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Reducing Departure Delays at LaGuardia Airport with Departure-Sensitive Arrival Spacing (DSAS) Operations

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***Abstract*— Air traffic management in the New York (NY) metropolitan area presents significant challenges including excess demand, chronic delays, and inefficient routes. At NASA, a new research effort has been initiated to explore Next Generation Air Transportation System (NextGen) Trajectory Based Operations (TBO) solutions to address lingering problems in the NY metroplex. One of the larger problems in NY is departure delays at LaGuardia airport (LGA). Constant traffic demand and physical limitations in the number of taxiways and runways cause LGA to often end up with excessive departure queues that can persist throughout the day.**

At the Airspace Operations Laboratory (AOL) located at NASA Ames Research Center, a TBO solution for "Departure-Sensitive Arrival Spacing" (DSAS) was developed. DSAS allows for maximum departure throughput without adversely impacting the arrival traffic during the peak demand period. The concept uses Terminal Sequencing and Spacing (TSS) operations to manage the actual runway threshold times for arrivals. An interface enhancement to the traffic manager's timeline was also added, providing the ability to manually adjust inter-arrival spacing to build precise gaps for two or even three departures between arrivals. With this set of capabilities, inter-arrival spacing could be controlled for optimal departure throughput.

The concept was prototyped in a human-in-the-loop (HITL) simulation environment to determine operational requirements such as coordination procedures, timing and magnitude of TSS schedule adjustments, and display features for the tower, Terminal Radar Approach Control (TRACON), and Traffic Management Unit (TMU). A HITL simulation was conducted in August, 2014, to evaluate the concept in terms of feasibility, impact on controller workload, and potential benefits. Three conditions were compared: (1) a baseline condition using new RNAV/RNP procedures (no TSS); (2) the new procedures + TSS; and (3) new procedures + TSS + DSAS schedule adjustments. Results showed that with a maximum arrival demand (40-41 arrivals per hour), departure throughput could be increased from 38 / hour (baseline condition), to 44 / hour (TSS condition), to 47 / hour (TSS + DSAS). The results suggest that DSAS operations have the potential to increase departure throughput at LGA by up to 9 a/c per hour with little or no impact on arrivals during peak traffic demand period.

Keywords: New York, Trajectory Based Operations, air traffic management, NextGen, scheduling, Terminal Sequencing and Spacing, Time Based Flow Management

I. BACKGROUND

Air traffic operations in and around the New York (NY) metropolitan area are notoriously complex. Traffic demand combined with a highly constrained airspace and uncertainty from factors such as weather creates a challenging operational environment and often, a brittle system. The complexity combined with the traffic demand results in chronic congestion and delays that have impact across the National Airspace System (NAS) [1].

Due to the level of arrival demand and the priority given to arrival aircraft for runway use in the NY metroplex environment, departure aircraft are often required to sustain delays and wait for opportunities to depart as they arise. An extreme, though not entirely uncommon, result of this situation is that delays often grow on the departure side until the departure queue extends to the point of arrival/departure gridlock. As identified by stakeholders and Subject Matter Experts (SMEs), long taxi times, departure queues and delays are a chronic problem at LaGuardia airport (LGA).

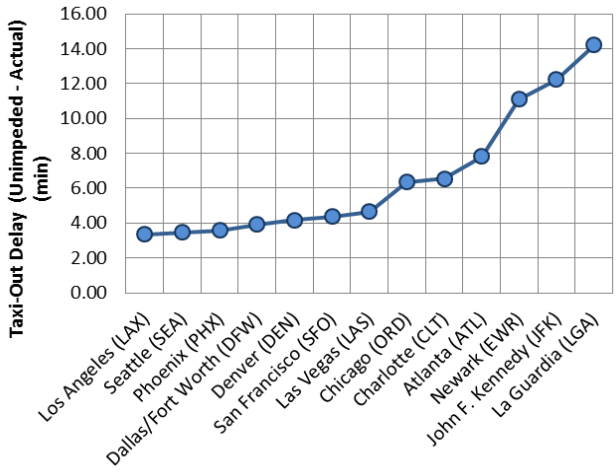


Figure 1. Average taxi-out delays between 2007 and 2012.

The NAS-wide significance of LGA delays was confirmed with data from the FAA's Aviation System Performance Metrics (ASPM) website. Figure 1 illustrates the taxi-out delays between 2007 and 2012 at the three primary airports in New York and the other 10 busiest US airports. It shows that among the busiest airports in the United States, LGA has the

largest departure delay. Departure delay at LGA is primarily due to the dependency between LGA's arrival and departure runways: LGA departures cannot begin to take off until arrivals have cleared the runway intersection. LGA experiences high arrival and departure demand throughout the day, high gate utilization, limited airport surface area, and a rapid turnaround time per flight. If one-in one-out operations (one arrival followed by a departure) are not maintained, and a significant arrival-to-departure imbalance occurs, the departure backup can persist throughout the rest of the day (see Figure 2). The impact can include surface congestion that delays gate access for arrivals and turnaround time, causing ripple effects throughout the NAS. A solution to this problem would enable LGA to better accommodate fluctuations in departure demand, improve aircraft turnaround time, and reduce the risk of surface gridlock. Airlines would also see reduced (taxi) fuel costs and improved schedule conformance.

Figure 2. Taxi-way congestion in LGA 31|4 runway configuration.

Although departure delay problems due to arrival-departure dependencies are most acute for LGA, similar problems exist at other high demand airports that have either 1) intersecting arrival-departure runways or 2) mixed arrival-departure mode operations on a single runway. Past research efforts, both in the U.S. and in Europe, have developed operational tools and concepts that propose to improve the departure throughput and/or reduce delays by adjusting the arrival spacing [2][3][4].

Diffenderfer and his colleagues [2] prototyped a tool called the Automated Integration of Arrival-Departure Schedules, which provided automated arrival spacing guidance based on the departure aircraft queued to a dependent runway, and evaluated the tool for the intersecting runways at the Ronald Reagan Washington National Airport. In Europe, arrival (AMAN) and departure management (DMAN) systems have been developed to support the inbound and outbound operations, and new arrival-departure coordination systems that can integrate the two systems have been tested for Frankfurt [3] and Heathrow airports [4] to improve tactical departure scheduling by adjusting the arrival schedule.

In this paper, a new Trajectory Based Operations (TBO) solution called, "Departure-Sensitive Arrival Spacing" (DSAS) is proposed to address this issue of enabling maximum departure throughput without adversely impacting the arrival traffic during the peak demand period. The concept uses Terminal Sequencing and Spacing (TSS) operations [5] to manage the arrival schedule to the runway threshold in a way that would ensure one-in one-out operations. Unlike previous efforts that provided the arrival spacing guidance early on but adjusted the precise spacing gaps close to the Final Approach Fix, DSAS leverages the TSS capability to create a Terminal Radar Approach Control (TRACON) schedule to the runway threshold and a mechanism for the controllers to conform to a precise arrival schedule throughout the TRACON airspace. With DSAS, the TSS arrival schedule can be adjusted to create optimal spacing for one or more departures between arrivals. A preliminary analysis of DSAS operations suggested that a significant increase in departure throughput could be gained with minimal impact on arrival throughput [6].

