

NEXTGEN OPERATIONS IN A SIMULATED NY AREA AIRSPACE

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Abstract

A human-in-the-loop simulation conducted in the Airspace Operations Laboratory (AOL) at NASA Ames Research Center explored the feasibility of a Next Generation Air Transportation System (NextGen) solution to address airspace and airport capacity limitations in and around the New York metropolitan area. A week-long study explored the feasibility of a new Optimal Profile Descent (OPD) arrival into the airspace as well as a novel application of a Terminal Area Precision Scheduling and Spacing (TAPSS) enhancement to the Traffic Management Advisor (TMA) arrival scheduling tool to coordinate high volume arrival traffic to intersecting runways. In the simulation, four en route sector controllers and four terminal radar approach control (TRACON) controllers managed traffic inbound to Newark International Airport's primary runway, 22L, and its intersecting overflow runway, 11. TAPSS was used to generate independent arrival schedules for each runway and a traffic management coordinator participant adjusted the arrival schedule for each runway 11 aircraft to follow one of the 22L aircraft. TAPSS also provided controller-managed spacing tools (slot markers with speed advisories and timelines) to assist the TRACON controllers in managing the arrivals that were descending on OPDs.

Results showed that the tools significantly decreased the occurrence of runway violations (potential go-arounds) when compared with a Baseline condition with no tools. Further, the combined use of the tools with the new OPD produced a peak arrival rate of over 65 aircraft per hour using instrument flight rules (IFR), exceeding the current maximum arrival rate at Newark Liberty International Airport (EWR) of 52 per hour under visual flight rules (VFR). Although the participants rated the workload as relatively low and acceptable both with and without the tools, they rated the tools as reducing their workload further. Safety and coordination were rated by most participants as

acceptable in both conditions, although the TRACON Runway Coordinator (TRC) rated neither as acceptable in the Baseline condition. Regarding the role of the TRC, the two TRACON controllers handling the 11 arrivals indicated that the TRC was very much needed in the Baseline condition without tools, but not needed in the condition with tools. This indicates that the tools were providing much of the sequencing and spacing information that the TRC had supplied in the Baseline condition.

Background

Over the past decade NASA has worked with the Federal Aviation Administration (FAA) and others to develop the NextGen transformation of the National Airspace System (NAS). More recently, NASA research has explored development of automation enhancements to fielded systems, leveraging new communication, navigation, and surveillance technologies to address specific NAS problems and inefficiencies. One of the more mature efforts in this area has focused on development of a capability called TAPSS [1]. TAPSS combines three elements: 1) new area navigation (RNAV) enabled descent procedures, 2) enhancements to the TMA, a traffic management tool used by the FAA for arrival metering to major NAS airports, and 3) new features in the Standard Terminal Automation Replacement System to display information in TRACON facilities for enabling controllers to precisely manage descending traffic along efficient descent trajectories.

NextGen Future Environments Research

NASA has initiated a NextGen Future Environments research effort to explore how TAPSS and other NASA efforts (e.g. efficient trajectory and flow planning, separation assurance, dynamic airspace configuration, and time-based metering) can be combined and adapted to improve operational performance in a particularly complex, high-demand airspace. The enabling NextGen technologies and

concepts have been categorized into three “Future Environments” (FEs), each corresponding to a particular time frame:

FE1) a NextGen Mid-Term environment (2018-2020), as described in the FAA’s “NextGen Implementation Plan” [2];

FE2) a Far-Term environment that references Joint Planning and Development Office (JPDO) recommendations [3]; or

FE3) a more advanced, post-2025 NextGen environment that achieves additional benefits by reallocating functions and responsibilities between air and ground, and humans and automation.

Each FE will address a set of related problems situated in a common airspace environment to enable investigation of interactions between operations. How particular functions are implemented will vary with the time frame represented, and should demonstrate how system capacity and performance will improve as air and ground technologies mature and/or functions are reallocated. We also hope to demonstrate the value of the public and private investments that are needed to realize NextGen by showing how successive enhancements can benefit operators, service providers and passengers. Integrated concepts for the three FEs will be developed, prototyped and tested in a human-in-the-loop (HITL) simulation test bed.

Test Airspace for Future Environments Research

One of the most common ways to evaluate NextGen technologies in simulated environments has been to increase traffic demand in moderately complex airspace without directly acknowledging the possibility that the benefit mechanisms that the technologies enable in this airspace might not transfer to the most complex airspace. However, the complex airspaces create the majority of the NAS-wide delays and therefore should be the true test bed for the efficacy of the NextGen technologies.

Thus the airspace that was chosen to provide the context for this research lies within and around the New York metropolitan area. This region presents a rich set of challenges to test the efficacy of new capabilities, including excess demand, chronic delays, severe weather, and airspace complexity. The resulting inefficiencies are of national as well as

regional importance, as indicated by numerous reports and testimonies before Congress by the Department of Transportation's Inspector General on New York area delays. Eleven such reports since 2000 are listed in a recent publication [4, p. 19]. According to a recent report, the New York area's

“high flight volume, coupled with dense airspace and limited capacity, have resulted in the 3 New York airports experiencing the highest delay rate among the 55 major U.S. airports....These delays not only affect aircraft travelling to and from the region but can also create a ripple effect as those aircraft fly throughout the Nation” [4, p. 3].

These delays continue to pose significant problems. A 2012 *NY Times* article indicated that in the first half of 2011, the area's airports (including Teterboro and Philadelphia International) handled 12% of all domestic flights but accounted for nearly half of all delays in the nation [5]. Also highlighted in the article was the fact that airline delays have a large economic impact; a study by the Senate Joint Economic Committee estimated the cost in 2007 to be \$41 billion. “That figure includes losses to the airlines, wasted time for passengers, and the overall cost to the economy [6].” Therefore, NextGen solutions that could demonstrably contribute to alleviating the problems in this airspace would provide significant value to stakeholders nation-wide. Testing in this complex airspace could also help identify limits to NextGen improvements and provide a driver for further development.

In the NextGen Futures Environments research, airspace operations during a variety of operational conditions from “severe clear” through convective weather and off-nominal failures will be investigated. System performance objectives have been established for each of these conditions, and a series of HITL evaluations are planned to compare how the different Futures Environments perform with respect to these objectives. The first simulation, which was completed in June 2013, compared efficiency and throughput of FE1 (Mid-Term) and FE2 (Far-Term) with a Baseline (current-day) condition under clear-weather conditions. A one-week follow-up experiment was conducted in August to complete the investigation of possible arrival capacity increases at EWR by improving converging runway operations. The August study is the focus of this paper.

Clear Weather Concept Evaluation

Clear weather operational objectives for this region include improving environmental performance (fuel efficient climbs and descents; reduced noise and emissions), as well as improving efficiency and predictability from the operator's perspective, such as reduced flight deviations, reduced fuel consumption, and improved on-time performance.

Clear Weather Challenges and Solutions

New York TRACON (N90) manages the arrival and departure operations for all of the major and regional airports in the New York metropolitan area. Because the airports are so close to each other, a highly constrained set of route structures and sectors have evolved to connect each airport's arrival and departure flows to and from four adjacent en route facilities: New York Center (ZNY), Boston Center (ZBW), Washington Center (ZDC) and Cleveland Center (ZOB).

