sector counts users incorporate into their decision making.

When users send a location to absorb delay preference the total aircraft delay is reduced from approximately 12.0 min per aircraft to approximately 11.1 min per aircraft. This 0.9 min per aircraft delay reduction is consistent with 0.5 to 1.5 min per aircraft delay reduction range for the location to absorb delay preference considered in isolation in Fig. 9. The right-most column in Fig. 11 shows the combined case where users send route ranking and location to absorb delay preferences. In this case the benefit of the location to absorb delay preference, when combined with the route ranking preference, is greater at approximately 2.4 min per aircraft (comparing the second from left and right columns) as compared to the case when the route ranking preference is not used with the location to absorb delay preference (comparing the left and second from right columns). This indicates that the effects of the route ranking and location to absorb delay preferences may not be additive and larger benefits may result from combining these preferences under some conditions. However, additional analysis of a larger range of scenarios is needed.

V. Conclusion

A fast-time simulation environment was used to evaluate route ranking and location to absorb delay preferences for a Cleveland center convective weather constraint under demand uncertainty and a range of capacity over- and under-prediction cases. We find that the users are benefiting from considering an aggregate congestion impact metric when sending a route ranking preference to the service provider. The location to absorb delay user preferences are observed to create a benefit for the under-prediction of sector capacity and deterministic cases since delay reduction was observed relative to the no preferences case and no demand to capacity imbalance remains.

Future work could focus on considering different behaviors for user preference generation and service provider acceptance or rejection of preferences. One alternative scheme for the route ranking preference would be for the users to send their route utility function and flight data, such as passenger connections, to the service provider and the service provider to use this information for ranking routes based on the user route utility function. This alternative route ranking scheme could leverage the better quality information that the service provider has when making route decisions as compared to the delay and sector count feedback. The delay and congestion feedback sent by the service provider to the users impacts the user route ranking decisions and alternative forms of service provider feedback could be considered in future work. The service provider criteria for evaluating user flight ranking preferences on the basis of congestion could also be varied by introducing parameters that result in different acceptance or rejection behavior in the evaluation of user route ranking preferences.

The behavior of the users in generating a location to absorb delay preference was simplified in this paper so that downstream was the preference for all flights. However, other behaviors could be considered where higher priority flights are assigned a downstream preference and lower priority flights are assigned an upstream preference. Future work could link the characteristics of the flight to a location to absorb delay preference. Similarly, the service provider behavior in attempting to meet the downstream location to absorb delay preference could be modified based on the severity of the congestion and the contribution of a flight to the congestion so that the preference is rejected and additional delay imposed to meet service provider objectives.

Appendix I

Calculation of the cost indices for the user route ranking utility function in Eq. (1) in Section II is described in this appendix. The fuel burn cost index, $I_{fuel,k}$, is obtained by estimating the fuel burn from the current position of the flight to the destination and normalizing to a range of [0,1] across all available alternative routes as shown in Eq. (3). The route that requires the minimum fuel burn is normalized to 0 ($I_{fuel,k} = 0$) while the route that requires the maximum fuel burn is normalized to 1 ($I_{fuel,k} = 1$) out of the set of route alternatives. In the cases where minimum and maximum fuel burns are equal then $I_{fuel,k} = 0/0 = 1$ is chosen as a convention. Higher values of the fuel burn cost index are considered worse.

$$I_{fuel,k} = \left(\frac{Fuel_k - Fuel_{\min}}{Fuel_{\max} - Fuel_{\min}} \right) \tag{3}$$

Where $Fuel_k$ is the fuel burn for route k, $Fuel_{min}$ and $Fuel_{max}$ are respectively the minimum and maximum fuel burns across all alternative routes. Excess fuel burn caused by delays is calculated as the product of total delay along the route and the average fuel burn per minute obtained from an unimpeded trajectory. Total delay is obtained by summing the delays at each sector along the route according to the service provider delay feedback.