II. LaGuardia Airport

In the following sections, the LGA runway configurations and traffic demand are described in more detail. Understanding the dependency between arrival and departure throughput for the different runway configurations will help the readers to understand the solutions provided by the DSAS operations.

A. *Runway Configurations*

LGA has two intersecting runways, 4-22 and 13-31. The most common operations in LGA assign one of these runways as the departure runway and the other as the arrival runway. Both runways are 7000 feet long and they intersect near the runway 13 and runway 22 thresholds. Based on ASPM data, the four most commonly used runway configurations (in order of frequency) are 22|13 (i.e., landing runway 22 and departing runway 13), 31|4, 22|31, and 4|13 (see Figure 3).

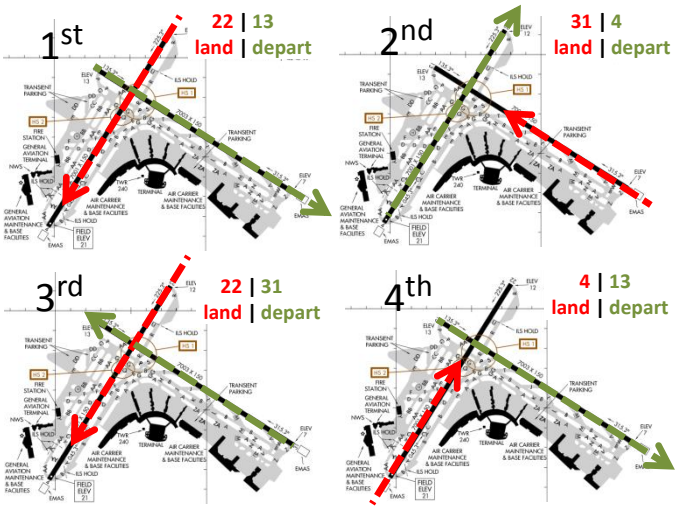


Figure 3. Four most commonly used runway configurations at LGA.

B. *Interactions between Arrival and Departure Spacing*

In LGA crossing operations, the departures queue on the taxiways waiting for an arrival to land and clear the runway intersection. Once the arrival clears the intersection, the local controller clears the next departure for takeoff. Since the distance from the arrival runway threshold to the intersection varies with runway configuration, the wait time before the

departure can be cleared for takeoff also varies with the configuration.

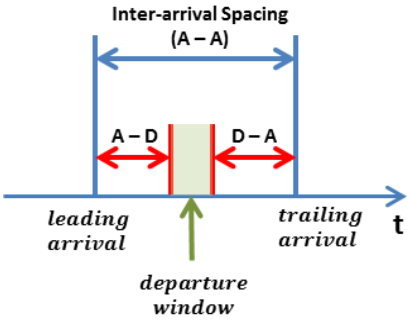


Figure 4. An example of one departure between an arrival pair.

Figure 4 illustrates the parameters that determine the spacing needed for one-for-one departure-arrival operations. Nominally, the minimum required inter-arrival spacing for departures can be decomposed into four parts. The interval between the leading arrival and the departure (A–D) begins when the arrival crosses the runway threshold and ends when it clears the runway intersection, and the departure can be cleared for takeoff. The D-A interval represents the time between when the departure is cleared for takeoff and when it clears the runway intersection, which must occur before the trailing arrival crosses its runway threshold. In order to ensure enough time for a departure to take off between two arrivals, the inter-arrival spacing (A-A) must be equal or greater than the sum of A-D and D-A.

The interval labeled "departure window" is the time available for the departure clearance to be issued. If this window is large enough, i.e., greater than the minimum inter-*departure* spacing, D–D (not shown), there may be time for two or more departures to take-off before the next arrival. To summarize: if A-A spacing is less than the sum of A-D and D-A, the departure slot is lost. Similarly, an A-A interval large enough for two departures must be equal or greater than the sum of A-D, D-D, and D-A time duration.

To estimate the size of these different intervals we sampled airport surface data at LGA during a busy day under Visual Flight Rules (VFR) conditions. The runway configuration was 22|31. Observed inter-arrival spacing was approximately 72 seconds, or roughly 2 to 2.5 nm in distance. In this configuration, the A-D interval, measured from when the leading arrival crossed the runway 22 threshold to when the departure on runway 31 started its take-off, averaged 17 seconds. The D-A interval was measured in two ways. The first used the LGA controller heuristic, which is that the departure can be cleared for take-off if the trailing arrival is more than 2 nm from the runway threshold. Using that criterion, the D-A interval was estimated to be 55 seconds. To be technically correct, however, the minimum D-A interval must simply provide sufficient time for the departure to cross the intersection before the 22 arrival reaches the runway threshold. This value was estimated to be approximately 40 seconds. Using this lower value, the window of opportunity to clear a departure between two arrivals is approximately 15 seconds (72 – (17+40) = 15). Conversely, if the inter-arrival spacing is smaller than 57 seconds, there would be no room for a departure between the arrival pair.

C. *Traffic Characteristics*

Despite a relatively small surface area with a limited number of runways and taxiways, LGA handles a large volume of traffic that normally starts around 7am local time and is maintained at steady, high levels until around 8pm in the evening. The initial traffic consists mostly of departures, but by the time the traffic nears its peak at around 10am it consists equally of departures and arrivals. The aircraft types at LGA are predominantly Larges, with a few additional Smalls and B757s throughout the day. The homogenous aircraft types simplify the inter-arrival and arrival-departure spacing requirements.

Table I summarizes the actual arrival rate at LGA observed in 2013 using ASPM data. The median arrival rate varied from 32 to 35 depending on the time of the day. The mode, which indicated the arrival rate that occurred most often, showed a high arrival rate of 38 and 39 during the afternoon until the evening. In current day operations, a one-for-one operation (one departure between each arrival pair) is targeted during high arrival traffic periods (e.g., 38 or 39 arrival rate). In general, under VFR a 2.5 nm inter-arrival spacing at the runway threshold is observed, allowing for a departure between each arrival pair while maintaining a high arrival rate. However, VFR operations do not guarantee this minimum inter-arrival spacing, thus a loss of departure slots and buildup of departure queues may occur.

TABLE I. SUMMARY STATISTICS OF THE ARRIVAL RATES AT LGA IN 2013

	Median	Max	Mode
Morning (6:00 – 11:59)	32	45	32
Afternoon (12:00 – 17:59)	35	47	38
Night (18:00 – 23:59)	32	47	39
Late night (0:00 – 5:59)	0	33	0

Paradoxically, the feedback from the New York SMEs was that sometimes the TRACON controllers reduce the arrival rates when there are excessive departure delays, thinking that the lower arrival rates will allow a greater number of departures to take-off. However, the reduced arrival rates could increase the inter-arrival spacing but not enough to allow two-for-one departure-arrival operations, which can increase both arrival and departure delays.

