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This paper assesses resilience of scheduled Performance-Based Navigation (PBN) arrival operations. Resilience is defined as an ability to recover from perturbed schedule. Results from Human-in-the-Loop (HITL) experiment including three off-nominal events to perturb schedule, 1) missed-approach, 2) unscheduled priority arrival due to a medical emergency, and 3) a series of late aircraft due to convective weather, are described here. The perturbed schedules were managed in three conditions, 1) automatic schedule adjustments by an algorithm, 2) manual adjustments by the Traffic Management Coordinator (TMC), or 3) no adjustments. Analysis showed that the simulated scheduled terminal area PBN arrival operations have inherent resiliency, recovering from more than the half of perturbed schedules with no schedule adjustments. Resiliency of operations with the same off-nominal events improved in both schedule adjustment conditions; an increased proportion of perturbed schedules recovered, and the average duration of perturbed schedules decreased. The HITL experiment also explored efficacy of automated schedule adjustments as compared to the TMC performed ones in coping with the off-nominal events. In the automated condition, more number of perturbed schedules occurred than in the TMC condition, but perturbations were less severe, and an increased proportion of perturbed schedules were recovered. The participants found that the TMC was quicker to adjust the schedule to mitigate off-nominal events than automation, and automation provided more consistency in how schedules were adjusted. The subjective workloads in both conditions were similar to the no schedule adjustment condition. Loss of separation was examined and a positive relationship between the total number of loss of separation and the subjective ratings of route conformance for the air traffic controller positions handling the off-nominal events were found.

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Assessing Resilience of Scheduled Performance-Based Navigation Arrival Operations

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***Abstract*—This paper assesses the resilience of scheduled Performance-Based Navigation (PBN) arrival operations. Resilience is defined as an ability to return to nominal operations following a schedule perturbation. Results from a Human-in-the-Loop (HITL) experiment that included off-nominal events to perturb the schedule are described. The schedule comes from a precision trajectory-based arrival manager. The experiment collected data regarding the response to perturbed schedules in three conditions, where: 1) a disturbance rejection algorithm made schedule adjustments automatically, 2) a Traffic Management Coordinator (TMC) participant made schedule adjustments manually, or 3) no schedule adjustments were made. Analyses showed that the simulation's scheduled PBN operations have inherent resilience, recovering from more than half of the perturbed schedules even with no schedule adjustments. Resilience to the same off-nominal events improved with schedule adjustments; an increased proportion of perturbed schedules recovered within the length of operation run, and the average duration of the schedule's perturbed state decreased. Compared to the manual schedule adjustments condition, a greater number of schedule adjustments occurred for the same off-nominal events in the automated condition. However, perturbed schedules were recovered more frequently and perturbations were less severe in the automated condition. Subjective and objective workload in the manual and the automated schedule adjustment conditions were similar to the no schedule adjustment condition.**

Keywords-component; resilience; scheduled arrival operation; Performance-Based Navigation

I. INTRODUCTION

Performance-Based Navigation (PBN) has introduced two types of navigation specifications, Area Navigation (RNAV) and Required Navigation Performance (RNP) [1]. Benefits of procedures using these specifications include shorter, more direct flight paths, fuel savings, a reduction in adverse environmental impact, and improved arrival rate [2,3,4]. However, these benefits become less pronounced when aircraft are routinely interrupted from staying on the PBN procedures with tactical air traffic control instructions such as heading change. The possible reasons for such interruption include the traffic density in busy terminal areas, as well as a lack of automation-aids for handling multiple types of procedures and the aircraft's navigational capabilities [5,6]. Therefore, facilitating uninterrupted PBN procedures is one of the key objectives for the United States' Next Generation Air Transportation System (NextGen) air traffic management modernization effort and the European Community's counterpart, Single European Sky ATM Research (SESAR) [7,8].

In the European Community (EC), significant research has been conducted to develop a method for achieving an Arrival Manager (AMAN) scheduled sequence at a merge point without the use of heading instructions. In one concept, air traffic controllers use speed and conventional direct-to instructions to achieve the sequence, as well as a predefined path extension prior to the merge point for larger delays, all without automation-aids. Human-in-the-Loop (HITL) experiments showed that this method is feasible in realistic wind conditions, and aircraft stayed on their lateral routing while maintaining the current day throughput level [11,12]. It is also worth noting that recovery from off-nominal events was not more difficult than in the current-day operations when the method was in use [13]. Another effort has been made to improve the existing AMAN to consider trajectories computed to the runway threshold, and then generate appropriate advisories to achieve the arrival sequence and schedule [14,15]. This improvement provided automation-aids for terminal area controllers' planning and decision-making tasks and enabled schedule negotiations between aircraft with an advanced Flight Management System (FMS) and the ground system over data link. HITL experiments with mixed FMS capabilities showed that an increased proportion of aircraft stayed on planned procedures, with an overall reduction in average flight time and distance when the automation-aids were provided [16,17].

In the US, extensive research has been conducted to develop a precision scheduling and spacing system that allows aircraft to maintain optimized descent profiles and follow PBN procedures as they adhere to the system-generated schedule [18,19,20]. This system consists of enhanced Time Based Traffic Management (TBFM) software that considers precise 4-D trajectories computed to the runway threshold when generating the arrival sequence and schedule, and a set of automation-aids to support the terminal area controllers in sequencing, spacing, merging aircraft and meeting the schedule [21,22]. In 2013, NASA, the FAA, and MITRE's Center for Advanced Aviation System Development (CAASD) demonstrated this system's ability to enable the consistent use of PBN arrival procedures in concert with a high-throughput schedule, with multiple types of procedures and aircraft

NASA's Airspace Systems Program

navigational capabilities [23,24]. Analyses of the data from these experiments indicated that interruptions to PBN procedures occurred more often when the schedule was executed less precisely [34].

