Shortfall Analysis of Departure Throughput During Convective Weather in Complex Airport Regions

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Abstract—**This study identified the pool of potential additional departures that could be achieved during convective weather days by providing traffic managers with enhanced information not available today, and by improving the information exchange with aircraft and airport operators. To quantify the shortfall of departures, historical data from the 2019 convective season at the three major airports in New York was evaluated. Route Availability Planning Tool (RAPT) data were used as a starting point for the quantification. RAPT is a real-time decision support tool used by controllers to identify departure routes out of busy terminal areas clear of convective weather so they can be used more efficiently. Additional effort was necessary to improve the fidelity of RAPT data and to include downstream sector capacity information (which is not currently captured by RAPT) into the analysis. An estimated total of 952 potential additional departure opportunities were identified for the entire convective weather season of 2019 for the three major New York airports. Over seventy days impacted by convective weather, an average of 13.6 potential additional departure opportunities were identified per weather day (~ 4.5 per airport). Benefits against this pool may be realizable by providing controllers, pilots and airline operators with training and additional information in the future which is not available today. The methodology presented in this paper can be adapted to other regions where convective weather impacts departure operations.**

Keywords-Convective Weather; Departure Throughput; NY Airports

I. Introduction

Convective weather impacts aviation operations during the summer months by reducing available capacity in terminal and en route airspace and causing large amounts of delays. In complex airport regions such as high-density airspace around major metropolitan areas (e.g., New York (NY), Chicago, London, Paris, Rome, etc.) these weather impacts can make it difficult to take full advantage of available capacity. This work was designed to provide the FAA Nextgen System Analysis and Modeling Division with a high-level shortfall analysis to identify the pool of potential benefit opportunities associated with existing and new capabilities in the 2026 to 2035 timeframe that could lead to additional departure opportunities in the New York metroplex region. The Route Availability Planning Tool (RAPT) is an existing capability which supports airlines, controllers and air traffic managers in identifying departure routes out of the New York airports that are free from convective weather. RAPT provides the impact of weather on the major departure routes for 45 minutes of flying time, but not the availability of downstream airspace being fed by those routes which is also affected by other aircraft flying in those regions. The objective of this study was to identify unused departure opportunities that could have been achieved with additional information provided to the air traffic managers including downstream airspace capacity availability. The quantification of the opportunities was achieved by analyzing historical data for the convective season of 2019. Although the New York Metroplex area is especially challenging in the US, convective weather also affects European airports in the summer. A similar approach as the one presented in this paper could be applied to evaluate additional departure opportunities in many high-density airports with challenging weather conditions in Europe and beyond.

The rest of the paper is organized as follows: Section II gives a description of the NY airports and impacts that convective weather has on them. Then the methodology to quantify the additional departure pool is described in Section III. Results from the application of the methodology to the convective weather season of 2019 are presented in Section IV. The paper ends with a summary of the results and conclusions of the study.

II. New York Metroplex Convective Weather Impacts

In the United States, during the summer months, convective weather is especially impactful to operations in the north-east region of the country where high traffic volumes coupled with dense airspace and limited runway capacity interact. The three major NY area airports of LaGuardia (LGA), Newark (EWR) and John F. Kennedy (JFK) are major contributors to the overall system delays in the NAS [1].

Figure 1 shows the complex interactions between the departure flows at these three airports in their most common departure configurations with 40 NM circles around each airport to provide scale. All 2019 departures from LGA using runway 13 (in pink), EWR runway 22R (in cyan) and JFK 22R

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(lime green) are presented. It is clear that when convective weather impacts this airspace, especially on the west side, significant disruptions to departure operations occur.

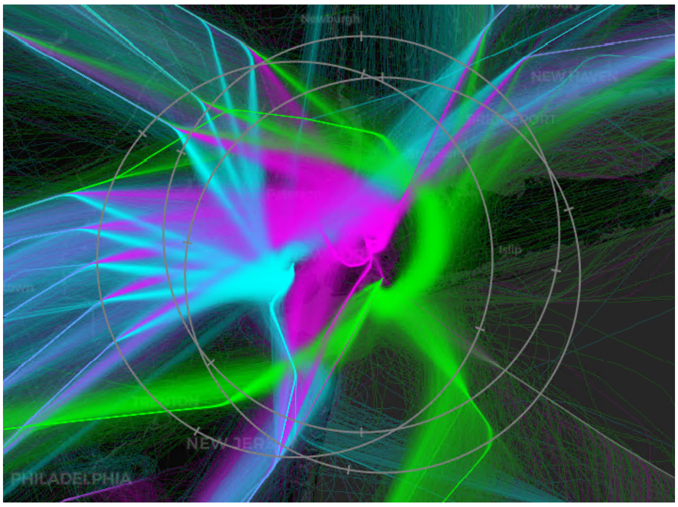

Figure 1. 2019 departures from New York airports LGA (pink), EWR (cyan) & JFK (lime green) with 40 NM range rings

From the FAA Aviation System Performance Metrics (ASPM) database [2], for the convective season of 2019 (between March and September) more than 4,850 hours of departure delays were experienced at the three NY airports (see Figure 2). Almost 85% of these departure delays were caused by weather impacting the airports. Each of the three airports experienced between 1,156 hours (LGA) and 1,489 hours (JFK) of weather-induced delays just during the convective season of 2019.

