SCHEDULING AND SEPARATING DEPARTURES CROSSING ARRIVAL FLOWS IN SHARED AIRSPACE

Eric Chevalley, San Jose State University / NASA Ames Research Center, Moffett Field, CA
Bonny Parke, Paul Lee, Faisal Omar, Hwasoo Lee, Nancy Bienert, Joshua Kraut, San Jose State University / NASA Ames Research Center, Moffett Field, CA
Everett Palmer, NASA Ames Research Center, Moffett Field, CA

Abstract

Flight efficiency and reduction of flight delays are among the primary goals of NextGen. In this paper, we propose a concept of shared airspace where departures fly across arrival flows, provided gaps are available in these flows. We have explored solutions to separate departures temporally from arrival traffic and pre-arranged procedures to support controllers' decisions. A Human-in-the-Loop simulation assessed the efficiency and safety of 96 departures from the San Jose airport (SJC) climbing across the arrival airspace of the Oakland and San Francisco arrival flows. In the simulation, the SJC tower had a tool to identify departures that could fly through predicted gaps in the arrival flow. When the timing of departures did not align with gaps in the arrival flows and separation could not be ensured, a safe but less efficient route was provided to the departures to fly underneath the arrival flows. Coordination using a point-out procedure allowed the arrival controller to control the SJC departures right after take-off. The simulation manipulated the accuracy of departure time (accurate vs. inaccurate) as well as which sector took control of the departures after takeoff (departure vs. arrival sector) in a 2x2 full factorial design. Results show that coordination time decreased and climb efficiency increased when the arrival sector controlled the aircraft right after takeoff. Also, climb efficiency increased when the departure times were more accurate. Coordination was shown to be a critical component of tactical operations in shared airspace. Although workload, coordination, and safety were judged by controllers as acceptable in the simulation, it appears that in the field, controllers would need improved tools and coordination procedures to support this procedure.

Introduction

Today in terminal environments, arrival and departure flows are decoupled and assigned to distinct arrival and departure sectors. This spatial segregation avoids interactions and procedurally provides for separation between aircraft. This results in safe but inefficient routes in places where efficient routes would otherwise overlap.

In metroplex environments, efficiency and delays can be further compromised by the density and complexity of operations. A metroplex is defined by the Joint Planning and Development Office (JPDO) as an area with high traffic demand served by two or more airports with arrival and departure operations that are highly interdependent [1]. Metroplex interdependencies stem from different traffic flows sharing common fixes, paths or airspace volumes within the metroplex airspace [2]. These interdependencies can be coordinated by either separating traffic across space or separating traffic across time.

These types of separation are control strategies that have different costs and benefits. Spatial separation decouples traffic demand and relies less on the precision of when aircraft cross a given point. However, having distinct routes in segregated airspace reduces airspace capacity. Routes may be longer and require altitude constraints to accommodate other routes and sectors, which also results in fuel and time inefficiencies. For controllers, the division of airspace spatially reduces traffic complexity. It clearly divides tasks and responsibilities between controllers. But this division has a cost when interdependencies exist between controllers. In current control facilities, Letters Of Agreement and Standard Operating Procedures regulate coordination needs between sectors and facilities.

Temporal separation involves dealing with multiple traffic demands and coordinating the use of shared resources, e.g., common fixes and runways. Today it is mostly used to space or merge traffic to a common destination or to intersecting runways.

Temporal separation optimizes the use of airspace by accommodating multiple interdependent demands, but it also requires precision in timing. Temporal separation can be managed on a first-come first-served basis, but it can be a suboptimal strategy to manage multiple conflicting demands or high traffic density. The use of shared resources can be exceeded by high demand and create choke points. Temporal separation can therefore benefit from scheduling technology [3, 4].

At NASA Ames Research Center, the Airspace System Project aims at developing scheduling and automation technologies for complex operational choke points in metroplex airspace. One of the objectives is to develop concepts and technologies to maximize performance for interacting arrival and departure operations. Recent modeling studies at NASA Ames have shown that the hybrid use of spatial and temporal separation supports more efficient routes in the metroplex environment [3, 4].

Our Study

In this study, we explore scheduling solutions to coordinate the demand of both arrivals and departures over common waypoints in temporally shared airspace. We use the term "Sharing Of Airspace Resources" (SOAR) to describe the concept of efficient arrival and departure routes crossing each other and sharing a common airspace.

We chose the NCT, or Northern California Terminal Radar Approach Control (TRACON) environment as a specific example of a generic problem.

Shared Airspace

The San Francisco Bay area is a metroplex environment with three large airports within 20nm of each other. San Francisco International Airport (SFO) and Oakland International Airport (OAK) are on each side of the bay 10nm apart from each other. San Jose International Airport (SJC) is on the south of the bay, 20nm apart from SFO and OAK. Today, departures from San Jose to the northeast fly the LOUPE1 departure. Aircraft on this departure route fly a 360 degree turn over the city while climbing to 12,000ft and then head to the north above arrival traffic coming into Oakland and San Francisco from the east. This highly inefficient route is designed to avoid the Oakland and San Francisco arrival flows, as shown in Figure 1.

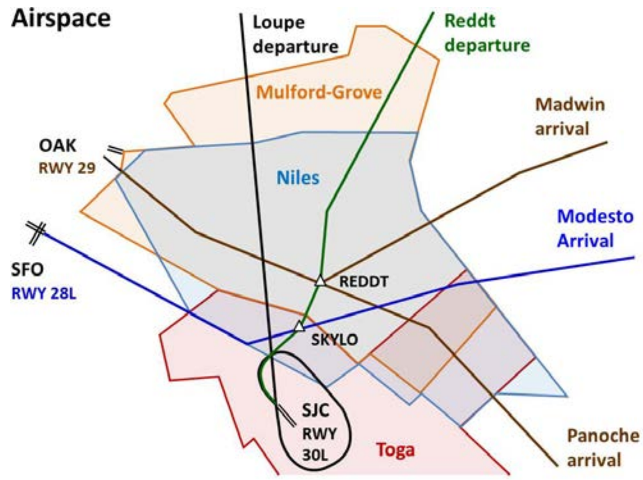

Figure 1. Routes and Sectors

We adapted existing Standard Instrument Departures (SIDs) and Standard Terminal Arrival Routes (STARs) to create a new departure from SJC that flies directly to the northeast, called REDDT1. The REDDT1 departure is derived from the SUNOL6 departure for turboprops. The new REDDT1 route crosses the airspace of both arrival routes (see Figure 2). The standard procedure is to fly this route safely under both arrival flows at 5,000ft, i.e. to cross both the SKYLO and REDDT waypoints at 5,000ft. On the arrival routes, traffic is expected to cross SKYLO at 7,000ft and REDDT at 6,000ft. The altitude restrictions at SKYLO and REDDT allow departures to fly the route safely in case of a loss of radio communication.

