FREE MANEUVERING, TRAJECTORY NEGOTIATION, AND SELF-SPACING CONCEPTS IN DISTRIBUTED AIR-GROUND TRAFFIC MANAGEMENT

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Abstract

A simulation of integrated air and ground operations was conducted at NASA Ames Research Center to evaluate three Distributed Air/Ground Traffic Management (DAG-TM) Concept Elements – En Route Free Maneuvering (CE 5), En Route Trajectory Negotiation (CE 6), and Terminal Arrival Self-Spacing (CE 11). Controller participants managed simulated traffic using Center Terminal Radar Control (TRACON) Automation System tools [1] while commercial pilot participants flew aircraft simulators equipped with a cockpit display of traffic information (CDTI) that had conflict detection and resolution and required time of arrival capabilities. Data were collected from twelve simulation runs to compare our current implementation of DAG-TM en route and terminal concepts against baseline conditions that approximated current day operations. Results suggested that potential improvements in efficiency and capacity may be gained without compromising safety or significantly increasing workload in the two en route conditions.

DAG-TM research is funded by Airspace Systems program as part of the Advanced Air Transportation Technologies project. DAG-TM activities are conducted by NASA Ames, NASA Langley, and NASA Glen Research Centers.

Introduction

The objective of the Advanced Air Transportation Technologies (AATT) Project is to improve the performance of the National Airspace System (NAS) by developing decision support technologies and procedures that target near-term, mid-term, and far-term operations. Distributed Air/Ground Traffic Management (DAG-TM) is a set of fifteen “Concept Elements” (CEs) for gate-to-gate NAS operations beyond the year 2015 that use distributed decision making among users (flight crews and/or airline dispatch) and air traffic service providers. Its goal is to enhance user flexibility and efficiency and increase system capacity without adversely affecting system safety [2].

Simulation research on three DAG-TM CEs—CE 5: En Route Free Maneuvering, CE 6: En Route Trajectory Negotiation, and CE 11: Terminal Arrival Self-Spacing—began in 2001 at the NASA Ames, Glenn, and Langley Research Centers [3-5]. It will continue through 2004, with regular simulation evaluations of the developing concepts, tools and procedures. Related prior research is presented in [5-9]. This paper describes a simulation conducted at NASA Ames in September 2002 to explore the potential benefits and viability of our current implementation of the three CEs. A related paper describes the potential benefits of trajectory-oriented time-based arrival operations implemented to support the three CEs in this simulation [10]. Planned future simulations will address severe weather, special use airspace, and an increased number of aircraft equipped with cockpit display of traffic information (CDTI). Joint simulations with NASA Langley and NASA Ames will begin in 2003.

CE 6 – En Route Trajectory Negotiation

The goal of CE 6 is an en route operational environment that supports enhanced trajectory coordination between controllers and pilots of properly equipped aircraft. Automated data link functions communicate winds, traffic flow management (TFM) constraints, and current aircraft state information between air and ground. Pilots and controllers use decision support tools (DSTs) that process this information to develop conflict-free, TFM-compliant flight path changes, which are sent as trajectory change requests (pilot to controller) or trajectory clearances (controller to pilot) using controller-pilot data link (CPDLC). While flight path changes can be proposed by either party, responsibility for maintaining separation in the CE 6 environment lies exclusively with the controller.

CE 5 – En Route Free Maneuvering

CE 5 uses the air-ground communication enhancements and DSTs that support trajectory negotiation in CE 6 to explore the potential benefits and feasibility of delegating responsibility for maintaining separation to flight crews of properly equipped aircraft. Under CE 5, free maneuvering aircraft may modify their flight path without the controller's approval, as long as they do not create conflicts while doing so. Note that controller is NOT responsible for separation between free maneuvering aircraft.

CE 11 – Terminal Arrival: Self-Spacing for Merging and In-Trail Separation

In CE 11, equipped aircraft use flight deck DSTs in the terminal area to maintain in-trail spacing (in units of time) with a lead aircraft and to merge into an arrival stream, upon controller's command. Terminal Radar Control (TRACON) controllers issue clearances to equipped aircraft that designate the lead aircraft and self-spacing time interval to be maintained.

DAG-TM 2002 Simulation

The goals of the September 2002 NASA Ames DAG-TM demonstration were two-fold: to form an initial assessment of the operational viability and potential benefits of the three CEs, and to assess the current and future simulation technology needed to adequately test these concepts.

Airspace

Our simulation airspace included portions of Fort Worth Center (ZFW) and Dallas-Fort Worth TRACON (DFW) (see Figure 1). Controller participants worked five test sectors in ZFW's northwest arrival corridor: three high altitude sectors (Amarillo in Albuquerque Center, Wichita Falls and Ardmore in ZFW), one ZFW low altitude sector (Bowie), and one DFW TRACON arrival position. Three retired controllers worked Ghost North, Ghost South and a second TRACON position to handoff traffic to the five test controllers.