As the development of scheduled PBN arrival operations progressed, impacts of off-nominal events on the operations and the means to mitigate adverse effects from these events have been investigated. References [25,26,27] describe mathematical models of off-nominal events in high-altitude airspace near the terminal area, and the use of fast-time simulations to study recovery strategies. Recovery from off-nominal events in the terminal area has been studied with HITL experiments where manual schedule adjustments made by a Traffic Management Coordinator (TMC), and alternative RNAV route assignments were available to the controllers to help return to nominal operation. These studies found that the time and effort required to recover from an off-nominal event depends significantly on the circumstance [28,29]. The role of the TMC in busy arrival operations was investigated in [37,38] and the potential use of automation-aids to expedite recovery was investigated in [30] and [31].

The research presented in this paper is intended to gain insights into the resilience of scheduled PBN arrival operations, where resilience[1] is defined as an ability to return to nominal operations following a schedule perturbation. A framework developed in [9,10] for investigating robustness and resilience with Air Traffic Management (ATM) system performance was adapted for this research. To determine whether a schedule perturbation exists or not, a threshold to declare nominal operations was defined based on schedule nonconformance. This threshold was then used to detect a schedule perturbation and assess resilience. Results from a HITL experiment conducted in 2014 assessed resilience using three off-nominal events to perturb the schedule; 1) a missed-approach, 2) an unscheduled priority arrival due to a medical emergency, and 3) a series of late aircraft due to convective weather.

Modifications were made to NASA's precision scheduling and spacing system for this HITL experiment. First, logic that allows schedule adjustments to impact only one runway was implemented. With this logic, if an off-nominal event only affects arrivals to one of the two runways, a schedule adjustment's impact is limited to the aircraft scheduled to land on that runway. Second, a disturbance rejection algorithm for automatic schedule adjustments was implemented. This algorithm detects future in-trail spacing violations and potential deviations from PBN procedures near the airport. When air traffic controllers do not correct the detected situation for a set period, the algorithm automatically triggers a schedule adjustment to mitigate the situation.

Perturbed schedules were managed in three conditions; 1) automatic schedule adjustments by the algorithm, 2) manual adjustments by the TMC, or 3) no adjustments. The efficacy of the automated schedule adjustments, as compared to the manual schedule adjustments, in coping with the off-nominal events, was examined.

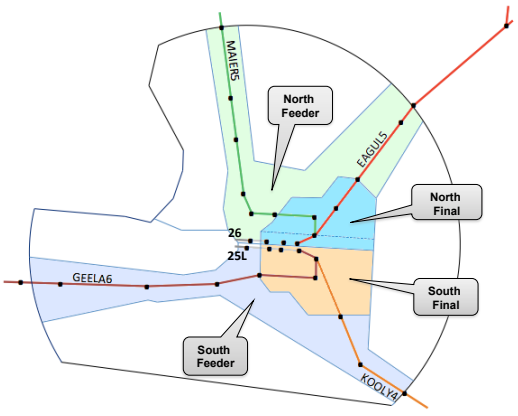

Figure 1. Simulation airspace

[1] Also defined as the ability of the ATM system "to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions" by Rogier Woltjer, et al.

II. Human-in-the-Loop Experiment

A. Airport and Airspace

This experiment focuses on Phoenix Sky Harbor International Airport (PHX) in Phoenix, Arizona, USA and the surrounding Terminal Radar Approach Control (TRACON) airspace (P50). The airport was configured for the West Flow operations, with arrival traffic landing on runways 25L and 26 where independent runway operations were assumed. Confederate pilots flew simulated aircraft under Instrument Flight Rules (IFR). Fig. 1 shows the PHX airspace, the four primary arrival routes, and highlights the Feeder and Final sectors. Runway 26 is located north of runway 25L in the figure.

B. Participants

Three sets of four TRACON air traffic controller positions, two Feeders and two Finals, and one Terminal Area TMC position were staffed during the simulation. The first set of participants took part in training the confederate pilots for simulating off-nominal events and baseline data collection runs, where the simulated traffic did not include off-nominal events. The other two sets of participants worked two different data collection periods, each simulating the same off-nominal events. Within each participant set, the four controllers rotated by one position per simulation run. The Terminal area TMC position remained consistent for all runs in each data collection period.

Half of the participants recently retired from P50 and the rest recently retired from Southern California TRACON (SCT). The participants with SCT experiences were able to learn Phoenix operations with minimal training.

C. Scenarios and Test Conditions

Two scenarios with heavy traffic on different routes were used. One scenario had heavy traffic on the Northeast route, and the other on the Southwest route, emulating the actual morning and the afternoon traffic respectively. The following were the same for both scenarios; 1) peak arrival rate of 91

aircraft per hour, 2) the mixture of aircraft weight classes, (large, heavy and 757), and 3) all aircraft were PBN capable jet arrivals[2].

The simulation examined three off-nominal events: 1) a missed-approach, 2) an unscheduled priority arrival due to a medical emergency, and 3) a series of late aircraft due to convective weather. Each simulation run contained a single off-nominal event, responded to by one of three types of schedule adjustments; 1) automatic schedule adjustments made by an algorithm, 2) manual schedule adjustments made by the TMC, or 3) no adjustments. In all three conditions, the TMC facilitated the arrival operation by communicating with the four terminal controllers.

