Eleventh USA/Europe Air Traffic Management Research and Development Seminar (ATM2015)

The Effectiveness of a Route Crossing Tool in a Simulated New York Airspace

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***Abstract*— Congested airspace is the cause of many delays in the terminal area and these delays can have a ripple effect on the rest of a nation's airspace. The New York terminal area is an example of where this happens in the U. S. An important goal, therefore, is to increase the efficiency of operations in congested terminal airspace where possible. Modeling studies of arrival and departure flows have shown that sharing of arrival and departure airspace increases efficiency in terminal operations. One source of inefficiency in terminal operations is that departure aircraft are frequently held level *under* arrival flows when it would be more efficient to climb the departure aircraft earlier. A Route Crossing Tool was developed to help controllers climb Newark (EWR) departures to the south earlier by temporarily sharing airspace with arrivals coming into LaGuardia (LGA) from the south. Instead of flying *under* the arrivals, a departure to the south could climb earlier by flying *through* the arrival airspace if there was a suitable gap between arrivals. A Human-in-the-Loop (HITL) simulation was conducted in this environment which compared three tool conditions: Baseline (no tool), a Single Route Crossing tool in which one route through the arrival flow was evaluated for crossing, and a Multi-Route Crossing tool in which five parallel routes were evaluated. In all conditions, the departures could be held level under the arrival flow. The results showed that controllers climbed a higher proportion of departures in the Multi-Route tool condition than in the other two conditions, with a higher proportion of departures climbed in smaller gaps and in front of trailing arrivals. The controllers indicated that the Multi-Route and Single Route tools helped them estimate distances more accurately and rated safety, workload, and coordination in the simulation as acceptable.**

Keywords*—air traffic control tools; terminal airspace; aircraft trajectory efficiency; aircraft fuel efficiency; decision support tools

I. BACKGROUND

A. Example of Terminal Airspace Congestion: New York

The New York terminal area is known for its limited airspace and airport resources. These limited resources and high demand are responsible for the high number of aircraft delays there: 46% of all U.S. National Airspace System delays occur in the New York/Philadelphia area despite the fact that this area handles only 12% of the domestic traffic [1, 2]. The combined arrival/departure delays were estimated to cost New York passengers and air carriers an estimated $2.6 billion in 2008 [2]; total delays in the U. S. National Airspace in 2007 were estimated to cost $41 billion by the U. S. Senate Joint Economic Committee Majority Staff [3]. To illustrate the volume and complexity of traffic in the New York airspace, five hours of traffic are shown in Fig. 1; the colored lines indicate aircraft flight paths to and from the region's airports.

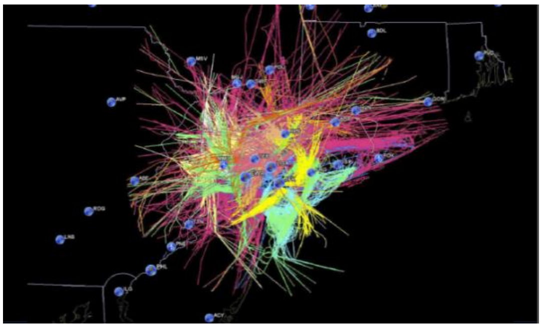

Figure 1. Five hours of NY area traffic (blue circles are airports). [4]

B. Studies Indicate Shared Airspace Increases Efficiency in the Terminal Area

The benefits of shared airspace have been suggested by two modeling studies [5, 6]. The objective of these modeling efforts was to determine the minimum time for arrivals to land and for departures to exit the terminal area. The planning algorithm could either (1) assign a departure to the longer spatially separated route or (2) schedule it to a gap in the arrival flow (shared airspace). If a gap was not present, the algorithm investigated the possibility of slowing down the arrival aircraft to build a suitable gap. The algorithm then chose either the shortened route into shared airspace or the longer route with spatial separation, depending on which choice minimized the total delay for both arrivals and departures. Being able to use shared airspace along with spatially separated airspace resulted in less overall system delay than if the aircraft used only spatial separation or only shared airspace.

C. Predicted Issues in Making Shared Airspace Operational

Some of these issues include the following:

- Additional coordination would be needed between controllers in departure and arrival sectors and

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between TRACON and tower with extra workload involved;[1]

- Difficult perceptual judgments would be needed from controllers to apply separation rules to aircraft in different and distant flows;
- Variability in aircraft departure times [7] and climb rates would make it difficult for departures to take advantage of a predicted gap in an arrival stream;
- Prediction and possibly control of gaps would be needed in the arrival flows;
- Adequate time for flight crews would be needed to prepare for different departure routes.

D. Previous Work

Expedite Departure Path (EDP) was an earlier NASA research program [8, 9] which gave TRACON controllers heading, speed, and altitude advisories for vectors "when unrestricted climbs were available for departing aircraft" with the goal of "eliminating inefficient tunneling beneath arrival streams when traffic allowed" [10]. This was in addition to EDP's many other goals, such as providing efficient aircraft sequencing, departure fix merging, and departure gate balancing. The EDP algorithm calculated: (1) all possible routes to the departure fix using different coordination points, (2) the sequence of departures based on merges at a downstream fix, and (3) any conflicts or undue delay—which would result in a recalculation of steps 1 and 2 until a clear and efficient route was found. Finally, the algorithm (4) assessed any conflicts in the pre-coordination zone where departures crossed arrivals flows in an unrestricted climb. Unfortunately, "inaccuracies in predicting aircraft weight, aero-propulsive model data, airline procedures/pilot interaction with controllers, and wind prediction were found to be significant"[8]. A later simulation of actual Potomac TRACON traffic showed that most EDP benefits would have come from the unrestricted departure climb [9].