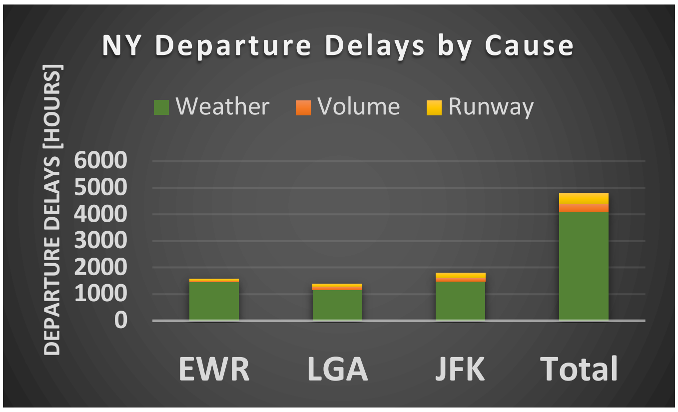

Figure 2. ASPM departure delays at NY airports during the 2019 convective season

For these reasons, mitigating the impacts of convective weather in congested airspace such as around New York has been the subject of multiple studies [3]-[7]. In [3] a connection between the uncertainty in the thunderstorm forecasts and the operational decisions based on this information was developed using the New York airports as a case study. The study acknowledges the challenges of Air Traffic Management during off-nominal weather and the difficulty of interpreting and managing uncertainty necessary to plan departure routes in these conditions. In [4] a detailed description is given of a convective weather event in New York and its effect on departure throughput, the response of traffic managers and the potential effect of using the RAPT decision support system on system performance were studied. A key challenge identified in the paper is that a static route definition of limited length into downstream airspace does not capture the full range of operational airspace use during highly dynamic convective conditions.

Starting from this knowledge, the study presented in this paper identifies the additional departure opportunities that could have been achieved using information that capture the uncertainty in the weather impact and controller workload along the departure routes out of the New York airports. This information is not currently available in an integrated way to traffic managers that have to make their decisions using multiple information sources while experiencing challenging off-nominal conditions. This analysis quantifies the potential benefits that might be realized by future decision support technology which addresses the issues identified in this study.

III. Methodology

To identify additional departure opportunities, a multi-step methodology was implemented as shown in Figure 3.

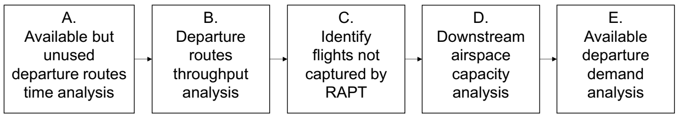

Figure 3. Study analysis methodology

The first step is to identify unused routes that could have provided a departure outlet but were not used. These were quantified as opportunity time periods. These time periods had to be converted to actual departure opportunities, and to do so, a measure of hourly route capacity was defined using historical data. Once the hourly route capacity was identified, the impact of airspace capacity along the route was defined, which reduced the pool of opportunities when downstream airspace capacity was already stressed. Lastly, it needed to be validated that demand was available to take advantage of the departure opportunity. Detailed descriptions of each step will be presented next.

A. Available but unused departure routes time analysis

To evaluate the usage of the departure routes in 2019 in the New York area major airports, RAPT data from this period was analyzed. RAPT was developed at MIT Lincoln Laboratory (MIT LL) and first deployed to users in New York Air Traffic Control (ATC) facilities starting in summer 2002, and has been available since then [8]-[9]. The RAPT basic display is shown in Figure 4. Based on the weather information of the Corridor Integrated Weather System (CIWS) [10], RAPT uses a model based on a statistical analysis of prior weather/traffic events to calculate the predicted overlap between convective weather and departure routes. It probes out to a 45 minute flight time from the departure airport and assigns a level of impact based on precipitation intensity, storm height, and expected pilot