Forecast and actual wind models were set to zero magnitude in the simulation. Table I depicts the experimental matrix that was used to collect data and the number of runs. This is a 3 x 3 matrix consisting of two independent variables; 1) type of off-nominal event (rows), and 2) type of schedule adjustment (columns). A total of 40 runs were conducted, including four baseline ones without off-nominal events in the first week. Each run was about 70 minutes in length.

TABLE I. EXPERIMENT CONDITIONS

	Automatic schedule adjustments	**Manual schedule adjustments (TMC)**	**No schedule adjustments**
Missed-approach	2 runs, week 2 2 runs, week 3	2 runs, week 2 2 runs, week 3	2 runs, week 2 2 runs, week 3
Unscheduled priority arrival	2 runs, week 2 2 runs, week 3	2 runs, week 2 2 runs, week 3	2 runs, week 2 2 runs, week 3
Series of late aircraft	2 runs, week 2 2 runs, week 3	2 runs, week 2 2 runs, week 3	2 runs, week 2 2 runs, week 3

D. Description of Off-Nominal Events

1) Missed-approach

In the experiment, the pilot initiated a missed-approach after the aircraft was cleared for approach. The pilot informed the tower controller, a confederate position, that the aircraft was executing the missed-approach procedure. The missed-approach procedure specified that the aircraft was to maintain 3000 feet Mean Sea Level (MSL), and continue flying the runway heading. Once the missed-approach aircraft was past the airport, the tower controller handed the aircraft off to the same final approach sector it came from (the missed approach procedure never crossed-over to the other runway). The Final sector then controlled the aircraft until it rejoined the arrival sequence to the original runway and eventually handed off to the tower controller. There were no missed-approach procedures connected to PBN approaches. During the handling of this off-nominal event the controllers often vectored several aircraft to create a gap in the arrival sequence for safe insertion of the missed-approach aircraft.

[2] Turbo-props were introduced only in off-nominal events as an unscheduled priority arrival.

2) Unscheduled priority arrival due to a medical emergency

The off-nominal event of an unscheduled priority arrival entailed a Lifeguard (MEDEVAC) turbo-prop flight, approaching P50 from the North or the South under Visual Flight Rules (VFR). This was the only aircraft in the experiment without PBN capability. Near the P50 boundary, the Lifeguard flight asked for a priority landing due to a medical emergency and the Feeder controller created a gap in the arrival stream to give the lifeguard flight the priority. The controllers typically created this gap by either vectoring or slowing down other aircraft.

3) Series of late aircraft due to convective weather

A series of late aircraft was caused by simulated convective weather activity near the North East corner of P50 for the morning traffic scenario and the South East corner of P50 for the afternoon traffic scenario. Pilots reduced their Indicated Airspeed (IAS) to 230 knots as they descended to enter P50, and informed the Feeder controllers that they could not increase speed due to turbulence. Only a single route was affected by this condition. This lead to several late aircraft in one arrival flow, creating potential merge conflicts with on-time aircraft with the same scheduled runway that were coming from the other routes without convective weather.

E. Schedule Adjustments

When off-nominal events affected arrival operations, scheduled adjustments were performed automatically by a disturbance rejection algorithm or manually by the TMC to expedite the return to nominal operations. The algorithm in the automated condition detects future in-trail spacing violations at the Final Approach Fix (FAF) by monitoring Estimated Times of Arrival (ETAs) to the FAF of aircraft in the Feeder sectors. If a pair of in-trail ETAs is closer than a set value and the Feeder controllers do not correct this situation within a specified period of time, the automation adjusts the arrival schedule. In particular, when a late aircraft that is leading an in-trail ETA pair is causing the conflict, the algorithm adjusts the schedule by moving Scheduled Times of Arrival (STAs) to the FAF into future, making the late aircraft on time and the trailing aircraft early. This enables the Feeder controllers to correct the situation by slowing down the trailing aircraft instead of speeding up the leading aircraft, which is difficult to execute in the terminal airspace.

For the aircraft that are in the Final sectors, the algorithm switches from monitoring in-trail ETA pairs to monitoring the difference between each aircraft's ETAs and STAs to the FAF. The purpose of this monitoring is to detect potential vectoring in the Final sectors. If the difference is larger than a set value and is not corrected for a set period, the algorithm delays aircraft in the Feeder sectors to provide the Final controller with more time and space, thereby mitigating the impact of vectoring. The algorithm does not change an aircraft's scheduled runway when performing schedule adjustments.

In the manual condition, the TMC was provided with Computer-Human-Interface (CHI) tools to adjust the schedule, allowing the TMC to create an arrival slot and to change an aircraft's scheduled runway. The TMC often created a strategy

to handle the off-nominal event, communicated this strategy to the controllers, and performed schedule adjustments using the CHI tools for the affected aircraft after the controllers had started acting on the strategy. For example, the TMC could decide that a Lifeguard aircraft coming from the North could fit behind an identified aircraft, and ask the North Feeder to create a gap in the arrival stream behind the identified aircraft. The TMC could then use the tools to create a slot for the Lifeguard that was not originally considered in the schedule. Once the slot was created, the TMC could adjust the STAs for the Lifeguard and all the following aircraft landing on the same runway. The TMC could also assign the identified aircraft to the other runway, making room to fit the Lifeguard aircraft in its place.

In the third condition, where no schedule adjustments were performed, data were collected to investigate the inherent resilience of scheduled PBN arrival operations, and to test the effectiveness of schedule adjustments in enhancing resilience.

F. Feeder and Final Controller Tools

The different schedule adjustment conditions with off-nominal events were evaluated using the Multi-Aircraft Control System (MACS) HITL simulation capability [35]. MACS was adapted to simulate major arrival elements of P50. To facilitate scheduled PBN arrival operations, several tools were provided. Fig. 2 shows the Feeder tools on the top, and the Final tools on the bottom.