Additional research that we have done in the Airspace Operations Laboratory (AOL) at NASA Ames has focused on the unrestricted departure climb under the auspices of SOAR (Sharing of Airspace Resources). In addition to using scheduling algorithms similar to the EDP project, we have tried to increase controller awareness of the crossing parameters, address coordination issues, and, in the current study, incorporate flexibility by including tactical options to adjust for the variability inherent in the problem. We started with two Human-in-the-Loop simulations—SOAR 1 and SOAR 2, where departures climbed through gaps in arrival flows in a simulated San Francisco Bay area metroplex [11,12,13]. In both simulations, new routes were created for San Jose airport west-bound departures to enable them to fly either beneath or through the flows to San Francisco and Oakland airports instead of spiraling up to fly over these flows. The "safe" routes were those flown under the arrival flows at 5,000 feet and by default the departure aircraft were kept there. When gaps opened up, controllers could clear the aircraft to 11,000 feet to fly through the arrival flows. This procedure therefore did not involve a change in lateral route, just in altitude.

a) Findings from SOAR 1 include:

- Departures could climb earlier if the tower handed the aircraft off to an arrival sector instead of a departure sector;[2]
- The point out procedure used for coordination between arrival sectors was overly cumbersome and time-consuming;
- Controllers successfully vectored opportunistically to take advantage of natural gaps;
- Although timelines gave some awareness of crossing parameters to controllers, it appeared that in the field, they would need improved tools [11].

b) Findings from SOAR 2 include:

- Pre-arranged Coordination Procedures (P-ACP) worked better than point-outs to coordinate departures in the arrival sectors [13];
- The two decision support tools tested had drawbacks. The tie boxes were static drawings on videomaps, and did not take into account wind and departure climb speed. The conflict probe, while dynamic, did not give path options to maintain separation [12].

In SOAR 2, separation was lost in a few instances [12]. This was due to variable aircraft climb performances (which reflect operations in the field) as well as not providing controllers with accurate estimates of separation between the departure and arriving aircraft. Controllers' awareness of the crossing parameters needed to be increased further still.

E. New Tool

SOAR 1 and SOAR 2 showed the need for a dynamic decision-support tool, one that used estimated times of arrival (ETAs) of a pair of aircraft at crossing fixes to assess their separation, as well as offered trajectory and path options to controllers to enable them to select the best crossing point. Such a tool would also take into account separation standards and winds. The tool we developed, the Route Crossing Tool, was described in detail in an earlier paper [14]. Our goal in this simulation (SOAR 3) was to adapt and test this tool in the New York airspace.

II. METHOD

A. Assumptions

We assumed a NextGen environment with RNAV/RNP arrival and departure procedures, and in our tool conditions, Terminal Scheduling and Spacing (TSS) technologies. The

[1] Sector shape may increase the need for coordination even further. Current sectors are designed for spatially segregated routes, usually with arrival sectors flatter and departure sectors thicker since aircraft descend at a shallow angle and climb at a steeper angle. Hence a departure aircraft traveling through arrival sectors might cross more sectors than usual.

[2] The arrival sector controller separated both departures and arrivals and could make the decision to climb earlier.

metering was based on the NASA Ames Traffic Management Adviser with Terminal Metering (TMA-TM) research [15]; the controller spacing tools were based on the NASA Ames Controller Managed Spacing (CMS) research [16]. TSS tools were emulated for departures (TSS-D) as well as arrivals. For all conditions, new Optimized Profile Descents (OPDs) were developed. For the flight deck, we assumed that the alternate departure routes were published and were already available in the FMS or could be uploaded rapidly.

B. Simulation Airspace

Figure 2 shows the airspace selected for the simulation, with the two main airports in bolded fonts, the LGA arrival routes in blue, a new departure route from EWR to the fix WHITE in black, and the intersection of the departure and arrival routes at the MOFT fix circled in red. The airspace was modified to accommodate the LGA arrival and EWR departure routes. The EWR departures to WHITE could be held level at 8,000ft to fly under the LGA arrivals at MOFT, or, if there were a sufficient gap in the arrivals, through the arrival flow at a higher altitude. The LGA arrivals were at 11,000' at the ARIAN fix and 9,000' at RABBA.

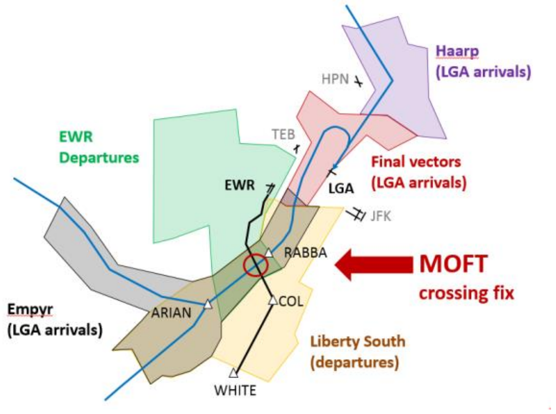

Figure 2. NY simulation airspace showing arrival routes (blue) into La Guardia (LGA) and a new departure route (black) from Newark (EWR) to the WHITE fix. The routes intersect at the MOFT fix (red circle).

C. Analysis of LGA Arrival Traffic for Possible Gaps

We analyzed the LGA arrival traffic to determine whether there were opportunities for EWR departures to climb through gaps in the arrival flow. Fortunately, every arrival from the north into LGA requires additional spacing in the southern arrival flow to enable the northern arrivals to be merged with the southern arrivals. Given the speed of the aircraft, and the need for required separation (described below) we estimated that the inter-arrival spacing would need to be at least 134 seconds to allow a departure to fly between arrivals with enough lateral separation. We found that 43% of all arrivals from the south in a 24-hour period were separated by 134 seconds or more.

D. Route Crossing Tool

1) The diverging separation rule: To create a dynamic route crossing tool, it was necessary to take into account the diverging separation rule. This rule specifies that the standard separation minima in the TRACON airspace (3nm laterally or 1,000 feet vertically) does not apply if aircraft have passed in front of each other, i.e., the routes have diverged [17]. We applied the diverging separation rule when the departure followed a leading arrival, as will be shown. However, for safety reasons, we applied the regular separation standards when a controller climbed the departure in front of a trailing arrival, even after the departure crossed in front of the arrival (see Discussion).

