AN EVALUATION OF DYNAMIC DENSITY METRICS USING RAMS

DRAFT

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16. Abstract

This report evaluates several dynamic density (DD) metrics by comparing controller performance data that was recorded in the real time human-in-the-loop FAA/NASA Air-Ground Integration Experiment (AGIE) with metrics from the Reorganized ATC Mathematical Simulator (RAMS) dynamic density interface. The study suggests that relationships exist between the participants' subjective workload data collected in real-time and the DD metrics that were examined in fast-time using RAMS. The aircraft density (A/C D) component of the FAA DD metric showed the strongest relationship to the human performance data. The measure of aircraft density is determined by the number of aircraft divided by the effective volume of airspace (i.e., only the amount of airspace the aircraft are using) within a given sector. Further analyses are required to compare all of the components of the FAA DD metric with the human performance data.

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EXECUTIVE SUMMARY

For many years researchers have identified essential factors that contribute to air traffic complexity in the terminal and enroute airspace. The quantification of these factors is the focus of current research aimed at developing and validating a dynamic density (DD) metric. DD is defined as air traffic control (ATC) taskload, which is the basis of controller subjective workload. DD is analogous to air traffic complexity or difficulty of a situation. DD is "a measure of control-related workload that is a function of the number of aircraft and the complexity of traffic patterns in a volume of airspace" (Laudeman, Brasil, & Branstrom, 1996). Primary variables comprising DD have been defined initially to include traffic density, complexity of flow, and separation standards. The calculation and prediction of these factors has been identified as a key issue for the assessment of controller workload for the future ATC system.

The purpose of this study was to evaluate several DD metrics using the output data from the Reorganized ATC Mathematical Simulation (RAMS). Performance data collected (i.e. workload) from the joint FAA/NASA Air-Ground Integration Experiment (AGIE) and from a similar scenario developed for the RAMS were compared. The study focused on one of the variables from the DD metric developed by the FAA, a linear model that was developed by NASA, and the DD metric that was installed in Release 2.4 of RAMS. Since the DD algorithm relies on position information from RAMS, flight profiles in RAMS were compared to data recorded in AGIE for consistency. The results of the comparisons revealed that the aircraft density (A/C D) component of the DD metric developed by the FAA yielded the strongest relationship to the AGIE workload data than the other two metrics. This was made evident by the higher partial correlation coefficients that were obtained for the A/C D variable. This study is a first attempt at quantifying sector complexity through fast time modeling.

BACKGROUND

Air traffic has exhibited steady long-term growth, and this trend is expected to continue. In addition to increasing volume, many regions of the airspace will experience more dynamic traffic flows as more user preferences are accommodated. As a result, the sector air traffic operations will be more dynamic. In order to accommodate user preferences, a variety of concepts such as collaborative decision-making, dynamic resectorization, user preferred routes, and shared separation are being explored. The core element of these concepts is the ability to measure and predict sector level complexity. The changes in the traffic flows can be better managed if such a measurement and prediction of sector level complexity is available.

Currently, the monitor alert parameter of the Enhanced Traffic Management System (ETMS) is used for the prediction of sector level complexity. It is recognized, however, that monitor alert, which is strictly based on predicted aircraft count, does not account for the range of factors that lead to increased complexity. Therefore, a better complexity measurement and prediction metric is necessary.

Origin and Definition of Dynamic Density

The term Dynamic Density (DD) originated in the RTCA Task Force 3 report. The report describes DD as "the essential factors affecting conflict rate in both en route and terminal airspace." These factors are traffic density, complexity of flow, and separation standards. The calculation and prediction of DD has been identified as a key requirement to assess workload associated with future traffic levels (RTCA Task Force 3 Free Flight Implementation Report, 1995).

DD is also defined as air traffic control (ATC) taskload, which is the basis of controller subjective workload. DD is analogous to air traffic complexity or difficulty of a situation. DD is "a measure of control-related workload that is a function of the number of aircraft and the complexity of traffic patterns in a volume of airspace" (Laudeman, Brasil, & Branstrom, 1996). Primary variables comprising DD have been defined initially to include traffic density, complexity of flow, and separation standards.