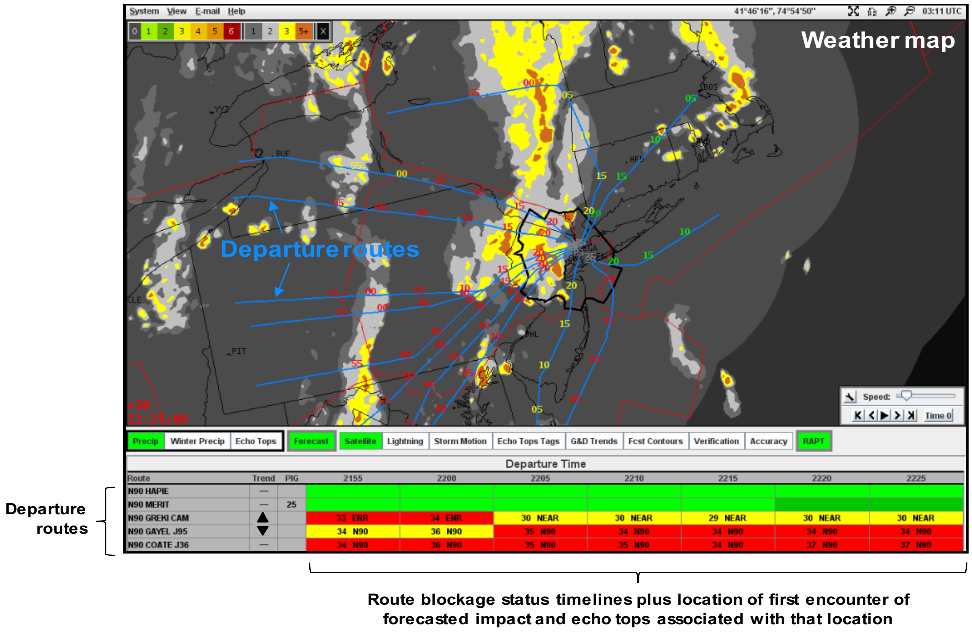

Figure 4. Route Availability Planning Tool (RAPT) user display

behavior. The information is color-coded green (route is free from any impactful weather for the entire 45 minute flight time, i.e., it is fully open), dark green (the route is only impacted by light precipitation, i.e., open), yellow (partially impacted by weather, i.e., monitor/restrict usage), and red (significantly impacted by weather, i.e., mostly closed). Each row of the color-coded table at the bottom of the display maps to a specific departure route out of the New York terminal area (designated N90) while the columns of the table indicate departure times in 5-minutes steps into the future. To further enhance user situational awareness, the text in yellow and red cells indicates how far away from the airport aircraft may encounter convective weather ("near" the airport, in the "N90" terminal area, or into en route (ENR) airspace) and the height of the storms being encountered (in 1000s of feet). Airlines, controllers and traffic managers use RAPT to make informed decisions about when a route will no longer be available as weather moves in, and when to reopen it as weather moves away.

RAPT provides real-time information to the users, and at the end of each day, the integrated set of data on the weather impact are stored for historical data analysis in the RAPT Evaluation Post-Event Analysis Tool (REPEAT) database maintained at MIT LL and available to the FAA users and other ATM stakeholders [11]. The database can be accessed in a calendar format (Figure 5 left). MIT LL meteorologists classify days into red (high impact), yellow (medium impact) and blue (no impact) weather days. This coding was used to identify weekdays in 2019 impacted by convective weather for the study. REPEAT also integrates RAPT information about availability of sets of routes (combined into "departure gates") together with the flight counts that actually used those gates using data extracted from the FAA Traffic Flow Management System (TFMS) data [12]. It should be noted (as seen on the right side of Figure 5) that REPEAT days are 28 hours long. This is necessary to capture convective weather impacts that spill into the next calendar day from a UTC perspective. An example for a weather impacted case day of July 2nd 2019 is shown on the right side of Figure 5. Weather during the next day spill over happens quite often, as can be seen by the yellow/red portions in the top of that panel.

Moreover, for each RAPT route, REPEAT records the Post-Impact Green (PIG) timer summary. A PIG is recorded every time a route has turned from red (closed) to green (open). The PIG times are only recorded for a maximum of 190 minutes following a route becoming green (with five minutes rounding error). In addition to the PIG start/end time and length of the PIG period, REPEAT keeps track of when the first flight used the route after it was free from weather again (green). This is captured in the PIG Time to First Departure (TFD) metric. The number of flights using the route each hour after the PIG is also counted for the three hours following the PIG start time or until weather impacts the route again.

Table 1. Example Post-Impact Green (PIG) timer summary

20190702					Total Departures			
Route	PIG Start (UTC)	PIG End (UTC)	PIG Period (Min)	PIG TFD (Min)	0-1 Hr PIG	1-2 Hr PIG	2-3 Hr PIG	Total PIG Period
HAPIE								
BETTE								
MERIT								
GREKI-NE								
GREKI-WEST								
GAYEL-J95								
NEION-J132								
COATE-Q436								
NEWEL-J60								
NEWEL-J64								
ZIMMZ-Q42								
ZIMMZ-Q480								
PARKE-J6	2320	2625	185	65	0	6	3	9
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
BIGGY-J75	2510	2800	170	20	5	3	n/a	8
WHITE	2645	2800	75	0	3	n/a	n/a	3
WAVEY								
DIXIE	2520	2705	105	10	4	n/a	n/a	4
SHIPP								
DEEZZ-J60	2215	2435	140	140**	0	0	n/a	0
DEEZZ-J64	2215	2415	120	120**	0	0	n/a	0
RBV-Q42	2615	2800	105	105**	0	n/a	n/a	0
RBV-Q480								
RBV-J6	2435	2745	190	110	0	1	1	2
RBV-J48	2440	2750	190	190**	0	0	0	0
RBV-J75	2510	2800	170	60	1	5	n/a	6

**=No Depart

Table 1 gives the PIG summary from July 2nd 2019. For the highlighted PARKE-J6 route, the PIG time started at 23:20 UTC