This complexity has resulted in some significant inefficiencies that are difficult to fix. For example, aircraft traveling from the south to EWR may fly a 30 nm level segment in the TRACON at 6000 ft. before reaching the airport, because the alternative descent profiles are blocked by arrival flows into LaGuardia Airport (LGA) and westbound departures out of LGA and EWR. In fact, a recent FAA "snapshot" of EWR operations reported that the average distance travelled in level flight from top-of-descent to the runway threshold was over 60.6 nm in 2012, with LGA and John F. Kennedy International Airport (JFK) not far behind at 59.3 nm and 40.7 nm. [7] These low-altitude level flight segments are not only fuel inefficient but also have adverse noise and emissions impacts on the local community.

Another challenge is the high demand for access to the region; its three major airports support an operational load at VFR capacity throughout most of the day. The decrease in capacity during IFR operations varies between airports, but with no gaps in the daily schedule, delays tend to accrue over the course of a day.

Capacity may also be reduced during visual meteorological conditions (VMC). For example, strong tailwinds or crosswinds can force airports to use less efficient runway configurations, or make it difficult for approach controllers to merge streams

arriving from different directions. Even brief operational disturbances, such as a missed approach or go-around, can be significant. One arbitrarily chosen go-around was estimated to have caused over 600 minutes of delay [8].

The Future Environments research is focused on a representative subset of the New York area problem space that includes EWR inbound flows that travel through ZDC. As Figure 1 shows, three high altitude sectors (Hopewell, Brooke, and Dupont) serially manage the arrival traffic for delivery to EWR, with a fourth, underlying sector (Swann) delivering traffic from the Potomac TRACON into the arrival flow.

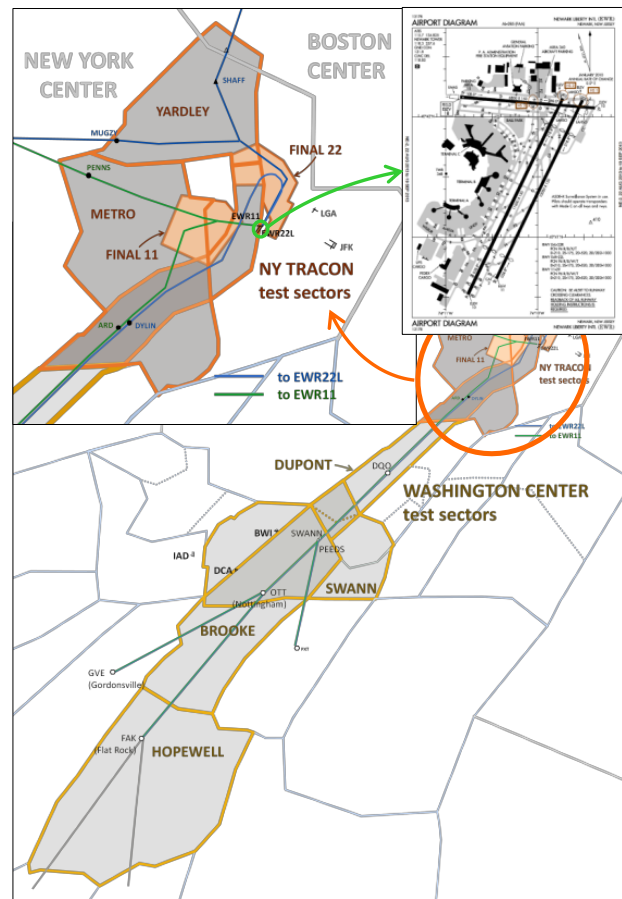


Figure 1. Simulation Airspace and Airport

A number of new capabilities have recently been introduced to improve operations at EWR, and have had some success. Time-based metering, using TMA to assign scheduled times of arrival (STAs) at the TRACON meter-fix, provides a better coordinated feed from the different en route facilities. New RNAV Standard Terminal Arrival Routes (STARs) and Required Navigation Performance (RNP)

approach procedures can reduce the lateral “footprint” and pilot-controller communication associated with arrivals, although they are not yet widely used despite the highly equipped fleets that qualify for the procedures visiting these airports. Over 90% of EWR arrivals are RNAV equipped but only 11% were using RNAV arrival procedures as recently as 2012. [9]

The Converging Runway Display Aid (CRDA) was introduced in December of 2009 at EWR specifically to reduce the number of go-arounds for the 22L/11 configuration [8]. The CRDA projects the ghost of a 22L arrival aircraft onto the path of the incoming 11 arrival on the Final 11 controller’s scope so that he or she can properly space the 11 arrival behind the 22L arrival. The CRDA reduced the number of go-arounds for the 22L/11 configuration from about 20/month in 2009 to 8/month in 2010. This was a significant improvement since one arbitrarily chosen go-around was estimated to have caused 622 minutes of delays in the system at an estimated cost of nearly \$38,000. There is also a safety impact to go-arounds associated with the increased controller and pilot workload they demand [8]. Go-arounds have not been completely eliminated at EWR due to 1) ties that occur when the airport is in another configuration (4R/11), 2) the effect of winds, and 3) controller skill. Since the CRDA is a passive, reflective tool, it does not take winds into consideration, which means that if there are winds, the Final 11 controller has to mentally adjust for their effect on two arrival streams coming from different directions [8].

Clear Weather Operational Concept

The NextGen Futures concept for clear-weather operations that is presented in this paper builds upon the capabilities described above. These include new OPDs supported by a TAPSS adaptation, with additional enhancements to explore how converging runway operations at EWR might be improved.

We began with the preferred airport configuration, using 22L as the primary arrival runway and runway 11 for overflow traffic. New experimental RNAV procedures that deliver aircraft from the top-of-descent to each runway’s threshold were designed for each runway and each inbound flow. For runway 22L, these included the CRANK1 arrival from the north, the PATTI1 from the west,

and the LOCKY1 from the south, and for runway 11 the SWEET1 from the west and the METRO1 from the south.

Figure 2 shows the lateral route through the TRACON with crossing restrictions for each of these procedures. Notice that arrivals to the two different runways might share a common lateral path in the en route airspace as they do today: the blue-green line arriving from the ZDC sector Dupont (in Figures 1 and 2) represent today’s PHLBO3 RNAV STAR (which feeds all EWR runways), as well as the LOCKY1 and the METRO1. Unlike the PHLBO3, however, which crosses ARD at 6000 ft., the new procedures’ descent profiles vary, along with their TRACON entry altitudes, depending on the flight distance to the runway threshold.

The TAPSS scheduler was adapted to use these new procedures, and to provide separate schedules with different arrival gates for each runway. As shown in Figure 2, runway 22L traffic on the LOCKY1 uses the meter fix ARD, with a crossing restriction of 19,000 ft. and 280 kts, while runway 11 arrivals on the METRO1 are delivered to the meter fix DYLIN at 12,000 ft. and 250 kts. TAPSS also provides slot marker display aids and speed advisories for the TRACON controllers [1], which reduces the complexity of merging aircraft entering from different gates that are flying OPDs.