Although the term DD is relatively recent, the factors that contribute to sector level air traffic complexity have been of interest to researchers for a long time. Mogford, Guttman, Morrow, and Kopardekar (1995) identified and reviewed air traffic complexity related literature dating back to 1963. Most articles reviewed in this technical note identified aircraft count, sector geometry, traffic flows, separation standards, aircraft performance characteristics, and weather as the most common factors that contribute to air traffic complexity or difficulty.

OBJECTIVE

The purpose of this study was to evaluate several DD metrics developed over the last couple of years. This was done by comparing real time human-in-the-loop (HITL) simulation workload ratings from the joint FAA/NASA Air Ground Integration Experiment (AGIE) with DD calculations obtained from an algorithm which uses output from the Reorganized Air traffic Control Mathematical Simulator (RAMS). Participants subjective workload ratings collected in

real time during the HITL were compared with several DD metrics. The three DD metrics examined in the study include: 1) an aircraft density (A/C D) metric developed by the FAA which divides the number of aircraft by the effective sector volume; 2) a weighted linear model developed by NASA; and 3) a DD metric installed inrelease 2.4 of RAMS which consists of an algorithm that calculates DD using detailed position reports that are recorded from the RAMS model. In order to account for any differences in the flight positions between the fast and real time scenarios during the simulation runs, comparisons were made between the times two flights would collide given no air traffic control action. This would assume that loss of separation between two flights occurred without any controller intervention.

Reorganized ATC Mathematical Simulator (RAMS)

RAMS is a fast time discrete event driven simulation model used for the study of airspace design, ATC systems and future ATC concepts. It was developed by the Eurocontrol Experimental Centre's Simulator Development Programme (SDP) located in Breignty-sur-Orge Cedex, France. The model is largely data driven and contains a resolution rule system that uses forward chaining artificial intelligence to represent and solve conflicts. The rule base was designed to provide operationally correct flight maneuvers that are used by ATC experts. RAMS resolves conflicts of two or more flights by using vectors, changes in flight level, speed adjustments, and/or moving a flight to a holding pattern.

The model was designed to mimic the planning and tactical controller functions of the ATC system. The model records tasks that are performed by controllers and are grouped into five categories. These include conflict search, coordination, flight data management, communication, and radar resolution. A weighting scheme applied to each of the subtasks was developed at Eurocontrol to predict controller workload. These tasks can be defined globally over an entire airspace, specialized by center, sector, navaid, or airport.

The simulation engine models 4D flight profiles for 300 currently supported aircraft types. All aspects of the airspace, such as general or specific separation minima, special use airspace (SUA), airport and runway activity, approach sequencing, holding patterns, restriction for Standard Instrument Departure (SIDS) & Standard Terminal Arrival Routes (STARS) requirements are modeled to achieve the closet possible replica of the ATC system. RAMS uses advanced conflict detection algorithms, combined with a rule base system to achieve conflict detection and resolution. The model maneuvers flights using vectors, level changes, speed manipulation, path stretching or air/ground holding as a means of separating aircraft. RAMS records position information, tasks of a controller, and general statistics concerning the flight dynamics of all simulated flights.

RAMS produces several output files that describe flight characteristics of each individual flight in the scenario as well as recording the detailed interaction of flights within the simulation time frame. These interactions include flights in conflict, location of conflict, resolution applied as a result of the conflict, and all flight maneuvers considered but not rendered due to the creation of new conflicts. In addition, several activity files are produced during each run of RAMS that include a conflict search log file, a resolution file, a position report file, and a summary of all the tasks preformed during the run.

