INVESTIGATING THE IMPACT OF OFF-NOMINAL EVENTS ON HIGH-DENSITY 'GREEN' ARRIVALS

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Abstract

Trajectory-based controller tools developed to support a schedule-based terminal-area air traffic management (ATM) concept have been shown effective for enabling 'green' arrivals along Area Navigation (RNAV) routes in moderately high-density traffic conditions. A recent human-in-the-loop simulation investigated the robustness of the concept and tools to off-nominal events—events that lead to situations in which runway arrival schedules require adjustments and controllers can no longer use speed control alone to impose the necessary delays. Study participants included a terminal-area Traffic Management Supervisor responsible for adjusting the schedules. Sector-controller participants could issue alternate RNAV transition routes to absorb large delays. The study also included real-time winds/wind-forecast changes. The results indicate that arrival spacing accuracy, schedule conformance, and tool usage and usefulness are similar to that observed in simulations of nominal operations. However, the time and effort required to recover from an off-nominal event is highly context-sensitive, and impacted by the required schedule adjustments and control methods available for managing the evolving situation. The research suggests ways to bolster the off-nominal recovery process, and highlights challenges related to using human-in-the-loop simulation to investigate the safety and robustness of advanced ATM concepts.

Introduction

The Next Generation Transportation System (NextGen) ATM initiative promotes trajectory-based operations for efficient control of aircraft to increase capacity and reduce environmental impacts [1]. Optimized Profile Descents (OPDs) along appropriately designed RNAV routes in the terminal area—so-called 'green' arrivals—can provide the required environmental benefits. However, executing OPDs in dense traffic conditions is inherently difficult. Even if aircraft are set up to arrive properly spaced [2], without excessive buffers some control is necessary to correct for disturbances that accrue during the descent (e.g., due to forecast wind errors, pilotage, etc.). Unlike current-day control techniques such as level-offs or vectoring that interrupt OPDs, speed adjustments enable uninterrupted OPDs—but without suitable tools controllers have difficulty applying speed adjustments alone [3].

A ground-based approach for sustaining OPDs during periods of high throughput has been developed as part of the Super Density Operations (SDO) research focus area of the NASA Airspace Systems Program. The approach is consistent with the SDO operational concept [4], and includes a precision terminal-area arrival-scheduling capability [5] and complementary 'Controller-Managed Spacing' (CMS) tools for using speed control to manage green arrivals. The feasibility and benefits of the CMS tools have thus far been demonstrated through human-in-the-loop simulation of nominal operations with moderately high-density arrival traffic [6].

The present research represents a step toward supplementing the feasibility/benefits case for CMS tools with a safety/robustness case—a prerequisite for operational implementation. Specifically, the research investigates how controllers might use the tools to control scheduled arrivals that require higher levels of delay, including delays arising from rescheduling to accommodate off-nominal events. It aims to provide a preliminary characterization of the off-nominal recovery process in terms of schedule changes required in various off-nominal situations, strategies and procedures for coordinating and implementing recovery plans, and the use of CMS tools for restoring nominal operations.

This paper first provides background on related research, and on the design and use of CMS tools in nominal operations. Previous CMS simulation research is also described, as it provides the basis for

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the current work. Next, the paper describes a spring 2011 human-in-the-loop simulation study conducted in the Airspace Operations Laboratory (AOL) at NASA Ames Research Center [7]. A sub-section that identifies the off-nominal events, additional tools and controller roles, and other issues included for consideration precedes the description of the experimental method. The paper next presents results from the study, including selected case study observations that illustrate key issues. The paper concludes with a discussion of possible methods for bolstering the off-nominal-recovery process, as well as challenges encountered in this research.

Background

A variety of automation systems and controller tools, such as the Relative Position Indicator (RPI) [8], have been designed to support ground-based merging and spacing in the terminal area (see the review in [6]). Assessing the safety and robustness of such enhancements—and ATM systems in general—presents challenges because of the complex time-dependent interactions that occur between humans, automation, physical subsystems, and the environment. Researchers have applied approaches ranging from probabilistic risk assessment, stochastic and agent-based simulations, to human-in-the-loop simulations; the applicability of a particular approach depends on the degree to which it adequately captures the required breadth of critical factors at a level of detail sufficient to provide the necessary insights [9]. A recent study on the SDO operational concept attempted to identify and rank the potential impacts of failure modes and their effects [10]. The present research, by contrast, takes a human-centric approach that leverages prior human-in-the-loop simulations in order to focus on the robustness of schedule-based arrival management using the CMS tools.

EUROCONTROL researchers also used human-in-the-loop simulation to study off-nominal situations arising when airborne spacing is used in the terminal area, with the expressed intention of refining associated procedures [11]. Off-nominal events, including go-arounds, emergencies, and radio failures, were briefed prior to the experimental trials in which they occurred, and controller participants agreed on an initial recovery procedure; controllers could also request that the simulation be frozen during the trials to provide time for additional discussions. The participants' comments proved valuable for identifying procedural refinements. While the present research takes a more 'organic' real-time approach (i.e., no pre-discussions, no simulation freezes) and seeks, in addition, quantitative characterizations of system performance, it places similar value on opportunities for identifying best practices and procedures for recovering from off-nominal situations.

Nominal CMS Operations

A sketch of the nominal schedule-based arrival-management concept underlying CMS research is shown in Figure 1; all aircraft are assumed equipped with a Flight Management System (FMS) and Automatic Dependent Surveillance-Broadcast (ADS-B)-Out. In en-route airspace scheduling automation assigns each aircraft a scheduled time-of-arrival (STA) at an assigned runway, based on the aircraft's estimated time-of-arrival (ETA) and specified scheduling and runway-assignment criteria. En-route controllers next apply some speed and/or path control to deliver aircraft to their respective meter fixes with schedule errors small enough (i.e., approximately 60 s early to 30 s late) to be corrected with speed adjustments in the terminal area.

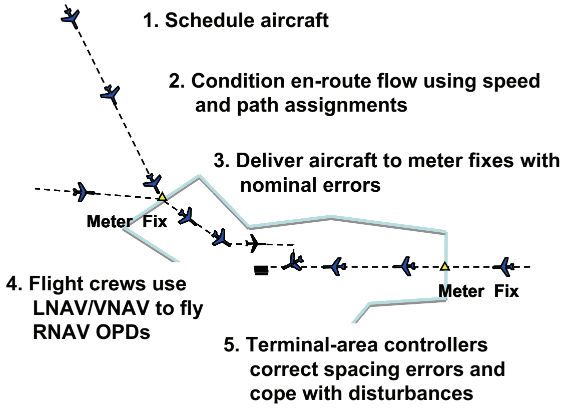


Figure 1. Schedule-Based Arrival

Once aircraft enter the terminal area, Feeder controllers use tools to issue speed instructions to further adjust aircraft toward their STAs. Flight crews use Lateral and Vertical Navigation (LNAV/VNAV) auto-flight modes to fly the FMS-computed vertical profile for the charted RNAV OPD, intervening as necessary to comply with speed-adjustment instructions. Final controllers then make speed adjustments to ensure safe inter-arrival spacing at the runway threshold. All of the CMS tools are based on trajectory predictions computed using the forecast winds. If the forecast winds are reasonably accurate, a few Feeder controller speed adjustments for a subset of the arrivals followed by a limited number of speed adjustments by the Final controller—typically including a last adjustment on final approach (e.g., "maintain 180 knots to the marker")—should be sufficient.