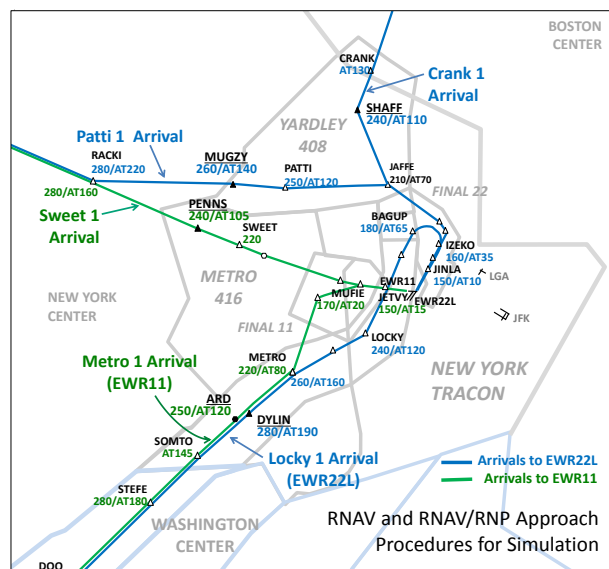


Figure 2. Test Procedures in TRACON

A key, further enhancement to TAPSS was proposed that would assign aircraft threshold times to

each runway that would assure that they would not be in conflict at the runway intersection point. Determining the feasibility of this TMA enhancement, and its potential for improving operations, was one of the main objectives of this study.

To summarize:

- New RNAV procedures provide more predictable and efficient descent trajectories, with a smaller lateral footprint and reduced environmental impact;
- TAPSS adaptation coordinates inbound flows from multiple gates for each runway;
- TAPSS scheduling and controller tools in the TRACON enable the controllers to manage and merge traffic using speeds, without needing to vector them off the RNAV procedure;
- A proposed new TAPSS enhancement provides ‘de-conflicted’ schedules for converging runway operations, further reducing the controller’s workload.

The above set of capabilities could all be implemented in the NextGen Mid-Term (FE1). However, some of the en route tools and procedures were more consistent with a Far-Term (FE2) environment. These en route tools and procedures included DataComm clearance delivery for appropriately equipped aircraft, trial planning, color coded traffic flows, TMA timelines and speed advisories. For simplicity, the test condition in this simulation is therefore referred to as the FE2 condition.

Method

Experiment Design

The experiment was a within-subjects 2x2 design. The two independent variables were Operational Environment (Baseline and FE2 conditions) and Wind Direction (SW and WNW conditions). Each condition was run twice using two different traffic scenarios. The Baseline condition assumed current day tools but with newly designed OPDs in the modified N90 airspace. The FE2 condition assumed NextGen technologies described in the previous section with the same OPDs and airspace as in Baseline. The wind conditions were

the dominant wind directions in each simulation run and created different challenges for the 11 and 22L arrivals due to different compression patterns.

The study was conducted over four days in August, 2013. Prior to the study, the En Route and TRACON controller participants familiarized themselves with the test airspace, operational environments, and tools during weekly “shakedown” sessions that spanned several months. During the study week, there was 0.5 day of briefing and refresher training, followed by 2.5 days of data collection runs. The study concluded with a debrief discussion and post-sim surveys, followed by some exploratory runs to test operational environments that were not included in the study. There were eight full data simulation runs in total.

Participants

Ten retired FAA personnel served as experiment participants. The four En Route controller participants were from Oakland Center (ZOA). The four TRACON controller participants worked in different TRACON facilities (e.g. Northern California, Dayton, Miami) as well as tower and center facilities. Their air traffic control experience ranged from 21 to 31 years and their retirement dates from 1 to 7 years ago. The other participants were retired Front Line Managers (FLMs) from ZDC and N90, who played the role of an En Route FLM and TRC, respectively.

In addition to the test participants, retired controllers from ZOA and SFO Tower performed the duties of “ghost” controllers responsible for all aircraft outside of the test airspace. One of the ghost controllers handled all aircraft entering the test sectors, another handled all EWR arrivals coming from north and west, and a third controller was the tower controller who landed all EWR arrivals. Finally, a TMC confederate managed the schedule for 22L and 11 arrivals. All of the simulated aircraft were flown by pseudo-pilots, who were active commercial pilots or students from the San Jose State University aviation department.

TRACON, En Route, Traffic Management Unit (TMU) and pseudo-pilots were located in four separate rooms within the AOL, as shown in Figure 5. En Route ghost controllers were located with the En Route team, and the tower ghost controller with the TRACON team.

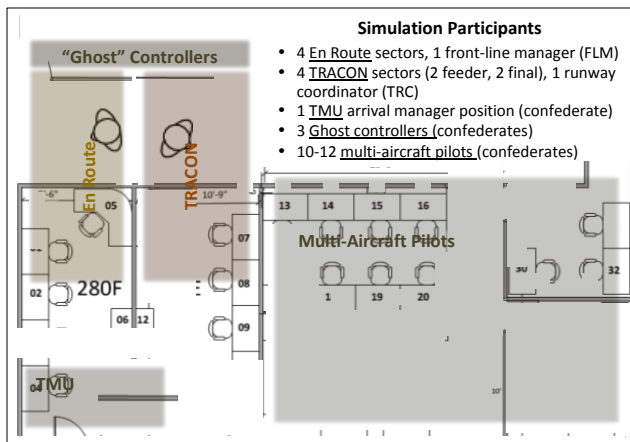


Figure 3. Simulation Layout and Participants

Traffic Scenarios

The simulation scenarios were built from actual traffic samples taken on days that had clear weather and maximum traffic throughput. These initial traffic demands were modified to increase the traffic demand to both 22L and 11 runways.

Two traffic scenarios were developed for the study. One of the scenarios had more arrivals from the south through the ZDC test sectors (78% from the south, 20% from the west and 2% from the north). The aircraft type distribution in this scenario had 42 Large, 4 Heavy, and 1 Small jets from the south. From the west and north, there were 12 Large jets. The second scenario had slightly lighter traffic from the south and more arrivals from the west and north through the ghost sector (64% from the south, 33% from the west and 3% from the north). The second scenario also had more arrivals in the scenario (64) than the first (59). The aircraft type distribution in this scenario had 35 Large, 5 Heavy, and 2 Small jets from the south. From the west and north, there were 21 Large and 1 Heavy jets.

In the ZDC test sectors, the traffic scenarios consisted mostly of EWR arrivals mixed with overflight traffic and arrivals to surrounding airports such as Teterboro Airport (TEB), LGA, and JFK.

The TMA freeze horizon for runway 22L was set at 400 nm from the airport as in today's operations. All aircraft landing 22L were in flight when they reached the freeze horizon. The schedules for runway 22L used a wake-vortex spacing matrix plus an additional .3nm buffer, to establish scheduled

times of arrival (STAs) for aircraft at the runway threshold on a first-come first-served basis.

Arrivals landing on runway 11 were typically regional flights flying much shorter routes. Runway 11's freeze horizon was set to approximately 120 nm from the airport. The runway 11 schedule used a 5nm spacing plus the same .3 nm buffer for all aircraft regardless of weight class. All aircraft entered the simulation at pre-scripted times; there was no active control of departure times during the simulation.