III. DSAS CONCEPT OF OPERATIONS

Given the potential loss of departure throughput due to sub-optimal inter-arrival spacing, one strategy for addressing the departure problem is to work toward developing an arrival

schedule that ensures release of departures without reducing arrival capacity or demand. This can be accomplished in the following two ways:

1. Ensure one-for-one departure-arrival operations by maintaining consistent inter-arrival spacing
2. Make small adjustments to the arrival schedule to create inter-arrival spacing that is optimal for one, two, or even more departures

A. TSS Operations to Ensure One-for-one Operations

In order to ensure one-for-one operations, TSS is used to create and deliver an arrival schedule that would minimize the loss of departure slots due to inconsistent inter-arrival spacing. TSS enhances the existing meter fix scheduler to create a Terminal Metering schedule. It utilizes new area navigation (RNAV) enabled descent procedures that extend from En Route airspace to the runway. Figure 5 shows an example of a TSS schedule for LGA for the 22|31 configuration. The right side of the graph shows the Scheduled Times of Arrival (STAs) to the Runway 22 threshold using wake vortex spacing under VFR conditions, which is greater than or equal to 75 seconds depending on the equipage types. The left side of the graph shows the Estimated Times of Arrival (ETAs). The numbers next to an aircraft's STA indicate the delay that the aircraft needs to absorb (in minutes) in order to conform to their STA.

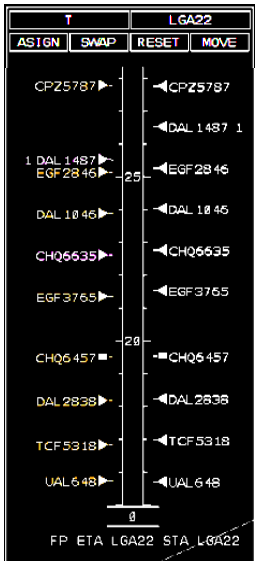


Figure 5. An example of TSS schedule for LGA.

Utilization of TSS to create and deliver the arrivals to a runway threshold schedule provides enough space for a departure between arrival pairs. In the runway 22|31 configuration, 75 seconds for inter-arrival spacing turns out to be sufficient for a departure to take-off between an arrival pair. Therefore, if the controllers can deliver the aircraft on their STAs, one-for-one operations can be preserved without any lost departure slots.

The TRACON controllers achieved STA conformance using TSS slot markers that indicated where an aircraft was scheduled to be along its RNAV route [7]. These slot markers represented the current "ideal" position and the indicated air speed of the aircraft as it descended from the meter fix to the runway along the 4-D path defined by its RNAV descent procedure and assigned STA. Figure 6 shows a TRACON controller display with slot marker circles, as well as the charted air speed for the route. Controllers issued speed or route amendments to put the aircraft in their slot markers to conform to their STAs.

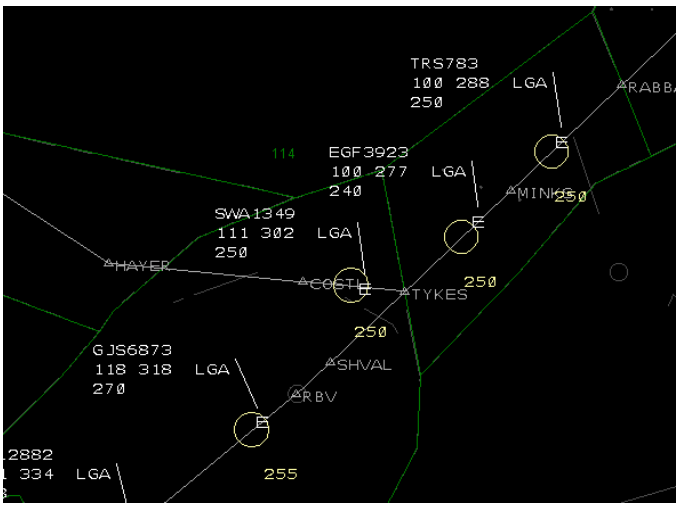


Figure 6. An example of TSS slot markers.

B. DSAS Operations for Increasing Departure Throughput

During peak arrival traffic scenarios, the inter-arrival spacing can often be greater than the spacing needed to allow one departure between an arrival pair but not enough to allow multiple departures. If the arrival spacing can be adjusted to match the exact spacing needed for one, two or more departures per arrival pair, more departures could be cleared given the same arrival demand. The DSAS concept is similar to the research efforts by Diffenderfer and his colleagues [2], but unlike their concept that provides the spacing guidance close to the Final Approach Fix, DSAS proposes to leverage TSS operations to nominally set up and adjust the TRACON schedule prior to TRACON entry, thereby creating a more strategic and stable schedule that can distribute the schedule conformance task across multiple TRACON controllers.

The DSAS concept assumes a new TMU Planner position (called "Planner" in our simulation), who can modify the schedule after the schedule is frozen and before the controllers start moving the aircraft to meet their STAs. In our concept evaluation, we assumed that the aircraft were frozen at 150 nm from the airport and only the TRACON controllers were responsible for the STA conformance, giving the Planner about 20 minutes for adjusting the schedule to optimize the departures before the arrivals entered the TRACON.

The Planner can adjust the schedule by assigning larger inter-arrival spacing to allow multiple departures. Figure 7 illustrates a schematic example of how the schedule could be adjusted. The left graph shows an example of an arrival schedule with only the TSS schedule. The inter-arrival spacing may be greater than the minimum wake vortex spacing (set to 75 seconds in this condition) but the spacing is not large

enough for multiple departures per arrival pair. Using DSAS operations, as shown on the right, the arrival schedule is modified to create 75 seconds minimum spacing for the first four arrivals, which then creates a larger 120 seconds spacing between the arrival 4 and 5, which is enough spacing to allow two departures in that gap.