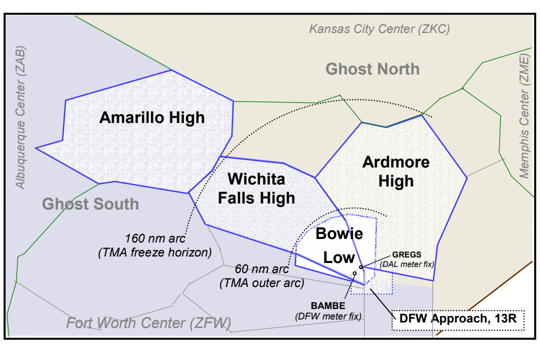

Figure 1. Simulated Airspace

Participants

Five full performance level controllers participated in the study: two from Oakland Center, one from Atlanta Center, one from Bay TRACON, and one from DFW TRACON. Eight commercial pilots also participated. Two pilots flew the Advanced Concepts Flight Simulator and six pilots operated desktop flight simulators with advanced DSTs. Seven private pilots flew all remaining aircraft in the simulation from Multi Aircraft Control System (MACS) workstations [6].

Equipment

During CE 5, CE 6 and CE 11 simulation runs, all aircraft had CPDLC, a flight management system (FMS), automatic dependent surveillance-broadcast (ADS-B), and self-spacing capabilities. The seven aircraft flown by the commercial pilot participants also had the CDTI with required time of arrival (RTA) capabilities and conflict detection and resolution (CD&R). These "equipped" aircraft were assigned free maneuvering status in CE 5 and could negotiate trajectories in CE 6.

Controller DSTs during CE 5 and CE 6 runs included the Center-TRACON Automation System (CTAS), Traffic Management Advisor (TMA), a timeline representation of the TMA meter fix schedule, a trajectory-based conflict probe, trial planning capability, color enhancements to the traffic display, and CPDLC. The controller's sector timeline provided a graphical representation of the TMA meter fix schedule, with expected time of arrivals (ETAs) on the left side and scheduled time of arrivals (STAs) on the right. Figure 2 shows a portion of the timeline for one simulation run, indicating the increasing delay assigned by the TMA to distribute ten aircraft predicted to reach the meter fix in a six minute interval.

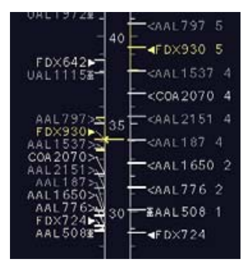

Figure 2: TMA timeline on controller's display

Controllers could request speed advisories computed for an aircraft's current route that would deliver it to the meter fix on the TMA's STA. Controller DSTs and air-ground procedures used in this simulation are described in greater detail in [6,10]. During the baseline condition runs, CPDLC and trajectory negotiation were unavailable and no aircraft had free maneuvering authority. Controllers used the TMA schedule (represented as a meter list) without the additional DSTs described above.

Scenarios

Arrival aircraft entered the scenario between 60 and 300 nm from DFW airport. The TMA was configured to create a schedule that delivered these aircraft at seven miles in trail across the Bambe meter fix. The unscheduled arrival flow was such that a mean delay of two minutes per aircraft was needed to conform to the assigned STAs. Delay magnitude increased throughout the course of the 75 minute run, with later aircraft often assigned 3-5 minute delays.

Aircraft in the CE 5 and CE 6 conditions received an initial STA uplink when they first entered the scenario and a second STA uplink when they reached the freeze horizon at 160 nm. This second STA was also the RTA at the meter fix for all aircraft. In CE 5, equipped aircraft modified their speed and routes in order to meet this RTA while maintaining separation from other aircraft. When conflicts were predicted between two free maneuvering aircraft, or between free maneuvering and controller-managed aircraft, priority rules were used to determine who was responsible for resolving the conflict. In CE 6, pilot participants could modify their speeds to meet the RTA without requesting controller approval but were required to negotiate any route modifications. In CE 5 and CE 6, the Wichita Falls and Ardmore controllers were asked to match the aircraft's ETA at the meter fix to its STA/RTA. At the meter fix, the Bowie controller and pilot participants (CE 5 only) were asked to deliver aircraft within 15 seconds of the meter fix STA/RTA.

The aircraft transited continuously between the en route and terminal concepts. Once an aircraft entered the TRACON, free maneuvering status was canceled automatically. Under CE 11, the TRACON controller could issue self-spacing clearances to any aircraft, delegating the task of achieving the assigned spacing to the pilots. Self-spacing clearances specified a lead aircraft and a time interval. The pilots used the CDTI and manage their speed to achieve the assigned temporal spacing.

The baseline condition approximated current day operations. The ZFW controllers issued tactical heading, altitude, and speed instructions to aircraft to meet STA for specific sector exit conditions. The exit condition for the high altitude controllers was referenced to a 60 nautical mile arc around the respective meter fix, which the aircraft had to cross at flight level 240 and 280 knots indicated air speed at the outer arc STA. The low altitude controller was instructed to provide seven nautical miles in trail over the meter fix to approach control, which the aircraft had to cross at 11000 feet and 250 knots.