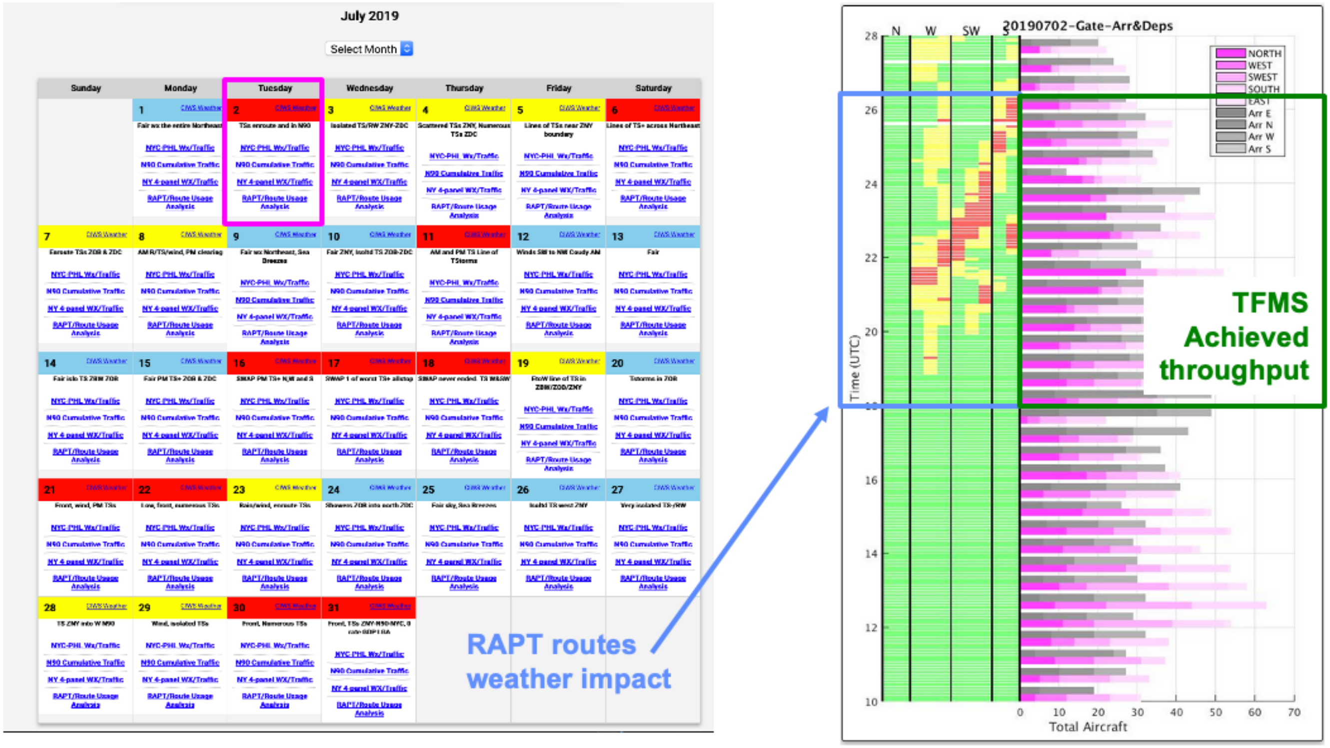

Figure 5. REPEAT database day selection page (left) and RAPT routes impact with TFMS throughput page (right)

and ended at 26:25 (July 3rd 02:25 UTC). This PIG lasted for 185 minutes, and the TFD was 65 minutes. This means that the first flight flew out of one of the airports using the PARKE-J6 route after it had been clear of adverse weather for 65 minutes. To visualize this, REPEAT also provides plots that integrate weather impacts and departures on the timeline under study. The PIG plot for the PARKE-J6 route can be seen in Figure 6. The departure timeline indicates that PARKE-J6 was used until weather impacted the route availability around 21:00. The PIG begins at 23:20, when the route is first free from weather. The first departure is at 24:25, 65 minutes after the route was clear. This is highlighted with the magenta box in Figure 6.

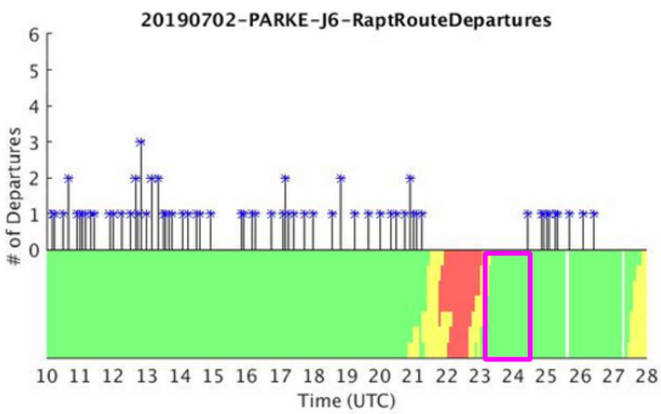

Figure 6. PARKE-J6 Post-Impact Green (PIG) Time to First Departure (TFD) plot

The sum of all the TFDs for each route for all of the weather days results in the number of minutes that routes were clear of weather impacts but were not used. This value provides an initial measure of the potential missed departure opportunities across all the New York routes in minutes.

B. Departure routes throughput analysis

To convert minutes of opportunity to additional departures, a measure of each route's capacity needed to be identified. Because the usage of each route can be affected by many factors, this measurement was done using a parametric approach applied to historical data of actual usage of the routes. First, to establish an upper bound for the throughput, the maximum observed number of flights per hour that used each route was calculated for each hour of the day. The data set included both fair weather and weather-impacted days. Not surprisingly, the highest throughput values were observed during fair weather days. However, during the later hours of the day, bad weather days provided higher throughput than during fair weather days (due to the buildup of demand created by the bad weather). Analyzing the entire day ensured that time-of-day variations were also captured. Additional throughput values were calculated during the same times as the PIG periods on a set of clear days (e.g., between 23:20 and 26:25 for the PARKE-J6 example). Averages and Standard Deviations (STD) on this throughput value were also calculated. The throughput evaluations were calculated using observed TFMS tracks. For each route with a non-zero PIG TFD, the capacity was then presented as a range between the maximum observed throughput, the average plus one STD (covering 68% of the throughput distribution if assumed

Gaussian) and the average, as shown in Figure 7 for the case of PARKE J6.

