AIR TRAFFIC CONTROLLER USAGE OF TERMINAL-AREA SPEED ADVISORIES

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Abstract

This paper analyzes data from multiple human-in-the-loop simulations, hoping to inform the design of air traffic controller decision support tools. More precisely, Terminal Area simulations including high-density arrival flows and precision runway scheduling presented controllers with speed advisories; suggested speeds that, if issued to the aircraft, would support delivering the aircraft to the runway on schedule while minimizing the need for vectors. Data from multiple simulations will compare the speed advisories displayed to the controllers against the speed advisories the controllers actually issued to the aircraft.

Introduction

In today's air traffic system, a busy Terminal RADAR Approach Control (TRACON) facility safely manages heavy arrival flows with multiple speed changes, altitude level-offs (step-downs), and heading vectors. These control techniques are effective; they help maintain safety and high throughput, but may also negatively impact descent profiles by increasing noise and emissions. Efficiency can be improved by descending arrivals on Optimized Profile Descents (OPDs) along Area Navigation (RNAV) routes. However, because current-day air traffic control techniques often include heading adjustments and step-down descents, RNAV OPD operations are only feasible during periods of light traffic demand.

Under NASA's Airspace Systems Program, the Super-Density Operations research focus area aims to safely sustain high runway throughput while minimizing environmental impacts through the use of fuel-efficient operations [1]. One approach for achieving this involves scheduling arriving aircraft along RNAV OPDs that include runway transitions connecting to instrument approach procedures. These advanced arrival procedures enable flight crews' use of Flight Management System (FMS) capabilities to fly down to the runway without needing radar vectors or altitude level-offs from the controller. Scheduling automation also leverages these arrival procedures to build accurate trajectory estimates that in turn are used to create runway Estimated Times of Arrival (ETAs) and Scheduled Times of Arrival (STAs) [2]. Assuming en route controllers employ speed and path adjustments as necessary such that aircraft enter the Terminal Area with reasonably small schedule errors, TRACON controllers then continue to refine runway schedule conformance by applying speed adjustments while ensuring safe spacing, and also coping with disturbances due to forecast wind errors, pilotage, and other factors.

Background

It has long been recognized and the subject of much research that Decision Support Tools (DSTs) are needed to help controllers primarily use speed control to manage fuel-efficient OPDs for busy arrival flows [3]. DSTs for merging and spacing aircraft in the terminal area have included 'ghosting' displays and/or clearance advisories; refer to Callantine [4], and Kupfer [5] for further review of previous research in this area.

The Traffic Intelligence for the Management of Efficient Runway scheduling (TIMER) concept included computer-generated controller aids to improve delivery precision. Control actions were expected at one or two specific control points along the nominal route between the meter-fix and 'aim point.' During their descent, as aircraft came upon TRACON routing 'segments' beginning with one of these control points, if a comparison of the aircraft's runway ETA and STA returned a mismatch, the controller was presented with a speed advisory in the aircraft's data block. The speed advisory, using Indicated Air Speed (IAS), consisted of a computed 'segment speed' designed to take effect over that segment and was predicted to put the aircraft on schedule (e.g., ‘S190’). Additionally, the TIMER speed advisories came with associated count-down/count-up times displayed in the data block advising the controller when to issue the speed. The speed advisory computations also incorporated certain assumed response times for the controller and flight crews to respond to the speed advisories [6].

Whereas the TIMER study in [6] examined speed-related DSTs only for the TRACON feeder controller, a second TIMER study focused solely on the final controller’s airspace. During one condition of the study, all aircraft turned onto the final approach course at a speed of 210 knots, after which speed advisories were available to aid the controller in issuing speed reductions to 170 knots (to be flown by the aircraft until the outer marker), thereby delivering aircraft properly sequenced for the runway; in this context, the study investigated two ideas for speed advisory presentation. One method displayed a graphic marker on the controller’s display to represent where to issue the speed advisory (a small circle enclosing an x). This design limited the display of the graphic markers to only when the aircraft was within 3 nmi of it. The other approach used was similar to the count-down/count-up display in the data block in [6], but instead represented “what-if” feedback on the predicted runway ETA/STA difference if the advisory were to be issued at that moment. This display option was known as DICE. As an example, a speed advisory of ‘S190’ with a DICE value of 10 indicated that if there controller were to issue a speed clearance of 190 knots now, the aircraft would be predicted to arrive at the runway 10 seconds late [7].

Another TRACON speed advisory, the Final Approach Spacing Tool (FAST), compared ETA predictions along an assumed nominal route against an aircraft’s runway STA. If FAST determined that a speed adjustment is necessary to deliver the aircraft on schedule, an IAS speed advisory (e.g., ‘210’) was available to display in orange in the data block [8]. Similar to the TIMER speed advisories in [6], the FAST speed advisories were associated with a geographic reference point where the speed instruction needed to be issued. Unlike the TIMER advisories in [6] however, the FAST speed advisories were not tied to pre-defined points; the advised clearance delivery locations could be at any point along the assumed nominal route. FAST’s ability to compute a speed advisory to be issued at any point along the nominal route meant that it could dynamically re-compute and update speed advisories if necessary, such as when an aircraft failed to execute a clearance, or when a missed approach occurred. New advisories were then computed to help work the aircraft back into the landing sequence [9].