Some modifications were made to ensure task equivalency across conditions. One important change was the use of ADS-B state data in the baseline condition. ADS-B data has a higher update rate (1 sec v. 12 sec) as well as increased accuracy compared to radar data. This change was necessary to ensure that any benefits observed in the CE 5 and CE 6 conditions were due to concept differences rather than better state information. A second important change was that the STAs and the required delays were shown to the seconds, unlike the one minute resolution in current day operations. The low altitude controller tried to deliver the planes on their STAs whenever possible, potentially creating a more difficult task than in the field today.

The air traffic scenario consisted of about 90 aircraft, 40 of which were arrivals. Seven of the 40 arrival aircraft were flown by the pilot participants. There were three scenarios with similar traffic density and complexity and each scenario lasted for about 75 minutes. The data were collected during four days with three simulation runs per day, totaling 12 simulations runs with four runs per condition – i.e. CE 5/CE 11, CE 6/CE 11, and baseline.

Results and Discussion

The main interest in the analyses was to determine whether there were any potential benefits attributable to CE 5 or CE 6 and if these concepts were operationally viable. Benefits were categorized into two broad categories: efficiency and arrival capacity. Many of the measures reported in this section are similar or identical to those in [11]. Operational viability was also examined in terms of safety (e.g. separation violations), and controller/ pilot workload. For CE 11, only the feedback from controller and pilot participants are reported since TRACON controllers' strategies evolved throughout the data collection during the simulation, rendering the quantitative data misleading.

Benefits

The following benefits analyses are based on the arrival aircraft only. The data from the aircraft were collapsed across run (7 CDTI-equipped aircraft; 40 aircraft overall), such that each run constituted a data point. From 84 CDTI-equipped aircraft in the simulation runs, three aircraft (two in baseline and one in CE 5) were excluded from the analyses because of software errors.

Efficiency

In support of CE 5 and CE 6 concepts, trajectory-based arrival metering was implemented, in which the ground side used CTAS tools (e.g. speed advisories, timeline, trial planning, conflict probe, etc.) to keep the planes on their 4-D trajectories and deliver them to the meter fix at their STAs. A potential benefit of using these tools in the context of CE 5 and CE 6 was that an aircraft could fly a more efficient route. It could stay on a preferred trajectory longer by using its vertical navigation descent and speed advisories to meet its STA instead of using vectors. In addition, improved CD&R capabilities allowed a reduction of non-preferred deviations. A free maneuvering aircraft in the CE 5 condition could have improved its efficiency further by using the air side DSTs to craft a custom route that fully accounted for the pilot preferences.

A desired efficiency metric would have been aircraft fuel consumption, but we could not measure it at the time. The metrics for flight time, distance, and altitude were used instead since fuel consumption is highly correlated with these metrics (i.e. shorter flight time, shorter flight distance, and higher mean altitude correlates with less fuel consumption).

Flight Distance. If an aircraft could fly its preferred trajectory in CE 5 and CE 6, then it would have deviated less from a direct route and therefore resulted in a shorter distance traveled during the flight. When the median distance traveled from the freeze horizon (160nm) to the meter fix (MF) was measured, the planes in the baseline condition flew a longer distance (174.5 nm) than CE 6 (167.1 nm) or CE 5 (165.8 nm; see Figure 3). The distance along the original flight path was 164 nm, suggesting that planes in CE 5 and CE 6 flew close to the original flight path while absorbing the necessary delay.

To see if free maneuvering aircraft in CE 5 had any additional benefits over corresponding aircraft in CE 6, the median flight distance of the CDTI-equipped planes were analyzed across conditions. Figure 3 illustrates that data trended towards added benefit of the CE 5 condition but the findings were inconclusive due to large variability.

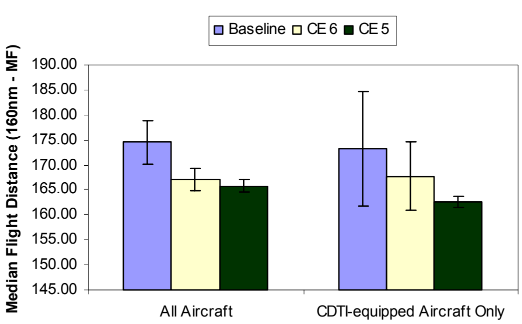

Figure 3: Median Flight Distance (160nm - MF) (4 samples/condition; error bars = +/- 2*std error)

CDTI-equipped planes in CE 5 seemed to fly a shorter distance (162.6 nm) than in CE 6 (167.8 nm) or in baseline (173.3 nm). Large variability might have been due to learning effects in the baseline condition (181 nm and 185 nm for the first two runs; 163 nm and 164 nm for the last two) and a longer flight distance (178 nm) in the last run of the CE 6 condition.