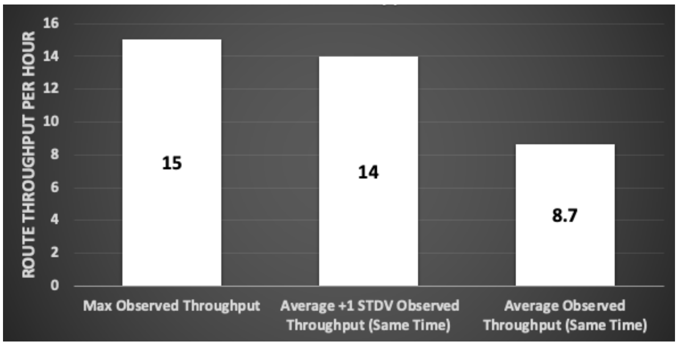

Figure 7. PARKE-J6 hourly observed throughput range

For the example in the previous section, Figure 7 shows that PARKE-J6 had a PIG TFD of 65 minutes. The maximum hourly throughput observed was 15 flights, the Average + 1 STD hourly capacity was 14 flights and the average was 8.7 flights. Depending on the level of conservativeness, any of these definitions of the PARKE-J6 capacity could be used. For the reminder of the paper all three values will be presented, but the middle value of the range is the authors' recommended value to use. The same process was applied for each route in each day with non-zero PIGs, and the opportunity departures were summed to calculate the total pool for the 2019 convective weather season.

C. Identify flights not captured by RAPT

The study was seeking to associate flights with departure routes using the REPEAT software and we found a number of flights unassigned to routes. As discussed in [4], a static route structure, such as the one used by RAPT, does not always well represent the dynamic use of airspace affected by convective weather. We then took the time to improve the software to associate more of these flights. It was discovered that if a flight did not fly close enough to the departure fix associated with the departure route, it was not counted. This was an issue when the objective of the study was to identify the number of daily additional opportunities, especially because it was expected that this number was going to be small on a per-day base. The REPEAT software was modified to better associate flight tracks with departure routes.

Further, more investigation revealed that there were a number of flights going from the New York area airports to the airports in the Boston area (i.e., Boston, MA; Manchester, NH; and Providence, RI) that were not captured by the REPEAT logic. One additional route named ROBUC was added to the current set of RAPT routes to capture these flights. This route is highlighted in Figure 8. It was also noted that a few flights per day fly between airports in NY, mostly to reposition aircraft for different airlines' needs. These "internal" flights were not counted towards the pool of opportunities.

Lastly, the biggest number of unaccounted flights were flights that were using the so-called "escape" routes out of NY called SERMN (EAST, NORTH & SOUTH). These routes are capped in the altitude that can be flown; therefore, they are less efficient from a fuel burn perspective but airlines will use them when they are the only option to get their flights to their destination in days impacted by weather when their schedules are already heavily delayed. A comparison of the RAPT routes with the SERMN escape routes is presented in Figure 8. It can be noticed that some of the SERMN NORTH routes are quite close to the "normal" RAPT routes, while others, especially some of the SERMN SOUTH and SERMN EAST routes,

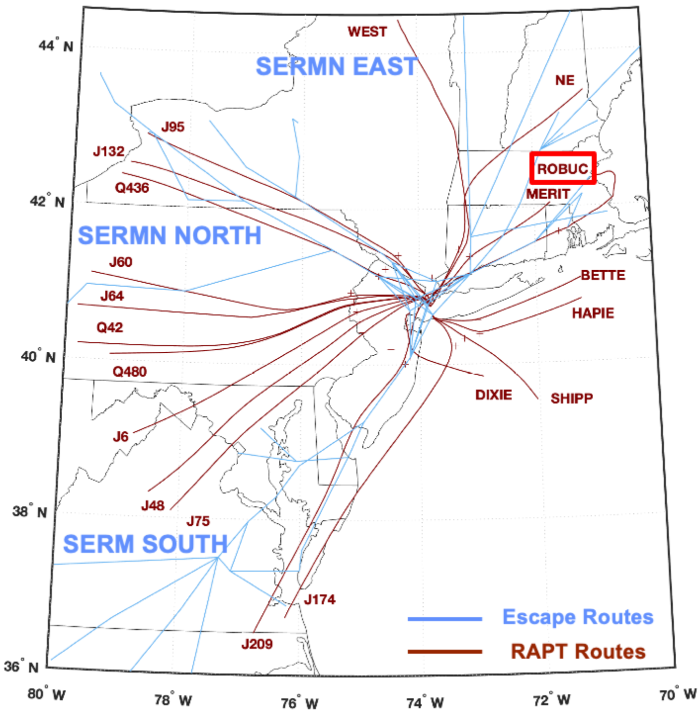

Figure 8. RAPT New York standard (red) and escape routes (blue)

diverge from RAPT routes, causing the system to drop them from the count. Flights that were not accounted for this reason were removed from the opportunity pool. For all the reasons mentioned in this section, an average of 15 flights per opportunity day were not accounted in REPEAT and reduced the pool of opportunities. These flights were able to leave New York but the system could not pair them to any of its routes, thus they were not considered part of the opportunity pool. As a result, the measure of additional departure opportunities can be considered conservative.