Currently, the MADWIN and PANOCHE STARs merge at the SUNOL waypoint. This waypoint is in class C airspace. Because the REDDT1 departures are flown only by jets, the SUNOL waypoint was moved to the west into class B airspace and renamed as REDDT. Moving that point also created a better angle between the Modesto and REDDT1 routes to allow divergence between traffic flows.

The REDDT1 departure provides two advantages over the LOUPE1 departure. First, the route is 32nm shorter to fly to LINDEN, the departure fix in the Oakland Air Route Control Center. Second, the altitude restrictions at SKYLO and REDDT can be lifted provided there is an available gap in the arrival flows. Combined with a

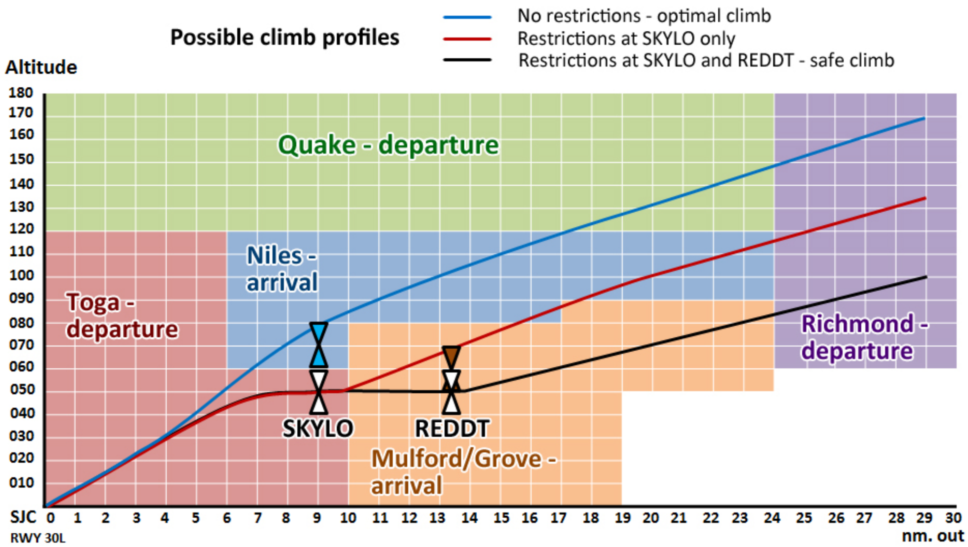

Figure 2. Possible Climb Profiles Across Sectors

scheduling tool, the departures could be temporally separated from the arrivals and climb more efficiently. This was the main operational goal of the study.

We did not create a sector around the REDDT1 departure since the REDDT1 departure flies across the standard arrival sectors until it reaches 12,000ft or 24nm out, as shown in Figures 1 and 2. The REDDT1 first flies in the Mulford-Grove combined arrival sector. If the aircraft is level at SKYLO and REDDT, it will stay in the Mulford-Grove sector. If the altitude restriction is lifted before REDDT, the aircraft will climb and eventually enter the Niles arrival sector. Figure 2 shows the optimal REDDT1 departure climb profile we used for B737-800 aircraft. It shows how the three different climb profiles of the REDDT route penetrate the arrival sectors. The black line shows the safe route where aircraft fly under the arrival routes and stay in the Mulford-Grove sector. The red line is the route of aircraft leveling at SKYLO and then climbing at or above REDDT, eventually entering the Niles sector. The blue line is the route of aircraft climbing continuously at or above both SKYLO and REDDT, also eventually entering the Niles sector. The departing REDDT1 B738 aircraft reach 5,000ft approximately 3nm before SKYLO, 4nm before laterally leaving the Toga sector. The triangles indicate the expected altitudes of the departures (in white), Modesto arrivals (in blue) and the Oakland arrivals (in brown).

As can be seen, the REDDT1 departures climb across one or two arrival sectors for a brief period of time before entering a departure sector again. This creates a need to coordinate control of the aircraft, especially since they may no longer be spatially separated from the Oakland arrivals, which creates a need to separate the departures temporally from the arrivals.

Coordination

The need to coordinate leads to two main questions. First, who makes the decision to climb the departures, and thus who is responsible for separating the REDDT1 departures from the arrivals? Second, how can the SJC tower enable REDDT1 departures to fly through gaps in the arrival flows in a timely manner? To answer these questions, we designed a coordination procedure to support the control of the departures, and we developed a scheduling tool to support the timed release of departures from the tower.

Coordination Procedures between Sectors

For this simulation, the Mulford-Grove controller (henceforth called Mulford) made the decision whether to climb REDDT1 departures to a higher altitude, and thus was responsible for separating them from arrival flows. Nominally, departures were expected to meet the crossing restrictions at SKYLO and REDDT. But when deemed appropriate by Mulford, an aircraft would be cleared for an unrestricted climb on the REDDT1 departure, climbing above the Mulford sector altogether. However, the Niles controller could veto the decision for an aircraft to enter the Niles sector in this manner. This coordination was done by point-out and was specified in a Standard Operating Procedure.

Another problem was the limited time for Mulford to decide whether to climb the departures. The departing REDDT1 departures would be on Toga's SJC departure frequency until shortly before entering Mulford airspace at which time the aircraft would already be maintaining 5,000ft. So we developed another Standard Operating Procedure to coordinate between Mulford and Toga, giving an earlier control to Mulford.

Both Standard Operating Procedures are further detailed in the Method sections.

Temporal Coordination: Scheduling Arrivals and Crossing Departures

Scheduling is the most efficient way to allocate the use of the same resource and thus reduce uncertainties in temporal demand. In our concept, both arrivals and departures were predicted to cross REDDT, the common fix. Assumptions about arrivals and departures were different. Arrivals flows have the most reliable time predictability, which was used as a known parameter to schedule departures. The arrival schedule allowed the creation of predictable gaps that could accommodate unreliable departure times. We used the Controller Managed Spacing (CMS) tools developed in the Airspace Operation Laboratory (AOL) [5]. These tools work with a scheduler that gives a precise time for aircraft to meet at the runway threshold (Scheduled Time of Arrival, STA). The scheduler computes time from the meter fix at the boundary of the TRACON down to the runway. The main tool in the suite of CMS tools is the "slot marker." Slot markers are circles that represent where aircraft should be along its nominal route to meet its STA. When an aircraft is inside its slot marker and flying the published procedure, it is predicted to arrive on time. Controllers can vector aircraft and use slot markers as a target. CMS tools are based on forecast winds and nominal routes with expected altitudes and speed restrictions (CMS tools also include speed advisories and Early/Late indicators that were not included in this simulation.).

In our study, the STAs of arrival aircraft were frozen on the schedule to the runways, meaning that the arrivals were committed to a STA. Controllers were instructed to keep arrival traffic on their route and in their slot marker. The departure times, on the other hand, were not frozen but floating to allow for flexibility. Departures did not use slot markers.