Each simulation run lasted 75 minutes. The scenarios were designed to maximize the throughput on runway 22L and to deliver roughly 25 arrivals per hour for runway 11 with manageable delays distributed across the ZDC test sectors. The TRACON traffic was very light at the beginning of the scenarios and built up to a sustained peak value at approximately 35 – 40 minutes into the scenarios.

Tools and Procedures

TMA Schedule Management

At the beginning of each run the NASA research version of the TMA provided independent meter fix schedules and runway schedules for EWR runway 22L and runway 11. A TMC confederate used modified DSR displays to monitor the en route and TRACON airspace that managed the EWR arrivals. The TMC also had a TMA traffic graphical user interface (TGUI) to monitor the different meter fix and runway timelines, and to modify the runway schedules when needed. Adjustments to the schedule for runway 22L were typically made to reduce delay or to assist en route controllers, by modifying an aircraft's STA, swapping or reordering a series of aircraft, or closing 'gaps' in the schedule.

During the FE2 condition only, the TMC had the additional task of adjusting STAs for aircraft landing on runway 11 by assigning them a threshold time that was not in conflict with aircraft landing on runway 22L. These manual schedule adjustments performed by the TMC enabled us to evaluate the operational feasibility of developing an enhanced TAPSS scheduler that would provide precise, de-conflicted threshold times for converging runways.

As Figure 1 shows, the runway intersection is located very close to the 22L threshold, and roughly a mile past the threshold for runway 11. Thus an aircraft touching down on 11 shortly after its 22L

“lead” would not be in conflict with it, since that aircraft would already have cleared the intersection. Since the next aircraft landing 22L would be at least 3 miles behind it, the earlier the 11 aircraft lands, the more likely it is to clear the intersection before that next 22L arrival touches down. The TMC’s strategy, therefore, was usually to schedule each 11 arrival to land shortly after an aircraft landed on 22L. Although this meant that most arrivals to 11 needed some slight adjustment to their STAs, the adjustments were rarely more than +/- 30 seconds because of the high throughput on 22L. These modest STA changes were easily managed by either the Dupont controller or the Metro feeder controller for runway 11.

The TMC coordinated all schedule changes to either runway with the FLM and/or the TRC before they were executed to insure that the controllers were informed of the changes and that the changes would work out for them. The FLM or TRC could also contact the TMC to request schedule changes as needed.

En Route Procedures and Tools

All ZDC test sectors were inside the 22L freeze horizon, and the en route controllers’ primary responsibility was to sequence and delay aircraft to meet the TMA-generated schedule. Typically, 22L arrivals had 2-5 minutes of delay that needed to be absorbed across 3 sectors: Hopewell, then Brooke, then Dupont. Hopewell was the first sector to work the arrivals, and was responsible for sequencing them and absorbing most of the delay. Typically, Hopewell passed less than 2 minutes of delay on to Brooke, who had a narrower sector and less room to maneuver. Brooke merged additional traffic from the west, established the vertical separation of the TEB, EWR11 and EWR22L flows, and absorbed most of the remaining delay before handing the aircraft to Dupont.

A low altitude test sector called Swann that was below Brooke and the southern edge of Dupont sector managed traffic into and out of Potomac TRACON. While Swann worked all of the simulation traffic for the DC area, the controller’s main responsibility was to sequence and deliver departures from DC area airports to Dupont on the METRO1 arrival for the EWR runway 11. The Dupont arrival sector thus received arrival traffic on the METRO1 from Swann and Brooke, and EWR 22L traffic from Brooke on the LOCKY1. Dupont was responsible for

managing these arrivals through their descent, and delivering them to the N90 feeder sectors for runways 11 and 22L in conformance to the meter fix crossing restrictions and on their assigned STAs. The FLM monitored en route operations and metering conformance, as well as coordinating any needed schedule changes with the TMC.

Controller tools and displays included more advanced features in the FE2 condition than in the Baseline condition for monitoring aircraft status, separation assurance, clearance trial planning and delivery, as well as monitoring and managing STA conformance. Among the key enhancements for the FE2 condition in this study were flight data block color coding by assigned runway, trial-planning with immediate feedback on delay when assigned speed or path changes were entered, and clearance delivery by DataComm for equipped aircraft. In the Baseline condition, meter lists were used that showed the callsign, the meter fix STA and the delay value in minutes for each EWR arrival. The delay value was also shown in the aircraft’s flight data block.

In the FE2 condition, metering information was presented on a color-coded timeline for each meter fix that showed aircraft estimated times of arrival (ETAs) and STAs. Trial plan changes to the ETA were also reflected on this timeline when controllers were using trial planning tools. Also in FE2, delay values were presented in the flight data block with 1-second precision.

TRACON Procedures and Tools

The two TRACON controllers working the Metro and Yardley sectors managed the inbound traffic from the adjacent en route facilities. Yardley, the feeder sector for Final 22L, had three inbound flows: arrivals from the north on the CRANK1, from the west on the PATTY1, and the LOCKY1 arrivals from ZDC. Yardley’s task was to sequence and space the traffic, merging the north and west arrival streams at JAFFE, and conditioning the traffic for the Final 22L controller to manage the last merge at IZEKO.

The Final 22L controller was responsible for safely and efficiently landing aircraft on 22L. In the Baseline condition, the IFR wake vortex separation criteria was the primary constraint. In the FE2 condition, however, the controller was also responsible for meeting an assigned STA for runway 22L. The STA was intended both to provide wake vortex separation for the aircraft landing on 22L, and

to coordinate their landing times with arrivals on the crossing runway 11.

Metro, the feeder for runway 11, was responsible for sequencing traffic entering from the west on the SWEET1 arrival with traffic from the south on the METRO1. Aircraft were handed off to the Final 11 controller before the merge at MUFIE.

Like the Final 22L controller, the Final 11 controller was also required to meet IFR wake vortex separation standards. He was also responsible for insuring separation between the 11 arrivals and the 22L crossing traffic. He did this by delivering each of his arrivals to the tower controller so it could land after its preceding 22L arrival had cleared the runway intersection, and with sufficient time to clear the intersection itself before the next 22L arrival.

The tower controller, who was a simulation confederate and not a test participant, issued the final landing clearance, and recorded any runway violations he observed, using criteria that will be described in the Results section.

The TRC's responsibility was to monitor the inbound traffic to both runways to make sure the runway 11 controller would have a workable problem. In the Baseline condition, his interventions might include sequencing or spacing advice to either of the feeder controllers or to the 22L Final controller to create an adequate gap between two aircraft landing on 22L. Alternatively, he could adjust the arrival time of an aircraft landing on either runway. In the FE2 condition, however, this spacing and sequencing advice was no longer needed, since the TAPSS runway schedules were designed to be conflict-free at the runway intersection.