Therefore, the results suggest that planes in CE 5 and CE 6 flew shorter paths than in baseline, and they also provided partial support for more direct paths for free maneuvering aircraft than controller-managed aircraft. It is possible that the benefits of CDTI-equipped planes in CE 5 was not sufficiently highlighted because the trajectories were close to optimal and the CE 5 and CE 6 conditions provided tools to maintain these trajectories. The CE 5 condition may need to be run in more stressful conditions (e.g. bad weather) to sufficiently differentiate the benefits of free maneuvering from controller-managed aircraft.

Mean Flight Altitude. An aircraft can maintain better fuel efficiency if it flies at higher altitudes. In current day operations, however, controllers often descend an arrival plane early for a number of reasons, such as delay absorption and conflict resolution. With trajectory-based arrival metering and improved tools in CE 5 and CE 6, controllers were expected to keep the planes on their preferred altitude until the top-of-descents (TODs) since the tools allowed them to manage the arrival flow and the conflicts with speeds and modest route modifications instead of using altitudes. Figure 4 illustrates the mean altitudes from the freeze horizon (160 nm) to the meter fix. As predicted, the planes flew at a lower mean altitude in baseline (26843 ft) than in CE 5 (28038 ft) or CE 6 (28064 ft).

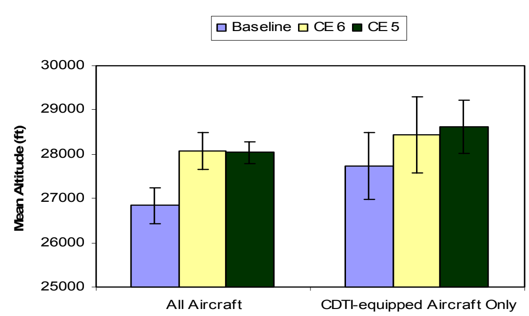

Figure 4: Mean Altitude from 160nm to MF

In CE 5, CDTI-equipped planes could have flown at higher altitudes than in CE 6 if pilots maintained higher altitudes than controllers in order to maximize fuel efficiency. However, trajectory-based arrival metering already facilitated controllers and pilots to keep the aircraft at high altitudes. This might have been why there were only small differences between CE 5 and CE 6 (28621 ft for CE 5, 28439 ft for CE 6, and 27737 ft for baseline).

Flight Time. Besides a shorter flight distance and higher altitude, a third component of an efficient flight path is a shorter flight time. The planes in the CE 6 condition were expected to fly shorter routes by avoiding excessive deviations from preferred trajectories. In addition, CDTI-equipped planes in CE 5 might have cut flight time further since pilots could spend more time creating the most direct path for their own planes than controllers.

As shown in Figure 5, the planes in CE 5 flew from the freeze horizon to the meter fix in less time (24.8 min for CE 5 vs. 26.2 min for baseline). The median flight time for CE 6 fell in-between (25.3 min), mainly due to the fact that the median flight time of the last run (26.0 min) in CE 6 was much longer than the other runs in CE 6. The median flight times of the CDTI-equipped planes showed a similar pattern of results (25.6 min for baseline, 24.7 min for CE 6, and 24.2 min for CE 5; see Figure 5) but were less significant due to large variability.

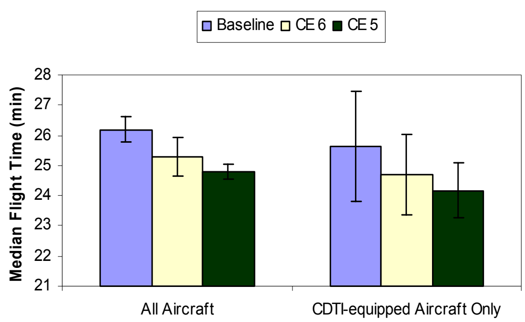

Figure 5: Median Flight Time from 160nm to MF

In summary, the results suggest that an aircraft in CE 5/CE 6 could fly a more efficient path, defined as shorter distance, higher altitude, and less flight time than in the baseline condition. The results also showed a trend towards less flight time and shorter distance in CE 5 compared to CE 6. To show significant advantage of the CE 5 concept, more free maneuvering aircraft and more stressful conditions may be needed.

Arrival Capacity

A limiting factor in arrival capacity is aircraft density in the airspace, which can be reduced if each aircraft fly a shorter and more direct path that takes less time. As shown in the previous section, the flight path and the flight time were minimized for the planes in CE 5 and CE 6, suggesting that it would be easier to increase the aircraft density in these conditions than in current day operations. Arrival capacity can also be increased if fewer "slots" are wasted when the planes are sequenced to be delivered to the approach control. An advantage of implementing trajectory-based arrival metering to support CE 5 and CE 6 concepts was that it allowed a delivery of the aircraft to the meter fix in a more predictable and evenly spaced flow. In CE 6, the ground side tools provided controllers with a timeline with accurate ETAs and STAs to the meter fix, which they could monitor and adjust using speed advisories and route modifications. In CE 5, pilots in the free maneuvering planes could meet their RTAs accurately using the air side tools.