We adapted the Departure Flow Management (DFM) system to schedule departures and to coordinate the crossing times with arrivals. DFM allows an airport tower to schedule aircraft in available time slots, which are representations of available times (i.e., free of traffic) at a departure meter fix, and are used to control flows into adjacent centers towards major destinations [6]. In this simulation, the tower scheduled a REDDT1 departure based on potential 'gaps' in the arrival flow as predicted at the fix where arrival and departure routes intersect (e.g., REDDT). Facilitating this process was a runway departure timeline. The runway departure timeline used a nominal flying time from the runway to the crossing fix to estimate when a departure would reach REDDT. With this information, the tower controller watched for opportunities where departures could cross REDDT during any gaps in the arrival flow. Gaps are comparable to time slots. Both gaps and time slots support the allocation and distribution of aircraft across time and space. However, gaps are reflective of the relative spacing between two arrivals and can be large at times. In our concept, gaps are controlled by the TRACON Traffic Management Unit (TMU). The TMU can decide to remove gaps or can set different buffer times between the gaps and the leading and trailing arrivals. The buffers provide a minimum separation with the leading or trailing aircraft with any aircraft inside the gap. This simulation used 90 seconds of buffer on the front and the back of gaps to allow for 3nm lateral separation. In the following example of a runway departure timeline (Figure 3), gaps are indicated in dark blue. Callsigns are color-coded by departure routes: yellow for the LOUPE1, turquoise for the SJC9, and magenta for the REDDT1. The figure shows a scheduled REDDT1 departure that is expected to cross REDDT inside the actual gap between arrivals on the Oakland arrival flow.

Precise departures times are more difficult to predict than arrival times. Today, Call For Release (CFR) procedures give departures a -1min +2min

departure time window. Even still, not all departures meet that time window. Such uncertainty leads to aircraft missing slots, increased delays and added workload for controllers [7, 8].

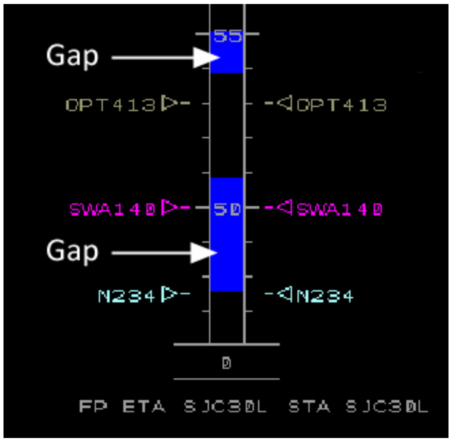

Figure 3. Timeline Display at SJC Tower

Precise departures times are more difficult to predict than arrival times. Today, Call For Release (CFR) procedures give departures a -1min +2min departure time window. Even still, not all departures meet that time window. Such uncertainty leads to aircraft missing slots, increased delays and added workload for controllers [7, 8].

Our scheduling concept allows for more flexibility in the departure time. For the tower, the gaps are not specific time slots, but rather a window of time when the tower can schedule departures depending on what is best for surface operations. Departures can be scheduled as soon as arrivals enter the TRACON and their STAs are known. This can be up to 20 minutes prior to departure. Today's DFM system eliminates the need for the tower to coordinate with the TRACON for a release time over the phone. Similarly, with the information available in the runway departure timeline in this simulation, the tower did not need to call the TRACON to coordinate the release of a departure. This concept also provides flexibility to the TRACON as they work departures that may possibly interact with arrival flows. The TRACON controllers can leverage the altitude restrictions on the REDDT1 departure: keep aircraft underneath the arrivals if necessary, or let them climb uninterrupted if the surrounding traffic allows it. To avoid unwanted departure times, the TRACON could require a conditional use of the gaps. For instance, if a gap was small, the TRACON could require the tower to call for release a departure to fly through that gap. This concept leverages the predictability of the arrival times and accommodates the uncertainty of departures times. It also minimizes the coordination process for releasing departures.

Method

We tested our concept in a high fidelity Human-in-the-Loop simulation at the AOL using the Multi Aircraft Control System (MACS) software [9].

Experiment Design

The simulation was a 2x2x2 full factorial design. Each of the following were fully crossed: First Sector (Toga vs. Mulford), Takeoff Time Reliability (Reliable vs. Unreliable), and Gap (REDDT vs. SKYLO).

First Sector

The first sector to control the REDDT1 departures was the Toga departure sector for half of the runs, and Mulford, the next arrival sector, for the other half of the runs. When Toga was the first sector, SJC Tower would request pilots to contact Toga's frequency, who would then later transfer communication to Mulford. When Mulford was first, SJC Tower would request pilots to contact Mulford's frequency directly. Depending on the condition then, Mulford had control of the aircraft either a few miles outside its boundary or just after the aircraft had taken off. We hypothesized that when Mulford was the first sector, they would have more time to coordinate with Niles and decide how to climb the departures, potentially leading to improved climb performances.

Takeoff Time Reliability/Departure Accuracy

In half of the runs, all the departures took off inside the predicted gap on the scheduler (Reliable Condition). In the other half of the runs, half of the departures took off outside of the predicted gap, and the other half inside the predicted gap (Unreliable Condition). The rationale for this manipulation was to test the impact of the reliability of the takeoff time on the controllers' decisions to climb safely above the nominal route. In each run, 8 departures were scheduled by the tower confederate. There were 4 positions of the departure time relative to the gap: 60sec and 30sec inside a gap, or 60sec and 30sec outside of the gap, as shown in Figure 4. These positions were also relative to the front and to the back of a gap. This yielded a total of 8 different possibilities. The order of the 8 positions was counterbalanced so that each run had a different order and an equal distribution of each position for each run.

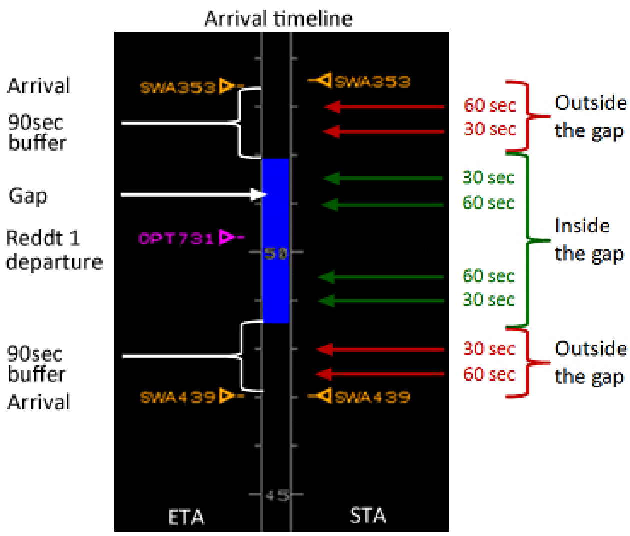

Figure 4. Departure Accuracy Conditions

The four relative positions of the departures were used to analyze Departure Accuracy. More specifically, the various positions were treated as more or less accurate departures to study the impact of the actual position of the departure on the controllers' decisions. We hypothesized that aircraft departing outside of the predicted gaps would be kept at level altitude until clear of arrival traffic more often than aircraft predicted to fly through gaps.