To address concerns of clutter, FAST speed advisories were displayed only when an aircraft needing speed adjustment came within 5 nmi of the advised clearance delivery point, at which time the clearance delivery point was also highlighted on the display, represented as an orange filled circle, similar to the graphic markers used in [7]. Schedule conformance information was able to be presented in the data block as well, showing the currently-estimated arrival time error in seconds, preceded by either an ‘E’ for early or an ‘L’ for late [10].

Research at MITRE developed the Terminal Routing Using Speed-control Techniques (TRUST) concept. TRUST, which has similarities to certain elements of both TIMER and FAST, was limited to speed reduction speed advisories. The TRUST concept leveraged RNAV routes down to the runway threshold: a given RNAV route was divided into three segments, each of which had a nominal/charted speed restriction. For example, when the TRUST automation detected runway schedule conformance errors for aircraft arriving too early, it would determine that the charted speed reductions for that route segment needed to be issued earlier than normal. TRUST would compute the geographic point at which the speed reduction should be issued such that the earlier speed reduction would correct deviations from scheduled runway times. This called for controller intervention, and was presented as an IAS speed advisory. Preliminary designs of the speed advisories consisted of displaying a red dot on the display to represent where the clearance should be issued, and optionally including the speed advisory in the third line of the data block (e.g., ‘SA 180’) as well [11].

CMS Speed Advisories

A schedule-based arrival management environment serves as the foundation of the Controller-Managed Spacing (CMS) concept (portrayed in Figure 1), which assumes all aircraft are

Flight Management System- (FMS-) equipped so as to enable Vertical Navigation (VNAV) descents along published RNAV OPDs. As a result of en-route controllers pre-conditioning the flow of arrival traffic, aircraft enter the TRACON airspace with schedule errors ranging from approximately 60 s early to 30 s late. These errors are small enough that they can be corrected with speed adjustments alone. TRACON Feeder controllers then use schedule information and other DSTs to issue speeds as required for adjusting aircraft toward their runway STA, while still keeping them on their assigned RNAV OPD. Final controllers issue speeds to remove any residual schedule errors, and ensure that aircraft are safely merged, established on the final approach, and delivered to the tower such that proper spacing will be achieved at the runway threshold [12].

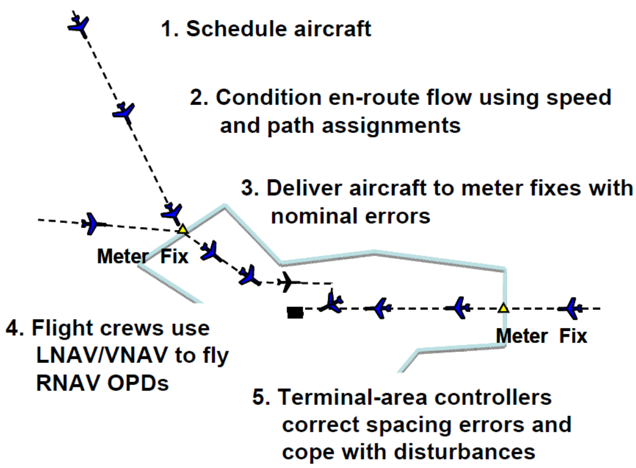


Figure 1. Schedule-Based Arrival Concept.

The CMS speed advisories are designed to help controllers issue trajectory-based speed clearances in the traditionally tactical TRACON environment [2]. The speed advisories consider the speed profile of the aircraft's "reference" or nominal trajectory; during the CMS simulations, the nominal trajectory was defined using the exact altitude and speed restrictions from the RNAV OPD routes. When an aircraft is predicted to arrive at the runway either too early or too late, the speed advisory attempts to calculate a speed that deviates from the nominal speed profile and is maintained until slowing to meet the charted speed restriction at a downstream waypoint, where the aircraft then rejoins the nominal speed profile. Flying the advised speed during the length of time it takes to reach the rejoin waypoint (more specifically, the deceleration point just before the rejoin waypoint) is expected to put the aircraft back on schedule by that point. Assuming the aircraft will follow the nominal/charted speed profile after passing the rejoin waypoint, it would then be predicted to arrive at the runway on time. The speed advisories are computed using forecast winds however, and can thus be subject to errors.

If an aircraft's runway ETA is sufficiently different from its STA, a speed advisory is presented to the controller in the third line of the aircraft's data block. CMS speed advisories contain two basic elements: an IAS and a waypoint. For example, if a speed advisory displays "210 CARBN," the controller could use this information to issue the clearance "Aircraft123, maintain 210 knots until CARBN." If an advised speed cannot be computed, either because the required speed is outside the available speed control envelope or the aircraft is already estimated to be on-schedule, an early/late indicator appears in the data block instead.