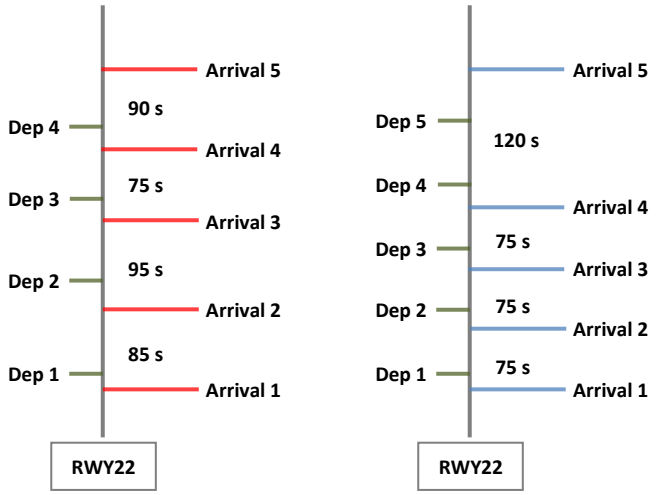
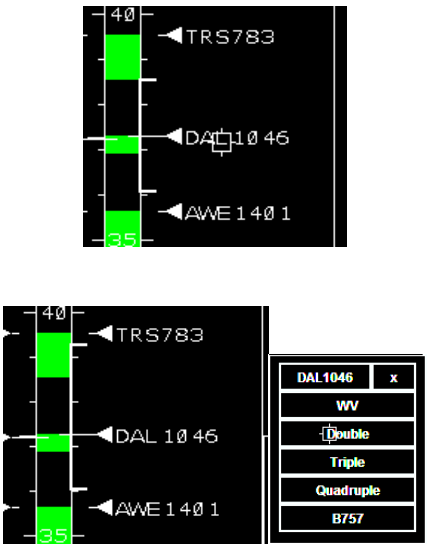


Figure 7. Original arrival schedule on the left graph (in red) and the arrival schedule modified with DSAS on the right graph (in blue)

Figure 8 shows our prototype interface for DSAS functionality. The top figure shows DAL1046 and a bracket that indicates the minimum wake vortex spacing for that arrival. The green bars indicate the "slack capacity" that is in excess of the minimum inter-arrival spacing that is needed. The middle shows the options presented to the Planner when the Planner has right clicked on the call sign, which brings up the options for different types and numbers of departures (e.g., WV for normal wake vortex spacing, Double for spacing needed for two departures, Triple for three departures, etc.).



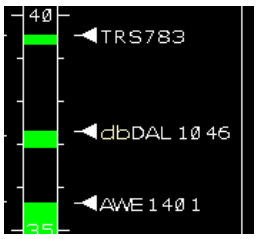


Figure 8. DSAS schedule adjustment sequence (from top to bottom).

When the Planner hovers over the item "Double" on the menu, the bracket for DAL1046 becomes larger to preview the spacing needed for two departures. As shown on the bottom figure, when the Planner assigns the "Double" spacing into the schedule, the word "db" for double appears next to the callsign DAL1046 to indicate that the larger spacing has been reserved for two departures and the green bar shows less slack capacity near the TRS78. The updated schedule and the "db" assignment are then propagated throughout the system to show the updated schedule to the impacted controllers. For the TRACON controllers, their STA conformance task remains the same as in TSS operations – i.e., the TSS slot markers automatically reflect the updated schedule created by the DSAS operations and the controllers conform to the STAs by putting the aircraft in their slot markers using speed and route amendments.

C. *Tactical Schedule Adjustment for TSS and DSAS*

If the Planner can modify the schedule prior to controller intervention, it has little impact on controller workload and minimum coordination is needed. However, in situations where tactical schedule adjustment is needed after the controllers have begun to take actions, more coordination is required. One of those cases occurs regularly when there is a B757 departure in the 22|31 configuration. At LGA, the 22|31 configuration requires a special inter-arrival spacing of seven miles when a B757 departs on runway 31 because the departure becomes airborne at the crossing point, needing a four mile wake vortex spacing between the B757 departure and the trailing arrival.

In current operations, when a B757 departure is at least seventh in the departure queue, the tower Cab Coordinator notifies the TRACON (either the Final controller, supervisor, or a "Sequencer" who monitors/coordinates the arrival sequence, depending on who is available). The Sequencer (or the Final controller if the Sequencer is not available) assesses the arrival traffic and timeline to determine which point within the arrival stream would be the best to build the necessary gap (~180 seconds) to allow for a B757 departure. The Sequencer checks with the affected feeder controller to see if the gap would be possible to make and that it would not interfere with anything else at the time. Once the appropriate arrival pair is identified for the gap, the Sequencer coordinates with the tower to specify the location of the gap. In the 22|31 configuration, the tower Local controller has access to an alternate taxiway where B757s can be taken out-of-sequence and held for up to approximately 10 minutes to wait the for the proper gap without being completely out of the departure queue.

In the TSS and DSAS operations, the Sequencer also calls the Planner so that the Planner can adjust the TSS/DSAS STAs

to match the gap that the TRACON controllers are building. Whenever the Planner adjusts the STAs, the slot markers "jump" to their new locations. With proper coordination, the TRACON controllers are aware of the change and are already moving the aircraft to the new locations. The Planner adjusts the schedule similarly in TSS and DSAS conditions, but DSAS has a couple of advantages. First, the DSAS tool has a special B757 spacing option in the fly-out menu that the Planner can use to assign the spacing. The assignment is then propagated across the system. Secondly, the Planner might have already created a double or a triple gap for multiple departures in the vicinity of where the B757 gap is needed. In that situation, the Planner can "re-purpose" the gap, which results in less controller workload due to similar gap sizes.

IV. Concept Evaluation

A human-in-the-loop (HITL) simulation was conducted in the summer of 2014 at the Airspace Operations Laboratory, NASA Ames Research Center to examine the potential benefits, feasibility, and issues regarding DSAS operations at LGA. New Optimum Profile Descent (OPD) routings, procedures, and prototype decision support tools were designed to support the TSS/DSAS operations.

A. Simulated Airspace

The simulated airspace consisted of a subset of the New York TRACON (N90) sectors that feed traffic into LGA Airport. Figure 9 shows the two feeder sectors (i.e., Empyr and Haarp) and one final sector (Final). These sectors have been modified from current sector configurations in order to accommodate OPD routes that have been newly designed for this study.

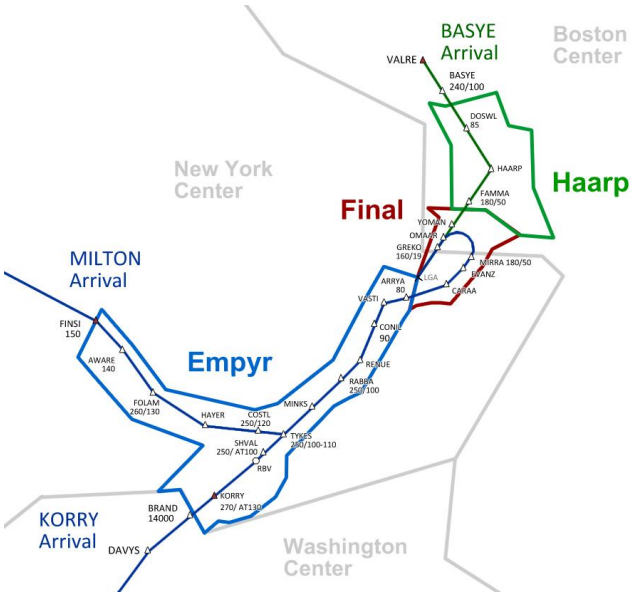


Figure 9. Simulated airspace: two feeder and one final sectors to LGA.