Gaps at REDDT and SKYLO

It became apparent in the first few runs that controllers were vectoring departures to separate them from arrival traffic at REDDT, but also at SKYLO. Controllers could then climb aircraft above the Modesto arrival flow, instead of keeping aircraft underneath it. REDDT1 departures then only occasionally crossed the REDDT waypoint where the gaps were. After repeating our 4 main conditions 2 times (8 runs) with gaps at REDDT, we ran the 4 conditions again with gaps at SKYLO (4 runs).

Participants

Five retired controllers, with an average of 27 years of experience in TRACON airspace, staffed five sectors. They had been retired for an average of 4 years. The two most recently retired controllers rotated through the Niles and Mulford positions. A third controller staffed Toga, the SJC departure sector. A fourth staffed Sunol-Cedar, the SFO and OAK arrival combined feeder sectors. A fifth staffed Final, the final approach sector to SFO (called "Foster" at NCT). One researcher was a confederate and acted as a local controller at San Jose Tower. Six pseudo-pilots participated. Each pseudo-pilot was responsible for flying aircraft in a sector. All pilots were students from the Aviation Department at San Jose State University.

Traffic Scenario

We developed two traffic scenarios derived from actual traffic data. Both had similar attributes. It created variability in traffic. Each scenario was used once for each experimental condition. Additionally, callsigns were also changed for each run. Arrival traffic was for SFO and OAK and departures from SJC. Some overflight and Visual Flight Rules (VFR) traffic were included for realism. The Modesto arrival traffic rate met the maximum landing capacity for the SFO runway 28R. Both Oakland arrivals were populated with more traffic than today. Gaps, or excess spacing between arrivals, occurred naturally in the Modesto flow. Large gaps occurred when GOLDN6 arrivals were scheduled to merge with the Modesto flow downstream of SKYLO. Large gaps were built into the Oakland arrival flow to allow for REDDT1 departures to climb. Departure aircraft from SJC were scheduled to either depart on the LOUPE1 departure or the SJC9 departure. There were 12 various departures per run and 12 runs total.

Apparatus

Standard Terminal Automation Replacement System (STARS) displays were emulated within the MACS software, and shown on large-format monitors similar to those used in current air traffic control facilities. Specialized keyboards like those used in the field helped to further replicate the look and feel typical of these facilities. MACS provides a high fidelity environment to prototype the scheduling tools, to simulate the air traffic and to collect data [10].

Three tools assisted controllers: slot markers, J-rings and timelines. J-rings are circles around aircraft that can be set at any size. In this study the size was set to the minimum separation (3nm).

Timelines depicted two relative positions of aircraft to a specific waypoint. One position showed an Estimated Time of Arrival (ETA) and the other showed an STA for aircraft at the waypoint. MACS computes aircraft trajectories to determine ETAs, based on flight plans, altitude and speed constraints, and forecast winds. MACS then uses ground-based trajectory and scheduling criteria, such as wake-vortex spacing values, to compute the STA. An STA shows when aircraft should cross the waypoint. An ETA is when it is predicted to actually cross.

There were different configurations of timelines: two timelines for the arrivals to OAK and SFO runways (OAK29 and SFO28R), and another timeline for the departure from SJC30L. In the case of the departure timeline, the time to the runway represented the time to takeoff. There was also a timeline to the crossing fix which depicted gaps and the departures' ETA and arrivals' ETA and STA to the cross point.

Operational Procedure

We developed operational procedures to schedules departures and for coordinating the control of the departures between the arrival sectors.

Scheduling Departures

In each scenario, SJC departures were filed to fly either the LOUPE1 departure to the northeast or the SJC9 departure to the south. The tower confederate acted as a cab coordinator who would coordinate with both the Clearance Delivery and the Local controller positions. The tower confederate looked at the departure timeline and checked which flight departure time would be likely to match a gap.

We assumed that pilots would accept an amendment to the standard LOUPE1 departure to a REDDT1 departure 10-15 minutes prior to take off because the REDDT1 is a shorter route. At SJC, the aircraft is likely to be at the gate at this time. At a busy airport, pilots can expect to amend their departure even while waiting near the runway. We assumed the pilots would load a new departure in their Flight Management System (FMS).

Once the pilots accepted the amendment, the controller inserted it in the ground system and assigned a new departure time, if that was necessary. We assumed that pilots would accept a few minutes of departure time delay since the flight distance of REDDT1 departures is 32nm shorter than that of the LOUPE1 departures. One or two minutes of delay at the time of departure would be compensated by the shorter time to fly the route.

For each run, the tower confederate scheduled aircraft either inside or outside the gap according to which Departure Accuracy conditions they were in. We counter balanced both scenarios and the Departure Accuracy conditions, thus providing a unique combination for each departure.

Controllers' Coordination: Point-out and Handoff

Once the REDDT departure took off, the tower confederate requested that the pilot contact the first sector, Toga or Mulford, depending on the experimental condition. The request took place when the aircraft was between 500ft and 1,000ft off the ground.

When radio contact was established with Toga first, Toga would immediately hand-off the datablock to Mulford. However, in this condition, the Standard Operating Procedure required Toga to wait until the REDDT1 aircraft reached 2,000ft and was 1.8 Distance Measuring Equipment from the SJC VHF Omnidirectional Range station to request that the pilots contact Mulford's frequency. When radio contact was established with Mulford first, the Standard Operating Procedure allowed Mulford to have control of that aircraft on contact and to display its datablock to Toga. Any lateral deviation from the routes required further coordination with Toga.

Once Mulford had control of the aircraft, s/he had to decide whether the REDDT1 departure altitude restriction could be lifted to allow the aircraft to climb through the Niles airspace. If traffic appeared to permit this, Mulford pointed out the aircraft to Niles. If Niles approved the point-out, Mulford could clear the aircraft to 11,000ft, the ceiling altitude of Niles sector, and could hand-off the datablock to Quake, a departure sector. If Niles or Mulford needed to vector the departure aircraft, verbal coordination was required. This point-out procedure was specified in a Standard Operating Procedure. Mulford also displayed the REDDT1 departure to the Foster sector, so that Foster would not descend any arrival aircraft until past SKYLO.

When lifting the altitude restrictions was not possible, Mulford did not point out to Niles and kept the aircraft at 5,000ft in Mulford's airspace.

The recommended procedure was for Mulford to keep aircraft under the Modesto arrival flow, and then decide whether to climb REDDT1 departure aircraft based on the gaps in the Oakland arrival flow. This was the safe procedure to follow when an uninterrupted climb was not possible.

Controller positions were dispersed across two control rooms. We allocated the positions in such a way that a neighboring airspace sector would be in a separate room. For instance, Mulford was separated from Toga and Niles. This was done to force controllers to use the point-out tool and the voice communication system, and avoid face-to-face coordination. This also reflects the actual allocation of the sectors across different control areas at NCT.