1) Timeline

Displayed on the Feeder controller display only is a list that depicts the schedule and the current progress of aircraft. Each timeline is specific to a schedule point or runway (e.g. PHX26) and displays the STAs on the right and the ETAs on the left, with the current time shown at the bottom.

2) Sequence Number

Determined by the scheduler, the aircraft's sequence to its runway was displayed to the controller in the first line of the data block, to the right of the aircraft identification. A "#" sign was prefixed to the sequence number to prevent confusion with aircraft Indicated Airspeed (IAS). In independent arrival operations, the sequence number is specific to the runway as was the case in the experiment.

3) Slot Marker

A circle of dynamic size, the slot marker is a graphical representation of the scheduled trajectory for a specific aircraft. The slot marker, with a diameter of 15 seconds of flying time, follows the planned lateral path and speed profile. The slot markers were displayed on both Feeder and Final scopes but were shown only up to 250 seconds to the runway ETA. After that the display switched to a de-clutter mode for the Final controllers, showing Automated Terminal Proximity Alert (ATPA) cones (described later) and aircraft IAS.

The slot markers of the aircraft whose STAs were adjusted more than 30 seconds during a schedule adjustment, either by an algorithm or by the TMC, changed their color to magenta, slowly moved to their new positions to indicate the new STAs, and then changed their color back to white. This color change and gradual movement was an indication to the controller that STAs of some aircraft had been adjusted.

4) Slot Marker Speed

Located next to the slot marker was its current IAS, indicated in three digits to distinguish it from the aircraft's IAS.

5) Aircraft Indicated Airspeed

Located next to the aircraft target symbol was the current automation-derived IAS of the aircraft. This was indicated in two digits.

6) Speed Advisory

Located in the third line of the data block was an automation-calculated airspeed advisory to get the aircraft back on schedule by a downstream schedule point. The controllers were asked to use the speed advisories as guidelines toward achieving the schedule.

7) Early/Late Indicator

If a speed advisory could not be generated within the allowed speed change range (typically 15% of the profile speed) to get the aircraft to the next schedule point on time, the amount of time that the aircraft was early or late was displayed in the third line of the data block. An "E" indicated the aircraft was early, and an "L" indicated the aircraft was late. For example, if an aircraft was late by 1 minute 10 seconds, "L 1:10" was displayed (not shown in Fig.2).

8) ATPA Cones

Displayed on the Final controller display only are ATPA cones. As soon as aircraft are within 250 seconds of the runway ETA, a cone is displayed with length equal to the minimum

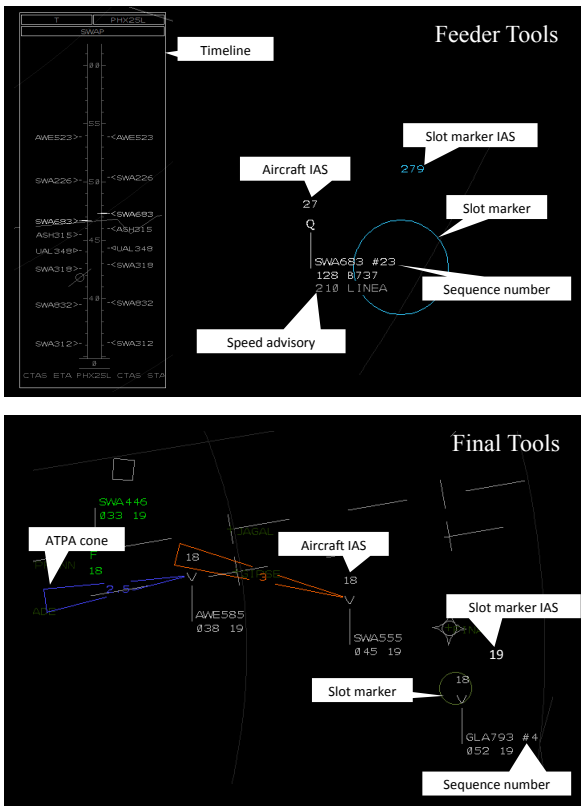

Figure 2. Controller tools

wake turbulence separation taking into account the size of the aircraft physically ahead of that aircraft.

A blue cone depicts no Loss of Separation (LOS) is predicted within 45 seconds, a yellow cone depicts 45 seconds to LOS, and an orange cone depicts 22 seconds to LOS. In the final approach of flight, relative spacing and sequencing come into effect and the cones help with those functions. ATPA cones are currently used in operations in the US, including at SCT.

III. Analysis Methods

A. Defining Nominal Operation

To determine whether a schedule perturbation exists or not, nominal operations are first defined. An earlier work [34] indicated that an increase in schedule nonconformance is related to a decrease in operational performance. This relationship is used for the definition of nominal operations.

1) Quantifying Schedule Nonconformance

The schedule nonconformance of an arrival aircraft, *nc,* is based on the aircraft's schedule conformance error, *e,* which is the difference between STA and ETA at a schedule point. For this paper, *e* at the FAF is expressed as a function of elapsed flying time *t* from the meter fix to the FAF (1). This metric is adapted from [34]. Fig. 3 shows an example of *e* vs. *t* at the FAF of an arrival aircraft. This figure shows that the aircraft was about 35 seconds early at the meter fix, became late by 10 seconds, then arrived at the FAF about 5 seconds early.