For this study, the 22|31 configuration was chosen from the four most common configurations illustrated in Figure 3. This required a fairly precise delivery of the arrivals on schedule in order to not miss the departure slots, thereby creating a challenging problem for evaluation. In addition, 22|31 required a last-minute tactical adjustment of the schedule to create the spacing for B757 departures, which provided an additional challenge for the DSAS concept.

The traffic flow into LGA for 22|31 has the following characteristics. The south feeder Empyr sector merges the traffic from the west on the MILTON arrival with the traffic from the south on the KORRY arrival. The north feeder Haarp sector handles the traffic from the north on the BAYSE arrival. The Final sector merges the north traffic from Haarp with the south traffic from Empyr before handing them off to the tower controller. The routes are RNAV OPD routes that are modified from current MILTON, KORRY, and BAYSE arrival routes. Unlike the current routes, however, the new procedures' descent profiles vary, along with their TRACON entry altitudes, depending on the flight distance to the runway threshold. The MILTON arrival enters N90 at FINSI at 15,000 ft., the KORRY arrival enters N90 at KORRY at 13,000 ft., and the BAYSE arrival enters N90 at BAYSE at 10,000 ft.

Due to the sector and route geometry, the Empyr sector has long routes that can absorb large delays using speed commands but not much lateral vectoring space. In order to maximize the speed envelope that controllers can utilize, the OPDs were designed to keep the aircraft above 10,000 ft. as long as possible, where the controllers can issue speeds greater than 250 knots. For the north traffic in the Haarp sector, there is more lateral airspace for vectoring but shorter route lengths for speed control, so the controller in the Haarp sector can issue vectors for delay absorption.

In addition to the N90 test sectors, En Route "ghost" sectors that feed the traffic into N90 were also simulated to support the simulation. These sectors were four large combined sectors, one that feeds the BASYE arrival, one that feeds the MILTON arrival, and two for the KORRY arrival. A LGA "ghost" tower sector was also simulated, albeit at much lower fidelity, so that a tower Local controller can land the arrivals and clear departures whenever appropriate inter-arrival spacing appears.

B. Experiment Design

The experiment was a within-subjects 3x2 design. The two independent variables were Operational Environment (Baseline, TSS, and TSS+DSAS – or DSAS for short) and Traffic Levels (Moderate and High). Each condition was run once, consisting of six total runs. The Baseline condition assumed current day tools but with newly designed routes and airspace. The TSS and DSAS conditions included what was described in the previous TSS and DSAS operations sections.

Two arrival traffic levels were tested. The Moderate Traffic condition delivered around 35 aircraft per hour, matching the median arrival rate from the ASPM data during peak traffic time periods (i.e., weekday afternoon traffic during VFR conditions). The High Traffic condition delivered around 40 aircraft per hour, which matched the airport arrival rate (AAR) typically assigned in the actual operations during similar high traffic periods.

The simulation runs lasted 100 minutes. The initial 20 minutes were populated with fewer arrivals to allow the

controllers to get acclimated to the traffic scenario and therefore were excluded from the data analyses. No departures were released during this period. The last 20 minutes were also excluded from the data analyses because none of the arrivals actually landed at the end of the simulation run. Therefore, the middle 60 minutes were used to provide the core data for the analyses.

C. Participants

Nine retired controllers, with experience ranging from 21 to 31 years and retired within 1 to 7 years, staffed three TRACON, one tower, and four En Route positions. The four En Route controller participants were from Oakland Center (ZOA). The four TRACON and tower controller participants worked in different TRACON facilities (e.g., Northern California, Dayton, and Miami) as well as tower and center facilities. The other participants consisted of a retired Supervisory Traffic Management Coordinator for ZOA who played the role of the Planner, and Front Line Managers (FLMs) from ZDC and N90 who played the role of an En Route FLM and TRACON Sequencer, respectively. One of the researchers also participated in the study as a tower Cab Coordinator. Eight pseudo-pilots supported the operations. Each pseudo-pilot was responsible for flying aircraft within one sector. All pilots were students from the Aviation Department at San Jose State University.

D. Apparatus

Multi-Aircraft Control System (MACS) software was used to emulate Standard Terminal Automation Replacement System (STARS) displays shown on large-format monitors similar to those used in current air traffic control facilities. Keyboards similar to those used in the field further helped to replicate the look and feel of these facilities. MACS software provides a high fidelity environment in which to prototype scheduling tools, to simulate the air traffic, and to collect data [8]. In addition to STARS displays, MACS software was used to prototype Planner, tower, and pseudo-pilot stations.

E. Operational Procedures

1) Freeze Horizon and Traffic Delivery prior to TRACON Entry: In the study, the arrival scheduler's freeze horizon was set at 150 nm from the airport, which froze most of the arrivals just prior to their tops-of-descent. Although aircraft schedules and delays were determined at this point, the procedures were designed to not show this information to the En Route controllers. Instead, the En Route controllers were asked to deliver the arrivals to the meter fixes no less than 8 miles-in-trail (MIT) apart across all three conditions, similar to current operations.

Although arrivals could have been metered in the En Route sectors, it was decided to keep the operations the same as current LGA operations. Instead of metering, LGA controls the departure times of the internal departures (e.g., departures from first tier Center airports) using the scheduler. Since internal departures contribute approximately half of the traffic to LGA, controlling the departure times from these airports has been sufficient and En Route metering was not required.

2) Runway Schedule Adjustments: The Planner station had a modified DSR (Display System Replacement) and STARS displays, set at different spatial granularities, to monitor the En Route and TRACON airspace that contained the LGA arrivals (Figure 10). The Planner also had a runway timeline embedded into the DSR and STARS displays that he could use to modify the runway schedules when needed. The Planner also had a display that showed the departure queue at the airport to view the current departure demand.

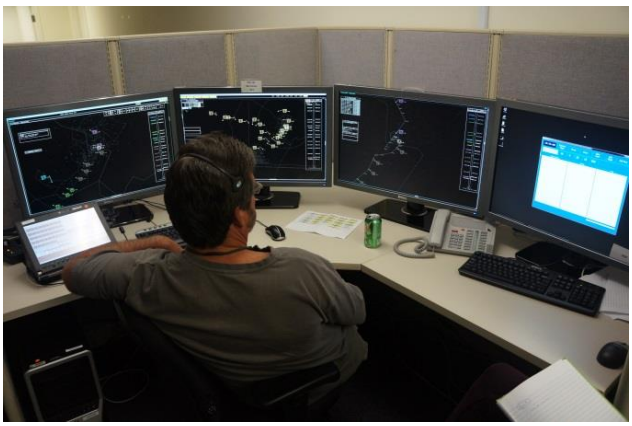


Figure 10. TMU Planner Station.

In the Baseline condition, there was no scheduling task and, therefore, the Planner's involvement was limited. Communications occurred primarily between the Center and TRACON supervisors and then with controllers to determine the proper sequence of arrivals.