Experimental Procedure

We tested our concept and MACS emulation with the participants several times prior to the study. The study itself took place over four days. On the first day, we briefed controllers about their tasks and responsibilities, and particularly about the operational procedures. Then controllers trained during four practice runs with our four main conditions using training scenarios separate from those used in the actual data collection runs. The following three days, controllers participated in twelve runs for data collection. Finally, a debrief discussion with controllers and pseudo pilots concluded the study.

Controllers answered questions after each run online and at the end of the study on paper. The questions pertained to workload, acceptability, feasibility and safety of the operation and coordination.

Results

Twelve runs produced 96 departures flying in arrival airspace, 8 REDDT departures per run. Each departure was treated as a single case since its departure time and therefore its position relative to other aircraft was never the same.

We analyzed data for coordination effort, climb efficiency, safety, and acceptability. We used time in seconds to measure the timing of action events, such as when point-outs or handoffs started and ended, and when the pilots were cleared to climb to 11,000ft. We also used altitude to measure climb performance, as well as nautical miles to assess the loss of lateral separation.

The following sections begin by presenting analyses for effects of First Sector X Departure Accuracy for the first 8 runs (N = 64) when the gaps were at REDDT. Then, we present analyses for runs with gaps at SKYLO (N = 32) and finally, we present results comparing scheduling to gaps at REDDT and SKYLO. No significant result was found for Takeoff Time Reliability.

Coordination: First Sector and Point-Out

Early coordination allowed controllers to make decisions about the REDDT departures earlier across all runs. In the first 8 runs, when gaps were situated at REDDT, we found significant main effects of First Sector on the timing of point-outs, as shown in Table 1 below. Point-outs started an average of 20 seconds earlier when the first sector to control departures was Mulford (M = 27.6 sec, SD = 18.2) than Toga (M = 47.6 sec, SD = 22.4), $F(1,60) = 14.9$, $p < .001$). Table 1 lists the mean time (and Standard Deviations) in seconds from takeoff, and aircraft altitude in feet, when cleared to climb to 11,000ft as a function of First Sector.

Table 1. Point-Out and Aircraft Altitude

	First Sector		
	Mulford *M (SD)*	Toga *M (SD)*	*F*
Gap at REDDT			
Point-out start time	27.6 (18.2)	47.6 (22.4)	14.9**
Aircraft altitude when cleared to 11,000ft	4,184 (1250)	4,632 (737)	3.0[a]
Gap at SKYLO			
Point-out start time	24.0 (19.0)	38.6 (18.8)	4.8*
Aircraft altitude when cleared to 11,000ft	3,450 (1,379)	4,187 (995)	3.0[a]
All runs (1-12)			
Point-out start time	26.4 (18.4)	44.6 (21.5)	19.9**
Aircraft altitude when cleared to 11,000ft	3,939 (1,326)	4,484 (848)	5.8*

* $p < .05$, ** $p < .01$., [a] $p = .09$.

We also tested whether early coordination had an effect on the aircraft's altitude when cleared to climb to 11,000ft. First Sector had a marginal main effect. Aircraft were at a lower altitude when Mulford was first (M = 4,184ft, SD = 1,250), than when Toga was (M = 4,632ft, SD = 737), $F(1,60) = 3.0$, $p = .09$ (ns) as shown in Table 1. This marginal effect would become significant ($p = .045$, one-tail) if we initially assumed a unilateral directional effect of First Sector (Mulford over Toga). Time wise, aircraft seemed to be cleared to climb to 11,000ft slightly earlier when Mulford was first (M = 138.0sec, SD = 46.3) compared to Toga (M = 151.7sec, SD = 35.3). However no significant main effect was found, $F(1,60) = 1.8$, $p = .18$ (ns).

The timing of point-outs correlated with the time it took for the controller to clear aircraft to 11,000 feet, as well as with the altitude of the aircraft at the time of the clearance. The later that point-outs started, the later aircraft were cleared to 11,000ft (r (64) = .29, $p < .05$) and the higher their altitude (r (64) = .28, $p < .05$).

In the last four runs, when gaps were at SKYLO, the results were similar. Point-outs started earlier when the first sector was Mulford (M = 24 sec, SD = 19) instead of Toga (M = 38.6 sec, SD = 18.8), $F(1,30) = 4.8$, p= < .05, as shown in Table 1. Also, First Sector had a marginal effect on when aircraft were cleared to climb to 11,000ft. Aircraft were at a lower altitude when the first sector was Mulford (M = 3,450ft, SD = 1,379ft), compared to Toga (M = 4,187ft, SD = 995ft), $F(1,30) = 3.0$, $p = .09$ (ns). This marginal effect would also become significant (p = .045, one-tail) if we assumed a unilateral directional effect of First Sector (Mulford over Toga). There was no significant correlation between the point-out time and when aircraft were cleared to 11,000ft.

When we considered the 12 runs together, the First Sector had a significant main effect on when aircraft were cleared to 11,000ft, $F(1,94) = 5.8$, p = .02, as shown in Table. Departures were at lower altitude when Mulford was first (M = 3,939ft, SD = 1,326ft) compared to Toga (M = 4,484ft, SD = 848ft). Also, point-outs started earlier when the first sector was Mulford (M = 26.4 sec, SD = 18.4) instead of Toga (M = 44.6 sec, SD = 21.5; $F(1,94) = 19.9$, p = .000). These results indicate that the aircraft climb performance benefitted from arrival controllers having control of the aircraft immediately after takeoff.

As expected, the First Sector condition was independent of the Takeoff Reliability/Departure Accuracy condition. Surprisingly, we did not find any Takeoff Time Reliability/Departure Accuracy effect on the altitude or the time aircraft were cleared to climb to 11,000ft for the first 8 runs, when the gaps were at REDDT. Two explanations are possible: first, controllers tactically tried to climb departures through gaps in the Modesto traffic at SKYLO. If successful, this helped to achieve a vertical separation with arrival traffic at REDDT, making traffic at REDDT no longer a constraint. Second, controllers vectored a large proportion (44%) of departures a few nautical miles to the left of the REDDT waypoint where they could fly above the arrival traffic, making these aircraft independent of arrival traffic and any gaps at REDDT. We describe this further in the decision analysis below. We then present significant differences between the runs with gaps at REDDT versus gaps at SKYLO.

Controllers' Decision Analysis

Figure 5 depicts the decisions controllers made for the REDDT1 departures when the gaps were at REDDT (left) for the first 8 runs, and at SKYLO (right) for the last 4 runs. Working from the left of Figure 5, the Mulford controller's first decision was either to leave a REDDT1 departure on its route or to vector it. The controller was looking for natural gaps in the SKYLO flow. Then, the second decision involved deciding whether to keep the aircraft level or to climb it at or before SKYLO. This decision was repeated for possible gaps in traffic at REDDT.