In the FE2 condition, controllers used a TAPSS "slot marker" advisory circle to help them deliver each aircraft on its assigned STAs. This slot marker represented the current "ideal" position and indicated air speed of the aircraft as it descended from the meter fix to the runway along the 4-D path defined by its RNAV descent procedure and its assigned STA. The slot markers can be seen in Figure 4, which shows the Metro controller's display in the FE2 condition. The runway 11 timeline is also shown in Figure 4, with each aircraft's callsign aligned with its ETA on the left side, and its STA on the right side. The timeline allowed the controller to easily check the aircraft sequence well before they reached the

merge at MUFIE, and to detect any problems with schedule conformance or spacing between aircraft.

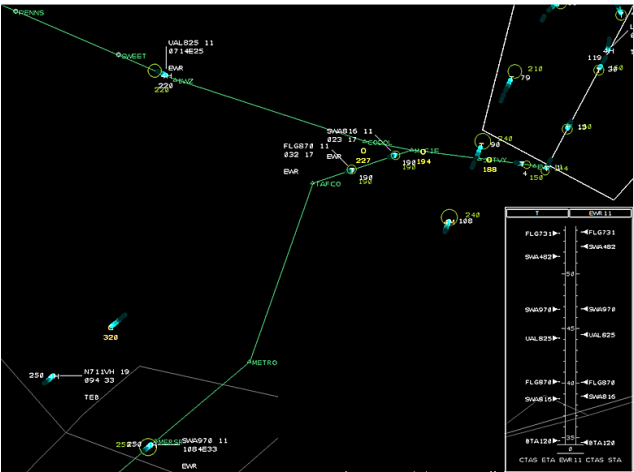


Figure 4. FE2 TRACON Display, with CRDA, Timeline and Slot Markers

In both conditions the Metro and Final 11 controllers also had the CRDA, a tool that is used in N90 today to manage the EWR intersecting runways. As described earlier, the CRDA shows a yellow target symbol and data block on the runway 11 final approach path, representing the relative position of aircraft on final approach for 22L. Figure 5 shows a close up of the CRDA target, and the slot marker circles that were present in the FE2 condition.

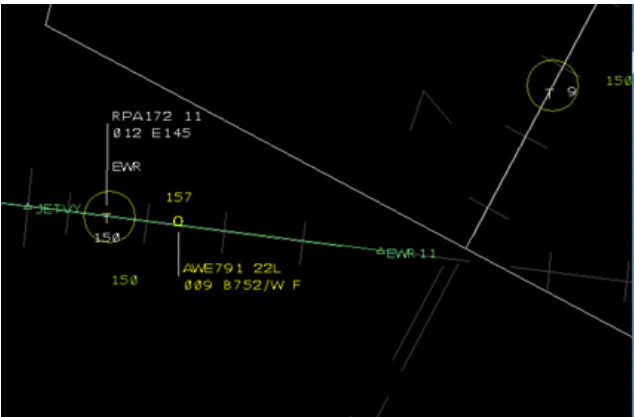


Figure 5. Final 11 Display Details

Workload and Participant Feedback

During the simulation runs, the controllers were prompted every three minutes to report their current workload on a scale of 1 to 6 using Workload Assessment Keypads (WAKs). Ratings of 1 and 2

were considered to be low workload, ratings of 3 and 4 were considered to be medium workload, and ratings of 5 and 6 were considered to be high workload.

After each run, the controllers responded to an online post-run survey, and after the simulation, they responded to a post-sim survey and participated in a debrief. Survey questions included those on workload, acceptability, feasibility and safety of the operations and coordination. The questions were typically binary (yes/no), or involved ratings on a 5-point Likert scale, ranging from 1 (lowest) to 5 (highest). Space was made available for comments on both survey instruments. WAK and post-run data were analyzed with repeated measures Analyses of Variance (ANOVAs).

Experiment Goal

The goal of the experiment was to test the following hypotheses:

1. More *efficient* RNAV descent procedures are compatible with converging runway operations.
2. A modified TAPSS capability with converging runway scheduling can further increase route *efficiency* by reducing the need for tactical vectoring.
3. Airport and airspace *throughput* can be *safely* maintained or increased with precision scheduling to converging runways.

4. These new operations can be *acceptable* to controllers from a *safety*, *workload* and *coordination* perspective.

5. While the Baseline condition may show similar throughput and efficiency, it may fail to satisfy *safety* and/or *acceptability* requirements.

The results section is thus organized to address issues of *efficiency*, *throughput*, *safety*, *workload*, and *acceptability*.

Results

Efficiency

Lateral Path Deviations

Figure 6 below shows that there were fewer lateral path deviations in the FE2 condition (left column, based on 198 simulation trajectories) than in the Baseline condition (middle column, based on 190 simulation trajectories). For comparison, the far right column shows 24 hours of actual operational data for arrivals from ZDC for Runways 22L or 11 on a clear weather day (June 27, 2011).

Controllers' Reports of Vectoring

Congruent with the above data, on the post-run survey controllers reported vectoring more aircraft in the Baseline condition than in the FE2 condition, as seen in Figure 7 (Baseline $M = 3.3$, FE2 $M = 2.3$; $F(1,6) = 32$, $p < .01$).

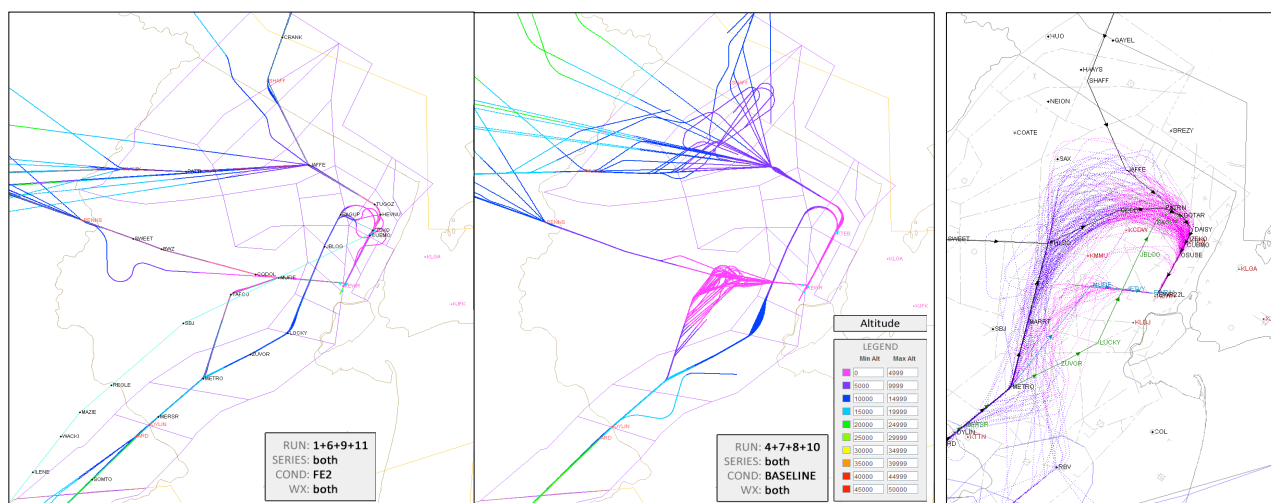


Figure 6. Trajectories from FE2 (Left), Baseline (Middle) and Operational Data, 6/27/2011 (Right)