Spacing. In our simulation runs, the TMA was set up to create a schedule to deliver the aircraft at the meter fix with a minimum spacing of seven miles, which was equivalent to 82 seconds between adjacent aircraft. Controllers and pilots were asked to deliver each aircraft at +/- 15 seconds from its STA. Given the improved DSTs in CE 5 and CE 6, better spacing was expected in these conditions.

As shown in Figure 6, the number of aircraft that were spaced within 15 seconds of the desired 82 second spacing was higher in CE 6 (104) than in baseline (64), with CE 5 in the middle (83). The number of aircraft below the 67 second spacing was 34, 21, and 26 for baseline, CE 6, and CE 5, respectively. Although spacing greater than 97 seconds might have been due to a legitimate gap in the STAs, more planes in this category for baseline (68) than CE 6 (40) or CE 5 (54) suggest that the planes were delivered with tighter spacing in CE 6/CE 5 than in baseline. Overall, the results suggest that the controller delivered planes with more consistent spacing in CE 6 or CE 5 than in baseline.

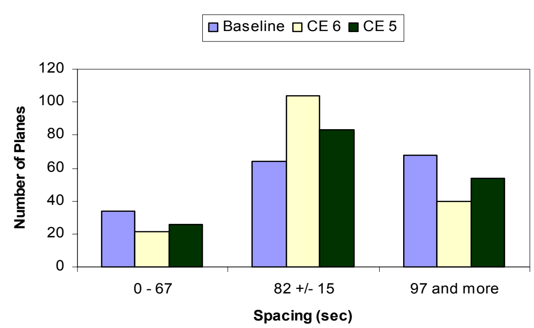

Figure 6: Spacing between planes at the meter fix

In addition, planes below 58 seconds spacing had less than five miles lateral separation and therefore needed to be separated by altitude at the meter fix. There were 17, 4, and 13 planes which had less than 58 seconds spacing in baseline, CE 6, and CE 5, respectively, suggesting that the planes in CE 6 best met the meter fix altitude constraints.

In general, the CE 6 condition delivered planes with better spacing than the CE 5 condition. One possible explanation is that the difference was due to the inability of the free maneuvering planes to meet their STA constraints. However, CDTI-equipped planes were few in number relative to the total number of planes, and the performance of the CDTI-equipped planes did not differ significantly between CE 5 and CE 6, suggesting that the performance of these planes was not the causal factor in the spacing difference (see Table 1). More analyses are needed to understand this difference.

Table 1: CDTI-equipped planes: Spacing between planes at the meter fix

	Spacing			
	0 - 58	**58 - 67**	**82 +/- 15**	**97 +**
baseline	2	5	13	6
CE 6	2	3	16	7
CE 5	2	4	14	7

Arrival Delivery Accuracy. If the controllers (and pilots in CE 5) could deliver the aircraft at the meter fix with sufficient precision, then the spacing buffers between planes could be reduced, resulting in an increase the arrival capacity. In the simulation, the controllers (and pilots in CE 5) were asked to deliver each plane at +/- 15 seconds from its STA. Given better DSTs (e.g. timeline) in CE 5/CE 6 than in baseline, the planes were expected to be delivered more accurately to their STAs at the meter fix. The pilots in CE 5 could have also delivered their own planes more accurately to their STAs since they had more time to monitor their own arrival times.

To determine the arrival delivery accuracy, the difference between the actual time of arrival (ATA) and the STA was examined. If the controllers and the pilots could deliver the planes more accurately, there should be less variability in ATA-STA difference. A closer look at the data, however, revealed two confounding factors that unfairly biased this metric. In our simulation runs, whenever an aircraft was off of its STA, the controllers normally took one of two actions. First, if there were no other slots available near its STA or if the aircraft was significantly off of its STA, the controllers re-sequenced the planes such that all other planes could still be delivered on their STAs and fit the non-conforming aircraft in the nearest available slot. Secondly, if the aircraft was near its original STA but was encroaching upon the STA of an adjacent aircraft, the controllers generally swapped the STAs of the two planes. Since the controllers did not have the ability to easily re-sequence the STAs, any plane that was re-sequenced would have an ATA that deviated significantly away from its STA, thereby weighing in heavily in the overall ATA-STA calculations. Similarly, the controllers often swapped two adjacent planes without using the pairwise swap function that was provided for them, thereby resulting in ATA-STA difference which would not have existed if the swap was properly executed.

Although swaps and re-sequences could suggest less accurate delivery of aircraft, they might have been corrected if the controllers were able to shuffle the Traffic Management Unit schedule, as they do in the field today. Therefore, the swaps and re-sequences were counted separately in the analyses. As shown in Table 2, the number of swaps and re-sequences were much greater in the baseline condition than in CE 6 or CE 5, suggesting less accurate delivery of aircraft in the baseline condition.