For purposes of the present research operations are considered 'nominal' when all arrivals are flying the same RNAV OPDs known to the ground-side automation, so that the CMS tools are properly configured and controllers need only apply speed adjustments to achieve schedule conformance and cope with disturbances.

CMS Tool Descriptions

The CMS tools are designed to provide terminal-area controllers with both temporal and spatial awareness of each aircraft's progress relative to its STA, as well as speeds they could issue to correct schedule errors [6]. Figure 2 depicts the tools that comprise the CMS tool set. First, schedule timelines (Figure 2a) show the ETAs and STAs (on the left and right sides, respectively) for each aircraft at scheduling points selected based on the needs of each terminal-area controller: timelines on Feeder-controller displays may show schedule information for a sector-exit point or downstream merge point, while timelines for Final controllers show runway schedules. In addition, early/late information is displayed in the third line of an aircraft's data block, so that controllers can obtain schedule conformance information without diverting their attention from an aircraft target of interest (Figure 2b).

Second, a 'slot marker' circle displays where a given aircraft would be if it were flying its assigned nominal OPD speed profile and were to arrive on schedule (Figure 2c). Thus, the slot markers convert the temporal schedule information into a spatial target controllers can work toward. The slot markers are temporally sized based on groundspeed, and therefore grow smaller as aircraft decelerate along the OPD. The indicated airspeed (IAS) of each slot marker is displayed adjacent to it. Dwelling on an aircraft's data block highlights its slot marker and timeline entries (Figure 2a/2d). It is important to note that, unlike position-based tools such as RPI, if the ground-based automation has an assigned RNAV OPD and an STA for an aircraft, it can compute a slot-marker position for that aircraft regardless of that aircraft's actual position or lateral path. Although OPDs may be interrupted, controllers can maintain schedule conformance using any means necessary to get aircraft into their slot markers.

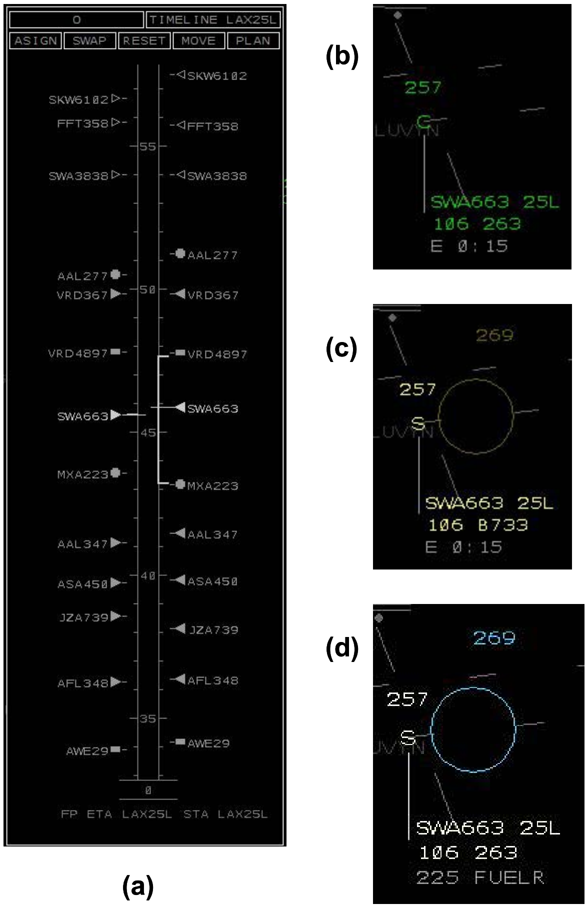


Figure 2. Controller-Managed Spacing Tools

Finally, when underlying trajectory-based computations yield a speed that—if flown until rejoining the nominal speed profile at a downstream waypoint—is predicted to result in the aircraft arriving on schedule, the advised speed and waypoint are presented in the third line of an aircraft's data block instead of the early/late indication (Figure 2d). Flight crews are expected to respond to the clearance "maintain X knots until Y waypoint" using VNAV speed intervention until reaching the specified waypoint. These speed advisories are the most complex trajectory-based tool in the CMS tool set, in terms of both the underlying computations and the possible ‘flavors’ of implementations (see [6] for a discussion of some issues surrounding speed advisories). Figure 3 shows a snapshot of a Final-controller display with the slot markers and speed advisories in use.

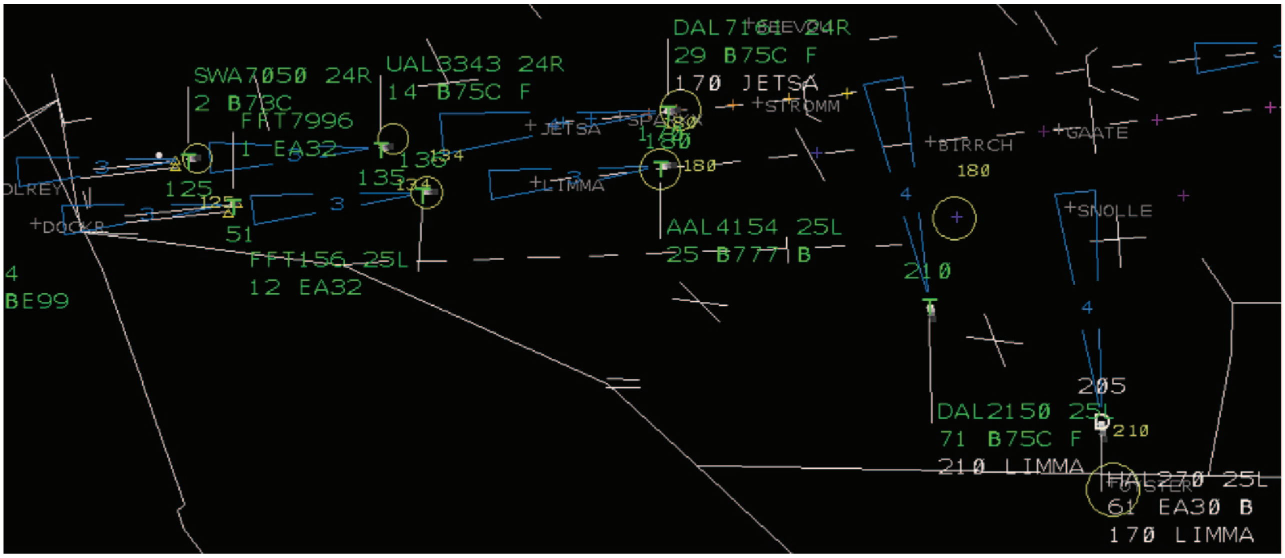


Figure 3. Final Controller Display with Slot Markers and Speed Advisories

Prior CMS Simulation Research

The Multi Aircraft Control System (MACS) used as the rapid-prototyping environment and simulation platform in the AOL (see [7]) enables researchers to configure scheduling criteria and CMS tools as desired. In prior research schedules have used a 0.5 nmi buffer, corresponding to approximately 15 s at final-approach speeds. Schedules have also allowed up to 30 s of time advance to avoid delaying trailing aircraft unnecessarily. The slot-marker radius has been set to 7.5 s, which provides good correspondence with the scheduling buffer. The scheduling freeze horizon has typically been set such that STAs are frozen 20 min from the runway threshold. MACS also includes emulations of other existing controller tools, and in prior research controllers have typically also used this functionality. In particular, Final controllers can opt to display ‘spacing cones’ available as part of existing terminal-area controller workstations to assess relative spacing between arriving aircraft (see Figure 3). Controllers can also display J-rings, and the FMS routes of individual aircraft.

