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Human factors assessment of disturbances to scheduled performance-based navigation arrival operations

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Abstract

The introduction of Performance-Based Navigation (PBN) specifications to air traffic management has resulted in many benefits during nominal operations, including shorter flight paths, reduced fuel costs, and improved terminal area arrival rates. However, these benefits become less noticeable during off-nominal operations where aircraft are routinely interrupted from staying on PBN procedures due to disturbances such as missed approaches. This human-in-the-loop (HITL) study used multiple types of disturbance events to perturb the arrival schedule. Perturbed schedules were managed with different types of schedule adjustments, including a condition with no adjustments. The study collected data on a host of dependent variables, including human factors measures on controller workload and system performance measures such as schedule nonconformance (*nc*). Initial analyses showed strong correlations between aggregated controller workload and aggregated *nc*, as well as benefits of both automatic and manual schedule adjustments for increasing system performance, such as reduced PBN procedure interruptions. The goal of this paper is to further test these initial findings. The results indicated that an increase in schedule nonconformance correlated with an increase in controller workload at specific time intervals, and automated schedule adjustments consistently reduced controller workload associated with nonconformance.

Keywords: workload; scheduled arrival operations; Performance-Based Navigation;

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1. Introduction

Performance-Based Navigation (PBN) has introduced two types of navigation specifications, Area Navigation (RNAV) and Required Navigation Performance (RNP) [1]. Benefits of PBN include shorter, more direct flight paths, fuel savings, a reduction in adverse environmental impact, and improved terminal area arrival rate [2,3]. However, these benefits become less pronounced when aircraft are routinely interrupted from staying on the PBN procedures by following 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 [4].

Extensive research has been conducted to facilitate uninterrupted PBN arrival procedures. A precision scheduling and spacing system has been developed that generates an arrival schedule and provides a set of automation-aids to support the terminal area controllers in sequencing, spacing, merging aircraft and meeting the schedule [5,6]. 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 together with a high-throughput schedule, with multiple types of approaches and aircraft navigational capabilities [7,8]. Data from this demonstration indicated that interruptions to PBN procedures occurred more often when the Scheduled Times of Arrival (STAs) were not met by the arrival aircraft precisely [9].

As the research and development of scheduled PBN arrival operations progressed, impacts of disturbance events on the operations and the means to mitigate adverse effects from these events have been investigated. Recovery from disturbance events in the terminal area were studied with human-in-the-loop (HITL) experiments where manual schedule adjustments by a Traffic Management Coordinator (TMC), and alternative RNAV route assignments were available to the controllers to help return to nominal operation [10,11]. The role of the TMC in busy arrival operations was investigated in [12,13] and the potential use of automation-aids to expedite recovery was investigated in [14,15].

Research in [16] used multiple types of disturbance events to perturb the arrival schedule, where Estimated Times of Arrival (ETAs) were forcefully deviated from STAs due to the disturbances. Perturbed schedules were managed with different types of STA adjustments (schedule adjustments), including cases with no adjustments. A strong correlation between aggregated controller workload and aggregated schedule nonconformance (*nc*) was found. Results from [16] also showed benefits in using various types of schedule adjustments during PBN arrival operations for increasing system performance, such as reduced PBN procedure interruptions. Findings presented in this paper are intended to gain insights into the effects of scheduled PBN arrival operations on controller workload during disturbed operations, beyond the findings in [16]. Perturbations in the schedule were compared with subjective workload at specific moments in time to analyze the impact of disturbance events on workload and assess system recovery based on type of schedule adjustment.

2. Method

2.1. Participants

Three sets of four Terminal Radar Approach Control (TRACON) air traffic controller positions (two Feeders and two Finals) and one Terminal Area TMC position were staffed during the simulation; one set per week for three weeks. During Week 1, participants took part in training the confederate pilots for simulating disturbance events and collecting data for baseline runs without disturbance events. Participants in Weeks 2 and 3 worked identical schedules of scenarios counterbalanced for schedule adjustment type and disturbance event. All TRACON controllers rotated one position per run, while the TMC remained at the designated TMC station.