Air Ground Integration Experiment Overview

The real time HITL Air Ground Integration Experiment (AGIE) was designed to examine the effects that proposed NAS concepts, (e.g., Free Flight) may have on flight operations. In addition, the experiment was intended to provide insight into the use of shared separation authority on flight operations when both air and ground have enhanced traffic and conflict alerting systems. The focus of the study was to investigate the impact of shared separation authority on controller/pilot workload, situational awareness, and performance. Sixteen full performance level (FPL) Air Traffic Control Specialists (ATCSs) from Memphis Air Route Traffic Control Center (ARTCC)[1] participated in this experiment. Two adjacent sectors of Memphis airspace (ZME044 and ZME021) were replicated in the simulation environment. There were four participants per week (2 per sector; each consisting of a radar and data position). Scenarios were developed which consisted of climbing and descending aircraft and a mix of overflight aircraft at cruising altitude, some of which were travelling between the two sectors. Three scenarios were extracted from the AGIE simulation and served as the input for the comparisons in the current study. The scenarios are referred to as 1) CO (current operating procedures/baseline), 2) CO: CDTI (current operating procedures and pilots have CDTI capability), and 3) SS (shared separation). A brief description of each experimental condition is included in the following section

> CO: A baseline scenario was developed to simulate today's ATC environment. This condition employed current 7110.65M ATC procedures for controlling traffic. In addition, the D-side controllers had the User Request and Evaluation Tool (URET), a conflict probe.
>
> CO: CDTI: This condition employed current 7110.65M ATC procedures for controlling traffic. In addition to the D-side controllers having URET capability, the flight crews used a Cockpit Display of Traffic Information and embedded Alerting Logic (CDTI/AL). In this scenario, pilots could request alternate routes to maximize fuel efficiency or when they detected potential conflicts using the CDTI/AL. However, controllers retained authority to deny pilot requests.
>
> SS: This condition emulated a subset of the RTCA definition of Free Flight environment where URET and CDTI/AL are operational and flight crews initially provided their own separation, but controllers had the option to cancel free flight.

DYNAMIC DENSITY METRICS

Aircraft Density variable of FAA DD metric

The FAA DD metric consists of the following: Aircraft density (A/C D), Convergence recognition index (CRI), Separation criticality index (SCI), Degrees of freedom (DOFI), and Coordination taskload index (CTI). The entire metric was not used in this study. Only the A/C D metric was evaluated. The A/C D metric is the instantaneous count of the flights within the boundary of the sector divided by the effective volume of airspace. This metric is determined by calculating the volume of airspace that encompasses the flights within the sector. This is estimated by averaging the latitudes and longitudes of each of the flights in the sector to determine the centroid of the polygon that defines the vertices as the flight

[1] Memphis ARTCC airspace was selected for the AGIE experiment as the User Request and Evaluation Tool was operational at the site, and the resident FPL ATCSs were fully trained on the tool.

position. This centroid represents the midpoint of the polygon and is used to calculate the area enclosed by the active flights. The volume of this polygon is the product of the surface outlined by the flights and the difference in altitude between the flights. If all of the flights are at the same altitude the volume of airspace assumes the surface area constructed by the flights. A/C D is one of five variables that are included in the FAA DD metric. An in-depth description of this metric can be found in Magyarits & Kopardekar (2000).

NASA DD Metric

The NASA DD metric (Chatterji & Sridhar, 1997) include the following components: heading change greater than 15 degrees, speed change greater than 10 knots, altitude change greater than 750 feet, minimum distance between two flights of 0-5 and 5-10 nautical miles, predicted conflict of 0-25, 25-40, and 40-70 nautical miles, and traffic density. The weights applied to these components that are used to determine the NASA DD metric are described as follows:

> NASA DD = 2.4 (heading change > 15 degrees) + 2.45 (speed change > 10 knots) + 2.94 (altitude change > 750) + 2.45 (minimum distance in 0-5 nmi) + 1.83 (minimum distance in 5-10 nmi) + 4.00 (conflict predicted in 0-25 nmi) + 3.00 (conflict predicted in 25-40 nmi) + 2.11 (conflict predicted in 40-70 nmi) + 1.00 (traffic density).

RAMS DD Metric

The components of the RAMS DD metric that was included in Release 2.4 of RAMS include the following:

- Instantaneous count of aircraft (Aircraft Count);
- The aircraft count divided by the usable amount of sector airspace (Aircraft Density);
- Conformance of traffic flow through a sector to the geometry of the sector (Airspace Structure);
- Climbing or descending aircraft (CoD);
- Number of aircraft that are in a threshold separation of each other at any instance in time (CPA);
- Aircraft proximity to sector boundary (PRX);
- Variance in direction of flight (VDF), angle of convergence of two flights in conflict;
- Conflict near sector boundary;
- Flights that are close to a conflict (aircraft neighboring conflict).