In prior research MACS has also been configured to display an aircraft’s IAS near its target symbol, opposite its data block, based on the assumption that IAS will be available in the ADS-B-Out message set (see Figures 2 and 3). Controller participants have proved adept at using this information to assess the actual winds and mentally adjusting speed advisories accordingly. Speed advisories in MACS may also be configured to be based on STA information from a particular schedule. Assigning STAs for aircraft at merge-points along their RNAV arrival routes and computing speed advisories based on the merge-point schedules is a key focus of SDO precision-scheduling research [5].

Winds used in [6] were oriented as a headwind off the landing runways that grew stronger as function of altitude; no directional errors were modeled. Actual wind speeds either matched the forecast winds (which were constant throughout the study), or were biased ten knots faster or slower than the forecast winds—a potential worst-case situation for trajectory predictions that concern aircraft merging from opposite directions. Winds were assumed known from field elevation up to 1,500 feet (and actual-to-forecast differences were only modeled at terminal-area altitudes). In addition, some means of acquiring planned final-approach speed information has been assumed available to support trajectory predictions.

CMS tools have been developed and their feasibility and benefits found favorable through human-in-the-loop simulations using charted routes and test sectors in Los Angeles International Airport (LAX) terminal-area airspace configured for west-flow operations (Figure 4). Continuous RNAV routes to runways 24R and 25L are designed with nominal speed and altitude restrictions to define an approximately 2.4-degree descent angle that allows for speed control. As shown in Figure 5, in all conditions in the most recent simulation aircraft mostly flew uninterrupted OPDs, and were never vectored off the charted RNAV arrival routes. Barring five isolated cases attributable to specific causes, aircraft also arrived properly spaced at the runway threshold [6]. The following section describes the simulation conducted for the present research.

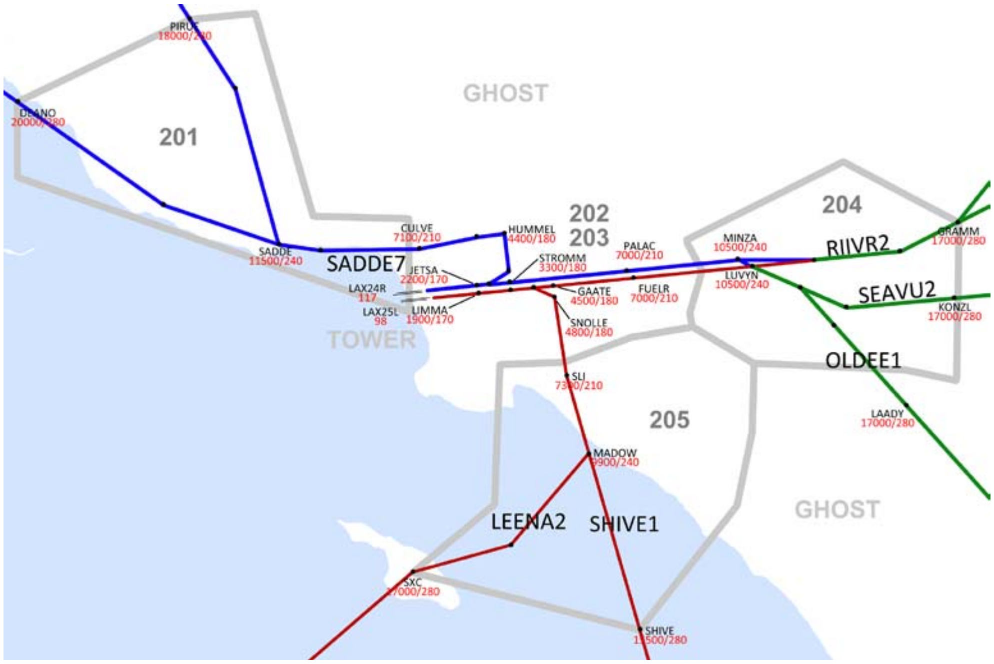


Figure 4. Test Sectors and RNAV Routes to LAX Runways 25L and 24R

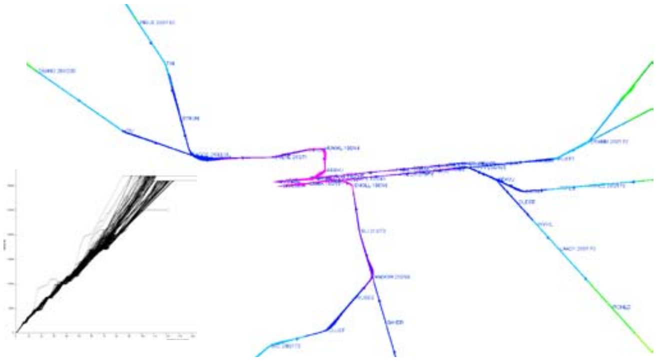


Figure 5. Nominal RNAV Route and OPD Profile Conformance (N = 900 Aircraft)

Simulation Study

A spring 2011 simulation was conducted to assess the robustness of the CMS arrival-management concept to off-nominal events—events that create situations where the schedule errors that need to be corrected in terminal airspace fall outside the '60-s-early-to-30-s-late' range. The simulation also provided an opportunity to investigate more complex actual and forecast winds and re-examine key assumptions from prior simulations. Before describing the simulation method, this section first describes scoping considerations and extensions to the prior research.

Scope and Extensions to Prior Research

An initial step in determining the scope of the simulation was to select the off-nominal events to include. Because of the ground-side focus, events that entail specific flight-deck procedures (e.g., engine-outs) were excluded. Departure aircraft returning to the airport for other reasons and off-nominal terminal-en-route situations were excluded due to simulation limitations. Other off-nominal situations (e.g., runway closures) were ruled out as too disruptive for initial research based on preliminary ‘shakedown’ simulations. These considerations led to the selection of the following off-nominal events for use in the simulation (cf. [10]):

- Pilot-initiated go-arounds (e.g., due to landing gear malfunctions).
- Tower-initiated go-arounds (e.g., due to an aircraft failing to clear the runway in a timely fashion).
- Radio outages (‘no radio,’ or ‘NORDO’).
- Serious on-board medical emergencies.

A scripting capability implemented in MACS was leveraged to implement the off-nominal events: scripts associated with each traffic scenario were specified with conditions that triggered a message to be sent to the relevant pseudo-pilot, who would then radio air traffic control or notify an experimenter as appropriate to initiate a planned event. NORDO events were triggered early, before the aircraft entered the Feeder controllers’ airspace. Medical emergencies were triggered such that they would be declared far enough from the runway for expedited handling to have an appreciable effect. Pilot-initiated go-arounds occurred in the region where a gear malfunction might first be detected, and tower-initiated go-arounds occurred after the preceding aircraft had landed, so that a problem with that aircraft clearing the runway could be cited. All of these types of off-nominal events are likely to require adjustments to the arrival schedules: go-arounds require reinsertion into the arrival flows, NORDO aircraft cannot be adjusted toward their STAs (affecting neighboring aircraft in the sequence), and medical emergencies warrant expedited handling (also affecting neighboring arrivals).