$$e(t) = STA_{FAF} - ETA(t)_{FAF} \tag{1}$$

Compared to the Feeder controllers, the Final controllers have less airspace and assignable speed range to correct for *e*. Therefore, *nc* is designed to emphasize schedule nonconformance near the FAF (2). Furthermore, *nc* is made to a dimensionless quantity with two parameters: 1) *c*, the update period of the ETA, and 2) $\Delta t_{\text{nominal}}$, the nominal transition time from the meter fix to the FAF, which is approximated by the difference in the meter fix STA and the FAF STA (3). To quantify the schedule nonconformance of all arrival aircraft in one run, $NC_{operation}$, the *nc* of all aircraft is summed, then divided by the number of aircraft (4), where *i* is the index of arrivals in the run, and l_{total} is the total number of landed flights.

$$nc = \frac{\int |e(t)| \frac{t}{\Delta t_{\text{nominal}}} dt}{\Delta t_{\text{nominal}} \times c} \tag{2}$$

$$\Delta t_{\text{nominal}} \approx STA_{\text{FAF}} - STA_{\text{meter\_fix}} \tag{3}$$

$$NC_{\text{operation}} = \frac{\sum_{i=1}^{l_{\text{total}}} nc_i}{l_{\text{total}}} \tag{4}$$

2) Quantifying Operational Performance

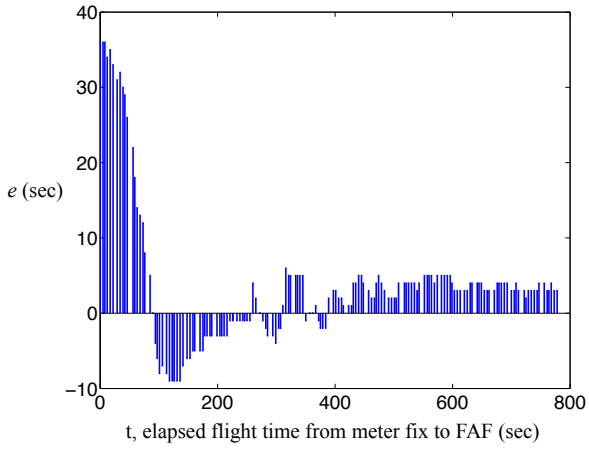

Figure 3. Example of *e(t)*

The performance of scheduled PBN arrival operations is quantified with the following six parameters:

a) Average delay

Delay is calculated by subtracting an aircraft's STA at the runway threshold from its Actual Time of Arrival (ATA). Average delay is then the sum of delay divided by the number of landed aircraft. This is expressed in units of seconds. A larger value indicates a greater loss in the arrival operation's time efficiency.

b) Median terminal area transition time deviation

Scheduled terminal area transition time is an aircraft's STA at the meter fix subtracted from its STA at the runway threshold. Actual transition time is the meter fix ATA subtracted from the runway ATA. Median terminal area transition time deviation is the median of the scheduled transition time subtracted from the actual transition time for all landed aircraft. This is expressed in units of seconds. A larger value indicates a greater fuel inefficiency and increased adverse environmental impact.

c) Proportion of arrivals with extra track distance

Extra track distance is the distance flown by PBN aircraft that laterally deviated from its route's centerline by more than 0.3 NM. The numerator of the 'Proportion of arrivals with extra track distance' metric is the number of flights with more than 1 NM of extra track distance. The denominator is the number of landed aircraft. In an ideal operation, this proportion is zero. When this proportion is larger than zero, it indicates a loss in the arrival operation's lateral route efficiency.

d) Average extra track distance

Averaging extra track distance is performed among the flights with more than 1 NM of extra track distance. This is expressed in units of NMs. A larger value indicates a greater loss in the arrival operation's lateral route efficiency.

e) Controller transmissions per landed aircraft

A modified version of an open-source audio processing program, Sound Exchange, is used to process voice recordings from the experiment to count controller transmissions. The number of transmissions from the four controllers are

summed, and divided by the number of landed aircraft. This is expressed in units of transmissions per aircraft. Based on the relationships between workload and voice communication found in [32] and [33], a larger value indicates higher objective controller workload.

f) Average NASA Task Load Index (TLX)

TLX values reported by the participant controllers at the end of each experiment run are averaged to estimate subjective workload. A larger value indicates a greater subjective workload. TLX values were weighted as done in [36] with participant ratings from a pre-experimental TLX questionnaire.

Correlations between the schedule nonconformance, $NC_{operation}$, and the six operational performance parameters are shown in Fig. 4. In this figure, circles represent data, and lines represent a first order least square fit. The unfilled circles represent the 12 runs with off-nominal events under the no schedule adjustments condition. The filled circles indicate the four baseline runs without off-nominal events.

Fig. 4 shows that an increase in schedule nonconformance is strongly related to increases in 'Average delay', 'Controller transmission per aircraft', 'Median transition time deviation', and 'Proportion of aircraft with extra track'. That is, the magnitude of schedule nonconformance is strongly related to the amount of time inefficiency, objective controller workload, fuel inefficiency, and lateral route inefficiency of scheduled PBN arrival operations. Also, compared to the 12 runs with off-nominal events, the four baseline runs have much lower schedule nonconformance and better operational performance. Therefore, the 97.5th percentile of all *nc* from the four baseline runs, 8.01, was selected as a threshold value to declare nominal operations.