To illustrate, Figure 3 shows four consecutive configurations of leading and trailing arrival aircraft with a departure aircraft. In Fig. 3A (upper left), the departure aircraft is at the point of divergence when the leading arrival is at the route crossing point. At this point of divergence, at x distance from the leading arrival, the departure must conform to separation minima, either altitude of 1,000' or lateral spacing of 3nm (plus a 1 mile buffer in our simulation). However, once the leading arrival has passed this point, at distance s, as shown in Fig. 3B, the departure may climb without risk of violating the separation minima. In Fig. 3C, the departure is at MOFT, and the requirement is for the departure to have 5.6nm separation (y) from the trailing aircraft if they are to have the 4nm necessary minimum separation ($y_{\min}$) after crossing, as shown in Fig. 3D. This follows from (1) below which shows that, if the aircraft are traveling at equal speeds and at constant headings with a course crossing angle of θ, the required separation at crossing ($y_{c,}$) of the departure and trailing arrival aircraft is

$$y_c = y_{min}/\cos(\theta/2). \tag{1}$$

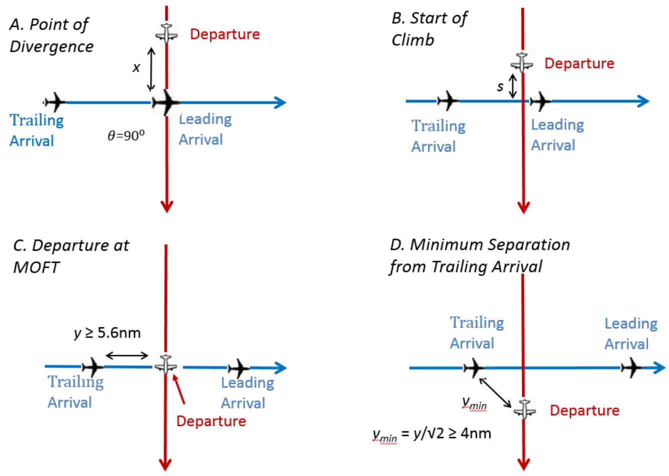

Figure 3. Four consecutive configurations of leading and trailing aircraft with a departure aircraft.

The required distance y of the departure at the crossing point with the trailing aircraft, 5.6nm, was incorporated into the Route Crossing Tool. The Route Crossing Tool also flagged the condition of $x < 4$nm to avoid premature climbing of a departure aircraft with a leading arrival in violation of separation standards.

2) Route structure: The departure aircraft's flying time is affected by the length of each departure route from the airport to the point at which it crosses the arrival route. Fig. 4 below is an illustration of a preliminary departure route "family" in the New York TRACON airspace. Controllers had a set of five parallel Standard Instrument Departure (SID) routes from which to assign aircraft departing from EWR: MOFT0, MOFT2, MOFT4, MOFT6, and MOFT8. The departure aircraft flew southwest until turning left at the particular RESE waypoint (RESE 0 through 6) which corresponded to the SID issued by the controller. While non-parallel routes could have been considered, equivalent flying time differences over alternative routes within the departure route family contributed to the transparency and ease of use of the route crossing tool.

The parallel route structure allowed for adjustments to be made to departures which could alter the tie point between them and an arriving aircraft. For example, a departure aircraft from EWR would intersect the LGA arrival flow approximately a minute sooner if the controller instructed a left turn at RESE0 rather than RESE4. Although the departure would get to MOFT0 about 1 minute *earlier* than it would get to MOFT4, the arrival would get to MOFT0 about 1 minute *later* than MOFT4. Hence the time between the aircraft on the timeline would increase by two minutes from MOFT0 to MOFT4, or 1 minute between each MOFT fix. The relative change in time enabled by the various route crossing points could be used to correct for departure time errors or climb rate variability. The set of routes as a whole, however, form a parallelogram which allows for the overall time to a downstream meter fix to remain unchanged.

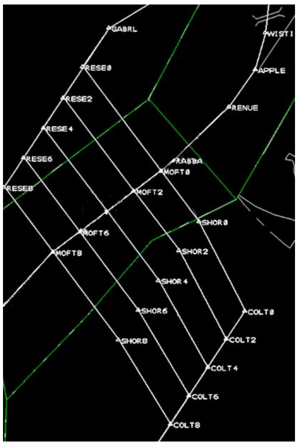

Figure 4. Alternate routes available on Route Crossing Tool.

3) Table of Values: The Route Crossing Tool is composed of three parts, a Table of Values, a graphic display of these values on the controller's scope, and a timeline. As can be seen from Fig. 5, in the first column of the Table of Values, the departure route or SID is displayed. The second and fourth columns, respectively, contain the call signs of the arrival aircraft that will cross the intersection point directly before (leading arrival) and after the departure aircraft (trailing arrival). The third and fifth columns, show the straight-line distances between the departure and those two arrivals. The distances are computed using the predicted locations of the two arrival aircraft at the predicted time the departure will cross the intersection point.

Graphical Display of Predicted Separation: The bottom of Fig. 5 shows the display of the predicted separation that appears on the controller's scope. In this example, the departure is on the REST4 default route (with a restricted altitude of 8,000') shown in the Table of Values and the distances shown in the graphical display are those distances displayed for REST4 in the Table of Values. The departure is 3.5nm from the leading arrival, and this distance is shown in red on the scope, since it is less than the 4nm that is required (3nm plus a 1nm buffer). The 10.8nm from the trailing arrival to the departure aircraft is shown in yellow, since 10.8nm is a sufficient distance for a departure to cross in front of a trailing arrival. Three small concentric circles highlight the point of intersection. The display indicates separations for other departure routes graphically when the controller hovers over them in the Table of Values.

The larger, unfilled circles on the graphical display are TSS slot markers for both the departure aircraft and the flow of arriving aircraft. These slot markers indicate the location the aircraft needs to be to meet its Scheduled Time of Arrival (STA) to an airport or a fix, taking into consideration winds. When a controller selects a new, non-default route with the Route Crossing Tool, the ground system updates the flight plan and the slot markers move along the newly selected route. Since all of the routes were designed to take equal time, the delay to the fix is not affected. Although the ground system was automatically updated, the controller needed to call the flight deck so that the FMS could be updated.