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

2.2. Scenarios and test conditions

Scenarios were developed and the simulation was conducted on the Multi-Aircraft Control System (MACS) HITL simulation capability [17]. The scenarios were set at the Phoenix Sky Harbor International Airport (PHX) in Phoenix, Arizona. The airspace included the surrounding TRACON airspace (P50). The airport was configured for West Flow operations, with arrival traffic landing on runways 25L and 26, assuming independent runway operations. Figure 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.

Two heavy traffic scenarios were used for this study. One scenario simulated PHX morning traffic, with dense traffic on the Northeast route, and the other scenario represented PHX afternoon traffic, with dense traffic on the Southwest route. Both scenarios had a peak arrival rate of 91 aircraft per hour, an identical mixture of aircraft weight classes (large, heavy and 757), and all aircraft were flown under Instrument Flight Rules (IFR) and were PBN capable jet arrivals. Wind and weather conditions were not simulated.

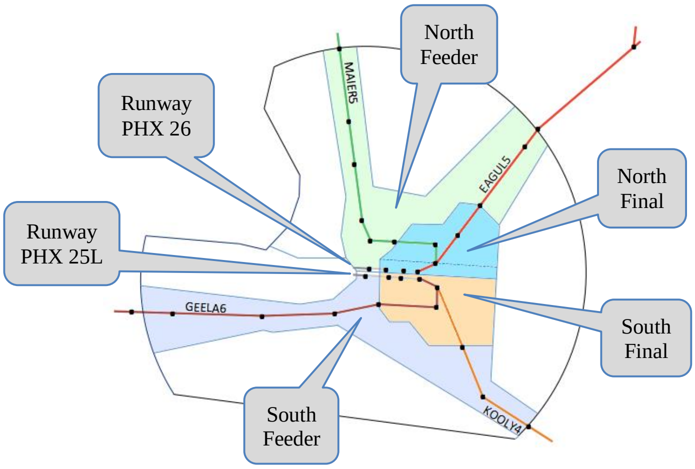

Fig. 1. Simulation airspace

A 3 (disturbance type) x 3 (type of schedule adjustment) test matrix was used for the study. Each simulation run included one of three planned disturbance events that always occurred on the (North or South) side with the heaviest traffic flow. These were: 1) a missed-approach, 2) an unscheduled priority arrival due to a medical emergency, and 3) a series of late arrivals due to convective weather. One of three types of schedule adjustments were used to respond to these events: 1) automatic schedule adjustments made by a schedule adjustment algorithm, 2) manual schedule adjustments made by the TMC, or 3) no adjustments. In all three schedule adjustment conditions, the TMC facilitated the arrival operation by communicating with the four terminal controllers. Nine unique combinations of disturbance type and type of schedule adjustment were used for runs. Each of these nine combinations was used twice in Week 2 and twice again in Week 3. A total of 40 runs were conducted, including four baseline ones without disturbance events in the first week. Each run was about 70 minutes in length.

2.3. Description of disturbance events

In the experiment, controllers could experience one of three disturbance events: 1) a missed-approach, 2) an unscheduled priority arrival, or 3) a series of late arrivals. During the missed-approach event, the pilot informed the Final controller of a missed-approach after the aircraft was cleared for approach and before being transferred to the tower controller, a confederate position. The missed approach segments did not have PBN specifications. During the handling of this disturbance event the controllers often vectored several aircraft to create a gap in the arrival sequence to safely insert the missed-approach aircraft.

The disturbance 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) and declaring medical emergency. This was the only aircraft in the experiment without PBN capability. The controllers typically created a gap in the arrival stream to give the lifeguard flight the priority by either vectoring or slowing down other aircraft.

During the series of late arrivals event, pilots reduced their Indicated Air Speed (IAS) to 230 knots as they descended to enter P50, and informed the Feeder controllers that they could not increase speed due to simulated turbulence. Only a single route per scenario was affected by this condition. This led to a series of late aircraft in one arrival flow, creating potential merge conflicts with on-time arrivals with the same scheduled runway that were coming from the other routes without convective weather.