Figure 2 illustrates the CMS speed advisory logic. The red line is the charted speed profile. In this example it starts with a segment at 210 knots, then a slow-down from 210 to cross waypoint GAATE at 180 knots, another slow down to cross JETSA at 170 knots, another slow-down to the approach speed and the final slow-down to the landing speed (not shown in Figure 2). CMS automation tries to find a speed profile that allows the aircraft to increase or reduce to a given speed now, then initiate the slow-down to meet the speed restriction at a downstream waypoint. This way the advised speed and the waypoint at which the nominal speed should be re-captured can be communicated in one clearance. Figure 2's example profile (a) would be implemented via a "maintain 190 knots until GAATE" air traffic control instruction. This assumes that at GAATE charted speeds are resumed. This early slow-down will cause the aircraft to arrive at GAATE later than the charted profile. Profile (b) reflects an increase to 220 knots and an assumed resume to charted speeds at JETSA. This will increase the aircraft speed, reduce the flying time and cause the aircraft to arrive earlier at JETSA. Profile (c) indicates an immediate slow-down to be maintained until the JETSA waypoint. While this action will initially leave the aircraft 10 knots slower

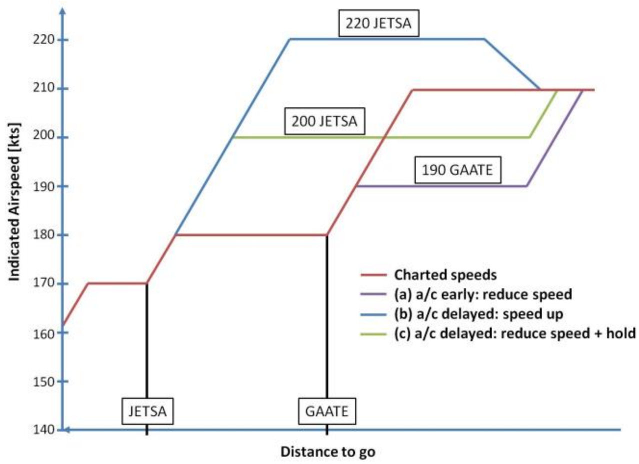


Figure 2. CMS Speed Advisory Logic.

than the charted speed, eventually the aircraft will be 20 knots faster, resulting in a net reduction in flying time and an earlier arrival at JETSA.

The CMS speed advisory logic has similarities to certain elements of both DICE and FAST. DICE's dynamically updated 'what-if' feedback told the controller when a given speed reduction would resolve the schedule conformance error. CMS speed advisories also incorporate schedule conformance 'what-if' feedback, but do so implicitly rather than explicitly. All CMS speed advisories are designed to completely correct any schedule conformance error, which means that they would always have a DICE-value-equivalent of 0. Rather than vary the location at which fixed speed reductions are issued (as in [7] and [11]), and rather than vary the speed to be issued at fixed locations (as in [6]), CMS speed advisories dynamically change both parameters as necessary to help the controller deliver the aircraft on schedule while minimizing the need for heading vectors (FAST uses a similar dynamic computation approach).

This dynamic quality is necessary, because the advisories are designed to be issued at the aircraft's current location, which itself is constantly changing. Continuously computed ETA predictions are central to the dynamic nature of the speed advisories, allowing the advised speed and/or rejoin waypoint to be updated if necessary. An aircraft that is predicted to arrive early, as it gets closer to the runway, will require larger deviations from the nominal speed profile (i.e., larger speed reductions) to arrive on time.

Using the situation illustrated by Figure 2's profile (a) as a starting point allows for a walk-through of an example scenario to better understand the dynamic nature of the CMS speed advisories. Beginning with an aircraft that is predicted to arrive early, suppose the controller is presented with and issues the '190 GAATE' speed advisory. If the aircraft's schedule conformance error does not improve (e.g., the pilot fails to execute the slow-down), the speed advisory would then update with a larger speed reduction (e.g., '180 GAATE'). If the schedule conformance error persists, as the aircraft gets closer to the waypoint GAATE, the speed advisory would update again, this time changing both the advised speed and the rejoin waypoint. The previous speed advisory was for 180 knots, which is the charted restriction at GAATE. A speed advisory of '170 GAATE', per the CMS speed advisory logic, always assumes the aircraft rejoins the nominal speed profile at the rejoin waypoint. Consequently, a '170 GAATE' speed advisory therefore expects the aircraft to slow to 170 knots, and then increase its speed when necessary to meet the 180 knots speed restriction at GAATE. For pilots and controllers alike, this is clearly an undesirable situation. Rather than '170 GAATE', the next update to the speed advisory could be '180 JETSA,' employing the slow speed over a longer distance to correct the schedule conformance error. If the situation still does not improve, a point will be reached where even slowing to the final approach speed for the rest of the flight (e.g., '170 JETSA') will not deliver the aircraft on time. At this point, the speed advisory is no longer displayed in the data block and is replaced with an early/late indicator (e.g., E 0:54).

The CMS speed advisories are intended only as suggestions for the controller, who is free to issue the speed advisory as presented, but can also issue a modified version if they feel it appropriate, or ignore the speed advisory completely. For these and a variety of other reasons, during simulations, controllers did not always issue the speed advisories as displayed.

CMS Simulations

The Airspace Operations Laboratory at NASA's Ames Research Center [13] has conducted various Human-In-The-Loop (HITL) simulations as part of ongoing Controller-Managed Spacing (CMS) research, whose focus is on developing DSTs that help controllers keep aircraft on fuel-efficient profiles, while meeting scheduled runway times. CMS tools have been shown to be useful for enabling RNAV OPD operations in HITL simulations with busy traffic levels [5].