D. Downstream airspace capacity analysis

RAPT only captures the impact of convective weather on the availability of departure routes, but convective weather is not the only factor that affects traffic managers' decisions to use a route. Convective weather causes highly dynamic disruptions to typical flight patterns. Therefore, uncertainty in the workload along a certain route needs to be accounted for in the decision making. For this reason, the study also evaluated the workload along the routes and into downstream airspace identified during the opportunity days. To do so, each RAPT route was overlaid on the high-altitude sectors that it crosses. Because RAPT routes extend outside the New York En route Center (ZNY), sectors in Cleveland (ZOB), Boston (ZBW), and Washington DC (ZDC) centers were included in the analysis. A map of RAPT routes overlaid on the high-altitude sectors can be seen in Figure 9.

After each RAPT route was paired with the sectors that it crosses, the capacity of each sector needed to be identified. Currently, there are multiple approaches to identify sector capacity in the literature. Majumdar et al presented a comprehensive review of the simulation-based approaches to calculate sector capacity in [13], but these approaches are often computationally costly and time-consuming to create. In a more recent study [14], Welch et al presented a statistical approach based on historical data to calculate sector capacity impacted by convective weather. This approach showed that current models can over-estimate sector capacity during challenging weather conditions.

The FAA's TFMS uses Monitor Alert Parameter (MAP) values to alert controllers of upcoming workload issues related to high traffic levels [15]. The MAP value of a sector is defined based on the average sector flight time using data for a consecutive Monday through Friday, 7:00 AM to 7:00 PM local time. For example, a smaller sector, with an average sector flight time of 3 minutes has an associated MAP value of 5. A larger sector, with an average flight time of 12 minutes or greater has a MAP value of 18. The table used by the FAA to convert flight times into MAP values, taken from [15], is presented in Table 2.

Table 2. FAA MAP value conversion table [15]

Average Sector Flight Time	MAP VALUE
3 min.	5
4 min.	7
5 min.	8
6 min.	10
7 min.	12
8 min.	13
9 min.	15
10 min.	17
11 min.	18
12 min. or greater	18

MAP values were calculated for the sectors around New York by evaluating the average flight times using TFMS

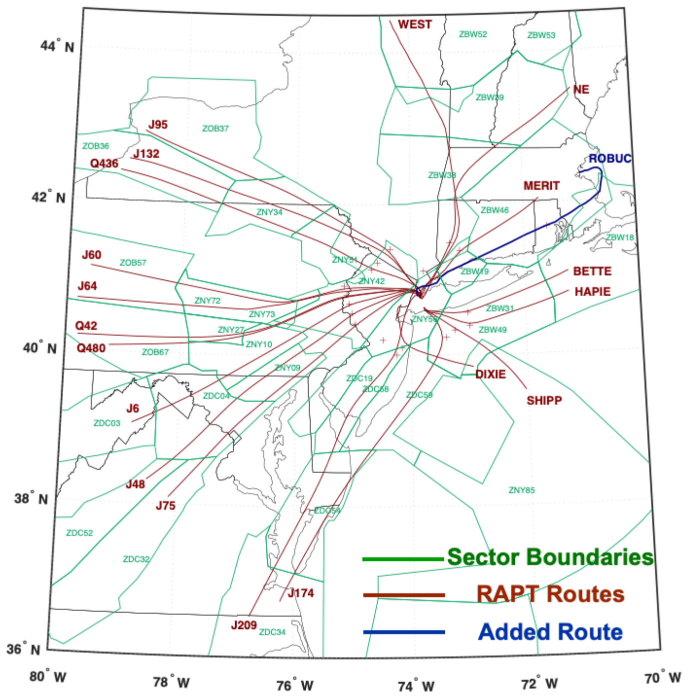

Figure 9. RAPT routes and high-altitude sector boundaries around the New York metroplex

historical tracks data over 10 weekdays in 2020 before the COVID pandemic affected traffic levels in March, using actual sector boundaries and evaluating flights between 10,000 and 24,000 feet. The results are presented in Table 3.

Table 3. MAP values calculated for the study

Sector	Avg Flight Time [Min]	MAP	Sector	Avg Flight Time [Min]	MAP
ZBW02	7.02	12	ZDC54	10.02	17
ZBW10	7.76	13	ZDC58	4.78	8
ZBW17	5.85	10	ZDC59	7.31	12
ZBW18	5.58	10	ZNY09	6.41	10
ZBW19	3.68	7	ZNY10	6.18	10
ZBW31	7.72	13	ZNY27	3.78	7
ZBW38	7.62	13	ZNY34	7.06	12
ZBW39	7.04	12	ZNY42	5.89	10
ZBW46	11.79	18	ZNY56	6.29	10
ZBW49	6.04	10	ZNY72	4.55	8
ZBW52	7.84	13	ZNY73	4.6	8
ZBW53	7.65	13	ZNY82	130.97	18
ZDC03	6.28	10	ZNY83	7.35	12
ZDC04	6.55	12	ZNY85	7.42	12
ZDC19	5.78	10	ZOB36	5.14	8
ZDC32	8.65	15	ZOB37	6.13	10
ZDC34	6.36	10	ZOB57	7.77	13
ZDC35	16.2	18	ZOB67	9.33	15
ZDC36	8.35	13	ZOB77	7.06	12

This particular altitude band was selected to capture the fact that RAPT routes are used to climb out of the New York Airports and therefore provide a good proxy of the workload along them during transition altitudes. These values were then compared to the actual number of flights in the sectors traversed by RAPT routes in 15 minute average counts. The values calculated in our study were slightly below the values currently used by the FAA. This could have been caused by the specific altitude band used that does not match exactly to high-altitude sectors, or by the ten days chosen to perform our analysis. Since the shortfall analysis was focused on days impacted by convective weather, this was considered acceptable based on the results presented in [14]. If one or more sectors traversed by the RAPT routes were estimated to be above their MAP value during an opportunity period, those opportunities were removed from the pool of benefits because the sector was considered to be fully loaded already. The impact of sector workload will be presented in the results section.