The index $I_{AOCimpact,k}$ represents the disruption that delaying a flight can have on other flights operated by the same user. Maintaining the flight schedule is important for flights with a high percentage of connecting passengers through hub airports. A buffer is first defined as the difference between the estimated time of arrival (ETA) to the destination airport and the scheduled time of arrival (STA) to the destination airport as shown in Eq. (4). This buffer is then used to specify the airline operations center (AOC) impact index in Eq. (5).

$$Buffer_k = ETA_k - STA_0 \tag{4}$$

$$I_{AOCimpact,k} = \left(\frac{Buffer_k - Buffer_{\min}}{Buffer_{\max} - Buffer_{\min}} \right) \tag{5}$$

Where $Buffer_k$ is the arrival time buffer for alternative route k, ETA_k is the estimated time of arrival for route k, and STA is the scheduled time of arrival to the destination airport. The ETA is the summation of unimpeded time along the route and average delays estimated from the service provider delay feedback. The STA is the unimpeded arrival time based on the flight following the nominal trajectory to the destination. $Buffer_{min}$ and $Buffer_{max}$ are respectively the minimum and maximum values of $Buffer_k$ across all alternative routes. In cases where the minimum and maximum buffer are equal, then $I_{AOCimpact,k}$ = 0/0 = 1 is chosen as a convention. Also, similar to the fuel burn index, $I_{AOCimpact,k}$ is normalized between 0 and 1.

The long-term benefit of on-time performance is reflected in the customer satisfaction index, $I_{sat,k}$. On-time performance is positively correlated with customer satisfaction, airline profit, and airfare. Long flight delays decrease customer satisfaction, especially for connecting passengers. To simplify the index the FAA's 45 min rule, where the FAA requests that at least 45 min are scheduled for passenger connections, is used as a criterion to scale the delays. The assumption is that flight delay of more than 45 min affects both connecting passengers and non-stop passengers. Flight delay between 15 and 45 min mostly affects connecting passengers. Flight delays less than 15 min are not included since the FAA considers less than 15 min of delay as on-time. The customer satisfaction index, I_{sat}, is defined in Eq. (7) based on the definition of scaled delay in Eq. (6).

$$S_k = \begin{cases} D_k & \text{if } D_k \geq 45\,\text{min} \\ D_k C_R & \text{if } 15\,\text{min} \leq D_k < 45\,\text{min} \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

$$I_{sat} = \begin{cases} S_k / S_{\max} & \text{if } S_{\max} > 0 \\ 0 & \text{if } S_{\max} = 0 \end{cases} \tag{7}$$

Where D_k is the delay along route k, C_R is the connecting rate at the destination airport, S_k is the scaled delay for route k, and S_{max} is the maximum value of S_k across all alternative routes. The delay D_k is the summation of average delays at each sector along the route according to the service provider delay feedback. The connecting rate, C_R, was obtained from the Bureau of Transportation Statistics based on the ratio of connecting passengers to the total arrivals at an airport. The convention $I_{sat,k}=0/0=1$ and normalization between 0 and 1 is applied as described for the fuel burn and AOC impact indices.

The NAS impact index, $I_{NASimpact}$, is an indicator of whether the users take into account sector congestion along the route based on service provider aggregate sector count feedback. This impact index is used to control how much the users consider service provider concerns in an attempt to lower the risk of a proposed route being rejected. The index is based on the total demand exceeding capacity along the route as shown in Eq. (8). A count of these sectors exceeding the threshold is then made in Eq. (9) with a peak of this count used to scale the NAS impact index in Eq. (10).

$$N_{j,k} = \begin{cases} \sum_t \left[q_{j,k,t} - c_{j,k,t} \right] & \text{if } q_{j,k,t} > c_{j,k,t} \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

$$N_k = \sum_j N_{j,k} \tag{9}$$

$$I_{NASimpact,k} = \begin{cases} N_k / \max_k \{N_k\} & \text{if } \max_k \{N_k\} > 0 \\ 0 & \text{otherwise} \end{cases} \tag{10}$$

Where the congestion $N_{j,k}$ is calculated using $q_{j,k,t}$ and $c_{j,k,t}$, respectively the demand and capacity of sector j during the time periods t that route k is projected to demand sector j. The demand $q_{j,k,t}$ is estimated using service provider aggregate sector count feedback. The total amount demand exceeds capacity along route k is referred to as N_k which is used to define the NAS impact index $I_{NASimpact,k}$ based on the ratio to the peak congestion for route k.

Appendix II

A mixed integer programming (MIP) model is described which minimizes aircraft delay subject to a location to absorb delay preference. The solution follows a 3-stage process. In the first stage the minimum delay solution is obtained. The second stage consists of modifying the minimum airborne delay solution to minimize the difference between an upstream and downstream location to absorb delay. If no solution is found for the stage 1 problem, then stage 3 is invoked which minimizes the time-weighted demand that exceeds capacity.

The MIP model makes delay decisions for one flight and does not attempt to perform system-wide minimization across all flights. This enforces the prioritization of flights in the same order as the service provider first-come-first served priority ranked list of flights.