Three of these simulations, conducted in June of 2010, April of 2011, and January of 2012 included dense arrival flows into the Los Angeles (LAX) and Dallas-Fort Worth (DFW) airports. The operational environments were not identical between simulations; however the availability of CMS speed advisories designed to help the controllers more efficiently utilize speed control when delivering aircraft according to the runway schedule was common to all. Data collected during these simulations provides an opportunity to examine how controllers used the speed advisories, and how they incorporated them into their control strategy. The following sections describe the pertinent similarities and differences between the three simulations.

Simulation 1

The first simulation investigated the performance of advanced trajectory-based controller tools for three possible implementation timeframes. Based on the degree to which they change current-day operations, three toolsets were developed, designed to reflect what could be implemented in notional near-, mid-, and far-term timeframes. The far-term tools condition included the largest set of advanced DSTs; among them timeline displays, slot markers, and speed advisories. Speed advisories were included only in the far-term tools condition, which was tested in six of the 18 experiment trials.

As shown in Figure 3, the operations simulated focused on LAX arrival traffic flying merging RNAV OPDs to runways 24R and 25L. Three TRACON feeder sectors delivered aircraft to two final controllers working the two runways. All traffic scenarios were 60 minutes in duration and were simulated with forecast wind errors; the forecast winds were either 10 knots stronger or weaker than the actual winds, adding uncertainty to the ETA calculations [5].

Simulation 2

The second CMS simulation covered in this

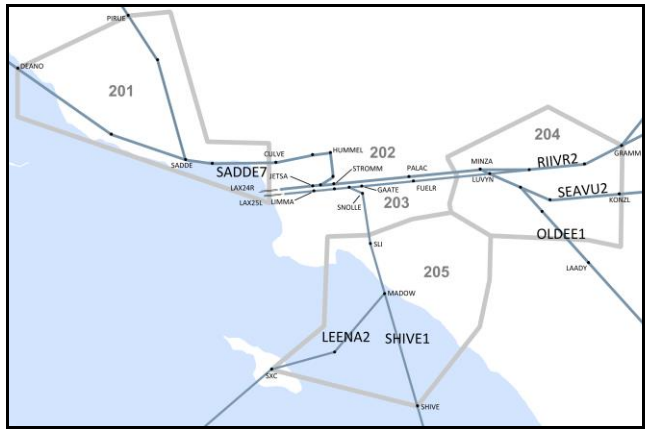


Figure 3. Test Sectors and RNAV Routes to LAX.

paper was very similar to the first simulation: the same airspace, sectors, and routes were used (Figure 3). The focus of this simulation was to investigate the robustness of the CMS concept and DSTs to off-nominal events such as go-arounds, on-board medical emergencies, and radio outages (‘NORDO’ aircraft). The off-nominal events were expected to disrupt the arrival flows enough to require schedule adjustments and, as a result, delays that would be too large for controllers to absorb with speed control alone (e.g., delays much larger than the ’60 s early to 30 s late’ range in [5]).

Consequently, there arose a need for additional DSTs to supplement the timelines, slot markers, and speed advisories. Path options in the form of named RNAV arrival routes were defined, in accordance with controller feedback, to help absorb larger delays and to help reinsert go-around aircraft back into the arrival flow. A traffic management supervisor responsible for making any necessary schedule adjustments was included as a study participant. The supervisor staffed a MACS workstation [13] with a traffic display and CMS runway-schedule timelines. The timelines included tools for manipulating the schedule by re-assigning, swapping, moving/shifting, and re-scheduling STAs, and also provided the ability to assign an aircraft to a different runway.

All tools were available in all of the 42 60-minute traffic scenarios. Forecast wind errors were included in all trials, with the forecast winds being either 13 knots stronger or seven knots weaker than the actual winds. Wind shifts were also simulated, similar to how a weather front might pass through. The actual wind direction changed either zero, one, or two times during a given trial, at which time the forecast winds were updated and the controllers were briefed about the changes. For trials with one wind change, the winds were scripted to change half-way through the trial; in trials with two wind changes, the changes occurred every 20 minutes.

Two other aspects of this simulation mark notable differences from the first simulation. At the MADOW waypoint on the SHIVE1 arrival, the altitude restriction was raised from 9,900 ft to 10,000 ft, to better accommodate the 250 knot speed limit under 10,000 ft. Also, in consideration of controller feedback from the first simulation, the speed advisory logic was modified to limit the speed advisory rejoin waypoint to sector-specific 'exit' waypoints. These waypoints were selected so as to align closely with where the controllers would normally hand-off aircraft to the next downstream sector. The two final approach fixes (JETSA and LIMMA), as well the waypoints CULVE, PALAC, FUELR, and SLI, served in this capacity.