Table 2: Total number of swaps and re-sequencing of aircraft in baseline, CE 6, and CE 5 (4 runs per condition at approx. 40 A/C per run)

	Swap	**Re-sequence**
baseline	9	8
CE 6	2	1
CE 5	1	1

The ATA – STA difference was calculated after excluding the re-sequenced planes and correcting the STAs of the swapped planes. After these corrections, histograms of ATA-STA difference were approximately normally distributed (see Figure 7).

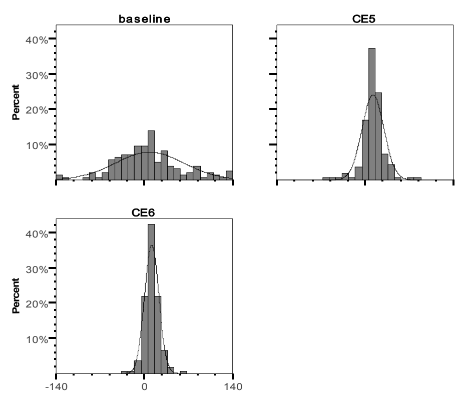

Figure 7: Arrival Accuracy (ATA – STA)

Although the means of the difference were similar across conditions (8.1, 11.4, and 12.3 sec delay for baseline, CE 6, and CE 5, respectively), there was significantly more variability in the aircraft delivery under the baseline condition (SD = 53.9) than either CE 6 (SD = 11.4) or CE 5 (SD = 17.2; see Figure 7). These results suggest that the planes were delivered more accurately using trajectory-based arrival metering and improved DSTs (e.g. timeline) than in current day operations.

The arrival accuracy of CDTI-equipped planes were examined across conditions to see if the pilots could deliver their own planes more accurately in CE 5 than other conditions. The pilots delivered their planes with less variability in CE 5 (SD = 20.3) than in baseline (SD = 51.0) but more than in CE 6 (SD = 11.9; see Figure 8). However, since the difference between CE 5 and CE 6 was due to few planes and the pilots were in general less familiar with meeting their RTAs than the controllers, the finding is inconclusive. These issues will be addressed in the next simulation so that the potential benefits/ disadvantages of CE 5 can be better examined.

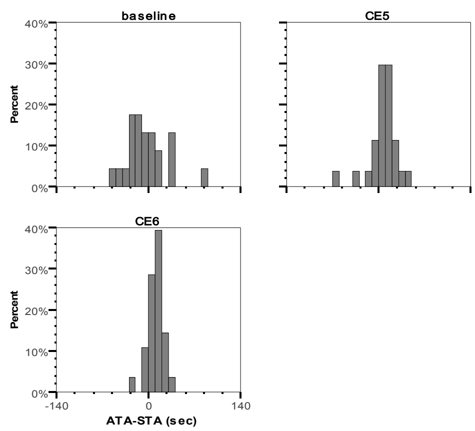

Figure 8: CDTI-equipped planes: Histogram of Arrival Accuracy (ATA – STA)

In summary, the planes were delivered more accurately and with better spacing in the CE 5 and CE 6 conditions than in the baseline condition. These improvements were likely due to trajectory-based arrival metering and the improved DSTs in these conditions. There was a slight advantage of CE 6 over CE 5, but the results did not seem to be due to the concept difference. The nature of this difference will be examined further in the future simulations.

Operational Viability

Safety

It is important that safety is not compromised by CE 5 and CE 6 concepts. One objective measure of safety is the number of separation violations. Table 3 shows the total number of separation violations in the en route sectors in our simulation runs. Five separation violations (3 in CE 5 and 2 in baseline) that involved a subject and a confederate controller were excluded from the analyses because they were likely due to idiosyncrasies of our simulation environment and not reflective of the overall concept. Another violation was excluded from the analyses because it was due to an equipment failure on a CDTI-equipped plane.

As shown in Table 3, the low altitude controller had one separation violation in baseline and none in CE 5 or CE 6. The high altitude controllers had one violation each in CE 5 and CE 6 but a large number of violations in the baseline condition. A high number of violations in the baseline condition might be a cause for concern since this condition approximated current day operations.

Table 3: Total number of separation violations (4 runs per condition at approx. 90 A/C per run)

	Low Altitude	High Altitude
baseline	1	6
CE 6	0	1
CE 5	0	1

However, our simulation did not have many of the safeguards given to the controllers in the field today. Most importantly, the number of violations would have been significantly reduced if our simulation had the conflict alert capability that exists in current day operations, which alerts the controllers about near-term potential conflicts. Also, there were no en route radar associate positions and the confederate controllers sometimes handed off aircraft with potential conflicts near the sector boundaries, which would not happen in the field today. Given the lack of safeguards in our simulation, these findings should be viewed as conservative measures and a lower number of violations should have occurred across all conditions if the controllers received equivalent support to that available in the field today.

The results suggest that CE 5/CE 6 operations did not decrease overall safety (as measured by the number of separation violations), which was critical for the viability of these concepts. In fact, safety in the high altitude sectors might have been increased, possibly due to the added functionalities of the ground and air side tools (e.g. 4-D conflict probe, data link, etc.).