2.4. Schedule adjustments

Arrival schedules were perturbed as controllers vectored and slowed aircraft in response to disturbance events. This forced the deviation of ETAs from STAs. Three schedule adjustment conditions were used to alter STAs in response to disturbance events affecting arrival operations. These were: (1) scheduled adjustments performed automatically by a schedule adjustment algorithm, (2) schedule adjustments performed manually by the TMC to expedite the return to nominal operations, and (3) no schedule adjustments to the disturbance events. The algorithm in the automated condition detects future in-trail spacing violations at the Final Approach Fix (FAF), or detects potential vectoring in the Final sectors. If the detected issue is not corrected within a set time period, the algorithm triggers schedule adjustments. The algorithm does not change an aircraft's scheduled runway when performing schedule adjustments. Additionally, the algorithm uses logic that allows schedule adjustments to impact only one runway. With this logic, if a disturbance 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. Details of this algorithm are published elsewhere [16].

In the manual condition, the TMC was provided with Traffic Management Advisor (TMA) 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 disturbance event, communicated this strategy to the controllers, and performed schedule adjustments using the computer-human interaction (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.

2.5. Quantifying schedule nonconformance

The schedule nonconformance, *nc*, of an arrival aircraft is based on the aircraft's schedule conformance error, which is the difference between STA and ETA at a schedule point (the FAF in this study). Compared to the Feeder controllers, the Final controllers have less airspace and assignable speed range to correct for schedule-conformance error. Therefore, *nc* is designed to emphasize schedule nonconformance near the FAF. *nc* also considers the update period of the ETA and the nominal transition time from the meter fix to each point along the flight path en-route to the FAF. Details of the characteristics of *nc* and equation for its calculation are published elsewhere [9,16].

Nominal operations were defined in [16] as any value within the 97.5th percentile of all *nc* from the four baseline runs (*nc* = 8.01). A perturbation in the schedule was then defined as when *nc* during operations exceeded the 8.01 threshold and remained above this threshold for longer than 120 seconds. When *nc* drops back to or below the threshold, recovery from the schedule perturbation has been achieved.

2.6. Quantifying operation stress

To analyze the impact of disturbance events on workload and assess system recovery based on type of schedule adjustment, perturbations in the schedule were compared with subjective workload at specific moments in time. Figures 2, 3, and 4 show a visual comparison between (a) schedule nonconformance and (b) controller workload for Runway 26 during the same runs, containing late arrival disturbance events. Controller subjective workload was collected once every 5 minutes during each simulation run on a scale from 1 to 6, (low to high) using the workload assessment keypad, and was examined for periods of operation stress by the type of schedule adjustment performed.

The highest mean workload rating during all nominal runs at all controller positions was 2.81 (*SD* = .75). Workload ratings that exceeded a score of 3 were coded as operation stress and ratings of 3 or less were classified as not stressed or recovered. For each position and each run, workload scores were examined chronologically, with a stress score being added to the stressed workload frequency; all consecutive stressed scores were considered part of the same stressed period (e.g. Figure 2b, Feeder). A stressed period continued until the workload rating dropped below 4, then it was added to the frequency of recovery instances. In some cases, recovery was never achieved (e.g. Figure 3b, Final). Multiple periods of stressed workload and recovery were possible per run (e.g. Figure 4b, Final).