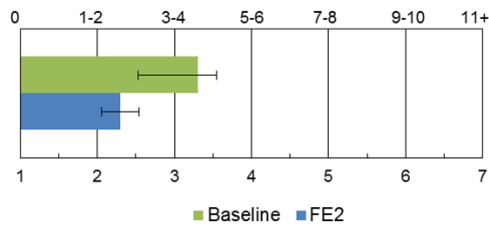


Figure 7. Post-Run Ratings of Aircraft Vectored (Error Bars = 95% Confidence Intervals)

Also, controllers were asked on the post-run survey to rate how much the "need for vectoring" was a factor contributing to the complexity of the task. On a five-point scale ranging from "not a factor" to "very much a factor," the controllers rated the need to vector as being more of a factor in Baseline than in FE2, (Baseline $M = 3.0$ vs. FE2 $M = 2.2$; $F(1,6) = 10.9$, $p < .015$). Interestingly, the rating fell most sharply from Baseline to FE2 for the TRC, from 5 to 1.5, and for the Final 11 controller (from 4 to 1), who merged the Runway 11 aircraft into the Runway 22L landing stream. The decrease for the Final 11 controller indicates that in the Baseline condition, the vectoring was being done at a low altitude, close to the tower, and in a busy airspace, as in fact, can be seen in Figure 6 (middle column).

Throughput

Aircraft Count

The experiment was designed to have equal throughput in both conditions, and although there were slightly more aircraft that landed in FE2 than Baseline, this was not statistically significant (Independent samples t-test: FE2 $M = 49.5$, $SD = 2.38$; Baseline $M = 47.5$, $SD = 0.58$; $t(6) = 1.63$, $p < .15$). Table 1 shows the total number of aircraft that landed on each runway, and the combined total, for each run.

In the post-sim survey, participants indicated that the number of aircraft per run was "about right" in both conditions. However as shown in Figure 8, when asked about how many more aircraft they could have handled in the two conditions, most reported that they could have handled a few more per run, and most indicated they could have handled even more in FE2. The average number of additional aircraft the controllers could have handled per run was between 1-2 in Baseline ($M = 2.5$) and at 3-4 in FE2 ($M = 3.1$).

Table 1. EWR Arrivals Landed per Runway

Condition	Run	EWR22L	EWR11	Total
FE2	1	37	14	51
	6	30	18	48
	9	29	18	47
	11	36	16	52
	Mean	33.00	16.50	49.50
	SD	4.08	1.91	2.38
Baseline	4	32	15	47
	7	30	18	48
	8	33	15	48
	10	29	18	47
	Mean	31.00	16.50	47.50
	SD	1.83	1.73	0.58

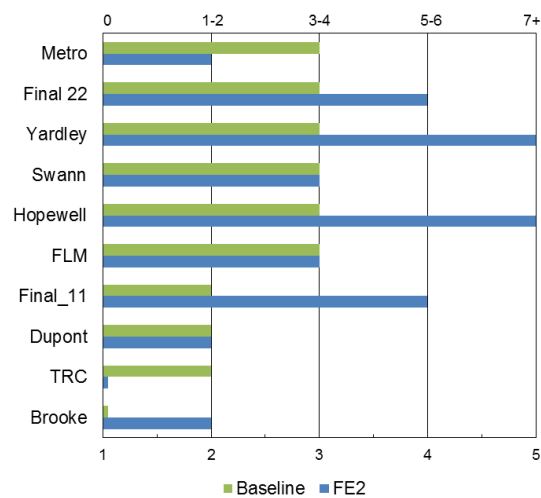


Figure 8. Additional Traffic the Controllers Could Have Handled Per Run

Landing Rates

Quarter-hour landing rates were calculated for each minute of elapsed run time by counting the number of aircraft that landed in the 15 minute interval surrounding a specific time. Figure 9 shows the individual runway landing rates, and the combined rate for each condition, averaging results for all 4 runs in each condition.

As can be seen, aircraft began landing roughly 2-3 minutes earlier on runway 22L in Baseline since

TRACON controllers were not constrained by the runway schedule, and could shortcut aircraft. As a result, the 22L and combined landing rates for the FE2 condition are offset to the right. This difference partially accounts for the lower observed landing rates in Baseline, since a similar number of aircraft were landed in a shorter period of time during the FE2 runs. No difference was observed for runway 11.

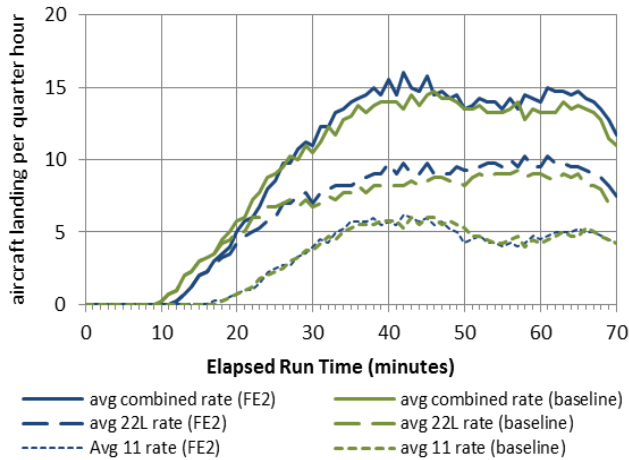


Figure 9. Plot of 15-Min. Landing Rates (Avg.)

Table 2 shows the peak quarter-hour landing rates for each run, by runway and combined runways. The equivalent hourly airport arrival rates (AARs) are shown in the right column; these were significantly higher in the FE2 condition (Independent samples t-test: FE2 $M = 67$, $SD = 2$; Baseline $M = 61$, $SD = 3.83$; $t(6) = 2.78$, $p < .05$).

For comparison purposes, the current VFR AAR rate for EWR with "excellent arrival configuration" is 46-52 [7]. It can be seen that the OPDs used in the Baseline condition result in substantially higher AAR rates ($M = 61$), even when controllers are following instrument flight rules. The addition of the tools provides yet a further boost ($M = 67$).

Safety

Loss of Separation

There was no loss of separation either in the en route or TRACON airspace.

Table 2. Peak Quarter-Hour Landing Rates

Peak Landing Rates per Runway, by Run and Condition					
Condition	Run	Peak Quarter-Hour Landing Rates			AAR Equivalent
		EWR22L	EWR11	Both	
FE2	1	11	7	17	68
	6	11	7	17	68
	9	10	7	16	64
	11	11	6	17	68
	Avg.	10.75	6.75	16.75	67.00
	SD	0.50	0.50	0.50	2.00
Baseline	4	9	6	14	56
	7	10	7	16	64
	8	10	7	16	64
	10	10	6	15	60
	Avg.	9.75	6.50	15.25	61.00
	SD	0.50	0.58	0.96	3.83

"Go-around" Violations

A "go-around" violation was defined as occurring if the aircraft landing on 11 was at the 11 threshold and the aircraft landing on 22L a) had not yet crossed the intersection with Runway 11 and b) was less than 1.5 miles out.