Consequently, a Traffic Management Supervisor responsible for making schedule adjustments was included as a study participant. The supervisor staffed a workstation that was configured with runway-schedule timelines. The supervisor could zoom the traffic display in or out as appropriate to visualize aircraft relevant to current rescheduling problems. Pre-existing MACS timeline-manipulation functionality was also enabled to support the following schedule manipulations by the supervisor:

- Re-assigning an aircraft’s STA.
- Swapping STAs for two aircraft.
- Moving a specified ‘block’ of STAs by a specified time.
- Rescheduling a specified block of aircraft.
- Assigning an aircraft to a different runway schedule.

The supervisor performed all of these operations by entering commands in the shortcut window on his workstation. Command strings can be composed using a combination of timeline mouse-selections and text entries. To aid the supervisor in performing schedule assessments, the timelines were also modified with green and red bars that indicated gaps and insufficient spacing in a schedule, respectively.

Path options in the form of named RNAV arrival/approach transitions were also added to absorb large delays. The options were designed in accordance with controller feedback obtained during the shakedown simulations (Figure 6). Feeder-controller path options include delay (and a few shortcut) routes; options for final controllers include base-turn modifications and ‘fanning’ routes. RNAV go-around routes were also designed to enable controllers to use the CMS tools to reinsert go-arounds into the arrival flows to runway 25L or 24R. ‘Long’ and ‘short’ go-around routes were defined to provide the supervisor with flexibility in rescheduling go-arounds (green routes starting at IGUPE and FUMBL in Figure 6).

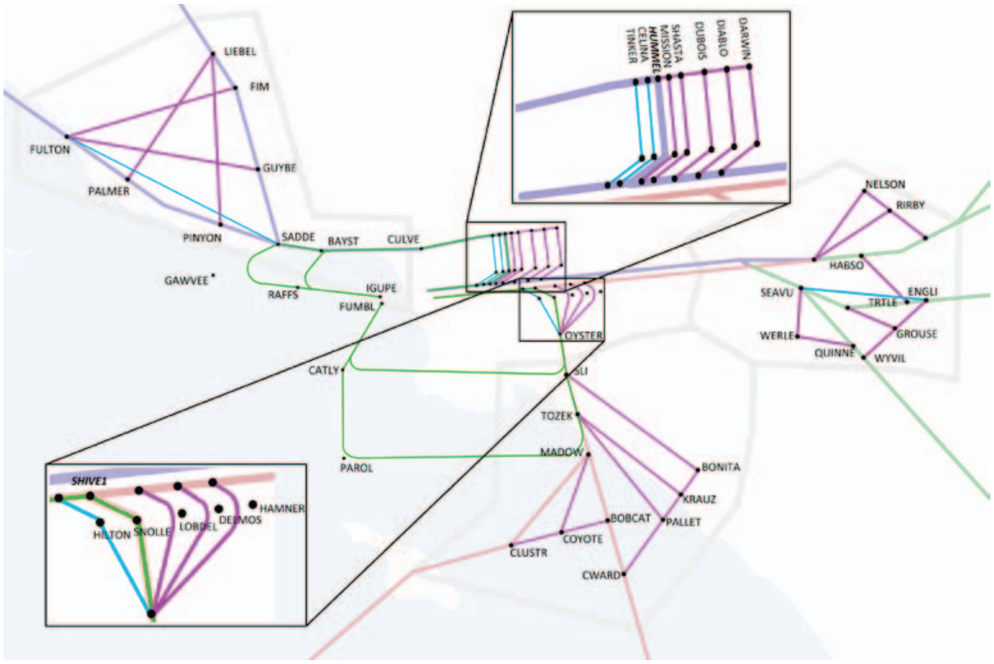
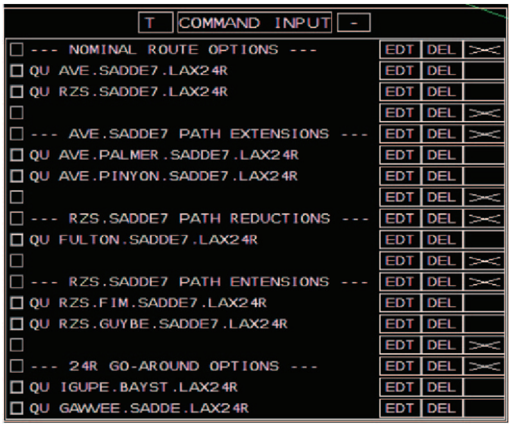


Figure 6. RNAV Transition Path Options and Go-Around Routes

To support the use of path options and go-around routes, a pre-existing MACS command input panel was adapted for the selection of applicable path options on each sector controller display. The panel, shown in Figure 7, enables controllers to display route options, and to specify a path option to the ground automation via a mouse-selection that places the relevant command into their shortcut window for execution. Although not consistent with Host-computer entries in today's operations, controllers could make successive path-option entries and see their effects on the associated aircraft's slot marker before clearing the aircraft to fly them—a 'what-if' capability that aids in path-option selection.



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☐ --- NOMINAL ROUTE OPTIONS ---
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☐ --- AVE.SADDE7 PATH EXTENSIONS ---
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☐ --- 24R GO-AROUND OPTIONS ---
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☐ QU GAWVEE.SADDE.LAX24R
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Figure 7. 201-Feeder Route Selection Panel

The current study also provided an opportunity to further investigate how winds and wind-forecast errors impact CMS operations. When actual winds were biased from the (constant) forecast winds by 10 knots [6], controllers had little difficulty assessing the wind differences and modifying advised speeds to be 10 knots faster or slower as appropriate. In the present research, 'odd' forecast wind biases were used to challenge the controllers: actual winds were biased to be 13 knots faster or 7 knots slower than the forecast winds at terminal-area altitudes (Figure 8). The assumption that winds are known below 1,500 feet was retained. The current study also includes 'quartering' winds from 45 degrees north or south of the runway heading, in addition to a pure headwind. In addition, the simulation explored the effects of wind shifts such as might be observed when a weather front passes; forecast winds were updated when the actual wind-direction changed, and controllers were briefed about the changes.

Finally, the study provided an opportunity to examine how operations could be affected if the assumption that aircraft IAS is available in the ADS-B message set is rejected. Controllers seemed unperturbed when IAS information was removed during shakedown simulations; nonetheless, a portion of the experimental trials were devoted to testing the CMS tools when aircraft IAS is not displayed beneath the aircraft target. The following subsection describes the experimental method in detail.