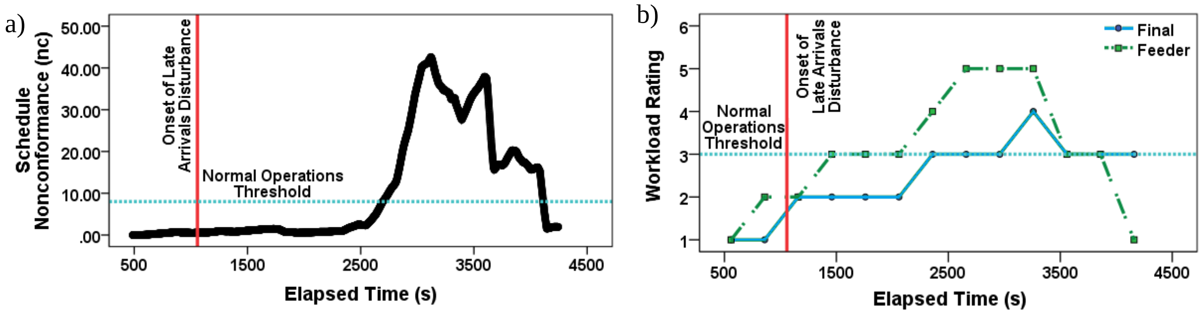

Fig. 2. (a) and (b) Schedule nonconformance and workload: Manual schedule adjustment (Runway 26)

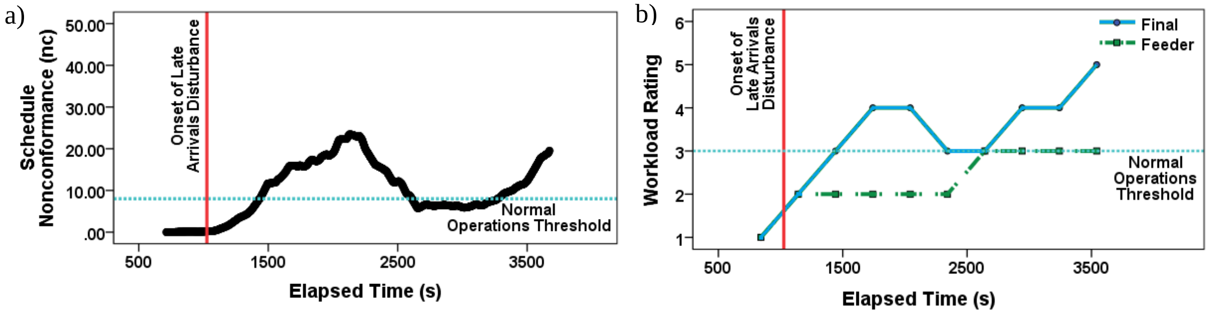

Fig. 3. (a) and (b) Schedule nonconformance and workload: No schedule adjustment (Runway 26)

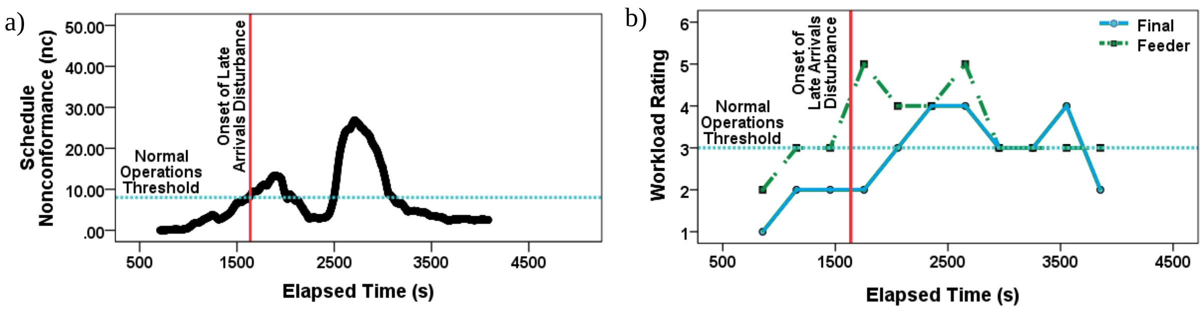

Fig. 4. (a) and (b) Schedule nonconformance and workload: Automatic schedule adjustment (Runway 26)