After all of the aircraft positions are determined, measures of heading change, speed change, and altitude change are determined from the active flights within the sector. In addition, the distances between the flights within the sector are determined and instantaneous aircraft counts recorded. The algorithm processes all of the flights until the last time sorted flight exits the sector. The weights applied to these components that are used to determine the RAMS DD are described as follows:

> RAMS DD = 0.172 (Instantaneous Aircraft Count) + 0.328 (Aircraft Density) + 0.0676 (Airspace Structure) + 0.1134 (Climb or Descent) + 0.0498 (Closest Point of Approach) + 0.200 (Proximity to Sector Boundary) + 0.0709 (Variance in Direction) + 0.0426 (conflict Aircraft neighboring) + 0.1070 (Convergence angle conflict) + 0.0754 (conflict near sector boundary. These components of the metric was taken from RAMS Release 2.4 Users Guide, 1999.

METHODOLOGY

An algorithm that uses the output of RAMS was developed to support the evaluation of the DD metric. The DD values of each metric were compared to the HITL simulation performance data that was collected in the AGIE study. The DD algorithm, aircraft density (A/C D), developed by

the FAA, sorts positional information from all flights contained within the simulation by first entry into the sector. All position reports that the program must estimate will be calculated using a great circle approximation between the two points laterally and longitudinally, and vertically by the climb and descent rates of the aircraft. The calculation of the density metrics was recorded at a one-second-update rate and averaged by a five-minute interval. This was done to replicate what was recorded in the AGIE experiment. In order to ensure that the RAMS positional information of the flights was similar to the AGIE study, an evaluation of the RAMS supplied position log file was conducted. A scenario was developed in RAMS without the conflict detection and resolution options. In this manner, potential collision times between the real and fast time experiments (given that no controller action to resolve the conflict had taken place) could be compared. The flights would maintain course heading, altitude, and speed as determined by RAMS without any ATC interaction. There were eight predefined conflicts consisting of flight pairs that were headed for a collision for sector ZME021 and ZME044. The points of collision between the two experiments yielded similar results. Sixteen pairs of flights that were expected to collide from the baseline (CO) HITL scenario had nearly the same collision times in RAMS. Since the conflict/resolution rules were nullified, this would suggest that the flight characteristics built into RAMS are fairly representative of the flight characteristics of the real time experiment that were taken from the system analysis report (SAR) tapes. That is, the climb, descent, and cruise profiles of RAMS without ATC intervention are consistent with the data representing the AGIE HITL baseline (CO) scenario. It is important that the flight profiles in the AGIE study are similar to the ones in RAMS. The RAMS derived DD metrics are determined from the position of the flights in sector ZME021 and ZME044 and must match the positions recorded in the AGIE scenario in order for any meaningful results to be obtained.

Scenarios from AGIE were used to build fast time simulation scenarios for RAMS. The SAR tapes developed for each of the AGIE scenarios was read into the Sector Design Analysis Tool (SDAT) for the purpose of building a RAMS scenario with the same routing structure and sector design contained in the real time study. The SAR tapes contain recorded position information of all flights that were observed in the HITL AGIE simulation. Since measures of airspace complexity may depend on structural and flow characteristics of the flights within a sector, it was determined that RAMS would be the appropriate simulation model for the comparisons. RAMS produces a file containing detailed positional information of all the flights in the simulation including handoffs, sector pierces, time and locations of all navaids, and any vector or altitude change provided by the RAMS rule base logic to avoid conflicts. Flight profiles are derived from the tracking information described by the SAR tapes and the flight characteristics defined by the aircraft type in service.

RAMS records position information on every flight within the scenario. This includes position of a flight within a sector by latitude, longitude, altitude, and time. This information generally is recorded at sector crossings, navaids, flight level changes, or ATC forced changes in aircraft position. The density algorithm sorts the flights by order of entry time into the sector. As the flights enter the sector the timing routine updates the position of each flight within the sector based on an update rate that is user defined. The algorithm uses the RAMS supplied position information that is generated in a log file. If the flight is determined not to reside on one of these points, the new location of a flight is estimated by a great circle approximation between two points along the arc of a curve. If there are altitude differences between the two points, the new vertical position is determined by the climb or descent rate of the aircraft. If more than 2 flights

are in the sector at a given time complexity measures are calculated according to the metrics described above.