Simulation 3

Part of a larger effort known as Air Traffic Management Demonstration-1 (ATD-1) [2], the third simulation's focus was two-fold: the first was the integration of the Interval Management Terminal-Area Precision Scheduling System (IM-TAPSS) components, specifically the CMS tools, an advanced arrival scheduler, and advanced avionics for Flight-Deck Interval Management (FIM). The second focus was to investigate the human factors issues associated with the operational procedures, and the issues associated with using the CMS tools for managing flows of scheduled arrival traffic in a mixed-equipage environment in which controllers manage the spacing of non-FIM equipped aircraft while FIM-capable aircraft use on-board automation to achieve precise spacing behind their lead aircraft [14].

Arrival traffic was simulated in the DFW airspace, with aircraft flying charted RNAV OPDs merging to DFW's runway 17C. TRACON controller participants staffed three feeder sectors and one final position, as depicted in Figure 4. In addition to the CMS tools, which include schedule timelines, early/late indicators, slot markers, and speed advisories, FIM status designators were added to the data block of FIM-capable aircraft to help controllers keep track of FIM operations.

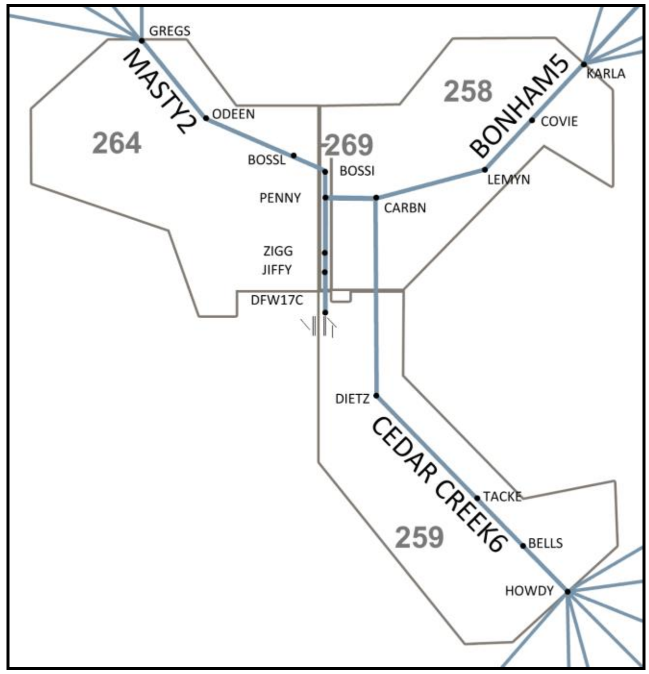


Figure 4. Simulated DFW TRACON Airspace.

Functioning as reminders that the controllers could enter, an '®' was displayed in the data block to indicate the FIM Required Time of Arrival (RTA) mode, and an 'S' was displayed to indicate the FIM paired-spacing mode.

Controller tool availability was varied across three conditions; only in the 'full tools' condition did the TRACON controllers have the speed advisories available to them. As in the first simulation, here the speed advisory logic did not include any limitations on the rejoin waypoint. Nineteen 60-minute trials were conducted, seven of which included the speed advisories and all other controller tools. Simulation constraints that have since been addressed did not allow winds to be included in this third simulation.

Results

The results in this paper analyze the usage data from three HITL simulations, referred to in this section as CMS3, CMS4, and CMS5; between them using two different logic types and taking place in two different airspaces. The analyses included herein examine what speed advisories were issued by the controllers as opposed to the speed advisories actually displayed, offering insights as to how well the speed advisories correspond to the control strategies used by the air traffic controllers.

Differences between what was issued and what was displayed will also serve as valuable feedback for improving the design of the speed advisory logic.

Speed Advisory Usage Data

The speed advisory usage results presented here analyze data independently across the speed advisory's two elements. For each speed advisory presented to the controller, what the controller actually issued may have included the advised speed as presented, the advised rejoin waypoint as presented, both, or neither. These possible usage outcomes are labeled in the figures in this section with the following conventions:

- No-No: The controller issued a speed other than that advised; the controller issued a rejoin waypoint other than that advised.
- No-Yes: The controller issued a speed other than that advised; the controller issued the rejoin waypoint as presented.
- Yes-No: The controller issued the speed as presented; the controller issued a rejoin waypoint other than that advised.
- Yes-Yes: The controller issued both elements of the speed advisory as presented.

Overall Findings

Across the three simulations, the speed advisory usage data indicates that the controllers modified the CMS speed advisories (i.e., issued something other than what was displayed) a majority of the time. A total of 7,733 speed advisories were issued by the controllers, 85.5% of which were modifications of the advisory (Figure 5).