In the TSS condition, all arrivals had scheduled times of arrival at the runway. However, since the En Route controllers were delivering the aircraft at MIT $\geq$ 8 miles, the arrival sequence sometimes differed from the TSS scheduled sequence. The Planner monitored those situations and adjusted, swapped, and/or rescheduled the STAs in ways to reduce the delays that the TRACON controllers would see at the TRACON entry point.

In the DSAS condition, the Planner was able to manipulate the schedule via a timeline interface to optimize the departure gaps. The Planner had access to a scheduling support tool via a flyout menu on the timeline that assigned a pre-determined gap size between arrivals to accommodate varying types of departures: single, double, triple, or a B757. Except for these new departure-sensitive scheduling adjustments, the procedures were the same as in the TSS condition.

3) Schedule Conformance in the TRACON: In the Baseline Condition, there was no scheduling task. The two feeder sectors, Empyr and Haarp, sequenced their respective traffic flows and the Final sector controller merged the two flows in his sector. A Sequencer position was staffed to monitor the traffic flows from the feeder sectors. When there appeared to be a tie between two aircraft in the Final sector, the Sequencer generally coordinated between the Haarp and Final sectors to vector an aircraft in Haarp to follow behind an aircraft in Final. This was due to the lighter traffic volume and the ample maneuvering space in the Haarp sector. The Sequencer also

coordinated the creation of a B757 gap when necessary, as described in an earlier section.

The Final controller was responsible for safely and efficiently landing aircraft on 22. The Final controller maintained 2.5 nm spacing between arrivals for nominal VFR wake vortex separation when able, but allowed less spacing when workload was excessive or the merge became challenging. This behavior mimicked those of Final controllers in current operations.

In the TSS and DSAS conditions, controllers used TSS slot marker advisory circles to help them deliver each aircraft on its assigned STAs. Their tasks did not differ significantly for the TSS and DSAS conditions, except they saw special spacing designations whenever the Planner assigned special spacing for multiple departures (e.g., "db" and "tr" on the timelines) in the DSAS condition. In both of these conditions, the slot markers implicitly coordinated the Empyr and Haarp traffic flows, so the Final controller or the Sequencer did not need to work hard to merge the flows in the Final sector.

4) Departure Clearance: The tower Local controller, who was a confederate and not a test participant, issued the landing and departure clearances. The simulation platform did not have a full surface simulation capability but was able to show aircraft taking off and landing on the runways on a radar-like display. The tower Local controller also had an emulation of the Departure Spacing Program (DSP) tool that the controllers use in the field (see Figure 11).

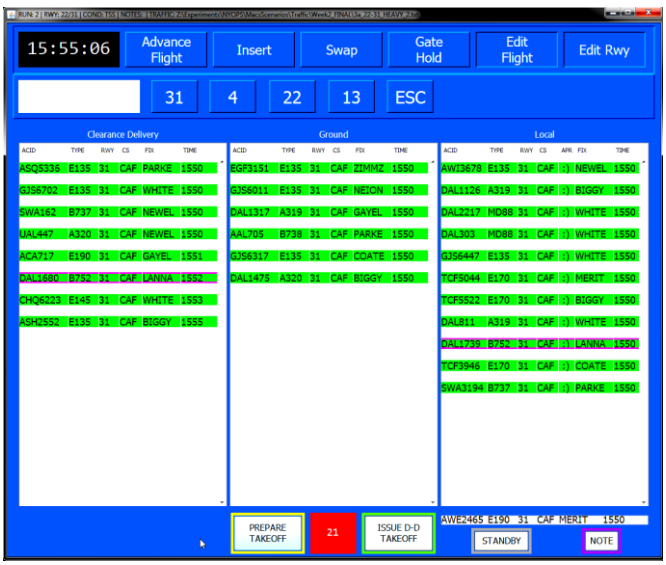


Figure 11. DSP tool emulation with custom departure clearance capability.

DSP shows the departures that are in the queue for the Clearance Delivery, the Ground controller, and the Local controller. This tool allowed the tower Local controller to view the departure queue on the taxiway (in the right column) and to put an aircraft on standby if needed (e.g., to hold a B757 departure to wait for its gap). In addition to the normal DSP functionality, a departure clearance capability was added to release the departures into the simulation environment.

Based on an LGA SME's input, the tower controller was given a clear set of guidelines on when he could issue the departure clearance. These were:

- Clear the departure after the arrival passes the runway crossing point. (The controller pressed the "prepare take-off" button when the arrival passed its runway threshold and the DSP tool estimated the time it took for the arrival to reach the crossing point before releasing the departure. This also allowed the controller to cancel the clearance if needed.)
- Do not clear the departure if the trailing arrival is within 2 nm of its runway threshold.
- When multiple departures are cleared, wait at least 45 seconds after the lead departure before clearing the trailing departures. (The 45 seconds was deemed sufficient spacing in VFR conditions based on the SME's input.)
- A B757 departure can be cleared if the trailing arrival is at least 6 nm from the runway threshold.
- Due to wake vortex spacing requirements, wait 94 seconds after the B757 departure to clear a second departure. (This time would allow the preceding 757 departure to be at least 1.5 miles off the end of the runway before the launching of the second departure).

At the beginning of each simulation run, the tower Local controller did not clear any departures until 20 minutes into the scenario. At 20 minutes, the DSP emulation tool was initiated with 10 departures in the Local queue and subsequently moved a departure into the queue every 75 seconds. The DSP tool recorded the number of departures cleared for take-off, the number of departures left in the queue, and the time that the departures spent in the queue. The results of these data are the main findings of the study and are reported in the following section.

V. Results

The comparison of the three operational conditions yielded many interesting results, detailed in [9]. In this paper, we highlight some of the main findings.

A. Departure Throughput

The main hypothesis of the HITL evaluation was that during busy traffic periods, TSS and DSAS operations could improve departure throughput and reduce departure delays without negatively impacting arrival throughput. The results in Table II confirmed the hypothesis for departure throughput. As shown in Table II, for the High Traffic condition, the arrival throughput was fairly steady at 40 to 41 per hour across the tool conditions, suggesting that the arrival throughput could be maintained during TSS and DSAS conditions. Examining the departure throughput, in the Baseline condition, 38 departures were cleared per 40 arrivals, suggesting that one-for-one operations could not be preserved. In the TSS condition, the departures increased to 44 per 41 arrivals, showing an increase of six departures from the Baseline condition, likely due to the TSS scheduling that maintained the one-for-one spacing for the

arrivals plus a few additional opportunities for multiple departures that came from the schedule. In the DSAS condition, there were three additional departures (47 in total) over those in the TSS operations, confirming the hypothesis that adjusting the arrival schedule to maximize departure throughput can provide benefits even during peak traffic periods. The number of total aircraft per hour increased from 78 to 85 to 87 in Baseline, TSS, and DSAS conditions respectively.

TABLE II. ARRIVAL AND DEPARTURE RATES IN THE SIMULATION RUNS.