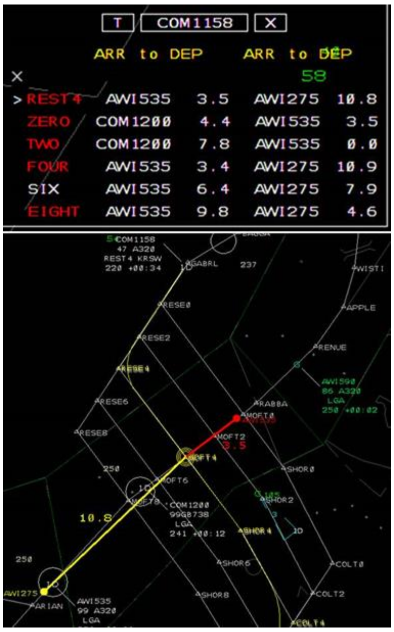

Figure 5. Route Crossing Tool with "Table of Values" (top) and the graphical display that appears on the controller's scope (bottom).

4) Timeline: A final component of the Route Crossing Tool is an integrated timeline with times for both the arrival and departure aircraft at the crossing point MOFT*n*. The departure aircraft was in a different color than the arrivals and was placed between the leading and trailing arrivals depending on which route had been selected. Any change in the departure route updated the timeline accordingly. The timeline offered similar information as the table and graphical display, but on the basis of time rather than distance.

E. Experimental Design

We ran the study in a high fidelity Human-in-the-Loop simulation at the Airspace Operations Laboratory (AOL) at NASA Ames using MACS software [18]. One hundred and forty-four departures were tested in a 3x(4x3) full factorial experimental design of 12 runs. Each of the following parameters was fully crossed.

1) Three tool conditions: Four runs were in a Baseline, no-tool condition, four were in a Single Route condition where controllers used the tool for the middle route only (MOFT4), and four runs were in a Multi-Route condition where controllers used the tool for all of the five route options, as shown above.

2) Four sizes of gaps between arrivals: The minimum inter-arrival spacing to climb a departure, as measured during pre-tests, was 134 seconds. This consisted of 54 seconds needed behind the leading arrival (given the 4nm separation necessary if the departure climbed before the leading arrival's route diverged, *x* in Fig. 3A) and 80 seconds in front of the trailing arrival (given the 5.6nm separation needed at MOFT*n*, *y* in Fig. 3C). These two values can be seen as buffers around the four different sized gaps that were created: 120 seconds or the "no gap" condition; 140 seconds with an actual gap of 6 seconds; 160 seconds with a gap of 26 seconds; and 180 seconds with a gap of 46 seconds.

3) Three departure positions relative to the arrivals: A quarter of the departure aircraft were placed 30 secs. in back of the leading arrival, a quarter of the departure aircraft were placed 30 secs. in front of the trailing arrival, and half of the departures were placed in the middle of the gap. In the no gap position, the departures were placed 50 secs. behind the leading arrival and 70 secs. in front of the trailing arrival.

Experimental setup, participants, and procedures: The experiment lasted for four days—one day for training and three days to gather data. Three scenarios were developed based on actual traffic data, with 12 WHITE departures from EWR in each run and therefore 48 in each of the three conditions. The scenarios were balanced by condition and the conditions were balanced across time. Three retired controllers rotated through the Empyr arrival sector in 12 one-hour runs. The controllers had worked an average of 15 years in a TRACON and as a controller in all facilities for an average of 24 years; they had retired an average of 2.3 years before the experiment.

The Empyr arrival sector was responsible for controlling the WHITE departures from EWR in addition to the arrivals to LGA—the flow which the WHITE departure would cross. The departures were initially cleared to 8,000', and if the decision was made to climb, Empyr cleared the departure to 11,000' and told the pilot to contact the next sector.

Coordination with the other departure sectors was accomplished using a pre-arranged coordination procedure first with the EWR departure sector and later, with the Liberty South departure sector (Fig. 2).[3] The speed of the arrivals was held constant at 250kts. The WHITE departure traffic data blocks were automatically displayed to the Empyr sector, as well as to the EWR departure and Liberty South sectors.

During the runs, the controllers were prompted every three minutes to report their current workload on a scale of 1 to 6 using Workload Assessment Keypads (WAKs). Ratings of 1 and 2 were considered to be low workload, ratings of 3 and 4 were considered to be medium workload, and ratings of 5 and 6 were considered to be high workload. After each run, the controllers responded to an online post-run survey, and after the simulation, they responded to a post-simulation survey and participated in a debrief discussion. Survey questions included those on workload, acceptability, feasibility and safety of the operations and coordination. The questions were typically binary (yes/no), or involved ratings on a 5-point Likert scale, ranging from 1 (lowest) to 5 (highest). Space was made available for comments on both survey instruments.

III. RESULTS

A. Where Aircraft were Climbed

Fig. 6 shows the vertical paths of the aircraft color-coded by altitude. Red indicates altitudes under 8,100'. As can be seen, the aircraft climbed above 8,100' (shown in green) earlier in the Multi-Route condition than in the Baseline and Single route conditions.

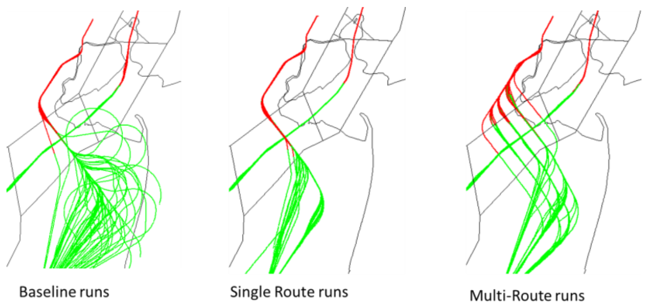

Figure 6. Aircraft tracks with altitudes under 8,100' in red showing earlier climb in multi-route runs.