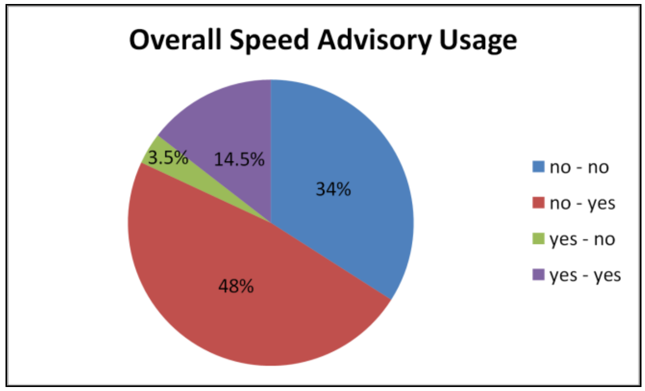
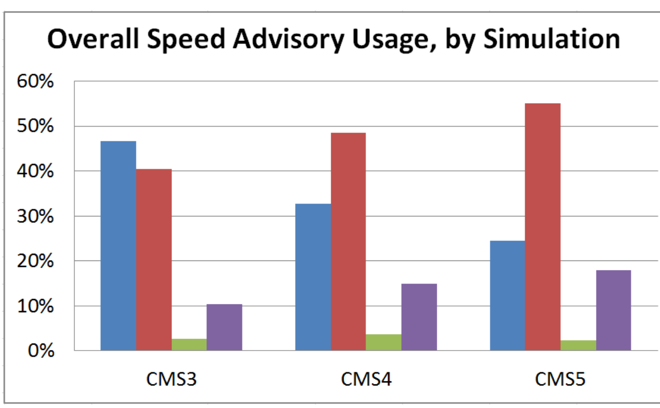


Figure 5. Overall Usage of Speed Advisories.

A comparison of data across the progression of simulations is shown on the left side of Figure 6, where several trends can be identified. First, the controllers issued increasingly more advisories that were in full agreement with the presented speed advisories. Also, the controllers issued increasingly fewer advisories where both speed advisory elements were modified. Thirdly, there was an increasingly higher proportion of issued advisories in which the controller modified only the speed element of the displayed speed advisory.

The right side of Figure 6 shows an analysis of the data when comparing usage between feeder and final controllers. Across the three simulations, the feeders and finals issued speed advisories where both elements were modified nearly equally as often. The feeder controllers issued speed advisories that matched exactly what was suggested roughly 20% more often than the final controllers, whereas the final controllers issued speed advisories with modifications only to the speed element roughly 20% more often than the feeder controllers.



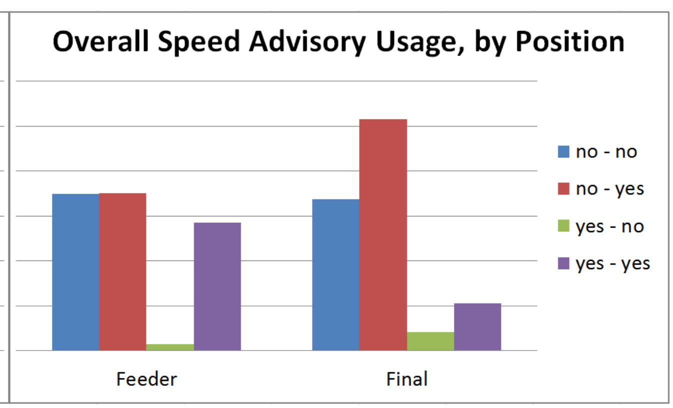


Figure 6. Usage Data Compared across Simulations (left) and Controller Positions (right).

Speed Advisory Modifications

More often than not, the controllers issued speed advisories that were modified versions of what was presented by the automation. An examination of modifications to the speed element, shown in Table 1, illustrates the amount by which the controllers modified the speed element of the advisory. Positive values in Table 1 indicate the controller issued a speed faster than that advised, while a negative number indicates the controller issued a speed slower than advised. Depending on the schedule error of the aircraft, modifications to the advised speed can be interpreted as a more aggressive action on behalf of the controller (e.g., issuing a speed faster than advised for an aircraft that is late, or issuing a speed slower than advised for an aircraft that is early).

When modifying both elements of the speed advisory, the difference between the feeder controllers' issued speed and advised speed always averaged out to a faster issued speed. This finding was most pronounced during the second simulation, where the feeder controllers issued speeds faster than those advised by a notably larger margin. In all cases, the occurrences of modifications to both elements of the speed advisory by controllers were associated with a larger standard deviation of issued-speed-to-advised-speed differences, suggesting that larger speed modifications were more likely to be accompanied by modifications to the waypoint element as well.

Table 1. Speed Element Modification Data.

	N	Mean	SD	Min	Max
CMS3					
Feeder					
no-no	82	5.78	28.53	-85	60
no-yes	75	6.55	13.53	-40	36
Final					
no-no	293	-29.59	27.90	-110	45
no-yes	246	2.55	12.21	-45	35
CMS4					
Feeder					
no-no	496	38.51	25.44	-30	100
no-yes	491	7.08	16.21	-70	100
Final					
no-no	1729	-11.97	27.69	-90	70
no-yes	2803	2.12	15.31	-70	60
CMS5					
Feeder					
no-no	18	18.61	11.98	-5	40
no-yes	32	-2.66	5.53	-10	5
Final					
no-no	23	-10.26	26.50	-65	29
no-yes	60	-29.58	12.86	-40	10

A comparative analysis of the controllers' modifications to the waypoint element is shown in Table 2. An along-track, geographic assessment was performed to categorize how the waypoint element issued by the controller related to the advised waypoint: If the rejoin waypoint of the controller's issued speed advisory was upstream of the suggested rejoin waypoint, a value of 1 was assigned; if downstream of the suggested rejoin waypoint, a value of -1 was assigned. Under this scheme, a high

Table 2. Waypoint Element Modification Data.