3. Results

3.1. Workload and schedule nonconformance

Correlation analyses were conducted on workload scores and schedule nonconformance. First, workload scores from all four controller positions were paired with the *nc* measure for their respective runways for the time at which the workload data were collected during the simulation (e.g., GEELA Feeder and Final workload scores at 540s into a scenario were paired with runway 25L *nc* scores at 540s into the same scenario). Raw data for *nc* were found to have a skew of 2.198 for aircraft arriving on PHX 26 and a skew of 3.700 for aircraft arriving on PHX 25L, thus a base 10 log transformation was used on the *nc* data to normalize the data prior to calculating the correlation (Figure 5). Correlation analyses revealed a strong, significant positive correlation between *nc* and controller workload for the runway 26 Final position (see Figure 5), $r = .594$, $n = 367$, $p < .001$. Moderate, significant positive correlations were found between *nc* and controller workload for the runway 26 Feeder ($r = .433$, $n = 377$, $p < .001$), runway 25L Final ($r = .375$, $n = 374$, $p < .001$), and runway 25L Feeder positions ($r = .328$, $n = 375$, $p < .001$). As schedule nonconformance increased, workload increased for all TRACON positions.

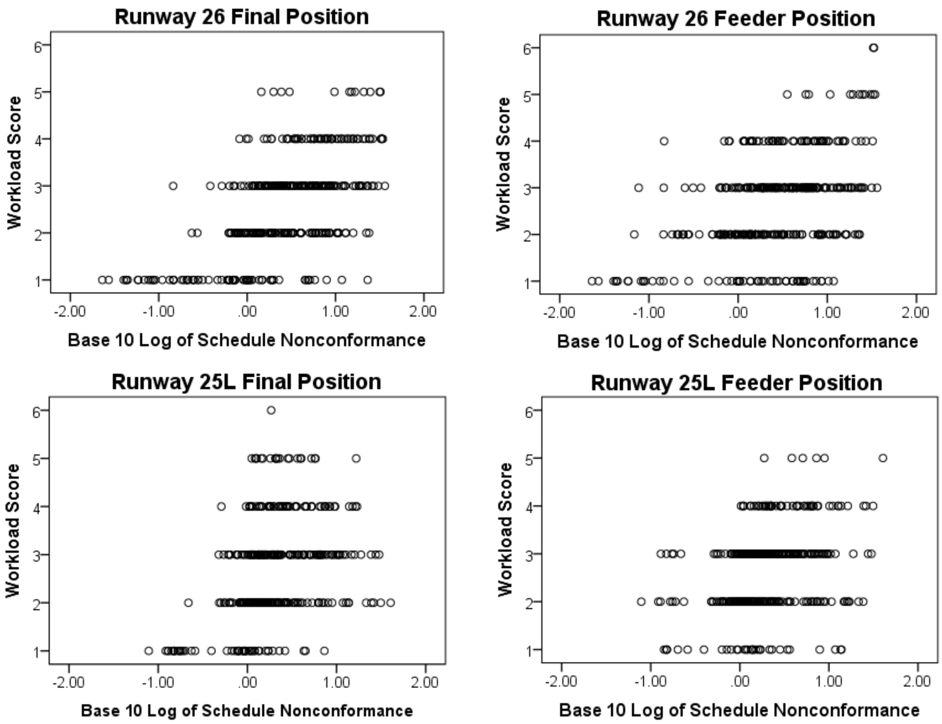

Fig. 5. Scatterplots of base 10 log of schedule nonconformance by controller workload for all TRACON positions across all conditions.