E. Available demand validation

The last step of the methodology involved verifying that when a departure opportunity was identified, departure demand existed to take advantage of it. This step was performed by analyzing historical data from the FAA ASPM database. This database has been used for many previous studies focused on airport delays during convective weather [16]-[17]. ASPM data report both the demand and the achieved throughput of departures for all the airports in the NAS in 15 minute intervals. For each opportunity period, the departure demand was compared to actual departure throughput in one-hour increments, and aggregated for the three airports in the analysis (LGA, EWR and JFK). If departure demand was lower than the departure throughput, the opportunity hour was removed from the pool because that period may not have had enough demand to take advantage of the available departure slots. For the entire opportunity pool, between July through September of 2019 convective season, only one hour recorded lower demand than the potential throughput in the ASPM data. That hour was removed from the benefit pool.

IV. RESULTS

The FAA considers the convective season between March 1st and September 30th each year. The methodology described in Section III was applied to the data in REPEAT between July and September 2019. The reason this could not be used for the early part of the 2019 convective season is that in the spring of 2019, an effort to update the NY RAPT routes began. These new routes were calculated using actual aircraft trajectories over the departure fixes. As a result, most of the original RAPT routes were modified and several new routes were added. MIT LL worked with personnel from N90 and ZNY to verify the routes were accurate and in June, the new routes were implemented and tested in the RAPT algorithm. On June 30th, the new routes were officially released. July 1, 2019 is considered the first full day of RAPT data with the new routes. The REPEAT software was updated to use the new routes as well. The results for July-September are presented first, followed by an extrapolation to the full convective weather season.

A. July-September Results

In this period, over 36 weather-impacted days, a total of 16,250 minutes (~270 hours) presented potential additional departure opportunities. In the same 36 days, 512 flights (an average of 14.2 per day) were not captured by RAPT and therefore removed from the pool. A summary of the results between July and September 2019 is presented in Figure 10, with different values of route capacity used for estimation (see Section III.B). The plot shows two different options: not considering the airspace capacity (green bars) and considering the airspace capacity (blue bars). The two bars on the left were calculated using the maximum observed throughput during fair and weather-impacted days for each route. The two bars in the middle were calculated using the average plus one standard deviation of the throughput observed during the same time of the opportunity periods in clear days. The two bars on the right use the average observed throughput during clear days.

Considering the middle throughput estimate (using the average plus one standard deviation route capacity measure) during the 36 weekdays identified with some opportunities, there were 561 additional departure opportunities if the downstream airspace capacity was neglected. The additional departure opportunities are reduced to 488 considering the impact of downstream airspace capacity, i.e., the airspace capacity reduced the pool of departure opportunities by approximately 13%.

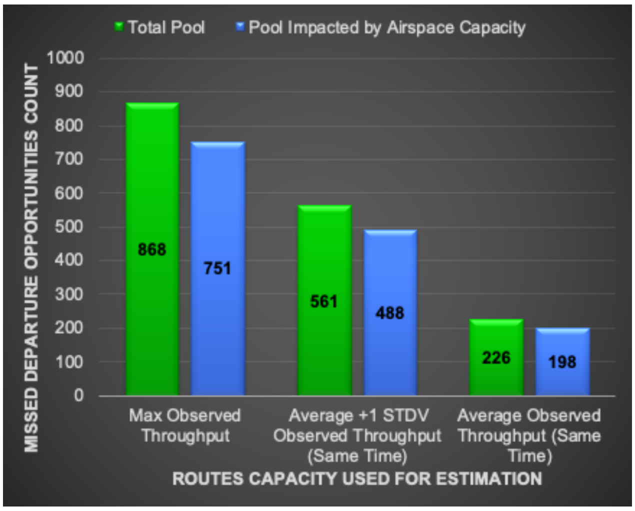

Figure 10. Aggregated departure opportunity results July-September 2019

B. *Extrapolation to full March-September convective season*

To extrapolate the results obtained between July and September to the entire convective season of 2019, historical data available in the REPEAT database calendar were used (see Figure 5 left). As mentioned before, based on the convective weather impact on the NY airports, MIT LL meteorologists classify days into red (high impact), yellow (medium impact) and blue (no impact). Figure 11 shows the red and yellow counts for the different months in the 2019 convective weather season.