In the first 8 runs (depicted on the left of Figure 5), controllers climbed 100% (64) of the aircraft before REDDT. They vectored 44% (28/64) of aircraft before SKYLO. Of the vectored aircraft, 46% (13/28) stayed level until they passed SKYLO and then climbed before crossing the Oakland arrivals (west of REDDT). Of the 56% (36/64) of aircraft staying on their route, 44% (16/36) climbed before SKYLO, and continued to climb at REDDT. The remaining 20 aircraft leveled at SKYLO, and then continued to climb before REDDT. Of all the departures with the gap at REDDT, 48% (31/64) climbed before SKYLO and continued to climb before REDDT. The remaining 52% (33/64) leveled before SKYLO, and then climbed before REDDT. There was no aircraft leveling at REDDT in the first 8 runs.

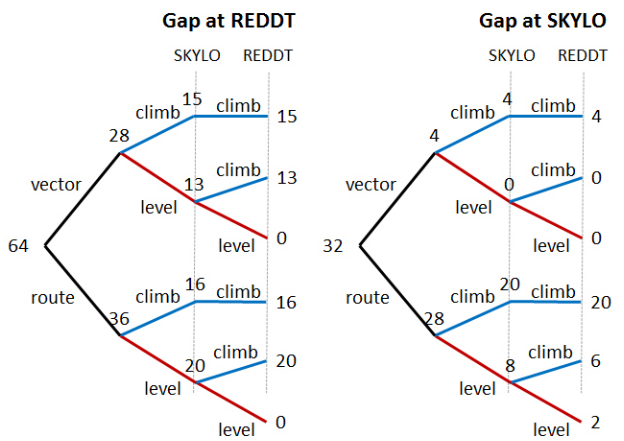

Figure 5. Decision Tree

In the last 4 runs, only 13% (4/32) of aircraft were vectored. These 4 aircraft were climbed before SKYLO and continued to climb before crossing the Oakland arrivals (west of REDDT). Of the remaining 87% (28/32) of aircraft that stayed on their route, 71% (20/32) of the aircraft were climbed before SKYLO, and continue to climb before REDDT. The remaining 8 aircraft were leveled at SKYLO. Of those 8 aircraft, 6 were then climbed before REDDT. Only 2 aircraft were kept level at SKYLO and REDDT.

Controllers gradually favored vectoring departures over keeping them on their route during the first 8 runs ($\chi^2(7, N = 64) = 18.3, p = .011$). A Somers' d test showed vectoring was dependent on the order of the runs ($t(7, N = 64) = .397, p = .004, d = .397$). In Run 1, 25% of the aircraft were vectored, in Run 6, 7 and 8, 75% of the aircraft were vectored. In the last 4 runs (9-12), controllers kept all but 4 aircraft on the route. According to the controllers, it was simpler to leave an aircraft on its route if it was scheduled to fit in the gap on the Modesto flow (at SKYLO). They did not have to find a better trajectory. This was not possible in the first 8 runs.

Climb Profiles

Overall, in the first 8 runs, controllers climbed aircraft before REDDT, whether they leveled aircraft at 5,000ft under the Modesto flow, or not. Table 2 shows the average altitude of aircraft for each decision. Aircraft that leveled under the Modesto flow and climbed afterwards crossed the Oakland flow (at REDDT) on average at 8,748ft. The arrival traffic crossed REDDT at 6,000ft. The departures were well above the arrival traffic by the time they crossed the Oakland arrival flow[1].

Table 2. Altitude at Crossing Fixes

Gap at REDDT Decisions			SKYLO	REDDT
vector	climb	climb	6,726	11,066
vector	level	climb	5,008	9,577
vector	level	level	N/A	N/A
route	climb	climb	7,712	10,850
route	level	climb	5,010	8,210
route	level	level	N/A	N/A
Gap at SKYLO Decisions			**SKYLO**	**REDDT**
vector	climb	climb	6,780	11,000
vector	level	climb	N/A	N/A
vector	level	level	N/A	N/A
route	climb	climb	8,432	11,036
route	level	climb	5,000	7,867
route	level	level	5,000	5,000

Controllers climbed aircraft before REDDT regardless of whether the aircraft was scheduled to fly inside a gap there or not. Departure Accuracy did not have a main effect on the altitude of aircraft when it crossed REDDT or nearby (60sec in (M = 9,567ft), 30sec in (M = 9,946ft), 30sec out (M = 10,113ft), 60sec out (M = 9,888ft), $F(3,60) = 0.4$, p = ns). The result was similar for aircraft that stayed on the route ($N = 36$). Climbing or leveling at SKYLO however, did have a significant effect on the altitude crossing REDDT. Aircraft crossed REDDT at a higher altitude when they were already climbing at SKYLO (M = 10,850ft, SD = 555ft), than when they were leveling at SKYLO (M = 8,210ft, SD = 910ft), $F(1,34) = 103.5$, $p = .000$. This result suggests that even after leveling at SKYLO, departures were able to top arrival traffic at REDDT with enough vertical clearance. All aircraft ended up climbing well above the Oakland traffic at REDDT.

[1] The climb rate used for B738 in our simulation was optimal.

In comparison, Departure Accuracy significantly influenced the aircraft altitude at SKYLO when departures were planned to cross gaps there. Table 3 shows the means of altitude and Standard Deviations of aircraft crossing SKYLO as a function of Departure Accuracy. The breakdown of the 4 accuracy conditions indicates that the relative position influences how early the aircraft is climbed. This suggests controllers could not climb aircraft before SKYLO due to a lack of lateral separation. There is a main effect of departure accuracy on the altitude of aircraft crossing SKYLO, $F(3,23) = 14.3$, $p = .000$. The more inside the gap the departure, the higher the altitude the aircraft crosses SKYLO. A departure scheduled 60 seconds outside a gap was only 30 seconds away from an arrival aircraft. In this case, aircraft were leveled at 5000 feet to maintain vertical separation. In contrast, aircraft scheduled 30 seconds or 60 seconds inside the gaps were, respectively, 120 and 150 seconds away from arrival aircraft, and thus could be climbed. Departures inside the gaps show the highest altitudes (8,009ft vs. 8,850ft, as shown in Table 3).

Table 3. Altitude at SKYLO by Accuracy

	Altitude at SKYLO	
	M	SD
Scheduled		
60sec inside gap	8,850	926
30sec inside gap	8,009	1,624
30sec outside gap	5,325	395
60sec outside gap	5,000	0

Another analysis of Departure Accuracy helped to understand its impact on the time and altitude of the aircraft when it is cleared to 11,000 feet, both for gaps at REDDT and SKYLO (See Figure 6 and 7). For comparison purpose, we used aircraft that were not vectored ($N = 63$). A significant interaction effect can be seen in Figures 6 and 7, which show the means of altitude and time, respectively, when departures were cleared to climb to 11,000ft.

There was an interaction effect of Departure Accuracy and Gap at SKYLO and REDDT on aircraft altitude (Figure 6) and time (Figure 7) between gaps at SKYLO and REDDT ($F(3,55) = 5.2$, $p < .01$ and $F(3,55) = 6.6$, $p = .001$, respectively). No main effects were found. However, when gaps were tested separately, Departure Accuracy had a significant main effect on altitude for gaps at SKYLO ($F(3,23) = 4.8$, $p = .01$), but not REDDT ($F(3,32) = 1.3$, p ns). Departure Accuracy also had a significant main effect on time when gaps situated at SKYLO ($F(3,23) = 9.0$, $p = .000$), but not at REDDT ($F(3,32) = 1.0$, p ns).