Additional results provide further evidence suggesting a clear relationship between schedule nonconformance and controller workload. Here, the raw *nc* data for each runway used in the previous analysis was coded as stressed, or schedule perturbation, defined elsewhere [16], with a *nc* value greater than 8.01) or recovered (not stressed; *nc* value of 8.01 or less). A one-way between subjects analysis of variance (ANOVA) revealed a significant difference in the runway 26 Final controller workload such that moments of perturbed schedule nonconformance ($M = 3.34$, $SD = .96$) resulted in higher workload than moments of no stress or recovery ($M = 2.36$, $SD = 1.01$), $F(1,365) = 58.019$, $p < .001$. Runway 26 Feeder controller workload was also significantly higher for stressed conditions ($M = 3.17$, $SD = 1.17$) than for recovery conditions ($M = 2.48$, $SD = .96$), $F(1,375) = 28.997$, $p < .001$. The ANOVA also showed a marginally significant difference in runway 25L Final controller workload for nonconformance conditions, with workload during schedule perturbation ($M = 2.97$, $SD = .81$) being higher than workload during non-stressed conditions ($M = 2.63$, $SD = 1.11$), $F(1,372) = 3.196$, $p = .075$. Runway 25L Feeder controller workload was found to be marginally higher for stressed conditions ($M = 2.89$, $SD = 1.06$) than non-stressed conditions ($M = 2.62$, $SD = .86$), $F(1,373) = 3.044$, $p = .082$.

3.2. Operation stress

Frequencies of workload stress and workload recovery instances were determined. Then, the ratio of the number of onsets of workload recovery to the number of onsets of stressed workload was calculated (Table 1). While Final controllers had the highest percentage of recovery (69.6%) from stressed workload under the no schedule adjustments condition, the frequencies of stressed workload instances were also the highest. The Feeder controllers had the highest percentage of recovery (72.2%) from stressed workload under the manual schedule adjustments condition. All controllers appeared to benefit equally under the automatic schedule adjustments condition (both Final and Feeder Positions recovered from stressed workload 65% of the time).

Table 1. Operation Stress.

	No Schedule Adjustments		Automatic Schedule Adjustments		Manual Schedule Adjustments	
	Final	Feeder	Final	Feeder	Final	Feeder
Frequency of Stressed Workload	23	10	17	20	20	18
Frequency of Workload Recoveries	16	4	11	13	11	13
Ratio of Workload Recoveries	.696	.400	.647	.650	.550	.722

4. Discussion

Workload and schedule nonconformance results show that as schedule nonconformance increases, controller workload for all positions increases. As seen in the ANOVAs, overall, controller workload becomes much higher once schedule nonconformance exceeds the threshold for normal operations. One possible effect of these results is seen with the controller interaction with the given automation aids. The participants reported that these aids, such as slot markers, are useful in reducing controller workload in nominal condition. When schedule nonconformance gets too large, these aids no longer provide useful information as they are based on STAs and aircraft are flying with ETAs that are much different from the STAs. In such situation, workload is no longer mitigated by the aids. Usefulness of these aids, including workload reduction, returns when schedule nonconformance is reduced back to the nominal range.

Operation stress and recovery differences were observed across controller positions. Without schedule adjustments, the Feeder controllers appeared to have difficulty recovering from stressed situations while they recovered at a greater rate with both manual and automatic schedule adjustments. Final controllers also appeared to benefit from automatic and manual schedule adjustments, as reflected in the lower frequencies of stress instances and the relatively high recovery rates. Frequency of stressed workload instances decreased with both manual and automation schedule adjustments in the Final positions, suggesting that some schedule adjustment ability is useful in unburdening the Final controller.

With manual adjustment, the TMC is more proactive in addressing disturbance events as they occur. They are able to plan with controllers and make schedule adjustments before the disturbance perturbs the schedule, which may result in the large percentage of recovery from stressed workload seen for Feeders in manual schedule adjustment. However, manual schedule adjustments could be planned and executed differently in similar situations since decisions are based on the individual TMC making the adjustments. In comparison, automation detects issues after schedule is perturbed, then triggers schedule updates if the detected issue is not resolved within a set period. The automation is designed to make similar schedule adjustments for similar situations. Automatic schedule adjustments seem to be more consistently capable of reducing controller workload than manual schedule adjustments when comparing the ratio of workload recoveries in Final and Feeder positions.

This study demonstrates the importance of minimizing schedule perturbations and providing aids to the controllers during schedule updates from a human factors perspective. The results in this paper offer more support to the findings published elsewhere [16] suggesting that during disturbance events, offering some means of schedule adjustment is beneficial to the overall performance and resilience of scheduled PBN operations.

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