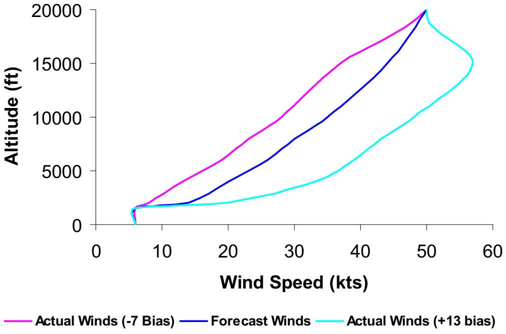

Figure 8. Actual and Forecast Wind Speeds vs. Altitude

Method

The spring 2011 simulation was designed for one week of data collection, followed by a one-week break, then a second week of data collection. Off-nominal events, traffic scenarios, and wind conditions constituted the main independent variables. All the CMS tools were available to controller participants in every experimental trial, with a subset of trials set aside to test whether not having aircraft IAS available for display had a noticeable effect.

Traffic scenarios were designed starting from three 'base' scenarios. The scenarios typically included 25 arrivals to each runway distributed along the RNAV routes shown in Figure 4, and lasted approximately one hour. Demand distributions for the various routes were adjusted from that observed in recorded LAX data to more evenly distribute aircraft to the Feeder sectors—which also produced slightly more merges on final approach. Off-nominal events were designated for one aircraft assigned to runway 25L and one aircraft assigned to runway 24R in each scenario. The events were assigned to simulation trials such that the controllers who might need to be involved with resolving them varied depending on the assigned RNAV route of the off-nominal aircraft and the routes of neighboring aircraft in the arrival sequence. Finally, aircraft flight numbers were randomized between trials and the individual scenarios were adjusted to yield reasonable initial schedules in the assigned wind conditions. For realism all the scenarios included LAX departures that did not nominally interact with the arrival flows.

Given the treatments, one-hour trials, required breaks, and (de-)briefing sessions at the beginning and end of each week of data collection, 23 experimental trials were planned each week. Twenty-one were 'main' trials; the last two were made available for repeating trials run earlier. During the second week of the study, the first week's trials were randomized and repeated to compare how participants handled the off-nominal event. Figure 9 shows a graphical depiction of the experimental design, including the trials that were repeated. The 'shape' of an individual trial encodes the type of off-nominal event scripted to occur in each runway's arrival flow, while its color encodes the wind conditions. For trials with one wind change, the winds were scripted to change halfway through the trial; in trials with two wind changes, the changes occurred every twenty minutes.

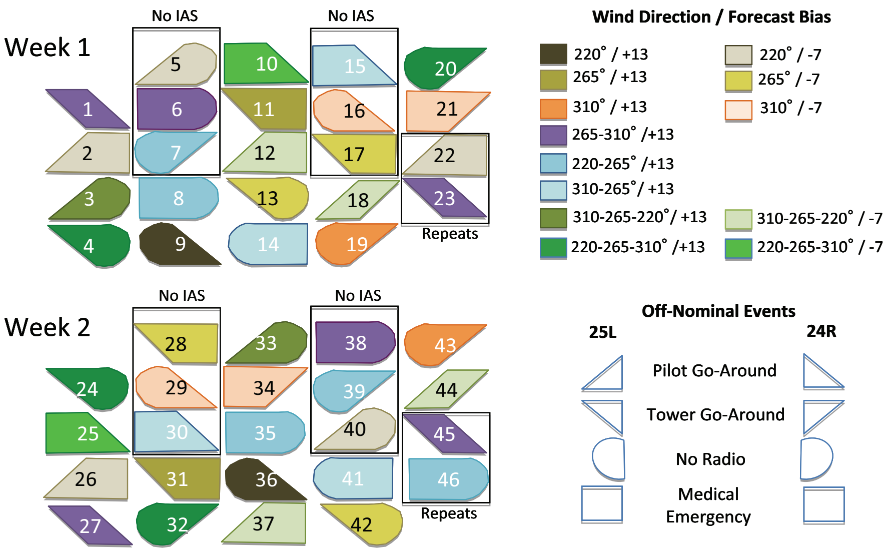

Figure 9. Experimental Trials

Study participants staffed the positions of the three Feeder controllers, two Final controllers, and the Traffic Management Supervisor. All were former controllers who had been retired an average of 2.8 years. All but two had participated in prior CMS simulation studies and were familiar with the CMS tools and operational concept. One of the new participants, the supervisor, was recruited specifically for his professional experience as a terminal-area traffic manager. All of the participants took part in most of the four half-day and three full-day shakedown simulations conducted during the five weeks preceding the study. Some participants staffed different positions during the shakedowns; once the study began each participant worked the same position for the duration of the study. Figure 10 shows a panorama of the terminal-area control room during the study (schedule timelines are projected on the wall above the Final controller workstations). Other retired controllers staffed 'ghost' controller positions for en-route and tower sectors. Active commercial pilots and aviation students served as pseudo-pilots.

Figure 10. Simulation Terminal-Area Control Room with (L-R) Final Controllers, Feeder Controllers, and Traffic Management Supervisor

Data collected during the study include aircraft states and computed-trajectory information, schedule and slot-marker states, pseudo-pilot and controller action events, controller workload-prompt inputs, and voice-communication and controller-display recordings, as well as post-run and post-study controller questionnaires. In addition, detailed observer notes were compiled for each experimental trial and debriefing. The following section describes results from analyses conducted thus far.

Results

This section first provides a general characterization of observed operations as a reference for descriptions that follow. Next, it presents metrics obtained from digitally recorded data. It then presents subjective questionnaire data that characterizes participant perceptions of the off-nominal events, workload, tool usage, and coordination. Finally, case study analyses provide detailed insights on timing, strategies, and tool usage for comparisons of selected experimental trials in Week 1 to their Week 2 counterparts.

Observed Operations

All experimental trials began with the first several aircraft descending into the Feeder controllers' airspace. The MACS scheduling automation established aircraft ETAs and STAs; the STAs were frozen in the region near the terminal-area boundary. Early in each trial the Traffic Management Supervisor began inspecting his timelines, identifying gaps to allow for scheduling flexibility and at times adjusting STAs to ensure high runway utilization. Feeder controllers began issuing speeds and/or path options as required to adjust aircraft toward their frozen STAs. Final controllers began accepting aircraft approximately ten minutes into a trial. Participants had considerable latitude in managing the traffic, including how they used the tools, whether they issued speeds, path options, or resorted to vectoring, and how they coordinated to formulate off-nominal recovery plans.

When a NORDO aircraft was identified, the supervisor typically began by setting its STA to match its ETA. He then assessed the schedule and how aircraft ahead or behind the NORDO aircraft could be affected. The supervisor usually consulted with the Feeder controller(s) to determine whether to swap STAs, and in some cases devised a contingency plan for having the aircraft ahead of the NORDO go around, should safe spacing be lost. For medical emergencies, the supervisor coordinated with the sector controllers to develop a plan for expediting the emergency aircraft; the plan could include schedule swaps, taking into account options for delaying affected aircraft. When go-arounds were declared, the controllers needed to formulate a plan for climbing them to a safe altitude and assigning the desired RNAV go-around route—again considering the schedule and the ease with which controllers could adjust neighboring aircraft in the planned sequence. In some cases, go-around aircraft were rescheduled to the other runway. For tower-initiated go-arounds, the controllers first also had to work out a plan to reacquire control of the aircraft from the tower ghost.