Table 3 shows the number of go-around violations per condition. As can be seen, 24% of the landings in Baseline met this criteria for a go-around, compared to only 6% in the FE2 condition ($\chi^2(3, N = 132) = 8.5$, $p < .01$).

Table 3. "Go-around" Violations per Condition

Condition	Go-around	Landed	Totals
Baseline	16 (24%)	50 (76%)	66 (100%)
FE2	4 (6%)	62 (94%)	66 (100%)
Totals	20	112	132

Participant Safety Ratings

On the post-run survey, participants (8 controllers and the TRC and FLM) were asked to rate the acceptability of operations regarding safety in their sector/area. The participants responded on a five-point scale ranging from "Not at all acceptable" to "Very acceptable." Overall, the participants viewed the acceptability of safety as high; the mean rating was 4.5. There was no significant difference in

the ratings between Baseline ($M = 4.4$) and FE2 ($M = 4.6$). Final 11 increased his rating from an average of 4 in Baseline runs to an average of 5 in FE2 runs and the TRC increased his ratings from an average of 3 in Baseline runs to an average of 5 in FE2 runs.

On a similar question in the post-sim survey, the participants' ratings were similar—Baseline $M = 4.1$, FE2 $M = 4.5$. The TRC, however, rated the acceptability of operations regarding safety as a 2 in the Baseline condition (between "Not at all acceptable" and "Somewhat acceptable") and a 5 ("Very acceptable") in FE2. Hence in the Baseline condition, the TRC did not view operations as acceptably safe, as indicated by both the post-run and post-sim ratings.

Workload and Acceptability of Workload

The within-run measure of workload (the WAK), based on the controllers' assessment of their workload every 3 minutes on a scale of 1 to 6, was low overall, and was slightly higher in the Baseline condition ($M = 2.5$) than the FE2 condition ($M = 2.3$) $F(1,6) = 14.3, p < .01$, as shown in Figure 10.

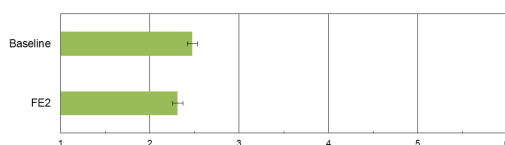


Figure 10. Average WAK Workload Ratings Per Run (Error Bars = 95% CIs)

Average WAK rating data for the Final 11 controller across time shows the details of the variation between the Baseline and FE2 conditions. As shown in Figure 11, the workload of the Final 11 TRACON controller, whose job it was to integrate the aircraft landing on Runway 11 with aircraft landing on 22L, was higher in Baseline than in FE2. This result suggests that in the Baseline condition, it was generally more difficult for the Final 11 controller to space the runway 11 arrivals behind its lead aircraft on runway 22L.

The WAK data for other key sectors show a similar pattern. In particular, all of the high altitude En Route sectors show higher workload in Baseline compared to FE2, suggesting that the en route tools successfully offloaded the controllers' tasks.

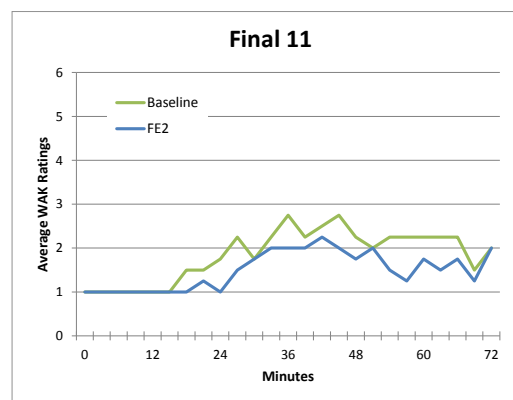


Figure 11. Average WAK Workload Ratings Over Time for Final 11

A post-run measure of workload was the question "In the last run, how much mental activity was required during the busiest time?" Responses were ratings on a five-point scale ranging from "Very low mental activity" to "Very high mental activity." All eight controllers and the FLM and TRC rated their mental activity during the busiest time as significantly higher in the Baseline condition ($M = 3.5$) than in FE2 ($M = 2.8$), $F(1,5) = 13.6, p = .01$, as shown in Figure 12.

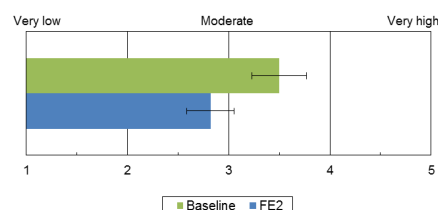


Figure 12. Average Mental Activity at Busiest Time; Post-Run Ratings (Error Bars = 95% CIs)

Figure 13 shows a significant participant by condition interaction in mental activity at the busiest time, with the TRC, Yardley, and Final 11 having the biggest drop from Baseline to FE2, followed by Brooke and Dupont, $F(9,45) = 2.7, p = .04$.

The acceptability of workload was based on participants' responses to a question asking how acceptable operations were in their sector/area regarding workload. Ratings were on a five-point scale ranging from "Not at all acceptable" to "Very acceptable." Overall, the participants viewed the acceptability of workload as high; the mean rating

was 4.5. There was no difference in the ratings between Baseline and FE2 conditions; both means were 4.5. Similar results were obtained from the post-sim survey (Baseline $M = 4.4$, FE2 $M = 4.9$).

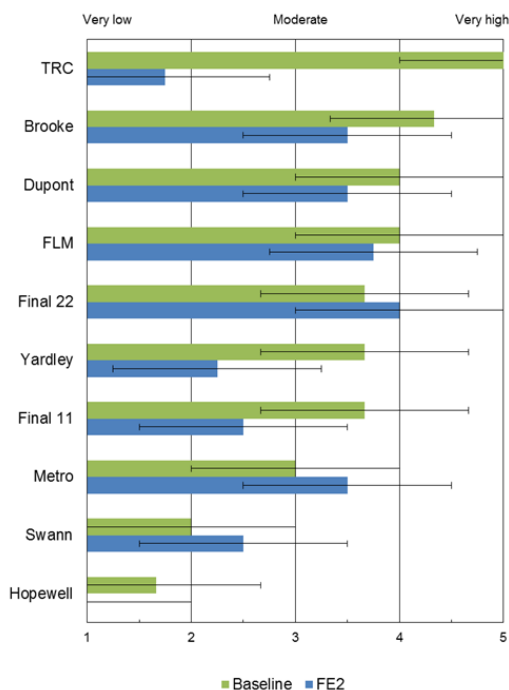


Figure 13. Average Mental Activity at Busiest Time; Post-Run Ratings (Error Bars = 95% CIs)

Winds and Task Complexity

Participants were asked on the post-run survey to rate how much winds were a factor contributing to the complexity of the task. On a five-point scale ranging from "not a factor" to "very much a factor," the controllers' average rating was low—1.9. However, participants differed in the degree to which wind affected them, as shown below in Figure 14, $F(9,54) = 22.4$, $p < .001$. Dupont, Metro, and Final 11 seemed to be most affected by winds.