When the gaps were situated at SKYLO, the more the departures were predicted to fly inside the gaps, the earlier the departures were cleared and the lower their altitude was. Departures scheduled 60 seconds inside the gaps were cleared at 3,136ft and 98 seconds after takeoff. Departures scheduled 30 seconds inside the gaps were cleared a little higher (3,829ft), and approximately 30 seconds later (124sec after take-off). Departures scheduled 30 or 60 seconds outside the gaps were leveled at around 5,000 feet when they were cleared around 3 minutes (176sec & 199sec respectively) after takeoff.

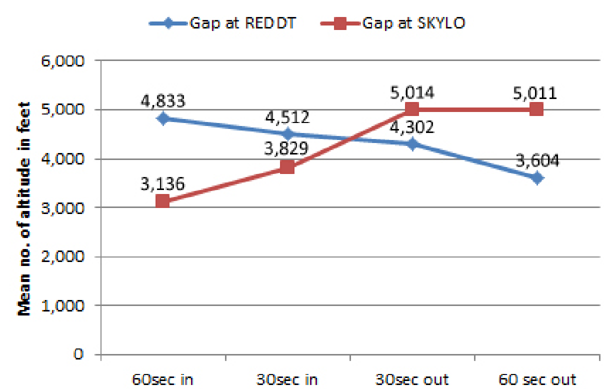

Figure 6. Altitude by Gaps and Accuracy

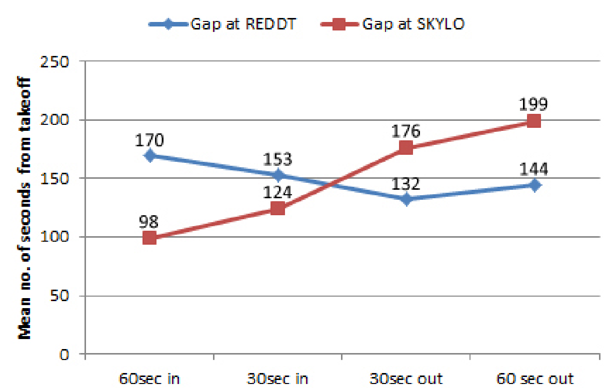

Figure 7. Time by Gaps and Accuracy

When gaps were situated at REDDT, time and altitude did not differ significantly. Altitudes seemed

Table 4. Lateral Separation

	Distance in nm of arrival aircraft to departure aircraft											
State of REDDT1 Departure	**-10**	**-8**	**-6**	**-4**	**-2**	**0**	**2**	**4**	**6**	**8**	**10**	**12+**
Crossing Modesto flow (SKYLO)												
a) Route / Level				1	4	8	3	4	4	1	3	
b) Vectored / Level				1			2	3	2	4	1	
c) Route / Climbing					2			1	1	3	7	22
d) Vectored / Climbing									3	5	3	9
Crossing Oakland flow (REDDT)												
e) Vectored / Climbing									3	5	3	10
f) Climbing (after level under SKYLO)	26	2	6	4	2	0	2	3	1	6	8	22

to follow an inverse pattern. Departures scheduled 60 seconds outside the gap seemed to be cleared to climb at a lower altitude (3,604ft) and earlier than for aircraft scheduled inside the gaps. It is possible controllers were trying to climb early to top the arrival traffic at REDDT. Overall, departures were cleared to climb before they reached 5,000ft.

These results show that gaps in the first arrival flow were used opportunistically to climb aircraft above the second arrival flow. However gaps scheduled at the first arrival flow were more sensitive to where aircraft were scheduled in relation to the gap, and showed a significant impact on the departures' climb profile.

Safety

Often, controllers opted to climb through gaps at SKYLO and climb departures above the arrivals at REDDT, instead of keeping departures under the Modesto flow and climbing them through gaps at REDDT. They also vectored departures to avoid arrival traffic at REDDT. Were those decisions safe?

Aircraft in the TRACON airspace need at least 1,000ft vertical separation and 3nm lateral separation. This rule applies as long as aircraft are on converging trajectories. Once one aircraft has crossed in front or behind of another aircraft, its trajectory is diverging, and the minimum separation requirement no longer applies.

We measured the distance of arrival aircraft relative to the departure aircraft when it crossed the Modesto flow (at or near SKYLO) and also when it crossed the Oakland arrival flow (at or near REDDT) for each type of decision the controller made for the departures as shown in Table 4. This table shows the number of arrival aircraft for a relative distance: minus numbers are distances of arrivals that have passed in front of the departures and thus are laterally diverging from departures, while the positive numbers are distances of arrivals that are converging. Letters a) through f) correspond to the possible states of departures in regards to the Modesto arrivals (a to d) and the Oakland arrivals (e & f).

In a) departures were leveled and stayed on their leveled route. Eleven arrival aircraft were less than 4 miles away (columns 0, 2) from SKYLO. In this case, climbing the departures would have caused a loss of separation. In b) departures were leveled but were vectored to the left of their route at SKYLO. Six arrival aircraft were within 4 miles of the departures (columns -4, -2, 0, 2, 4). Two arrival aircraft were less than 3 miles away. As with letter a), departures could not be climbed due to traffic. In c) departures were on their route but were climbed before crossing SKYLO. In this case, no aircraft should be found less than 3 miles of SKYLO, otherwise a separation violation would occur. There were 2 arrival aircraft that were within 2 miles but they had past SKYLO, i.e., were diverging. In d) departures were vectored and climbing. No traffic was within 4 miles of the departures. In e) no arrival aircraft was found within 4 miles of the departures. In f) departures had leveled at SKYLO and then were climbed before REDDT. This requires that there be no traffic at REDDT within a 3nm lateral distance or that departures are cleared vertically to top arrivals. There were at least 6 arrival aircraft that were within 3 miles of the departures, and the departures were able to fly above them. However, given the short distance from the Modesto flow and the Oakland flow (4nm), these departures often came close to the minimum lateral separation while being still within 1,000ft of vertical clearance. These 6 departures should have been kept at a level altitude to fly under the arrival flow. In one instance, a departure came close to losing separation.

Overall, controllers were able to tactically vector and climb aircraft. Controllers tried to climb departures early and had to vector them to keep them safely away from arrivals. However, most of the time, controllers kept departures on their trajectory and cleared them to climb. This decision is only safe if aircraft can climb prior to SKYLO. Otherwise, departures could risk losing minimum separation.

Workload and Acceptability

Controllers responded to an online survey at the end of each run and a post-simulation survey at the end of the simulation. Answers were either binary (yes/no), or were scored on a 5-point Likert rating scale, ranging from 1 (lowest) to 5 (highest). The controllers could also provide additional comments if they desired. The post-run data was analyzed with repeated measures ANOVAs.