RESULTS

For the purpose of this evaluation, correlation coefficients were calculated for each DD metric and corresponding human performance metrics for each of the three scenarios. The results of a correlation analysis produce a correlation coefficient (or *r* value) that ranges from –1.0 to +1.0 and indicates the strength of the relationship between two variables. A coefficient of 0 means that no relationship exists, while –1.0 and +1.0 indicate perfect relationships. A positive coefficient (or direct relationship) means that as the value of one variable increases, the other variable also increases. A negative coefficient (or inverse relationship) means that as the value of one variable increases the other variable decreases. A correlation coefficient is considered to be statistically significant if its absolute magnitude exceeds a given critical value, which depends upon the number of degrees of freedom in the experimental design. Usually, a *p* value (or significance level) is reported, which represents the probability that the calculated coefficient could exceed the critical value by chance alone.

The partial correlation coefficients for all scenarios are located in Table 1. A snapshot of the airspace and traffic flows for baseline (CO) scenario is displayed in Figure 1. The figure illustrates the effective volume of airspace that was used in the calculation of the A/C D metric. Graphical representation of these relationships can be found in the subsequent figures. Although all three of the DD metrics yielded significant correlations to the human performance data, the A/C D metrics' relationship was the strongest. Figures 2 through 7 illustrate the correlations obtained for the different metrics across the three scenarios by sector.

Table 1. Partial correlation coefficients between the DD metrics and the HITL workload data.

Scenario		**Baseline (CO)**		**CO:CDTI**		**Shared separation (SS)**	
Position assignment		**Radar**	**Data**	**Radar**	**Data**	**Radar**	**Data**
Sector	**Metric**						
ZME021	FAA	.7256**	.9269**	.6096**	.6735**	.8387**	.8589**
	NASA	.6034**	.4735*	.5807*	.6524**	.7621**	.7141**
	RAMS	.591*	.527*	.5341*	.5107*	.6271**	.6321**
ZME044	FAA	.6516**	.6130**	.5809*	.6614**	.7777**	.7426**
	NASA	.6378**	.5156*	.4633*	.5171*	.6630**	.4890*
	RAMS	.5431*	.4981*	.7231**	.4636*	.7577**	.7182**