B. Quantifying Resilience

To quantify the resilience of scheduled PBN arrival operations, schedule nonconformance is calculated during the operation using $NC(t_e)$ (5), where t_e is an elapsed time from the beginning of the operation, a_{te} is the number of aircraft between the meter fix and the FAF at t_e, i is the index of all aircraft, and $nc_i(t_e)$ is the schedule nonconformance of aircraft i at t_e. Furthermore, prior to calculating $NC(t_e)$, aircraft are grouped for each scheduled runway. That is, at t_e, $NC(t_e)$ for runways 25L and 26 are calculated separately. Once the calculations are performed over the entire run, a moving average, with a 60-second averaging period, is applied to smoothen any abrupt changes in $NC(t_e)$ over time. These changes are due to aircraft entering and exiting the airspace between the meter fix and the FAF over time.

$$NC(t_e) = \frac{\sum_{i=1}^{a_{te}} nc_i(t_e)}{a_{te}} \quad (5)$$

A perturbed schedule is detected when the moving-averaged $NC(t_e)$ becomes larger than the previously defined nominal operations threshold of 8.01, and remains so for more than 120 seconds. Recovery from the perturbed schedule is achieved once $NC(t_e)$ becomes the same or less than this threshold.

Fig. 5 presents examples of simulation runs with an unperturbed schedule (top), a perturbed schedule (middle), and a recovery of a perturbed schedule (bottom). A missed

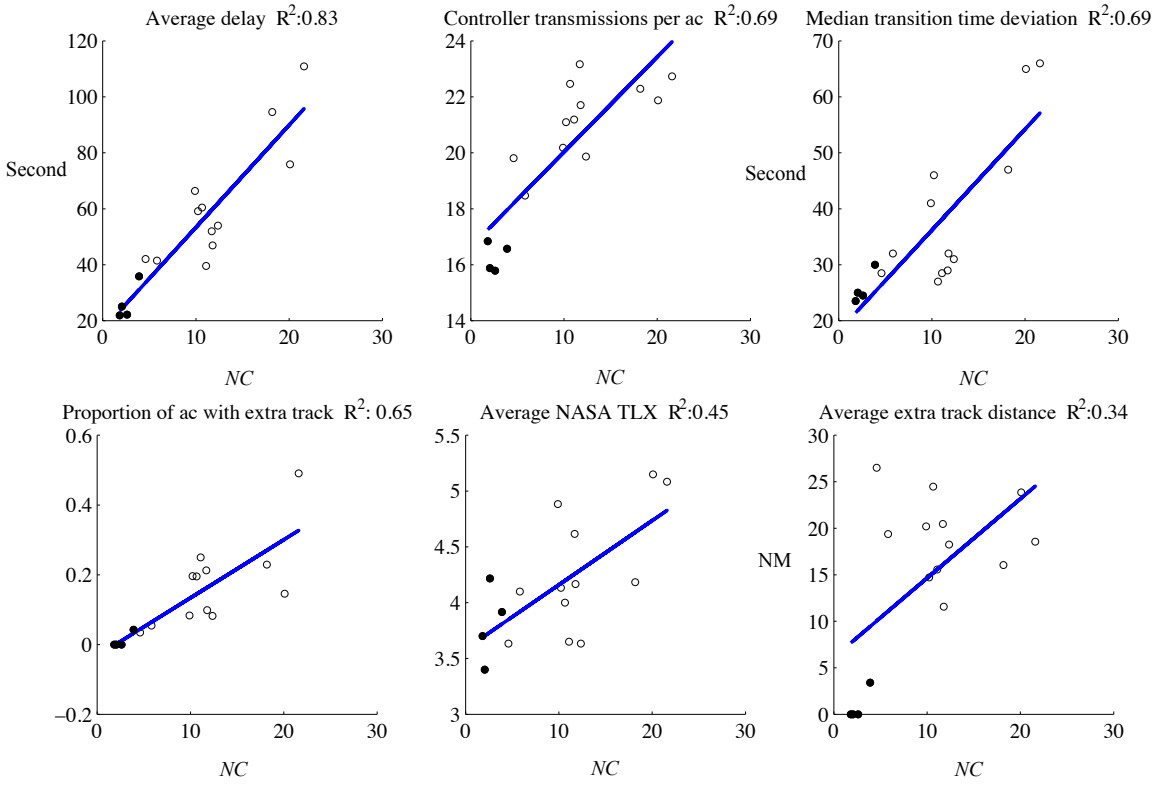

Figure 4. Relation between Schedule Nonconformance and Operational Performance

approach occurred in these examples, and no schedule adjustments were made. In each figure, the dashed horizontal line is the nominal operations threshold, black dots represent $NC(t_e)$ values, and solid lines represent the moving-averaged $NC(t_e)$ values.

Resilience of a single run is quantified in terms of proportion of the number of recoveries to the number of schedule perturbations, the perturbations' duration in seconds, and the perturbation's maximum $NC(t_e)$ value for recovered schedules.

IV. Results

A. Comparing Resilience

The resilience of the different schedule adjustment conditions, 1) None, 2) Automatic, and 3) Manual (TMC), is presented in Table II and Fig. 6. Each condition saw 12 runs with the same off-nominal events. For each box plot in Fig. 6, the bottom of the box is the 25th percentile, the centerline is the median, and the top of the box is the 75th percentile. Each pair of whiskers contain most of the data (99 percent, if normally distributed), and outliers are shown in "+".

TABLE II. RESILIENCE of OPERATIONS

	No schedule adjustments	**Automatic schedule adjustments**	**Manual schedule adjustments**
Number of schedule perturbations	21	26	13
Number of recoveries	13	23	10
Ratio of recoveries to schedule perturbations	0.62	0.88	0.77
Median perturbation duration	792 seconds	324 seconds	388 seconds
Median peak *NC* in recovered schedule	19.6	15.2	16.9

Results showed that the simulation's scheduled PBN operations have inherent resilience, recovering from 62% of perturbed schedules with no schedule adjustments. While some perturbed schedules near the end of experiment runs could have been recovered if the runs were longer, these potential recoveries were not counted.