[3] The choice of an arrival sector handling the EWR departure using pre-arranged coordination was based on the results of the earlier simulations—SOAR1 and SOAR2.

This is shown more clearly in Fig. 7 where the average altitude at MOFT*n* indicates an earlier climb in the Multi-Route condition (M = 9,600') than in the Single route (M = 8,860') and the Baseline (M = 8,860') conditions, $F(2,132)$ = 10.0, $p < .001$.

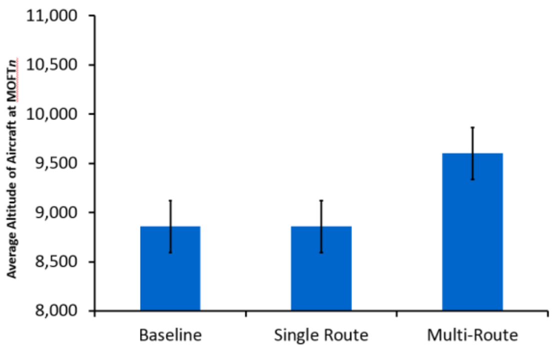

Figure 7. Average altitude of aircraft at MOFT*n* in the three tool conditions (error bars are 95% CIs).

Consistent with this, the highest proportion of departures were climbed before MOFT*n* in the Multi-Route condition, as shown in Fig. 8. Of those that could be climbed, 54% (26/48) were climbed in Baseline, 63% (30/48) in the Single Route condition, and 83% (40/48) in the Multi-Route condition, $F(2,132)$ = 6.5, p = .002.

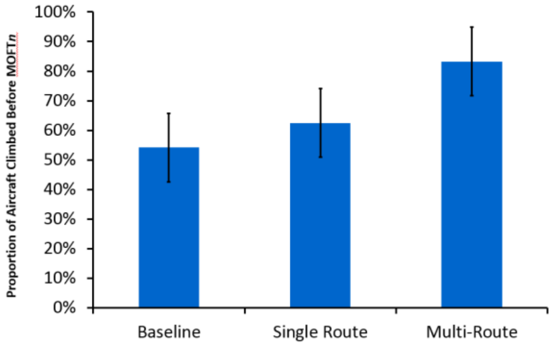

Figure 8. Proportion of aircraft climbed before MOFT*n* in the three tool conditions (error bars are 95% CIs).

B. *Arrival gap size*

In general, the larger the gap size between the arrivals, the higher proportion of aircraft that were climbed before MOFT*n*, as would be expected.[4] However, it can be seen in Fig. 9 that even when there was no gap (120 seconds), 67% (24/36) of the aircraft were climbed in the Multi-Route condition. This was much higher than the 25% (9/36) for the Single Route and the 8% (3/36) in the Baseline that climbed in the no gap condition, $F(2,35)$ = 5.1, p <.01. This indicates that the Multi-Route tool was helping the controllers take advantage of the divergent separation rule to climb aircraft closer to the leading aircraft when conditions permitted (ANOVA not significant for the entire sample $F(6,132)$ = 1.12).

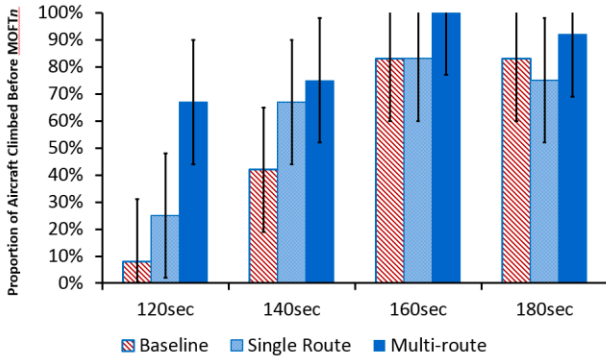

Figure 9. Proportion of aircraft climbed before MOFT*n* by gap size and condition (error bars are 95% CIs).

C. *Departure position relative to the arrivals*

Fig. 10 shows that overall, there were twice as many aircraft that were climbed when they were behind the leading arrival (81% 29/36), than when they were in front of the trailing arrival (39% 14/36), $F(2,107)$ = 19.93, $p < .001$. This is due to the diverging separation rule—controllers can climb earlier if they are closer to the leading aircraft, as previously described.

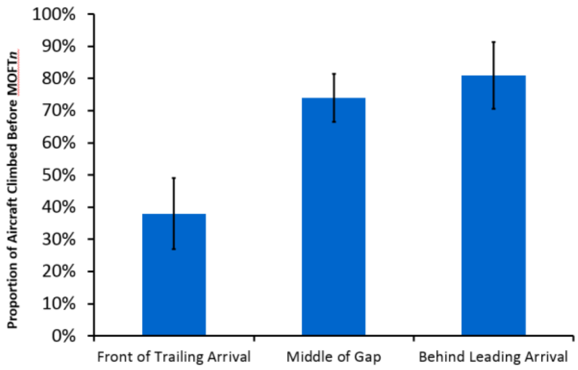

Figure 10. Proportion of departure aircraft climbed before MOFT*n* by position relative to arrivals (error bars are 95% CIs).

However, Fig. 11 shows that even when the departure aircraft were in front of the trailing aircraft, the Multi-Route tool enabled a high climb rate—83% (40/48) vs. 18% (9/48) in Baseline and 9% (4/48) in the Single Route condition, $F(4,107)$ = 6.3, $p < .001$. The Multi-Route tool appears to have been especially beneficial in helping the controllers

[4] Of those that could be climbed, 33% (12/36) were climbed when the inter-arrival spacing was 120 seconds, 61% (22/36) when the spacing was 140 seconds, 89% (32/36) when the spacing was 160 seconds, and 83% (32/36) when the spacing was 180 seconds. Similarly, aircraft were climbed later when the inter-arrival spacing was 120 seconds (M = 8,270') compared to 140 seconds (M = 8,960'), 160 seconds (M = 9,420') and 180 seconds (M = 9,780'), $F(3,132)$ = 13.9, $p < .001$. The mean altitude in the 140 second spacing was also significantly different from the 180 second spacing, $F(3,132)$ = 17.5, $p <$ .001.

estimate the distance between the departure and a trailing arrival.