* p <.05; ** p < .02

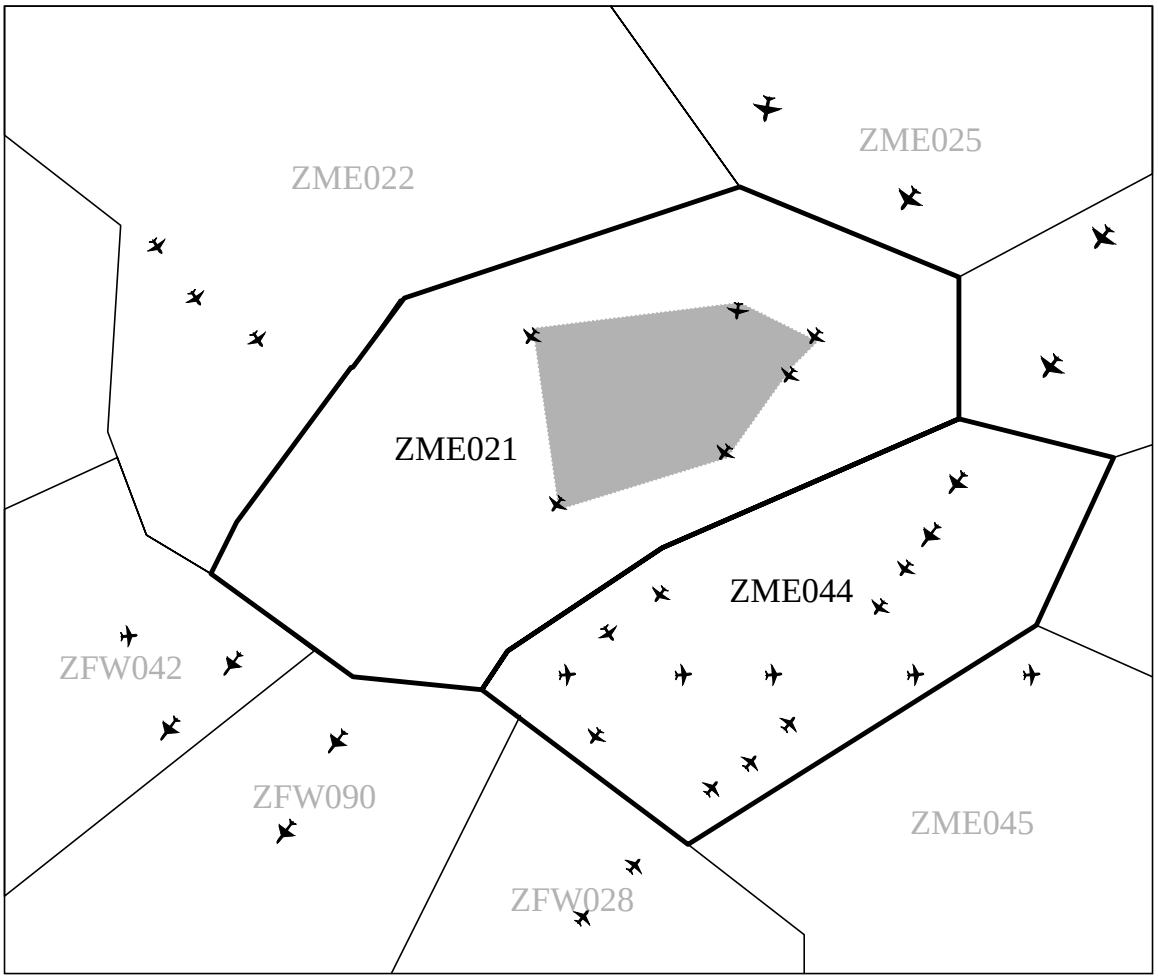

Figure 1. ZME sectors 021 and 044. Gray region depicts the effective airspace volume for sector 021 used in the calculation of the FAA Aircraft Density metric.