	N	Mean	SD
CMS3			
Feeder			
no-no	82	0.49	0.88
yes-no	5	-0.20	1.10
Final			
no-no	293	-0.84	0.54
yes-no	16	-0.50	0.89
CMS4			
Feeder			
no-no	496	0.98	0.22
yes-no	17	0.88	0.49
Final			
no-no	1729	-0.55	0.84
yes-no	231	-0.32	0.95
CMS5			
Feeder			
no-no	18	0.11	1.02
yes-no	2	0.00	1.41
Final			
no-no	23	-0.57	0.84
yes-no	2	1.00	0.00

frequency of waypoint modifications to points upstream, when averaged across all data, would approach a value of 1; a controller who more often modified the speed advisories by issuing downstream waypoints would produce an average value closer to -1. Using a rejoin waypoint upstream of the advised waypoint can also be considered as an action by the controller to more aggressively address the schedule error.

When modifying both elements of the speed advisory, feeder controllers more often issued upstream waypoints, whereas final controllers more often issued downstream waypoints. During the second simulation, the feeder controllers more consistently modified the advised waypoint, showing a strong tendency to issue rejoin waypoints upstream of that advised.

Other Factors

The impact of the approach taken in the second simulation to associate the speed advisory's rejoin waypoint with fixed sector exit points is investigated in Figure 7. A possible hypothesis for this logic style is that it would result in a higher acceptance rate with fewer modifications to the speed advisories (i.e., fewer no-no and yes-no usage outcomes, and more no-yes and yes-yes usage outcomes). The final controller's usage trends followed this hypothesis, with the exception of the yes-no data, which did not show much change between the rejoin waypoint logic types. The feeder controller saw a proportionately larger increase in advisories issued with both elements matching the presented advisory, which contributed to a slight decrease in cases where both elements were modified and in cases where only the speed element was modified.

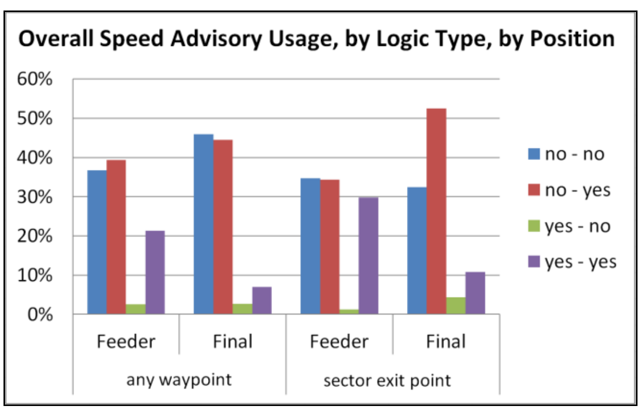


Figure 7. Usage Data across CMS Speed Advisory Logic Types.

Figure 2 (profile b) illustrates a possible speed profile computed by the automation in which an aircraft estimated to arrive late could correct its scheduling error by initially slowing down. Although this advisory is able to deliver the aircraft on time, the counter-intuitive nature may be undesirable, or at the very least confusing, for the controllers. Figure 8 highlights how this type of speed advisory was received by the controllers. Data for this analysis was not directly available, but an approximation thereof was obtained by filtering the raw data set so as to only include aircraft that were, at the time a speed advisory was presented, predicted to arrive late, and whose speed advisory suggested a speed slower than the aircraft's current speed. The data in Figure 8 indicates that the feeders modified both elements more than 56% and the finals modified both elements for one-fourth of these counter-intuitive advisories. However, they were both able to work with the automation to some degree, as evidenced by the feeders accepting just over one-fourth and the finals modifying the speed element for 70% of these advisories.

Across the three simulations, the automation provided speed advisories to the controllers in either 5- or 10-knot increments. As shown in Figure 9, the speed element of the advisories issued by the controllers was always in 10-knot increments. In all instances, when presented with a speed advisory containing a 5-knot increment speed, the controllers modified either just the speed element, or both the speed and rejoin waypoint elements.

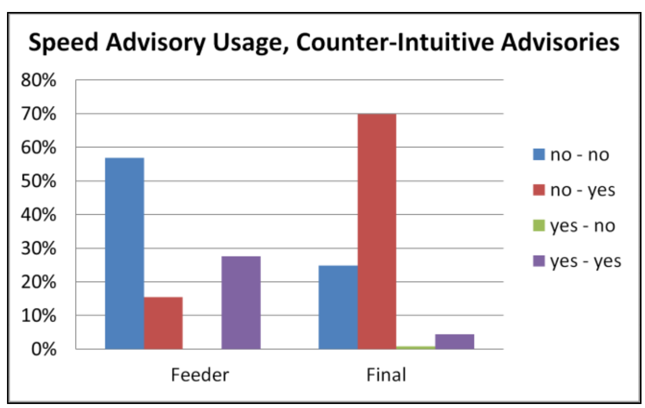


Figure 8. Usage Data in Response to Counter-Intuitive Advisories.