Overall, the extent to which wind was a factor in the post-run surveys did not differ by condition. However, it did differ for Final 11, who on the post-run surveys rated winds as being "Somewhat a factor" in the Baseline condition ($M = 3$) and close to "Not a factor" in FE2 ($M = 1.25$). Furthermore, in the post-sim survey, Final 11 was asked, "How much did the winds negatively impact your ability to manage the aircraft in your sector?" On a 1 to 5

scale, from "Not at all" to "Very much," Final 11 responded "Very much," (5) in the Baseline condition to each of the two wind conditions. In FE2, this was reduced to a "2" for each wind condition—between "Not-at-all" and "Somewhat." The Final 11 controller commented,

"The winds could cause a large disparity between Runway 11 and 22. For example: A 5 knot headwind on 22 can mean as much as a 10 knot difference in ground speed between 11 and 22. In FE2, all I had to do was stay in the slot marker—much easier."

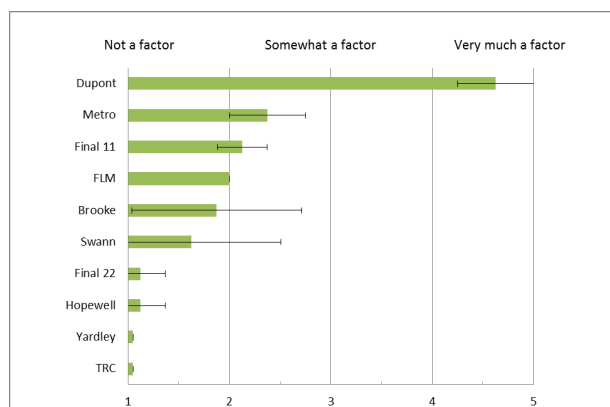


Figure 14. Average Post-Run Ratings on How Much Winds were a Factor in Adding to the Complexity of the Task (Error Bars = 95% CIs)

Coordination

The acceptability of coordination was based on participants' responses to a post-run survey question asking how acceptable operations were in their sector/area regarding coordination. Ratings were on a five-point scale ranging from "Not at all acceptable" to "Very acceptable." Overall, the acceptability of coordination was viewed as high; the mean rating was 4.6. There was no difference in the ratings between Baseline ($M = 4.5$) and FE2 conditions ($M = 4.6$).

Post-sim ratings confirmed the post-run ratings (Baseline $M = 4.4$, FE2 $M = 4.9$). However the TRC rated the acceptability of coordination in the Baseline condition as a 1 ("Not at all acceptable") and in FE2 as a 5 ("Very acceptable").

Regarding schedule changes, respondents indicated that if there were any schedule changes that affected them, they were generally informed about these changes in advance in both conditions.

Coordination and the Role of the TRC

Post-sim ratings by the TRACON controllers indicate that the TRC was most needed in the Baseline condition, and generally, "Not at all" needed in the FE2 condition, as shown in Figure 15. These ratings were in response to the question, "How much was a TRACON Runway Coordinator needed to help space/schedule aircraft in your sector in the following conditions?" Final 11 commented that in the Baseline condition, the TRC informed him of conflicts and advised speeds or vectors. In the FE2 condition, the tools and procedures generally performed these functions or rendered them unnecessary. However, despite the controllers' responses, the TRC himself judged that someone in his role would be necessary in both conditions "to be a final authority to make decisions" and "to handle non-routine situations."

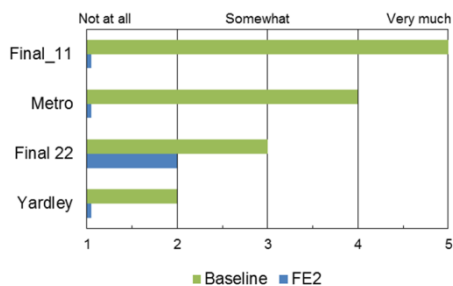


Figure 15. TRACON Controllers' Post-Sim Ratings on How Much the TRC was Needed in Both Conditions

Discussion

In this study, new OPD arrival routes were designed into the EWR airspace. The arrivals were managed using a novel application of a TAPSS enhancement to the TMA arrival scheduling tool to coordinate high volume arrival traffic to intersecting runways. Past research involving TAPSS has demonstrated that controllers can provide precise delivery of the arrival aircraft to the runway threshold with minimal vectoring. This study leveraged the delivery precision and extends the framework by providing a coordinated schedule between the two intersecting runways.

The results suggested that the efficient RNAV descent procedures were compatible with converging runway operations using the modified TMA and the controller tools. In the FE2 condition, the controllers were able to deliver arrival aircraft precisely on OPDs at a high throughput rate for both 22L and 11 runways with less vectoring, fewer lateral path deviations, and a lower workload.

A more important result was that a coordinated schedule across the two intersecting runways at a high throughput rate was successfully managed with minimal coordination using the TAPSS tools. In the Baseline condition, the coordination of the intersecting runways was performed by the Final 11 controller keeping the 11 arrivals behind its lead aircraft on 22L using CRDA. This sometimes resulted in bad pairings due to the relative positions between the two aircraft by the time that the CRDA presented the 22L ghost target on the 11 approach. The TRC tried to resolve this problem by coordinating with both Final 11 and Final 22 controllers, but such coordination was both time-consuming and frequently inadequate, as indicated by the increased number of runway violations in the Baseline condition. The difficulty using CRDA was exacerbated in even minor wind conditions, with the Final 11 controller having to mentally adjust the ground speeds of the ghost target on 22L with that of the approaching 11 aircraft coming from a different direction.

The FE2 condition, in contrast, allowed the controllers to deliver their aircraft to the slot markers with the assurance that the slot markers represented a location of the aircraft that was conflict-free at the intersecting runways taking into consideration the winds. The coordination effort in FE2 was remarkably different from that in the Baseline condition. In FE2, the TRC hardly needed to coordinate between the two Final controllers, and the Final 11 controller needed to make only minor adjustments to the 11 arrivals to place them behind their lead aircraft on 22L.

The peak landing rates as reflected in 15 minute mid-stream arrival intervals were greater in both Baseline and FE2 conditions using IFR separation criteria than the current maximum landing rate at EWR with VFR. However, the increase in runway violations in the Baseline condition would, in real operations, likely lead to an increase in the miles-in-

trail spacing between runway 11 arrivals, from the 5nm used in the simulation back to 7nm, which is the current buffer. This would result in a lower throughput. Hence an increase in throughput with acceptable safety margins is unlikely without the tools present in FE2.

Summary and Next Steps

The results of the simulation confirm that TAPSS can enable more energy efficient, trajectory-based RNAV descent procedures to be used without sacrificing throughput even in the very challenging New York environment. In addition, the results further suggest that enhancements to TAPSS to coordinate the threshold times of aircraft landing on converging runways could safely increase throughput for EWR from today's VRF maximum of 52 to over 65 arrivals per hour.

Additional analyses are needed to clarify the trajectory modeling requirements for TAPSS automation to successfully separate aircraft on converging runways by precisely coordinating their runway threshold times. This simulation also assumed that all arriving aircraft were RNAV equipped, and the mixed-equipage case has yet to be studied. Another open question is what support these tools might provide under less ideal conditions; i.e., what throughput improvements might be achieved during one runway operations? Could these tools and procedures continue to support operations during convective weather? These are some of the issues raised by our study that we hope to explore in the coming year.

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