The pilots had responsibility for monitoring separation of their own aircraft in CE 5. An increase in violations for CDTI-equipped planes in CE 5 over CE 6 would suggest decreased capability of pilots and controllers to maintain separation in a mixed airspace of free maneuvering and controller-managed aircraft, compared to the ability of the controllers to maintain separation of 100% managed aircraft. Since there was only one violation each for CE 5 and CE 6, there was no evidence that CE 5 was more difficult than CE 6. Zero violation in the low altitude sector for CE 5 was especially encouraging since 75% of potential conflicts existed in that sector if the traffic were to run with no controller intervention. This suggests that both controllers and pilots were adequately handling the high density of arrival traffic. Two out of a total of nine separation violations involved a CDTI-equipped plane, both in the baseline condition. Since neither violation occurred in the CE 5 or CE 6 condition, the results further support the viability of these two CEs.

The separation violations occurred mostly between two arrival planes or between an arrival and a departure (see Table 4). Although the causal factors that lead to the operational errors were not closely analyzed, the type of violations provided some insights. First of all, only one violation occurred near the meter fix where the heaviest congestion existed, suggesting that the controllers (and the pilots in CE 5) were handling the traffic workload adequately. Secondly, violations that occurred just inside the sector boundaries were likely due to reduced monitoring of the sector boundaries during heavy traffic since controllers took action to avert the conflicts but not quickly enough to avoid separation violations. These types of violations would likely have been averted if there were radar associates. Finally, there were three violations in the baseline condition that involved a plane in a descent phase and another plane in a climb phase. This problem might be due to lack of training since the controller participants improved handling this issue as they became more familiar with the sectors. Interestingly, these violations only occurred in the baseline condition. Controllers' comments suggest that differentiation between departures and arrivals were made easier in CE 5 and CE 6 due to different color assignments (yellow for arrivals and green for departures), perhaps allowing them to identify departures and arrivals on crossing paths quicker thus allowing more time to take corrective actions.

Table 4: Aircraft pairs in separation violations

	arrival-arrival	departure-arrival
baseline	3	4
CE6	0	1
CE5	0	1

Workload

Viability of CE 5 and CE 6 concepts are also dependent on maintaining acceptable workload for controllers and pilots. For the controllers, there were two possible outcomes to the workload measures. First, it was possible that their workload was reduced in the CE 5 and CE 6 conditions due to improved DSTs (e.g. CD&R capability). The workload could have been reduced further in the CE 5 condition since the separation responsibility of the free maneuvering aircraft was shifted to the pilots. Secondly, trajectory-based arrival metering might produce greatest workload benefit at the downstream sector (i.e. low altitude sector) if the upstream (i.e. high altitude sectors) controllers delivered the planes closer to the TMU schedule, thereby creating a better flow to the low altitude sector.

The controller workload was measured using modified NASA-TLX ratings, such as mental demand, effort, frustration, and performance, after each simulation run. The controllers were also asked to rate their workload every four minutes during the simulation run using Air Traffic Workload Input Technique (ATWIT) ratings. Due to space limitations, only the mental demand/workload ratings are reported but the other ratings were consistent with these ratings. As shown in Figure 9, the ratings generally supported the hypothesis that workload benefits mostly occurred in the downstream sector. When the mental demand ratings for the two upstream sectors (i.e. Ardmore and Wichita Falls) were combined and rated across conditions, the data only showed a weak trend towards less workload for CE 5 (3.38) than CE 6 (3.75) and baseline (3.75). However, the low altitude sector showed much lower ratings for CE 5 (2.20) and CE 6 (2.25) compared to baseline (3.75).

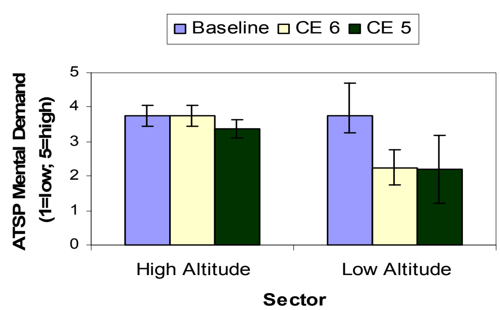

Figure 9: Mental Demand of En Route Controllers

However, one should not infer too much from these workload benefits since they may be due to the fact that the low altitude controller was trying to deliver the planes on their STAs whenever possible in the baseline condition, creating higher workload in this condition. If the controller were to deliver the planes on their STAs in CE 5 and CE 6 but not in baseline, the workload would likely have been less in the baseline condition, but the delivery accuracy and spacing might have suffered even more since the task would not have required the planes to be delivered on time. Regardless, the results demonstrate the operational viability by showing acceptable levels of controller workload in the CE 5 and CE 6 conditions.