In trials with wind shifts and associated forecast-wind changes, which could cause the slot-marker positions to change, controllers had to compensate for changes with appropriate adjustments. In extreme cases, this involved issuing alternate paths or vectoring. Overall, operations were generally smooth in cases where a plan could be formulated reasonably quickly, most affected aircraft needed small adjustments, and the means to make any required larger adjustments were available (e.g., a suitable path-option lay ahead). However, if the supervisor had to try multiple schedule changes before settling on one, controllers sometimes experienced difficulties and the situation occasionally degraded into one in which substantial vectoring was required before nominal operations were restored.

Spacing Accuracy

A key arrival-management metric is the accuracy with which controllers are able to achieve safe wake-vortex spacing for each pair of arriving aircraft. The spacing error for a given aircraft pair was measured at both the Final Approach Fix (FAF) and runway threshold to examine how uncertainties affected spacing after the Final controllers transferred control to the tower-ghost controller. The histogram in Figure 11 shows the Final controllers largely provided sufficient spacing at the FAF, and errors at the runway threshold are centered near the 0.5 nmi scheduling buffer value (M=0.66 nmi; SD=0.87 nmi)—similar to the results shown in [6].

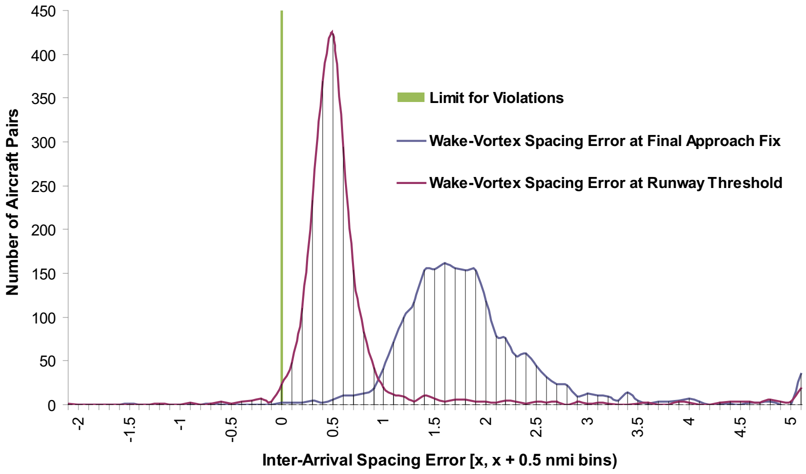

Figure 11. Observed Spacing Errors (N_{FAF} = 1,978 Aircraft Pairs)

The spacing accuracy results include the first experimental trial, in which critical pseudo-pilot errors complicated operations. Both of the violations measured at the JETSA FAF to runway 24R (out of 1,978 aircraft pairs) occurred during the first trial, as did 9 of the 28 total violations at the runway threshold. Two-thirds of these violations occurred for arrivals to runway 24R—perhaps because the responsible controller rarely used the spacing cones to carefully assess relative spacing. A detailed analysis of the runway-threshold violations revealed that only 16 of the 28 are attributable to insufficient spacing prior to transferring control to the tower; others were due to simulation artifacts and pseudo-pilot errors, yielding an overall error rate of 0.81%.

Schedule Conformance

Figure 12 shows histograms of runway-schedule conformance measured at key altitude-restricted waypoints along the RNAV arrivals (see Figure 4), illustrating how controllers were able to progressively reduce schedule errors as they recovered from off-nominal events and aircraft neared their destination. The results show that the Feeder controllers were almost always able to deliver aircraft to the Final controllers with no more than 20 seconds of remaining schedule error.

These results reflect positively on the ability of the study participants to correct large schedule errors in terminal airspace, particularly considering that the en route ghost controllers did not always let the scenarios play out as designed. In resolving en-route conflicts outside the study airspace, they sometimes forced Feeder controllers to deal with large runway-schedule errors at the meter fix—even before any off-nominal events occurred. The range of observed meter fix schedule errors extends beyond that shown in Figure 12, from approximately 145 s early to 110 s late.

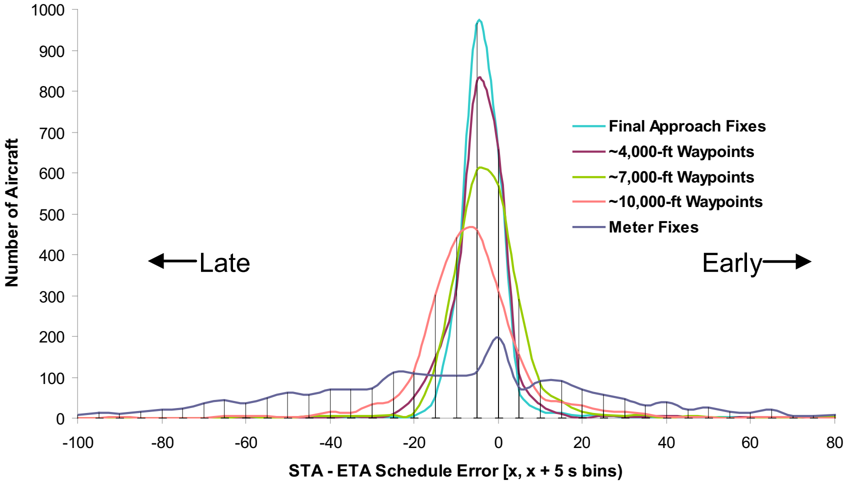

Figure 12. Observed Schedule Conformance (N = 2,101 Aircraft)

Path Options

An analysis of the terminal-area path options was conducted to assess the impact this additional control option had in helping controllers to absorb large delays. Figure 13 plots the average number of path options issued per experimental trial by test sector (error bars represent one standard deviation; numerical values are the total number of path options issued). The 201-Feeder controller issued the most path options, followed by the 202-Final controller (runway 24R), and the 204-Feeder controller; the 203-Final controller issued very few. The large size of sector 201 and the close correspondence of the 201 path options to current-day re-routing procedures likely helped bolster their acceptance. While the 201 controller consistently used all but one option, the two options used most were the shortest and longest options. The 202-Final controller mostly used the shortest base-extension option. These results may reflect individual preferences, as well as learned acceptance of certain path options for managing recurring situations.

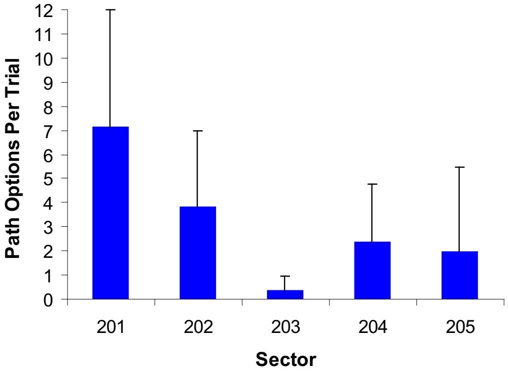

Figure 13. Average Path Options per Trial

Controllers also entered path options as ‘what-if’ queries to first verify how an option would affect an aircraft’s slot marker position. An analysis shows an aggregate ratio of what-if queries to path options issued of approximately 1:2.5. However, for the 202-Final controller, the ratio is closer to 3:4. This could reflect a need to check which of the finer-grained base-extension path options might work best. In general, the path options illustrate how a capability to alter the lateral path of an aircraft, and of its slot marker, can be valuable for absorbing delays while maintaining trajectory-based operations in the terminal area.