Fig. 6 shows that compared to no schedule adjustments, both automatic and manual schedule adjustments decreased the median perturbation duration, and decreased the median peak *NC* value in recovered schedules under the same off-nominal events. These results indicate that with schedule adjustments, perturbed schedules recover quicker, more often, and with less severe perturbations, effectively enhancing the resilience of scheduled PBN operations in the presence of off-nominal events.

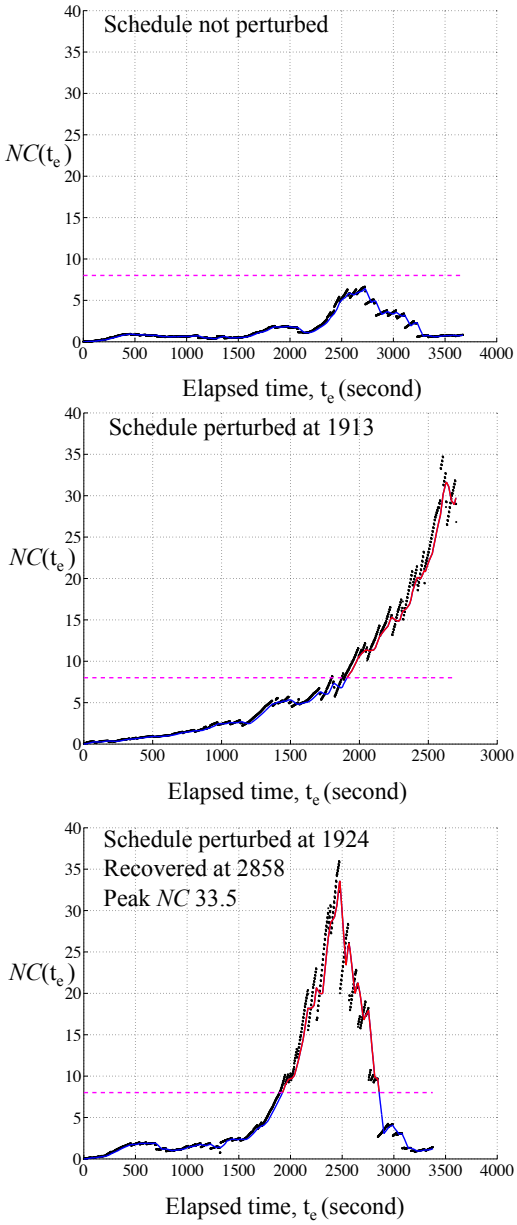

Figure 5. Examples of Unperturbed schedule, Perturbed Schedule, and Recovery

B. Comparing Automatic and Manual Schedule Adjustments

When compared to the automatic schedule adjustments condition, Table II shows that the number of detected schedule perturbations decreased for the same off-nominal events in the manual condition, from 26 to 13. Figure 7 shows that more schedule adjustments occurred, affecting more aircraft and triggering more display changes on the controller's scope (i.e. slot marker color change and movement) in the automatic condition. However, Table II also shows that perturbed schedules were recovered more frequently and perturbations were less severe in the automatic condition than in the manual condition, with recovery ratios of 0.88 vs. 0.77, and peak *NC* values of 15.2 vs. 16.9, respectively. Additionally, the mean

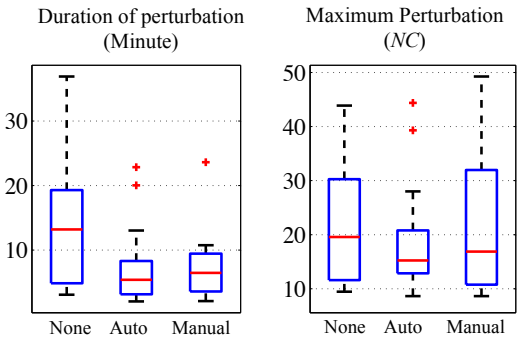

Figure 6. Schedule perturbations with different types of schedule adjustments

and the standard deviation of the magnitude of schedule adjustments were 20.3 ± 49 seconds in the automatic condition, and 16.6 ± 93.2 in the manual condition. That is, while the mean magnitude of schedule adjustments in the manual condition was smaller than in the automatic condition, the variation of the magnitude was much greater in the manual condition. These results indicate that the manual schedule adjustments performed by the TMC can increase the robustness of an operation by preventing schedule perturbations from occurring, and that the algorithm used in the automatic condition can reduce the severity of perturbations using schedule adjustments with smaller variation in magnitude.

C. *Subjective Data*

During each simulation run, participants were prompted at five-minute intervals to report workload on an integer scale from one to six, one indicating the least workload and six the most. Workload was reported by pressing a numeric value on the controller's keyboard or clicking on the scale that was displayed at the top of the controller's radarscope. Additional subjective workload measures were collected at the end of each operation using a survey that included the TLX rating scale. TLX responses were weighted with participant ratings from a pre-experimental TLX questionnaire.

Analysis of the subjective data showed that magnitude of the peak workload reported during a run by each terminal controller participant correlated with the magnitude of the participant's weighted TLX score for the run, $r(204) = .668$, $p < .001$. Subjective workload was also compared for the baseline and three schedule adjustment conditions by performing a one-way analysis of variance (ANOVA) on the weighted TLX scores. The ANOVA showed a marginally significant difference between the conditions, $F(3, 206) = 2.457$, $p = 0.064$. A Tukey post-hoc test, performed to compare means for individual conditions, revealed that marginally significant differences exist between the baseline runs without off-nominal events and runs with off-nominal events in two conditions: no schedule adjustments condition ($p = .056$) and manual schedule adjustments condition ($p = .082$). There was no difference in subjective workload between baseline runs and runs with off-nominal events in automatic schedule adjustments condition ($p > .1$). Subjective workload measure from the automatic and the manual schedule adjustments conditions were not different from the no schedule adjustments condition ($p > .1$). This finding was also supported by the same trend in 'Controller transmissions per aircraft', an objective workload measure. Table III shows both subjective and objective workload data.