The operational viability also hinges on acceptable workload for the pilots, especially for the free maneuvering aircraft that had the separation responsibility and the RTA requirement. Figure 10 illustrates the pilot mental workload ratings during en route and transition phase of the flight. The en route phase consisted of level flight prior to the TOD, and the transition phase was from the TOD to the meter fix. The en route phase roughly corresponded to the high altitude sectors and the transition to the low altitude sector. The data suggest a slight increase in the workload in CE 5 and CE 6 (2.69 for CE 5; 2.75 for CE 6) compared to baseline (2.22) during the en route phase and possible workload increase in CE 5 (2.84) compared to CE 6 (2.59) and baseline (2.53) during the transition phase.

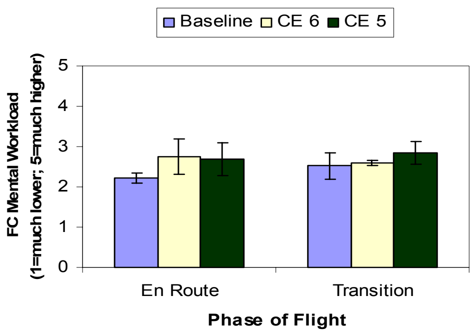

Figure 10: Mental Workload of Pilots

In summary, the workload in the CE 5 and CE 6 conditions was acceptable compared to baseline, with slight increase in workload for the pilots in CE 5/CE 6 and slight decrease in workload for the controllers.

CE 11 – Controller and Pilot Feedback

Our TRACON controller generally liked the self spacing concept. He had no problems operating our user interface that provided in-trail spacing and advisory information in an expanding data block. However, the controller had difficulties determining when and how to apply self-spacing. The main difficulty seemed to rise from a mismatch between distance-based radar separation requirement and time-based in-trail spacing. Both the controller and the pilots in the free maneuvering aircraft were asked to follow a specified number of seconds behind a lead aircraft. This resulted in spacing much larger than the minimum 3, 4, or 5 nm separation requirement near the en route meter fix when the planes were flying at a faster speed, but the distance separation would have gradually narrowed as the planes slow down. This time-based strategy seemed to run counter to the current day strategy of keeping the distance spacing and speed relatively constant and then slowing the aircraft just before the final approach. In particular, the controller seemed to be unsure of the pilot's responsibility when aircraft spacing was less than the in-trail time requirement but was greater than the minimum distance separation requirement.

The pilots in general felt that the self spacing concept was safer and more efficient than current day operations. Analogous to the controller feedback, the pilots seemed to prefer distance-based over time-based spacing. One of the pilots expressed that the spacing interval should be based on distance rather than time, while another wanted a miles vs. time comparison so that he could easily convert the time into the corresponding distance. A third pilot wanted the ability to specify minimum distance when using the spacing tool. In summary, both pilots and TRACON controller liked the self spacing concept but had some difficulties implementing an effective strategy to maintain time-based spacing. Most of these difficulties should be resolved through better training of time-based spacing.

Conclusion

The simulation described in this paper demonstrated some evidence of potential benefits and operational viability of DAG-TM CE 5 and 6. Although the results are based on a preliminary implementation of DAG-TM concepts, they are nevertheless quite encouraging. They suggest improvements in efficiency and capacity without compromising safety or significantly increasing the workload. Given the small sample size (4 runs per condition) and the number of subjects (e.g. 5 controllers; 3 controllers working the same sectors throughout the data collection), one must be careful in drawing general conclusions from these results, but a conservative conclusion may be that the concepts have shown initial viability that merits further research.

The free maneuvering aircraft in CE 5 did not show significant advantage over the corresponding aircraft in CE 6, but perhaps this should have been expected since the main advantage of free flight, namely the ability for the pilots to craft an efficient route based on user preferred parameters, was not fully utilized in this simulation. For example, benefits in efficiency might not have been apparent because the original path of the free maneuvering aircraft was already close to optimal, and the reduction of controller workload might not be visible due to the low number of free maneuvering planes. These issues will be examined further in future simulations.

Acknowledgment

Distributed Air-Ground Traffic Management (DAG-TM) research is funded by the Airspace Systems program as part of the Advanced Air Transportation Technologies Project. The simulation described in this paper owes its success to many dedicated individuals including, at NASA Ames Research Center, Todd Callantine, Michael Downs, David Encisco, David Jara, Nancy Johnson, Kevin Jones, Vick Kelkar, Parimal Kopardekar, George Lawton, Sandy Lozito, Ron Miller, John Moses, Bassam Musaffar, Travis Perkins, and the staff of the Advanced Concepts Flight Simulator. We are also grateful for the assitance of Paul Mafera and Katja Helbing of Booz-Allan Hamilton, and Jean-Francois D'Arcy and Nicole Sacco Racine of Titan Systems, who contributed long hours to this project. This work could not have taken place without the active support of the Air Line Pilots Associaton, the National Air Traffic Controllers Associaton, and the Air Traffic Services Office of the Federal Aviation Administration. The authors deeply appreciate their interest in and support of our research.

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Keywords

distributed air ground traffic management, free flight, cockpit display of traffic information, trajectory oriented metering, CTAS, conflict probe, CPDLC.

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