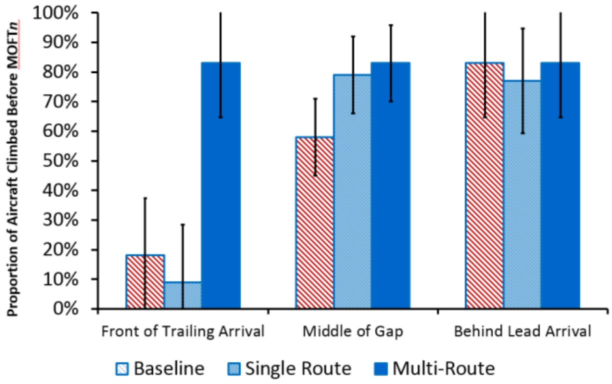

Figure 11. Proportion of departure aircraft climbed before MOFT*n* by position relative to arrivals by tool condition (error bars are 95% CIs).

D. Safety

There were no losses of separation in the simulation, although the 1nm buffer was breached by four departures. One of these departures slightly breached the 1nm buffer before a leading aircraft. However, it was a malfunctioning aircraft that climbed without controller or pilot input, as described below. Three departures crossed before a trailing arrival at MOFT*n* with sufficient separation, but came within the longer buffer for the trailing arrival after crossing and route divergence had been established. Discussed below are the distances of the departures 1) from the trailing and leading arrivals, and 2) when climbed, from the point of divergence with the leading arrival.

1) Distance at crossing of departure aircraft from trailing and leading arrivals: Fig. 12 below shows that the departures fell into four different quadrants (labeled "a," "b," "c," and "d"), depending on how far the departures were from the leading arrivals when they were at the divergence point (*x* in Fig. 3A) and the trailing arrival when they both were at MOFT*n* (*y* in Fig. 3C). The departures that climbed before MOFT*n* are depicted with red squares; the departures that climbed after MOFT*n* are depicted with blue triangles. As can be seen, none of the departures fell into quadrant "c." Hence no departures were both less than 4nm from the leading arrival when that aircraft was at MOFT*n* (point of divergence) and less than the 5.6nm boundary set for the trailing arrival at MOFT*n*. Most of the departures that climbed before MOFT*n* (red squares) fell into quadrant "b." Here the departures were both over 4nm from the leading arrival when that arrival was at the point of divergence (*x* in Fig. 3A) and over the 5.6nm boundary set for the trailing arrival (*y* in Fig. 3C). Three departures fell slightly below this boundary into quadrant "d" and came within 4nm of the trailing arrival after they crossed in front of that arrival and route divergence had been established (y_{min} in Fig. 3C). However, the closest point of approach of any of these three departures was 3.3nm so only the additional 1nm buffer was penetrated, and that buffer was the longer buffer for distance from the trailing arrival after crossing in front of it (see Discussion). Two of these departures were in the Baseline condition and one was in the Multi-Route condition. Most of the departures that controllers chose not to climb (blue triangles) were in quadrant "d," likely due to their proximity to the trailing arrivals.

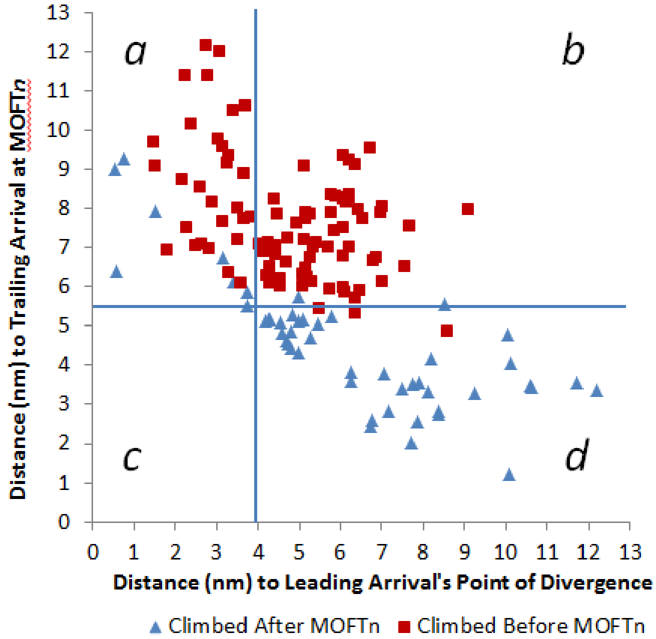

Figure 12. Distance of departure to the leading arrival at the point of divergence (x) and to the trailing arrival at MOFT*n* (y).

Distance of departures at start of climb from the point of divergence with the leading arrival: The many departures that were climbed before MOFT*n* in quadrant "a" reflects the cases where controllers were taking advantage of the divergent separation rule, i.e., climbing departure aircraft near the leading arrival after the leading arrival crossed in front of it (*s* in Fig. 3B). To verify that the controllers climbed these aircraft after divergence was established, we subtracted the distance from MOFT*n* when the departure was climbed above 8100' from its distance to the leading arrival's point of divergence at MOFT*n* (*x-s* in Fig. 3). The results are shown in Fig. 13 below. As can be seen in quadrant "a" of Fig. 13, the departures that were climbed less than 4nm from the leading arrival's point of divergence were climbed over 1nm after divergence was established, likely due to the time it took the controller to direct the departure to climb and the flight deck to comply. There was one aircraft in quadrant "c" that was less than 4nm (3.8nm) away from the leading arrival when route divergence was established. It had climbed earlier at 5.9nm before divergence was established. Further examination revealed that this aircraft malfunctioned and had climbed above 8,000' by itself without being cleared by the controller.[5] As can be seen in quadrant "d" of Fig. 13, five other departures also climbed well before route divergence was established and for these aircraft the controllers had anticipated separation. However, the tool was designed to make this a safe option if done far enough ahead of time. Since these five aircraft were further than 4nm away from the point of divergence when they began to climb, these aircraft would not have violated separation standards with the leading arrivals.