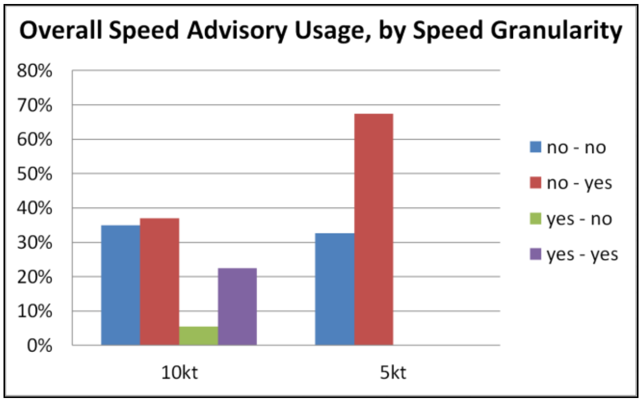


Figure 9. Usage Data across Granularity of Advised Speeds.

Discussion

These results indicate the controllers were able to use the CMS speed advisories as part of their sector operations. Over the three simulations, the controllers modified both elements increasingly less while accepting speed advisories and/or modifying just the speed element increasingly more often. This positive result suggests the speed advisories, even with their shortcomings, were of some utility to the controllers.

Several factors appear to have impacted the usage of the speed advisories, to varying extents; the simplest of which is the 5- vs. 10-knot speed increment. Advising speeds in 5-knot increments did not fit at all with the controllers' management of arrival traffic; they all completely avoided these types of speeds and clearly preferred to issue speeds in 10-knot increments.

The design aspect with the farthest-reaching effect is almost certainly the rejoin waypoint logic. Likely resulting from a combination of factors and exemplified in the feeder's data for the second simulation in Table 1, the speed element of presented speed advisories were more heavily modified. By examining off-nominal operations, the second simulation more often saw situations in which aircraft were behind schedule, when compared to the other two simulations; a result of schedule manipulations made in response to arrival-flow disruptions. Meanwhile, the feeder controllers' speed advisories were limited to sector exit points all of which had charted altitude restrictions at or near 7,000 ft. Just as in the real-world, aircraft during these simulations were not allowed to fly faster than 250 knots when below 10,000 ft, a constraint which was designed into the speed advisory logic. In sector 201 for example (Figure 3), this meant that if an aircraft was late, the fastest speed advisory possible was '250 CULVE.' Not only would such an advisory fail to deliver the aircraft for an on-time arrival, it often had the potential to worsen the situation by appearing to suggest a *slow-down*, since often the aircraft was descending from a higher altitude and still flying a faster speed (e.g., 300 knots).

Using the sector exit point as the speed advisory's rejoin waypoint also impacted the final controller. Depending on how early the final controller took the hand-off from the feeder, the aircraft may still have been upstream of the feeder's sector exit point. The final controllers typically wanted to issue corrective speed clearances to the aircraft as soon as possible after taking the hand-off, but situations occurred where the speed advisory for the aircraft just coming under the final controller's control was still displaying a speed advisory for the feeder controller's sector exit point. These cases left the final controller with little choice but to issue a modified speed advisory. This issue also helps to explain waypoint modification data in Table 2 for the final controller in the second simulation. The equivalent sector exit point used for the final's speed advisories was the final approach fix, but Table 2 indicates that modifications were made to the rejoin waypoint element of the presented speed advisories in the *downstream* direction. Again, due to the final controller's early acceptance of the hand-off from the feeder, the displayed speed advisory was still referencing the feeder's sector exit point. Speed advisories issued by the final controller to aircraft in these situations then, naturally included rejoin waypoints downstream from that advised.

Figure 7's data suggests that the idea of using sector exit points for the speed advisory's rejoin waypoint appears to have some value though, as evidenced by fewer modifications of both elements and more accepted advisories. But perhaps certain flexibilities could be introduced to the speed advisory's logic, to help further improve the acceptability of the speed advisories. Aircraft with late ETAs for example, could be treated differently than aircraft with early ETAs, perhaps with different rejoin waypoints whose altitude does not impose additional constraints on suggestible speeds.

Controller ownership (track control) could also be considered by the speed advisory logic, such that the rejoin waypoint would not be exclusively determined by which closest sector exit point is in front of the aircraft, but could also take into account which controller owns the aircraft, and use that controller's sector exit point.

While these suggestions can be seen as attempts to enhance the speed advisory's schedule awareness or to add some form of ownership awareness, they share in common the goal of improving the speed advisory's relevance to the task at hand, its *contextual awareness*.

Conclusion

The data presented here details how the controllers interacted with the speed advisories during three HITL simulations. Over the three simulations, TRACON operations in two different airspaces were simulated, and two types of speed advisory rejoin waypoint logic were investigated. Although more often than not modified by the controllers, they were able to incorporate the CMS speed advisories into their work flow.

Between the three simulations there were several differences, such as winds simulated, participants used, and objectives studied. While these differences were able to bring to light various issues associated with the controllers' usage of the CMS speed advisories, they also potentially limit the generalizability of the conclusions drawn from observed trends in the data.

Results highlight the impact of certain aspects of the speed advisory's design on the tool's ability to help controllers work busy periods of arrival traffic in runway scheduling environments. Suggestions have been offered to improve the speed advisory's relevance to controller's task, but need to be carefully considered with regard to possible trade-offs associated with such changes. Additionally, work has already begun on a new speed advisory design, which does not include a displayed rejoin waypoint [15].

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