From Figure 11, it can be seen that there were 40 yellow/red weekdays between July and September in the REPEAT database. Not all the yellow/red days presented PIG TFD opportunities. In fact, only 36 of the 40 presented opportunities. Since good REPEAT data were available also for the month of October 2019, it was decided to use them to calculate the extrapolation multiplier. There were 12 yellow/red weekdays in October. Of these 12 days in October, only one presented departure opportunities. Therefore, between July and October there were 52 (40+12) yellow/red weekdays of which 37 (36+1)

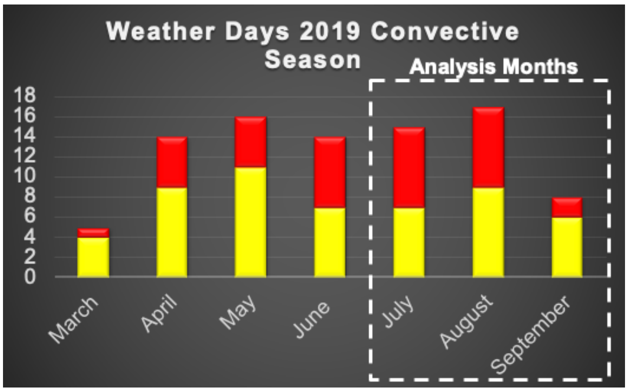

Figure 11. Red/yellow weather days as classified in REPEAT

presented departure opportunities. That is, roughly 71% of yellow/red days provided departure opportunities.

Between March and June of 2019 (the period with no valid REPEAT data), there were 49 yellow/red weekdays. Using the 71% multiplier identified during the period with good REPEAT data, these 49 days would provide only 34 days with departure opportunities. Therefore, a total of 70 opportunity days were identified: 34 days were extrapolated during March and June; and 36 days were calculated using REPEAT data between July and September. A summary of the results for the entire convective season of 2019 are presented in Figure 12.

Neglecting the airspace capacity (green bars), the total additional departure opportunities for the convective season of 2019 in the NY airports were between an upper bound of 1693 (24.2 per weather impacted day) using the maximum observed route throughput, to a minimum of 441 (6.3 per day) using the average observed throughput during the same time of opportunity periods. The middle value in Figure 12, obtained using the average plus one standard deviation throughput, shows 1094 additional departures (15.6 per day). Including the effects of airspace capacity (blue bars), the additional departure opportunities vary between 1465 (21 per day) to 387 (5.5 per day). The middle value, which is the recommended final assessment of the study, presents 952 additional departure opportunities, an average of 13.6 per opportunity day. This translates into an average of 4.5 additional departure opportunity per weather impact day for each of the three major airports in the NY area if opportunities are divided equally between them.

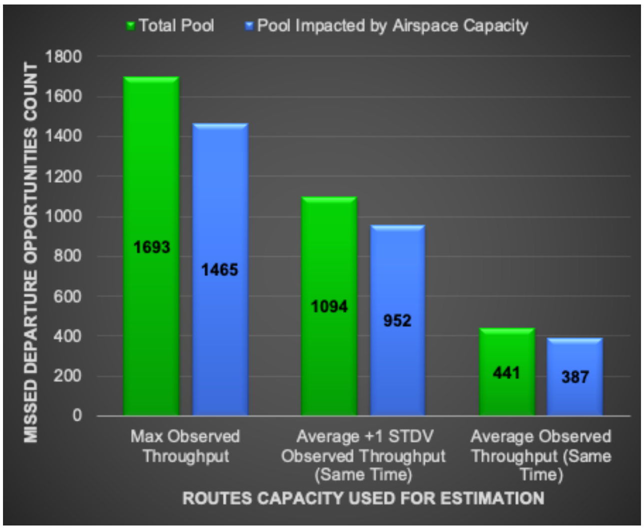

Figure 12. Final results March-September 2019

V. Summary and Conclusions

The study of the usage of departure routes in New York at the three major airports during the convective weather season of 2019 has showed that some additional potential departure opportunities could be achieved with existing and new capabilities in the near future. A combination of currently available convective weather impacts provided by the Route Availability Planning Tool (RAPT), and currently unavailable information (such as the sector capacity impacts along these routes) could enable some delivery of benefits relative to the pool calculated in this study. To achieve the full pool of benefits, additional information exchange needs to be available between, traffic managers, airport operators and other stakeholders in the NAS. This is necessary to quickly take advantage of departure opportunities in a very dynamic environment that is caused by convective weather at busy airports. Data exchange mechanisms such as the System Wide Information Management (SWIM) [18], Data Comm [19], and the Collaborative Trajectory Options Program (CTOP) [20] that are being implemented are good candidates to support the FAA in achieving the benefits presented in this paper in the future.

The recommended average pool of benefits identified in this study, constitutes a total of 952 additional departures during the entire convective season of 2019 for the three major airports in NY of LaGuardia (LGA), Newark (EWR), and John F. Kennedy (JFK). During 70 week days in the convective season of 2019, an average of 13.6 more departures per weather impacted day could have been achieved by presenting traffic managers with integrated weather and sector capacity information. This translates into an average of 4.5 additional departure opportunities per weather impacted day per airport. The fact that this number is relatively small is testament to the great work that New York controllers and traffic managers perform during challenging weather conditions, but there appears to be potential for additional benefits if appropriate capabilities were provided to assist ATC.

Many international airspace and airport regions have similar operational complexity and weather challenges. For example, In Europe, the airports most affected by convective weather are Paris Charles De Gaulle (CDG), Rome Fiumicino (FCO), and Munich (MUC). A recent study [21] reports that, in a typical recent year, CDG experienced almost 60 hours of thunderstorms, MUC more than 80 hours and FCO more than 200 hours (since the convective season extends well into November in Italy). European airports set their maximum capacities using Instrument Flight Rules (IFR) capacity [22], therefore they are less impacted by challenging weather conditions than US airports such as EWR, LGA and JFK. Nonetheless, a similar approach to the one presented in this paper could be applied to quantify the missed departure opportunities that could be achieved by providing European traffic managers with a combination of weather-free routes and airspace congestion data used in this study.

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