Participant Reports on Off-Nominal Recovery

The time and effort required to recover from off-nominal events exhibited a high degree of situation-specificity. However, the post-run and post-simulation questionnaires contained questions that help characterize, in general terms, how study participants perceived the impacts of different types of off-nominal events.

On average controller participants estimated that a suitable plan was in place for resolving off-nominal events in approximately three minutes. The 2 minutes 45 seconds that they estimated it took to plan to resolve medical emergencies was significantly less ($p = 0.005$) than for the other types of off-nominal events. Tower-initiated go-arounds and NORDO aircraft were most disruptive and time-consuming to resolve, and also received the highest workload ratings. While NASA TLX workload ratings did not differ significantly across trials with different off-nominal events, the 3.73 mean overall mental demand rating in this study was notably higher than the 3.11 mean rating reported in [6], indicating that recovering from off-nominal events is more workload-intensive than the nominal CMS arrival-management task.

Controller participants most often reported using speed clearances to recover from off-nominal events, including speed clearances based on speed advisories (63% of the time). However, for managing tower-initiated go-arounds controllers reported using speed clearances 60% of the time, and resorted to vectors 22% of the time. For pilot-initiated go-arounds, controllers reported using path-options and vectors each 18% or more of time.

When asked how often they used the CMS tools for managing off-nominal events, controller participants reported that they used one or more tools only 77% of the time. Slot markers were always included in the set of tools used; timeline and speed-advisory usage fluctuated around 25%. For managing go-arounds controllers reported using one or more tools 64% of the time versus 95% of the time for NORDO aircraft and medical emergencies. Slot markers were also cited as the most useful tool for dealing with situations involving vectoring, unanticipated schedule changes or special requests from the supervisor, or unplanned go-arounds. These results exhibit similarities to the results in [6], which showed controllers prefer the slot markers to the other CMS tools.

Reported strategies mirror the clearance- and tool-usage responses. When operations went smoothly controllers reported ‘following the slot markers’ and ‘using speed to put aircraft in the slot markers.’ For go-arounds controllers ‘used speed adjustments after waiting for the supervisor to reschedule the go-around;’ for NORDO aircraft and medical emergencies the predominant strategy was ‘use speed adjustments after the supervisor adjusts the schedule.’ However, when situations became disordered controllers reported needing to vector aircraft (e.g., ‘vectored aircraft so its slot marker could catch it from behind’). Controllers most often reported that, in hindsight, they would not have chosen a different strategy.

Controllers always reported coordinating with someone else when resolving off-nominal events—for 90% of the go-arounds and NORDO events, that person was the Traffic Management Supervisor. On average controllers found the supervisor to be ‘quite helpful and useful,’ with a response range from ‘a little helpful’ to ‘very helpful.’ While only small differences between mean helpfulness ratings for the various off-nominal events were observed, the supervisor was rated most helpful for managing pilot-initiated go-arounds and least helpful during tower-initiated go-arounds—perhaps because of the limited time available for planning.

Participant comments from runs with no IAS displayed for the aircraft targets indicate having IAS information is helpful for monitoring clearance compliance, eliminating voice communications devoted to confirming speeds, and coordinating with other controllers. Because they typically issued easy-to-remember speed assignments upon taking control of aircraft, IAS information was less important to the Final controllers—in some cases they appeared not to notice the IAS information was missing. On average participants reported that wind shifts had ‘some effect.’ There were three reports of wind shifts having a ‘large effect’ and one report of a ‘very large effect’ that a controller had to make large adjustments to compensate for. From experimental observations, wind shifts that ‘undo’ previous control actions seemed most frustrating to the controllers, particularly if they created a sudden need to ‘catch up’ to a slot marker.

Off-Nominal Recovery Case Studies

Several pairs of matching experimental trials, one from each week of the study, were analyzed in detail by examining the audio/video recordings in conjunction with other data. The case studies reveal how different strategy choices and contextual differences can have interesting effects on the process of recovering from an off-nominal event.

As one example, Trials 19 and 43 had a tower-initiated go-around in the runway 24R arrival flow, and a NORDO aircraft in the flow to runway 25L. The initial situations in both trials were very similar, with a small gap in the runway 25L schedule. In Trial 19, the supervisor opted to schedule the go-around to runway 24R according to the ETA computed after assigning the corresponding 'long' go-around route. In Trial 43, by contrast, the supervisor took advantage of the schedule gap by changing the scheduled arrival runway for the go-around and assigning the 'short' go-around route. Besides landing the go-around aircraft much sooner, the strategy of using the schedule gap in Trial 43 helped minimize the impact on trailing aircraft. While 10 aircraft had to be rescheduled to accommodate the go-around, the total delay added to the schedule was 7.6 min, so that each affected aircraft needed less than a minute of delay on average. By contrast, the go-around affected 8 trailing aircraft in Trial 19, but the total delay added to the runway 24R schedule was nearly 14 min—an average of 1.7 min of delay per affected aircraft. As a result, controllers needed to issue larger numbers of vectors, path options, and speed clearances to recover from the go-around in Trial 19.

However, the runway-change strategy in Trial 43 impacted the NORDO aircraft which, as a result of inserting the go-around, ended up more ahead of schedule than it did in Trial 19. In Trial 19, the supervisor consulted with the Feeder-205 controller who, based on his assessment of the current winds, felt the NORDO would fall back toward its slot marker; the supervisor therefore decided to let the NORDO continue, and the situation worked out as anticipated. In Trial 43, however, the supervisor opted to swap the NORDO with its lead aircraft, so it would have adequate spacing. This increased the required delay for the lead aircraft from less than 1 min to 3 min, and resulted in delay vectoring. Thus, the more efficient go-around in Trial 43 was accompanied by a large penalty for the aircraft affected by the NORDO aircraft.

As a second example, Trials 23 and 45 involved go-around events on both runways. For the 25L tower-initiated events, in Trial 23 the supervisor spent nearly 4 min adjusting the schedule, impacting 13 aircraft and adding nearly 9 min of delay to schedule; in Trial 45, on the other hand, the supervisor opted to reorganize slack to create a gap in the schedule, which took only slightly more than 2 min, affected only 5 other aircraft, and produced a schedule with 47 s of delay *savings*. Interestingly, in both cases nominal operations were interrupted only for the go-around and one other aircraft; other affected aircraft were managed along their nominal RNAV routes using speed clearances alone. However, controllers issued 9 vectors to the two aircraft in Trial 23, and only 2 in Trial 45, and it took more than 10 min—almost 6 times longer—to fully restore nominal operations. It should be noted that the recovery times identified via case-study analysis are often significantly longer than those controllers reported in the post-run questionnaires.

The 24R-pilot-initiated go-arounds in Trials 23 and 45 were also interesting, as they were accomplished without any vectoring. In Trial 23, a schedule-gap was available to accommodate the go-around, such that the supervisor needed only 55 s to assign the go-around STA and reschedule one additional aircraft. The required delays were minimal and were achieved with speed adjustments alone. In Trial 45, after the go-around route was assigned the supervisor needed only 75 s to reschedule 7 aircraft. Each needed to absorb an average of 55 s of delay, which was accomplished using 8 path options and 17 speed clearances. In two situations, however, a speed reduction was followed by a speed increase.