A. Stage 1 Model

1. *Minimize Delay Objective*

In stage 1, the objective is to minimize delay without consideration for airline preferences as shown in Eq. (11).

$$\min \sum_{j} d_j + d_G \tag{11}$$

Where d_j is a decision variable representing the delay to be absorbed in sector j and d_G is a decision variable representing the delay to be absorbed on the ground. For the stage 1 model the delay to assign for each sector is calculated so that total delay is minimized and sectors with demand equal to or exceeding capacity are avoided. Equations (11)-(21) define the first stage of the model. Decision variables and coefficients appear on the left hand side and constants on the right hand side of each of these equations.

2. *Air/Ground Delay*

If an aircraft is on the ground and upstream delay is preferred, then airborne delay is constrained to zero as shown in Eq. (12).

$$\sum_{j} d_j = 0 \tag{12}$$

Conversely, if an aircraft is airborne or downstream delay is preferred then an explicit constraint to prevent ground delay is added in Eq. (13). Since the preference is either upstream or downstream only one of Eq. (12) or Eq. (13) is included in the stage 1 model. If a feasible solution cannot be found then these constraints are relaxed in the stage 3 model.

$$d_G = 0 \tag{13}$$

Ground delay is also used to specify the entry time to the first sector in Eq. (14). By convention the unimpeded departure time occurs at a time of zero:

$$d_G - t_0^{entry} = 0 \tag{14}$$

Where t_0^{entry} is a decision variable representing the entry time to the first sector along the route.

3. *Sector Entry Time Constraint*

The entry time to a sector is constrained to the exit time from the previous sector as shown in Eq. (15).

$$t_j^{entry} - t_{j-1}^{exit} = 0 \qquad \textit{for } j=2,\ldots,m \tag{15}$$

Where t_j^{entry} and t_j^{exit} are decision variables representing entry and exit times from sector j respectively and m is the total number of sectors for which delay will be applied. The first sector entry time is constant.

4. *Time in Sector Constraint*

Equation (16) sets the decision variable representing exit time from a sector based on the entry time, delay absorbed, and the minimum traversal time through the sector.

$$t_j^{exit} - t_j^{entry} - d_j = ETE_j \qquad \textit{for } j=1,\ldots,m \tag{16}$$

Where ETE_j is a constant representing minimum en route traversal time through sector j.

5. *Time of Sector Entry or Exit Relative to Congested Sector Time Start or End*

Binary decision variables are introduced to determine whether the time of entry to a sector is earlier or later than the time a sector has demand equal to or exceeding capacity. The first of these equations, Eq. (17), specifies that the time of entry can be earlier or later than the demand that exceeds capacity but not both. There may be multiple time periods that demand exceeds capacity for a sector. Each of these time periods where demand exceeds capacity is assigned an index *k*.

$$LT_{j,k}^{entry,start} + GT_{j,k}^{entry,start} = 1 \qquad \textit{for } j=1,\ldots,m \quad k=1,\ldots,n_j \tag{17}$$

Where $LT_{j.k}^{entry,start}$ is a decision variable that equals 1 if the time of entry to sector *j* is less (earlier) than the start time of time period where demand exceeds capacity *k* for sector *j*, and 0 otherwise. The first subscript for sector *j* refers to the first superscript of entry and similarly the second subscript for demand exceeding capacity *k* refers to the second superscript for start. Another decision variable, $GT_{j,k}^{entry,start}$, equals 1 if the time of entry to sector *j* is greater (later) than the start time of demand exceeding capacity *k*, and 0 otherwise. n_j is a constant representing the count of demand-to-capacity imbalances in sector *j*. Corresponding to Eq. (17), Eqs. (18) and (19) are used to set the decision variables for the relative times:

$$t_j^{entry} + r_{j,k}^{start} LT_{j,k}^{entry,start} \geq r_{j,k}^{start} \qquad \textit{for } j=1,\ldots,m \quad k=1,\ldots,n_j \tag{18}$$

$$t_j^{entry} - M \;\; GT_{j,k}^{entry,start} \leq r_{j,k}^{start} \qquad \textit{for } j=1,\ldots,m \quad k=1,\ldots,n_j \tag{19}$$

Where $r_{j,k}^{start}$ is a constant representing the start time of demand exceeding capacity *k* for sector *j* and *M* is an arbitrary number larger than t_j^{entry}. Equations (17) to (19) are for the time of entry to a sector relative to an imbalance start. Similar equations are required for three additional conditions: time of entry to a sector relative to an imbalance end, time of exit from a sector relative to an imbalance start, and time of exit from a sector relative to an imbalance end.