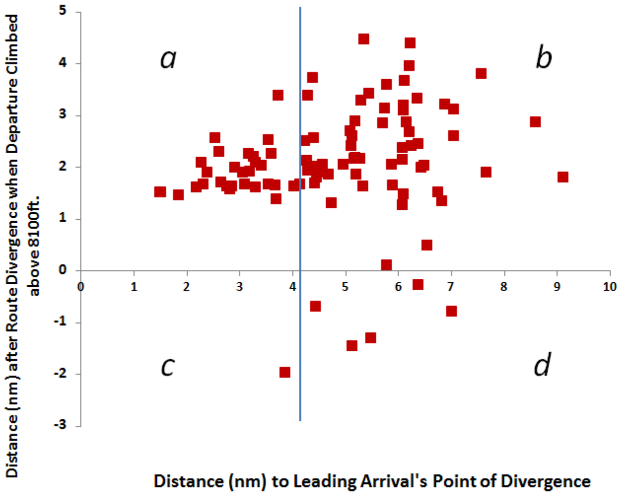

Figure 13. Distance after route divergence when the departure climbed above 8,100' (n = 94 departures that climbed).

E. Controller Strategies for Using the Tools

One of the controllers wrote that in the Baseline and Single-Route conditions, he developed his own route crossing tool, using "a 3 mile circle on the lead aircraft and a 5.6 mile circle on the following and varied this depending on aircraft position." In the Multi-Route condition, this controller felt confident using the Route Crossing Tool.

Towards the end of the simulation, one controller chose some route options that were red and thus deemed unsafe instead of the white (safe) option to climb departures. He had gotten used to the tool and used the numbers provided by the tool to adjust the departure's speed so that it would change from a red option to a white option.

F. Controller Assessment of the Tools and Procedures

1) Safety: The controllers rated the conditions as all acceptably safe in the Empyr sector. They were asked "In this run, how acceptable in terms of safety were operations in your sector?" All of the ratings were either 4 or 5 on a scale of 1 to 5, with 1 being "Not at all acceptable, and 5 being "Very acceptable." In the post-simulation survey, the same question was asked, and all responses were fives.

[5] The Mode Control Panel (MCP) altitude was set at 8,000' yet the departure climbed through it. The controller didn't actually clear the departure to 11,000' until it had route divergence with the lead. The departure had breached the 1nm buffer, but there was no separation violation.

2) Workload and acceptability of workload: All of the standard workload measures indicated that the workload was equally low in all conditions. On a scale of 1 to 6, with 1 being lowest, the means on the WAK assessment for the three conditions were almost identical: Baseline—2.2, Single Route—2.2, and Multi-Route—2.3. The post-run data on mental activity also did not show any differences in workload in the three conditions. The controllers were asked, "In the last run, how much mental activity was required during the busiest time?" The responses were all 2s and 3s on a 5-point scale, with 1 being "Very low mental activity and 5 being "Very high mental activity." This was also the case for time pressure ("In the last run, how much time pressure were you under during the busiest time?").

However, when the controllers were asked, "In this run, how difficult was it to assess distances so that you could decide whether to climb EWR departures before they crossed the LGA arrival flow?" they indicated that it was most difficult in the Baseline condition, as shown in Fig. 14 (means are Baseline 2.8, Single Route 1.8, Multi-Route 2.0).

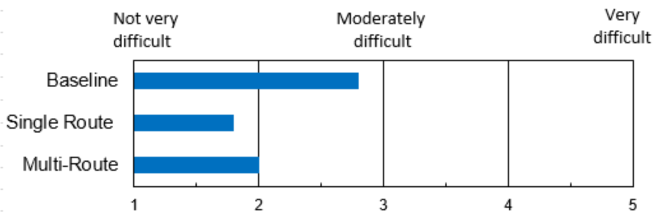

Figure 14. Assessing distances for climb most difficult in no tools condition.

The controllers indicated that focusing on the EWR WHITE departures did not distract them from their usual LGA arrival spacing task. (On a scale of 1-5, with 5 being the most distracting, the ratings were all 1's and 2's in all conditions.) In all runs, the controllers rated the difficulty of providing the required arrival flows to LGA as 1's on a scale of 1-5. Our goal in this simulation was to test the tools and therefore we used the actual LGA flow and did not add other complexities. One controller wrote, "If the arrival flow were conditioned [spaced] poorly, I think it could be very busy." We did add winds in one of the exploratory runs at the end of the study, which meant that the LGA arrivals did need conditioning. The same controller commented that this exploratory run "was much more realistic when the arrival flow needed some work."

Controllers indicated in the post-run survey that they were equally comfortable in all conditions with the decisions they made to climb or not to climb (means are 4.25 for each condition on a scale of 1 "Not very comfortable to 5 "Very comfortable").

3) Tool reliability and effectiveness: When asked after each run to rate how frequently they used the Multi-Route tool in that condition, the controllers indicated "Always" (all fives on a scale from 1 to 5, "Never" to "Always"). They were somewhat less likely to use the Single Route tool condition in that condition (M = 4.5 on the same scale where 4 = "Most of the time").

The controllers were also asked after each run how often they looked at the integrated arrival/departure timelines. On average they responded about 8-10 times in the Single Route condition and about 4-7 times in the Multi-Route condition.

On the post-simulation survey, the controllers were asked how reliable the tools were on a scale of 1-5, with 1 being "Not very reliable" and 5 being "Very reliable." The integrated arrival/departure timeline received a fairly low average rating of 3.7. The Single Route tool was rated as 4.7, and the Multi-Route tool received an average rating of 5.0—all fives. Some written comments were, "Great! It took a while to figure it out, but it worked very well!" and "The crossing tool was very accurate! Better than my eyes when the aircraft were far apart."

On the post-simulation survey, the controllers were asked "How difficult was it to assess relevant distances using the following tool?" On a scale of 1 – 5, with 1 being "Very easy" and 5 being "Very difficult," the controllers' average rating was 1.0 for both the Single and Multi-Route tools, and 3.3 for the integrated arrival/departure timeline.