	Aircraft/hr.	Baseline	TSS	DSAS
High Traffic	Arrival	40	41	40
	Departure	38	44	47
	Total	**78**	**85**	**87**
Moderate Traffic	Arrival	35	35	34
	Departure	45	46	50
	Total	**80**	**81**	**84**

In the Moderate Traffic scenario, the arrival throughput was steady at 34 to 35 across the conditions. Fewer arrivals meant that any missed slots could be recovered later due to the slack in the schedule. The results seemed to validate this hypothesis, as the number of departures was similar between Baseline and TSS conditions (45 for Baseline; 46 for TSS). For DSAS, however, optimizing the arrival schedule for departures added five departures to the Baseline throughput. The total operations increased from 80 to 81 to 85 in Baseline, TSS, and DSAS conditions respectively.

B. *Departure Delays*

Another method of examining the departure benefits was to calculate the taxi-out delays. In each simulation run, departures were added every 75 seconds (i.e., a rate of 48 aircraft per hour). During the simulation runs, the queue length increased gradually over the first 40 minutes of departure operations and stabilized during the last 20 minutes. Averaging the time in the queue during the last 20 minutes of the simulation, the time in the queue was reduced from 23.7 min. per aircraft in Baseline to 17.2 min. in TSS and 13.3 min. in DSAS during the High Traffic scenarios (see Table III).

TABLE III. DEPARTURE TIME IN QUEUE AND TAXI-OUT DELAY SAVINGS (MIN.) DURING THE LAST 20 MIN OF THE SIMULATION RUNS

		Baseline	TSS	DSAS
High Traffic	Time in Queue	23.7	17.2	13.3
	Delay Savings	**-**	**6.5**	**10.4**
Moderate Traffic	Time in Queue	17.4	16.5	11.9
	Delay Savings	**-**	**0.9**	**5.5**

The delay savings were calculated by subtracting the TSS or DSAS time from the Baseline time. The results showed that departures in the TSS and DSAS conditions had an average of 6.5 and 10.4 minutes less taxi-out time respectively compared to the Baseline conditions. In Moderate Traffic, the TSS condition produced little delay savings (0.9 minutes) while DSAS condition reduced the delays by 5.5 minutes, mirroring the benefit characteristics found in the throughput data.

C. *Inter-arrival Spacing*

An examination of the inter-arrival spacing data verified how the arrival spacing changed across the conditions in order to improve the departure operations. Figure 12 illustrates the inter-arrival spacing data taken during the simulation runs across the conditions. The spacing data in the Baseline condition shows how the spacing values were distributed between 60 and 120 seconds, with few outliers with larger spacing. (In the Moderate Traffic scenario, there are natural gaps in the arrival schedule which resulted in larger spacing.) The Baseline condition also had a number of spacing values below 60 seconds (shown in red), which resulted in missed departure slots due to insufficient spacing.

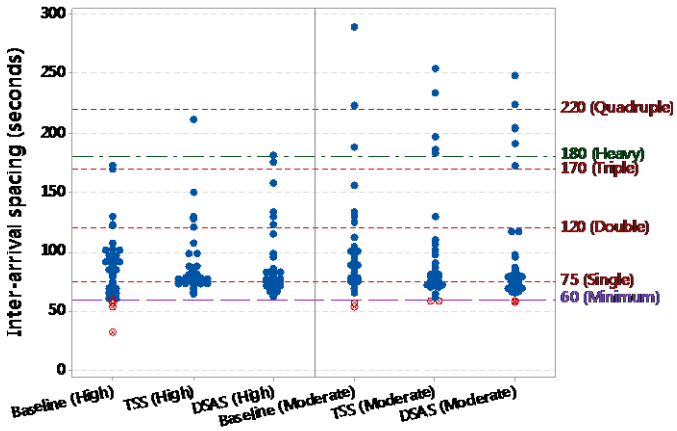


Figure 12. Inter-arrival spacing across conditions. The dotted lines indicate the different inter-arrival spacing parameters in the TSS and DSAS schedulers.

Compared to Baseline, the TSS condition resulted in fewer spacings under 60 seconds and a greater number of spacings around 75 seconds, where the TSS scheduler set the wake vortex spacing. The graph suggests that the controllers were able to deliver the arrivals to their schedule. Similarly, DSAS operations also resulted in most spacing values around 75 seconds and very few below 60 seconds. In the High Traffic condition, DSAS spacing also seems to be clustered around double and triple departure spacing times, probably due to the Planner's assignment of double and triple departure spacing. This pattern does not seem to appear for the Moderate Traffic, likely due to a natural slack in the schedule which reduced the need to force the arrival schedule adjustments.

D. *Task Load Distribution*

The tool conditions also influenced the distribution of the task load across sectors. Table IV shows the distribution of clearances across sectors for each tool condition in High Traffic runs. As can be seen, there was a shift in task load between the Final and the feeder sectors, Empyr and Haarp. In the Baseline run, Final issued 59.6% of the clearances

(236/396), compared to 25.5% (101/396) by Empyr and 14.9% (59/396) by Haarp. In contrast, in the TSS run, Final issued 14.6% of the clearances (36/247), compared to 55.4% (137/247) by Empyr and 30.0% (74/247) by Haarp, showing the shift in the task load distribution, with fewer clearances by Final but more by the feeder sectors compared to Baseline. Similarly in the DSAS run, Final issued 3.6% of the clearances (6/166), compared to 56.0% (93/166) by Empyr and 40.4% (67/166) by Haarp. χ^2 (4) = 226.8, p <.0001.

TABLE IV. CLEARANCES PER SECTOR IN HIGH TRAFFIC RUNS

Clearances	Empyr	Haarp	Final	Total
Baseline High	101 (25.5%)	59 (14.9%)	236 (59.6%)	396 (100%)
TSS High	137 (55.5%)	74 (30.0%)	36 (14.6%)	247 (100%)
DSAS High	93 (56.0%)	67 (40.4%)	6 (3.6%)	166 (100%)
Total	331	200	278	809

Table V shows the distribution of clearances across sectors for each tool condition in Moderate Traffic runs. Similar to the High Traffic runs, there was a shift of task load between Final and the feeder sectors, Empyr and Haarp. In Baseline, Final issued 57.3% of the clearances (145/253), compared to 29.6% (75/253) by Empyr and to 13.0% (33/253) by Haarp. In TSS, Final issued 6.1% (10/164) of the clearances, compared to 68.3% (112/164) by Empyr and 25.6% (42/164) by Haarp. In DSAS, Final issued 6.9% of the clearances (9/131), Empyr issued 64.1% (84/131), and Haarp issued 29.0% (38/131). χ^2 (4) = 168.8, p <.0001.

TABLE V. CLEARANCES PER SECTOR IN MODERATE TRAFFIC RUNS.