Post-Run Survey

No significant effect of First Sector and Takeoff Time Reliability were found in the survey responses.

Across all runs, the Mulford controller reported a higher mental activity during the busiest time (between "moderate" & "somewhat high", $M = 3.3$, $SD = 1.0$) compared to the other controllers (between "very low" & "somewhat low", $M = 1.7$, $SD = .4$), $F(1,11) = 31.6$, $p < .001$. Mulford also reported a higher time pressure ("moderate", $M = 2.9$, $SD = 0.7$) than other sectors (between "very low" & "somewhat low", $M = 1.3$, $SD = 0.2$) at the busiest time, $F(1,11) = 76.5$, $p < .001$. The Mulford controller also reported being less able to maintain adequate separation ("somewhat high" $M = 3.9$, $SD = 1.2$) than other controllers ("very high", $M = 4.7$, $SD = 0.3$; $F(1,11) = 4.7$, $p = .05$).

Although Final and Niles gave a maximum score of 5, or "Very acceptable," to all questions about the acceptability of allowing the REDDT1 departure through the arrival airspace in regard to workload, coordination and safety, Mulford's answers were in between "Somewhat acceptable" and "Very acceptable", $M = 4$ ($SD = 1.1$) for workload, $M = 4.2$ ($SD = 0.9$) for coordination, and $M = 4$ ($SD = 1.2$) for safety ($F(1,11) = 9.4$ for workload, 9.2 for coordination, 8.3 for safety, $p < .05$ for all).

One controller stated twice that "Had Mulford been in communication with the REDDT departure in a more timely fashion, it could have been turned and climbed more efficiently." This comment was made after the case of the near loss of separation, when Toga was the first sector to control the departures.

The Mulford controller thought the coordination was cumbersome at times. Mulford used point-outs during every run, and engaged in additional verbal coordination during 10 of the 12 runs. Mulford initiated the point-out coordination with other sectors, whereas the other sectors only responded to Mulford's requests, sometimes after a delay. The time pressure was therefore on Mulford's shoulders. Mulford reported having time pressure on at least one coordination in each run for 33% (4/12) of the runs; Niles and Final reported none. Mulford indicated that at times he had to wait for other sectors to accept point-outs, qualifying these as "late point-outs". Typical comments were "Had to wait on Niles to accept point-out when I would have liked to start the aircraft climbing (Run 1) and "Needed to call Niles to get him to accept point-out" (Run 11). Mulford controller considered coordination as being accomplished in a timely fashion in 10 of the 12 runs. Point-outs accepted by Final and Niles sectors referenced other aircraft only 25% and 20% of the runs, respectively, which was thought not to be enough by Mulford in the post-simulation questionnaire.

Post-Simulation Survey

These results confirmed the finding that having "Mulford first" worked better operationally and "in this simulation" was acceptable in terms of workload safety, and coordination than having direct departures go through Toga first. However, the two Mulford controllers thought the SOAR concept would be only "somewhat acceptable" or less in the field. One gave a rating of 3 or "somewhat acceptable," the other a rating of 2. Finally, the Mulford controllers stated that there should have been more referencing of other traffic in the point-outs.

Communication Analysis Results

According to the procedure, a point-out assumed that aircraft would stay on its route. Mulford had to call other sectors if additional coordination was needed, such as vectoring the departure. Since Mulford opted to vector many aircraft, controllers came up with their own convention to reduce verbal coordination. During the first five runs, Mulford controller called Niles controller each time he intended to vector a departure. Quickly, requests became minimal (Run 4, Mulford to Niles: "Point-out [for callsign X], about to go northbound with him", Niles: "Approved"). In the 6th run, Mulford asked to obtain control for climb and turn for *all* the REDDT departures:

Niles: "Niles."
Mulford: "Yeah [name] can I have control for these REDDT guys west of the routing and climb as well."
Niles: "Yes you can."
Mulford: "Thank you sir."
Niles: "[initials]."

After that run, Mulford contacted Niles and set the same pre-arranged coordination procedure for the departures for all remaining runs in the simulation. Overall, verbal coordination decreased across the runs, from 12 exchanges in the first four runs, down to seven in the second four runs, to six in the third four runs, to five in the last four runs. Verbal coordination became exceptions to the pre-arranged coordination. Controllers were trying to minimize their coordination effort by establishing rules that do not require verbal repetitions. Such ad-hoc rule-making is a strategy commonly used by people to minimize their effort to understand each other [11].

Discussion

Arrival and departure airspaces in metroplex environments are usually independent. Routes are segregated and can be sub-optimal. Arrival and departures flows could be better integrated with more precise scheduling capabilities. We presented a more optimal departure route from SJC flying across arrival sectors in the San Francisco metroplex. Departures were scheduled at the runway to cross gaps in arrival flows. We manipulated the sector which controlled the departure after takeoff, as well as the accuracy of the departure time. Results show that the earlier the arrival controller could coordinate the departure aircraft with other sectors, the earlier the departures could climb to higher altitude, and thus climb in a more efficient way. Controllers reported that time pressure was an important factor for the coordination and the control of the departure aircraft. Controllers preferred Mulford, the arrival sector, to control the departure first rather than Toga, the departure sector. An early control of the aircraft gave the arrival sector more time to make a decision and improved climb performance.

Departures were scheduled to cross gaps at REDDT in the second arrival flow (Oakland arrivals) they were crossing, and needed to cross below the first flow (Modesto arrivals) at SKYLO. However, controllers crossed both flows opportunistically and took advantage of natural gaps in the first flow to climb aircraft before they had to level-off at 5,000ft. For the first eight runs departures were scheduled to cross gaps in the second arrival flow, and for the last four runs, they were scheduled to cross gaps in the first arrival flow. Results showed that during the first eight runs controllers climbed all the departures before crossing the second flow regardless of the accuracy of the departure times, instead taking advantage of an early climb to stay above the arrivals. They also vectored departures to avoid separation losses. In the last four runs the scheduling tool did become relevant to support the controllers' decision to climb aircraft early. When departures were mis-timed and were going to miss the predicted gap, controllers kept them at level altitude. When the departures were on time and were going to fly through the predicted gap, they could be climbed early. The results showed that the more inside the gap the departures were, the earlier aircraft were climbed and the higher their altitude when crossing the second arrival flow.

Overall, controllers rated the departure procedure as safe and acceptable within the simulation, but Mulford controllers rated the procedure as only "somewhat acceptable" or less in the field, and also reported high time pressure and mental activity on occasions. The Mulford controllers, who had the responsibility to climb departures, reported that point-out coordination could take longer than expected. During the second half of the simulation, the Mulford controller would ask the Niles controller permission to climb and turn aircraft for all departures at the beginning of each run. This pre-arranged coordination became a procedure for all REDDT1 departures.

Although workload, coordination, and safety were judged by controllers as acceptable in the simulation, it appears that in the field, controllers would need both improved decision support tools and coordination procedures to support SOAR procedures. Decision support tools and pre-arranged coordination procedures, as well as various climb performance of departures are explored in follow-up studies.

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