6. Avoid Time When Demand Exceeds Capacity

To avoid the time when demand exceeds capacity a constraint is added in Eq. (20) that specifies that the flight must exit the sector before the start time or enter after the time when demand exceeds capacity.

$$LT_{j,k}^{exit,start} + GT_{j,k}^{entry,end} = 1 \qquad \textit{for } j=1,\ldots,m \quad k=1,\ldots,n_j \tag{20}$$

7. Delay Increment

It is possible that the model introduces delay in increments that are too short for the controller to effectively increment. For example, a one-min delay may be feasible solution to the model but not reasonable. To account for this a minimum delay increment is introduced in Eq. (21):

$$d_j - \alpha_j d_j^{\text{int}} = 0 \qquad \textit{for } j=1,\ldots,m \tag{21}$$

Where α_j is a constant coefficient representing the minimum increment of delay for sector *j* and d_j^{int} is a general integer decision variable that applies the increment to d_j.

B. Stage 2 Model

Solving the stage 1 model defined in Eqs. (11) to (21) yields the minimum total delay d^*_{total} if the problem is feasible. The stage 2 model modifies the stage 1 model to meet either an upstream or downstream location to absorb delay objective. The stage 3 model in the next section is used when a solution cannot be found to the stage 1 model. However, there may be alternative solutions as to where to allocate this delay to better accommodate airline preferences.

Equation (22) first specifies that the delay should not be increased above the minimum delay:

$$d_{total}^{*} - \sum_j d_j = 0 \tag{22}$$

Where d^*_{total} is a constant representing the minimum total delay obtained from the stage 1 solution.

The objective function in Eq. (11) is then modified to place lower weights on upstream delays or lower weights on downstream delays as shown in Eqs. (23) and (24) respectively. The total delay is still held at the minimum value, but if there is any alternatives to shift the delay upstream or downstream to meet that objective then the model will find that solution.

$$\min \sum_{j} (j-1) d_j \qquad (23)$$

$$\min \sum_{j} (N-j) d_j \qquad (24)$$

Where *N* is the total number of sectors along the route. For the upstream delay objective shown in Eq. (23), ground delays are given a weight of 0 and delays for more downstream sectors, i.e. those with higher *j* indices, are given higher weights. For the downstream delay objective shown in Eq. (24), ground delays are not considered, since they are restricted to zero by the Eq. (13) constraint, and delays for more upstream sectors, i.e. those with lower *j* indices, are given higher weights.

C. Stage 3 Model

The following formulation is used when a feasible solution is not found for the stage 1 model. The stage 2 model also has no solution if the stage 1 model is infeasible. The objective of the stage 3 model is to minimize the product of *(time over capacity)* and *(demand minus capacity)*. In the stage 3 model, the amount that demand exceeds capacity is a constant since the delays assigned to higher ranked aircraft are considered fixed. The problem is to minimize the contribution of this aircraft to the magnitude that demand exceeds capacity.

If a flight is on the ground then both ground delay and airborne delay is permitted in order to consider the largest possible solution space. If both ground delay and airborne delay are permitted then neither Eq. (12) nor Eq. (13) is enforced. If a flight is airborne then ground delay is not possible and Eq. (13) is enforced.

For the stage 3 model, the Eq. (20) constraint in the stage 1 model is deleted and replaced with Eq. (25) to allow demand to exceed capacity which is then penalized in the objective function.

$$LT_{j,k}^{exit,start} + GT_{j,k}^{entry,end} + I_{j,k} = 1 \qquad for\ j=1,\ldots,m \quad k=1,\ldots,n_j \qquad (25)$$

Where $I_{j,k}$ is a decision variable that equals 1 if demand exceeding capacity during time period *k* in sector *j* cannot be avoided, and 0 otherwise. The objective function for the stage 1 model defined in Eq. (11) is replaced with the stage 3 objective function minimizing the time-weighted demand exceeding capacity defined in Eq. (26).

$$\min \sum_{j} \sum_{k} \left(I_{j,k} \left(q_{j,k} - c_{j,k} \right) \left(t_{j,k}^{end} - t_{j,k}^{start} \right) \right) \qquad (26)$$

Where $q_{j,k}$ is a constant representing the demand, $c_{j,k}$ is a constant representing the sector capacity, $t_{j,k}^{end}$ is the end time, and $t_{j,k}^{start}$ is the start time all for sector *j* during time period *k* when demand exceeds capacity.

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