Clearances	Empyr	Haarp	Final	Total
Baseline Mod	75 (29.6%)	33 (13.0%)	145 (57.3%)	253 (100%)
TSS Mod	112 (68.3%)	42 (25.6%)	10 (6.1%)	164 (100%)
DSAS Mod	84 (64.1%)	38 (29.0%)	9 (6.9%)	131 (100%)
Total	271	113	164	548

Figure 13 graphically represents the clearances. Each dot in the graph indicates an altitude, speed, or heading clearance by the controllers. The graphs show that the Final controller, who issued many clearances in the Baseline condition, issued very few clearances in the TSS and DSAS conditions. In contrast, the Empyr sector issued many more speed clearances in the TSS and DSAS conditions compared to Baseline. The results suggest that the TSS/DSAS tools redistributed the task load across the sectors, making the problem much easier to manage for the controllers as a whole. The findings were supported from the subjective ratings of the workload, which mirrored the task load data shown here.

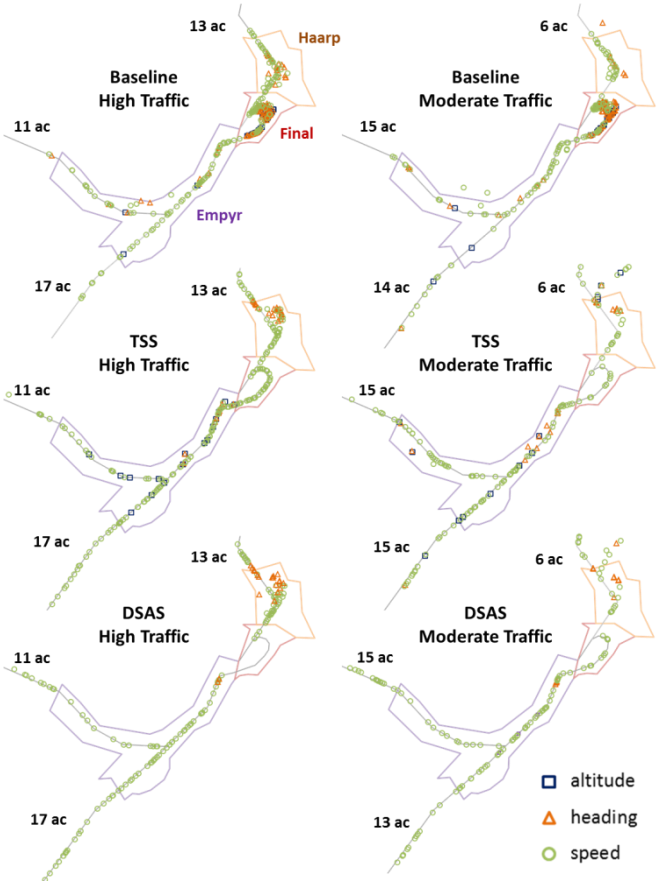


Figure 13. Task load distribution across Empyr, Haarp, and Final sectors.

E. *Tactical Rescheduling for B757 Departures*

For TSS and DSAS operations to work in the field, the operations needed to adequately handle tactical rescheduling scenarios, which can occur when arrival schedule conformance deteriorates or during events such as B757 departures in the 22|31 configuration. In the B757 departure scheduling scenario that was tested in the simulation, the arrival spacing had to be modified inside the Final control sector in order to create sufficient gaps for a B757 departure, which added a level of coordination complexity to the operation.

Based on the subjective feedback, the added coordination with the Planner for the B757 departures in the DSAS condition worked well. The Cab Coordinator called the Planner to coordinate B757 gap spacing when the B757 departure was somewhere between 7th and 9th in the queue. The B757 departure needed to stand by until the designated gap arrived. Table VI shows the average time from when the coordination was initiated until the B757 was cleared for takeoff. On average, the coordination took slightly less time in the TSS condition than in the Baseline and DSAS conditions. For the DSAS condition, the Moderate Traffic condition resulted in earlier take-off times relative to the onset of the coordination than the other conditions, whereas the High Traffic condition for DSAS resulted in much later takeoff times.

TABLE VI. AVERAGE TIME FROM INITIAL COORDINATION TO TAKEOFF FOR B757S (MIN:SEC)

	Baseline	TSS	DSAS
High Traffic	12:05	10:46	19:08
Moderate Traffic	10:19	10:37	7:37
Average	11:12	10:42	13: 23

This later average B757 takeoff time for the DSAS High Traffic condition was caused by an anomaly in the creation of one B757 departure slot. When the Cab Coordinator from the tower requested a B757 departure slot from the Sequencer, the Sequencer used a natural gap that the Planner had already created for two departures much further back and converted it to a B757 departure gap so as not to disrupt the existing schedule. In hindsight, the Cab Coordinator said he should have insisted on a closer slot. In general, the timeline in the TSS and DSAS conditions enabled the controllers to fit the 757 departures into natural gaps without vectoring other aircraft as frequently as they did in Baseline.

F. Participant Feedback on the TSS and DSAS Tools

Post-simulation debrief discussions with the participants showed an overall positive response. The participant who controlled the Final sector in the simulation commented, *"I think it's a great tool [DSAS]. ...it takes a lot of pressure off me, I could see exactly what was coming. With the timelines, I knew where the slot markers were and knew where I had to be. That's how I was getting them from [the feeder controllers], I just had to make very minor speed adjustments and that was it. In the last two days, I don't think I vectored anybody off the routing. So it was good. It's a nice tool."*

Another participant with extensive LGA experience added, *"Bottom line after 40 years of getting killed at La Guardia, seeing a tool that could ease the pain, I think it's a good way to go, and I hope this builds to something they can use in the field. . . I was thinking from a Final controller's perspective, if he doesn't have to worry and it's just kind of laid out there for him, and stays within the markers, the pressure is off. I mean, that's the bottom line. You're not sitting there with, what is it, 10 minutes of sheer terror and 15 minutes of nothing. It's a good way to go."*

VI. CONCLUSION

The DSAS concept was prototyped and evaluated in a HITL simulation. Results showed that with maximum arrival demand, departure throughput increased for TSS and even more for DSAS, showing the benefits of both. Interestingly, the TSS benefits disappeared during moderate arrival demand but the DSAS benefits remained. Tactical rescheduling of B757 departures was also feasible in both TSS and DSAS operations, but the results from the DSAS operations suggest that the Cab Coordinator needs to maintain vigilance to get appropriately timed slots for the B757 departures. An added benefit of TSS and DSAS operations was that the TRACON scheduling simplified the controllers' tasks and re-distributed the workload from the Final sector to the upstream feeder sectors and delivered more consistent inter-arrival spacing compared to Baseline.

In summary, DSAS operations demonstrated a concept that can improve the chronic departure delay problems at LGA. The concept was demonstrated to various stakeholders who have shown significant interest in the proposed solution. Although the results suggest benefits that are specific to LGA operations, the concept and the associated benefit mechanisms should be applicable to other airports with similar arrival-departure dependencies. Since the concept builds on TSS technology which is currently in the FAA's NextGen Implementation Plan, the next step for the concept evaluation would be to test both TSS and DSAS in a more realistic environment with different winds, runway configurations, traffic scenarios, and with off-nominal situations.

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