On the post-simulation survey, for all three tools, the controllers were asked to rate the benefit of the tool and its ease of use on a scale of 1 to 5, with 1 = "Low," and 5 = "High." Again, the integrated arrival/departure timeline received relatively low marks, an average of 1.7 for benefit and 2.7 for ease of use. The Single Route tool received an average of 4.0 for benefit and 4.7 for ease of use. The Multi Route tool received average ratings of 4.7 for both benefit and ease of use.

When asked to describe any issues that they might see with Empyr handling both arrivals and departures, all of the controllers responded that there could be a potential workload issue if the arrivals needed to be conditioned.

4) Coordination and acceptability of coordination: In both the post-run and post-sim surveys, the controllers rated the acceptability of coordination as very acceptable—as either fours or fives on a scale of 1-5, with 1 = "Not at all acceptable" and 5 = "Very acceptable."

The controllers coordinated most with Liberty South, the departure sector to which they handed off the WHITE departures. They rated the amount of this coordination as "Moderate," or 3.3 on a 1-5 scale, with 1 = "No coordination," and 5 = "Very much coordination." They rated their coordination with the other controllers as very low (averages of 1 or 1.3). There was no difference by condition in how much they reported coordinating (an average of 1.7).

IV. DISCUSSION

1) The Multi-Route Crossing tool was an effective decision support tool: By building on the results of the earlier SOAR 1 and SOAR 2 simulations, the Multi-Route Crossing tool and associated procedures fulfilled the goal of helping controllers decide whether to climb departure aircraft in a shared airspace environment. By incorporating scheduling for both departures and arrivals and at the same time providing alternate routes, the tool allowed for tactical adjustments to possible departure delays and differences in aircraft climb rates. Overall, the tool increased controller awareness of crossing parameters, and made it easier for controllers to make difficult perceptual judgements and apply separation rules to aircraft in different and distant flows.

2) Separation requirements: Although the Multi-Route Crossing tool increased the proportion of departures climbed compared to the Single Route tool and having no tool, it is possible that even more departures could have been climbed in the two tool conditions had we required a less conservative distance than 5.6nm between the departure and the trailing arrival (as depicted in Fig. 3C). If this distance had been 4nm, it would be equal to the distance of the departure to the leading arrival (*x* in Fig. 3A). However, due to safety considerations, we increased the buffer to the trailing arrival on the recommendation of many experts in the field. This approach appeared to be successful since all controllers felt comfortable with their decisions to either climb or level off the departures in all conditions. Even with the additional 1.6nm buffer, the Multi-Route condition reduced the distance the controllers naturally chose to separate the departure aircraft from the trailing arrivals from an average of 8nm in the Baseline condition to 7.3nm in the Multi-Route condition (7.9nm in the Single Route condition).

3) Workload and automation: Since the purpose of this simulation was to test the tools in the New York airspace, we duplicated the actual rate of the arrivals to LGA. However if this flow needed more conditioning, the workload of the Empyr controller would increase, thus reducing the time to assess which route would be best for the departures. Suggestions to keep the workload low are to have the tool pre-select the best route and have the controllers make the decision to climb, which could be done at a somewhat later stage.

One controller suggested that the slot marker could follow the best route with the default altitude set to 8,000.'[6] The controller would keep the aircraft in the slot marker and make the decision to climb only if the tool indicated it was safe. This use of automation would complement the controllers' ability and need to make the final decision to climb, which in turn could be done based on the recommendation of the automation in the tool.

4) Flight deck requirements: The Multi-Route Crossing tool could be used with "Direct to" or heading instructions to the pilots if the assumptions we made about flight deck equipment and procedures were not yet met (i.e., that alternate routes were published and were available in the FMS or could be uploaded rapidly).

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[6] In our study the alternative routes did not have altitude restrictions, and having the default altitude set to 8,000' on the alternative routes would have prevented the Mode Control Panel error described earlier in Section III D2.

5) Wake vortex considerations: We did not integrate wake vortex separation standards into the tool. No WHITE departures from EWR are heavy aircraft, and only a few arrivals to LGA are heavies; furthermore, wake vortex separation standards may change soon due to re-categorization. However, in a future build of the tool, wake vortex separation could be incorporated.

V. CONCLUSION

The Multi-Route Crossing tool worked as designed to help controllers share their arrival airspace with a series of departure aircraft. This tool enabled controllers to climb a higher proportion of departures through gaps in a simulated LGA arrival flow than without a tool, or with only the Single Route Crossing tool. The Multi-Route tool accomplished this by providing alternate routes to correct for variability in departure time and aircraft climb rate, and by helping the controllers estimate distances more accurately, as indicated by the higher proportion of departures that were climbed within smaller gaps and in front of trailing arrivals in the Multi-Route condition. On the post-run and post-sim surveys, the controllers confirmed that the tool made it easier for them to estimate distances when deciding to climb a departure. One controller wrote that "The crossing tool was very accurate! Better than my eyes when the aircraft were far apart." The controllers also rated the tool as being beneficial and reliable. There were no losses of separation in the simulation, and the controllers rated the level of safety as acceptable. Coordination was accomplished through Pre-arranged Coordination Procedures (P-ACP) with the other sectors and was judged as acceptable. In the simulation, workload was rated as low in all conditions. Although the LGA arrival rate was based on actual traffic, if the arrival traffic had needed more conditioning, workload could be an issue. To reduce potential workload, the Multi-Route Crossing tool could select the best route and the controller could decide whether to climb the departure above the default altitude level.

Although the Multi-Route Crossing tool was tested in the New York airspace, the tool could be used wherever departure routes are held level under arrival routes. Example airports in the U. S. where this occurs are Phoenix, Atlanta, Los Angeles, Dallas-Fort Worth, Washington, D. C., and San Francisco.

ACKNOWLEDGMENT

The authors would like to thank the skilled air traffic controllers who participated in this study.

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