Controllers also handled the medical emergency in Trial 12 without vectoring. Upon being notified about the emergency by the 201-Feeder controller, the supervisor identified a potential schedule-swap to expedite it. The supervisor then consulted the 204-Feeder controller, who thought he would be able to delay the affected aircraft. The supervisor then implemented the swap, but first warned the controllers to wait before starting to control to the new schedule. After confirming the slot markers would be achievable, the supervisor informed the controllers to go ahead with the plan. The 204-Feeder controller used speed adjustments to accomplish the swap before handing the aircraft off to the 203-Final controller. A schedule-swap was also used to manage a medical emergency in Trial 17; there, however, the controller opted to use vectoring to effect the change. Because the slot markers continued along the nominal routes, they were of no use in recovering from the off-nominal. The situation was also complicated because the pseudo-pilot became overloaded when vectoring multiple aircraft.

However, vectoring was sometimes used to good effect in conjunction with the slot markers, as in managing the 25L-pilot-initiated go-around in Trial 44. In order to make up time the controller vectored the aircraft into its slot marker, which was following the assigned go-around route. Figure 3 also illustrates an example of using a slot marker as a vectoring target—the controller has issued a shortcut vector to DAL2150 to make it intercept its slot marker. Examples like this illustrate how the slot markers can support current-day control techniques that are sometimes useful in off-nominal situations.

Discussion

The results of the present research suggest that the CMS arrival-management concept could yield consistently robust performance vis-à-vis off-nominal events, particularly if the tools for adjusting the schedule and absorbing any required large delays are improved, and criteria for applying specific recovery strategies (i.e., particular schedule and traffic characteristics) are well understood. First, the pre-existing MACS schedule-adjustment functionality could be streamlined and extended to enable 'schedule trial-planning,' so that the implications of planned adjustments could be assessed prior to effecting the changes in the actual ground automation. This would eliminate problems with reversing proposed changes, and generally reduce how long the schedule—and the associated slot-markers positions—are in flux. Preliminary research on an automated approach to developing off-nominal recovery plans is described in [12]; key elements of the approach are providing an initial 'proposal' that the supervisor could then adapt, and providing some information about the control actions that would be required to implement the proposal.

Data communications could enable a second major improvement—terminal-area trial-planning. This capability would help ensure that green arrivals could continue uninterrupted and that the trajectory-based tools would always be synchronized with the currently assigned RNAV routes. Beyond known problems with charting path options for multiple terminal areas and including them in FMS databases, the charted path options were not always useful to controllers, either because aircraft had already passed suitable options, or controllers did not have time to select and implement them. However, the present research does illustrate how an efficient means for applying path-control that supports 'what-if' queries would improve the robustness of trajectory-based terminal-area operations.

In the absence of tool improvements, off-nominal recovery procedures require refinements. The present research provides the basis for developing specific procedural guidance for managing some particular types of off-nominal events; case-study analyses illustrate how some approaches (e.g., strategic use of schedule gaps) out-performed others in effectively restoring nominal operations. Further research is needed to ensure off-nominal-recovery procedures are specified at the correct level of abstraction and conditions for applying a particular procedure are clearly defined.

Finally, the research reified how human-in-the-loop simulations of off-nominal scenarios can unfold in unexpected and complex ways, placing more complex demands on pseudo-pilots, MACS terminal-area simulation capabilities, and automated data-processing support. The study is already proving useful for developing initial solutions to some of these problems. Key challenges remain, however, including finding ways to prevent pseudo-pilots from becoming overloaded when one or more of the aircraft under their control are subject to frequent vectoring or a go-around aircraft requires close supervision—as these sorts of problems can lead to errors that impact controller participants.

Conclusion

Research to investigate the robustness of a green arrival-management concept using ground-based scheduling and controller tools extended previous CMS human-in-the-loop simulations. Results indicate recovery from off-nominal events is most efficient when rescheduling is accomplished reasonably quickly and controllers are able to use the tools to make the required adjustments. Some challenges regarding the use of human-in-the-loop simulation to investigate the safety and robustness of trajectory-based ATM concepts were also identified. While the research represents but a first step toward establishing the necessary safety case for CMS operations, the results are promising, and should help pave the way for future controller-tool, procedure, and simulation-capability development.

References

[1] Joint Planning and Development Office, September 30, 2010, Concept of Operations for the Next Generation Air Transportation System, Version 3.2, Washington, DC.

[2] Ren, L., and J-P. Clarke, 2007, Separation Analysis Methodology for Designing Area Navigation Procedures, Journal of Guidance, Control, and Dynamics, Vol. 30, No. 5, Reston, VA, AIAA, pp. 277-297.

[3] Davison-Reynolds, H., T. Reynolds, and R. J. Hansman, 2005, Human Factors Implications of Continuous Descent Approach Procedures for Noise Abatement in Air Traffic Control, Baltimore, Proceedings of the Sixth USA/Europe Air Traffic Management Research and Development Seminar.

[4] Isaacson, D., J. Robinson, H. Swenson, and D. Denery, 2010, A Concept for Robust, High Density Terminal Air Traffic Operations, AIAA-2010-9292, Ft. Worth, Proceedings of the AIAA Aviation Technology, Integration, and Operations Conference.

[5] Swenson, H., J. Thippavong, A. Sadovsky, L. Chen, C. Sullivan, and L. Martin, 2011, Design and Evaluation of the Terminal Area Precision Scheduling and Spacing System, Berlin, Proceedings of the Ninth USA/Europe Air Traffic Management Research and Development Seminar.

[6] Kupfer, M., T. Callantine, L. Martin, J. Mercer, and E. Palmer, 2011, Controller Support Tools for Schedule-Based Terminal-Area Operations, Berlin, Proceedings of the Ninth USA/Europe Air Traffic Management Research and Development Seminar.

[7] Prevot, T., P. Lee, T. Callantine, J. Mercer, J., Homola, N. Smith, and E. Palmer, 2010, Human-in-the-Loop Simulation of NextGen Concepts in the Airspace Operations Laboratory, AIAA-2010-7609, Toronto, Proceedings of the AIAA Modeling and Simulation Technologies Conference.

[8] Shepley, J., 2009, Near Term Terminal Area Automation for Arrival Coordination, Napa, CA, Proceedings of the Eighth USA/Europe Air Traffic Management Research and Development Seminar.

[9] Calanni Fraccone, G., V. Volovoi, A. Colon, and M. Blake, 2011, Novel Air Traffic Procedures: Investigation of Off-Nominal Scenarios and Potential Hazards, Journal of Aircraft, Vol. 48, No. 1, Reston, VA, AIAA, pp. 127-140.

[10] Ganji, M., and J. Krozel, 2011, Failure Mode and Effects Analysis for Super Dense Operations, AIAA-2011-6529, Portland, OR, Proceedings of the AIAA Guidance, Navigation, and Control Conference.

[11] Boursier, L., E. Hoffman, L. Rognin, F. Vergne, and K. Zeghal, 2006, Airborne Spacing in the Terminal Area: A Study of Non-Nominal Operations, AIAA-2006-7783, Wichita, KS, Proceedings of the AIAA Aviation Technology, Integration, and Operations Conference.

[12] Callantine, T., 2011, Modeling Off-Nominal Recovery in NextGen Terminal-Area Operations, AIAA-2011-6537, Portland, OR, Proceedings of the AIAA Modeling and Simulation Technologies Conference.

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