TABLE III. SUBJECTIVE and OBJECTIVE WORKLOAD

	TLX score		Controller transmissions per aircraft	
	Mean	**Standard deviation**	**Mean**	**Standard deviation**
Baseline (no off-nominal events)	3.5	1.6	16.3	0.5
No schedule adjustments	4.2	1.1	21.2	1.4
Automatic schedule adjustments	4.0	1.2	20.9	1.9
Manual schedule adjustments	4.1	1.2	22.0	4.0

In the survey, participants reported that the TMC was quicker to adjust the schedule to mitigate off-nominal events than the automation, but that the automation provided more consistency in how schedules were adjusted. Also, in the automatic schedule adjustments condition, the TMC informed the terminal controller participants to ignore a schedule adjustment triggered by the automation when it did not make sense. This helped the controllers to determine whether to use or discard automation-aids that were affected by the schedule adjustment. These findings and the comparison results between the automation and the TMC suggests that future research should investigate the efficacy of an interactive schedule adjustment method where the TMC accepts, rejects, or adjusts automation-suggested schedule adjustments in enhancing resilience.

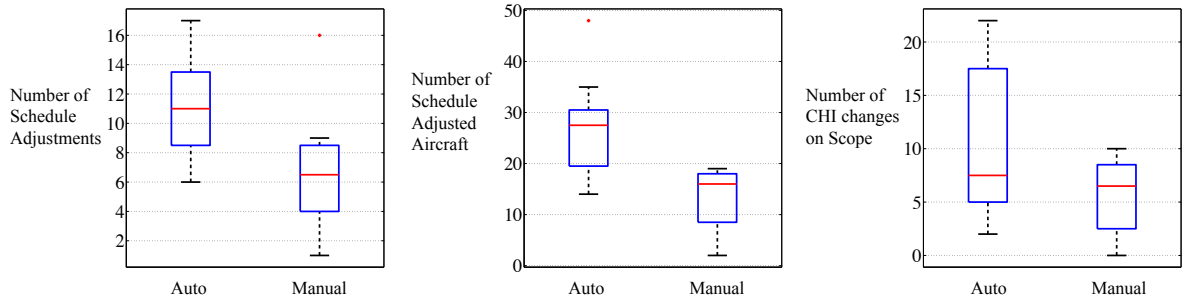

Figure 7. Automatic and Manual (TMC) schedule adjustments

D. Operational Error

The simulation gathered LOS data for each run. Data from the ATPA cones were used, then visually verified. For example, if the ATPA data indicated a LOS, the lead aircraft type was verified visually with video recordings of the controller scopes. In the airspace where ATPA cones were not shown, software was used to detect LOS events, using 3 NM or 1000 ft as the minimum separation. Any such results were then visually verified.

The number of LOS events increased in arrival operations with off-nominal events compared to the operations with no off-nominal events. The number of LOS events in the automated and the manual schedule adjustments conditions were similar to the no schedule adjustments condition.

A Pearson correlation coefficient was calculated to determine the relationship between the total number of LOS events and the subjective ratings of route conformance from the final controller positions for each run. A rating of one indicated that all aircraft were perceived to be on route, and a seven rating indicated no aircraft were perceived to be on route. There was a positive correlation between the two variables: $r(39) = .351$, $p = .024$. This correlation affirms that predictable, lateral movement of aircraft is an important attribute of maintaining separation in scheduled PBN operations.

V. Conclusion

This paper assesses the resilience of scheduled PBN arrival operations. Resilience is defined as the ability to return to nominal operations following a schedule perturbation. Results from a HITL experiment assessed resilience using three off-nominal events to perturb the schedule: 1) a missed-approach, 2) an unscheduled priority arrival due to a medical emergency, and 3) a series of late aircraft due to convective weather. Perturbed schedules were managed in three conditions where: 1) automatic schedule adjustments were made by an algorithm, 2) manual schedule adjustments were made by the TMC, or 3) no schedule adjustments were made.

Analyses showed that the simulated scheduled PBN operations have inherent resilience, recovering from more than half of the perturbed schedules, even with no schedule adjustments. The resilience of the operations can be further enhanced with schedule adjustments; for the same off-nominal events, an increased proportion of perturbed schedules recovered and the average duration of the schedule's perturbed state decreased with both automatic and manual schedule adjustments.

The HITL experiment also explored the efficacy of schedule adjustments made in response to the off-nominal events, whether by the automation or the TMC. When compared to the automated schedule adjustments condition, the number of schedule perturbations decreased for the same off-nominal events in the manual condition. However, perturbed schedules were recovered from more frequently and perturbations were less severe in the automated condition. This indicates that the manual schedule adjustments performed by the TMC can increase the robustness of the operation by preventing schedule perturbations from occurring, and that the algorithm used can reduce the severity of the perturbations. Participants found that the TMC was quicker to adjust the schedule to mitigate off-nominal events than the automation, while the automation provided more consistency in how schedules were adjusted. These objective and subjective findings indicate that interactive schedule adjustments where the TMC works with suggestions from automation could be effective in further enhancing resilience.

While effective in enhancing resilience, schedule adjustments did not increase subjective or objective workload. LOS data was examined and a positive relationship between the total number of LOS events and the subjective ratings of route conformance for the final controller positions was found. This indicates that predictable aircraft paths are an important attribute of maintaining separation in scheduled PBN operations.

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