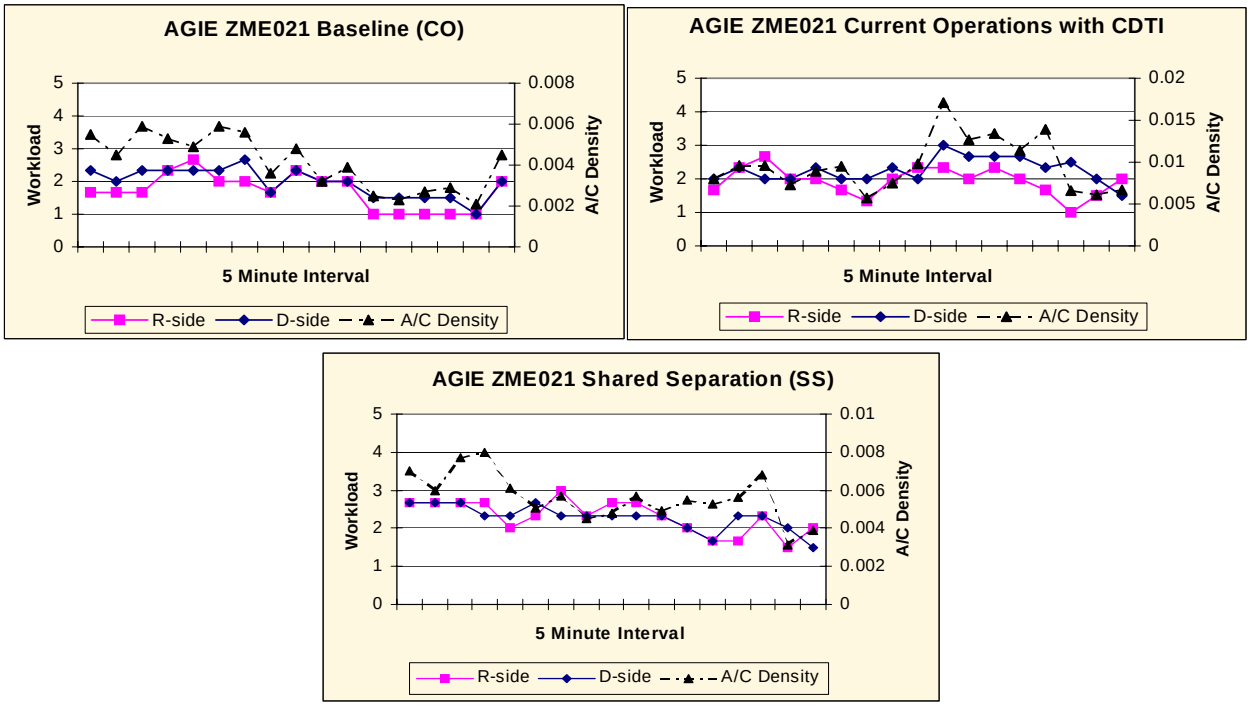

Figure 2. . FAA Aircraft density output and mean subjective workload ratings for ZME021 baseline, CO:CDTI, and shared separation scenarios.

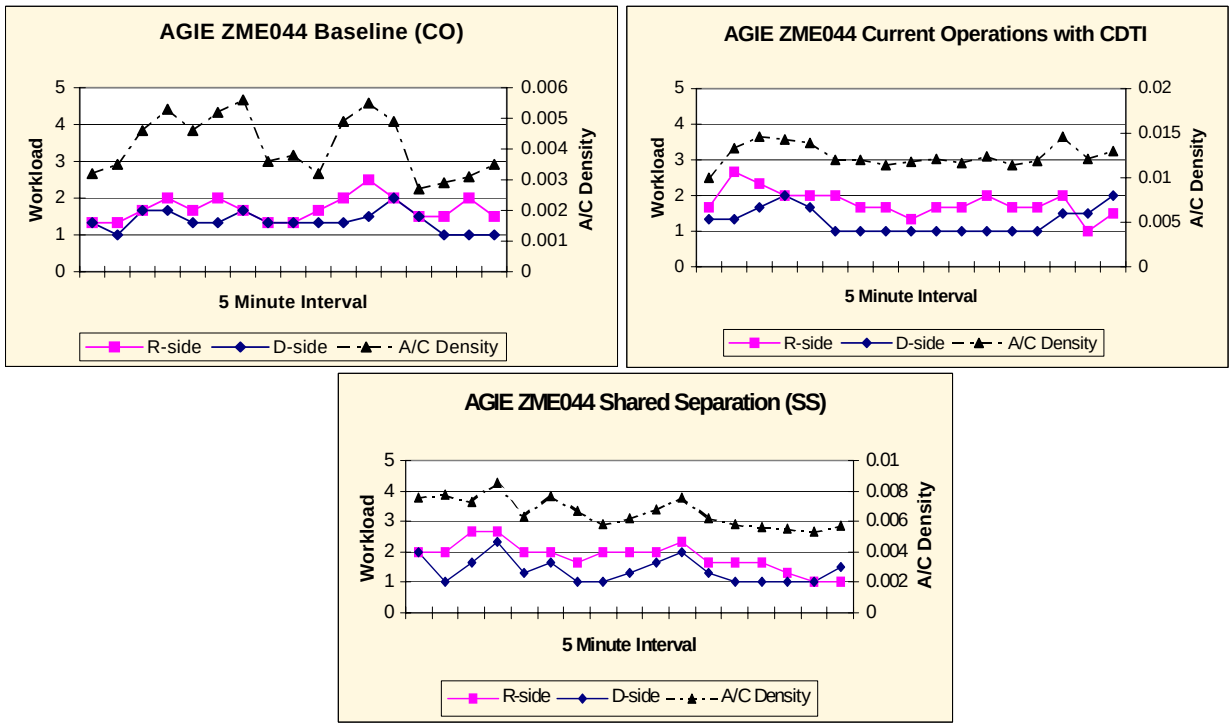

Figure 3. FAA Aircraft density output and mean subjective workload ratings for ZME044 baseline, CO:CDTI, and shared separation scenarios.

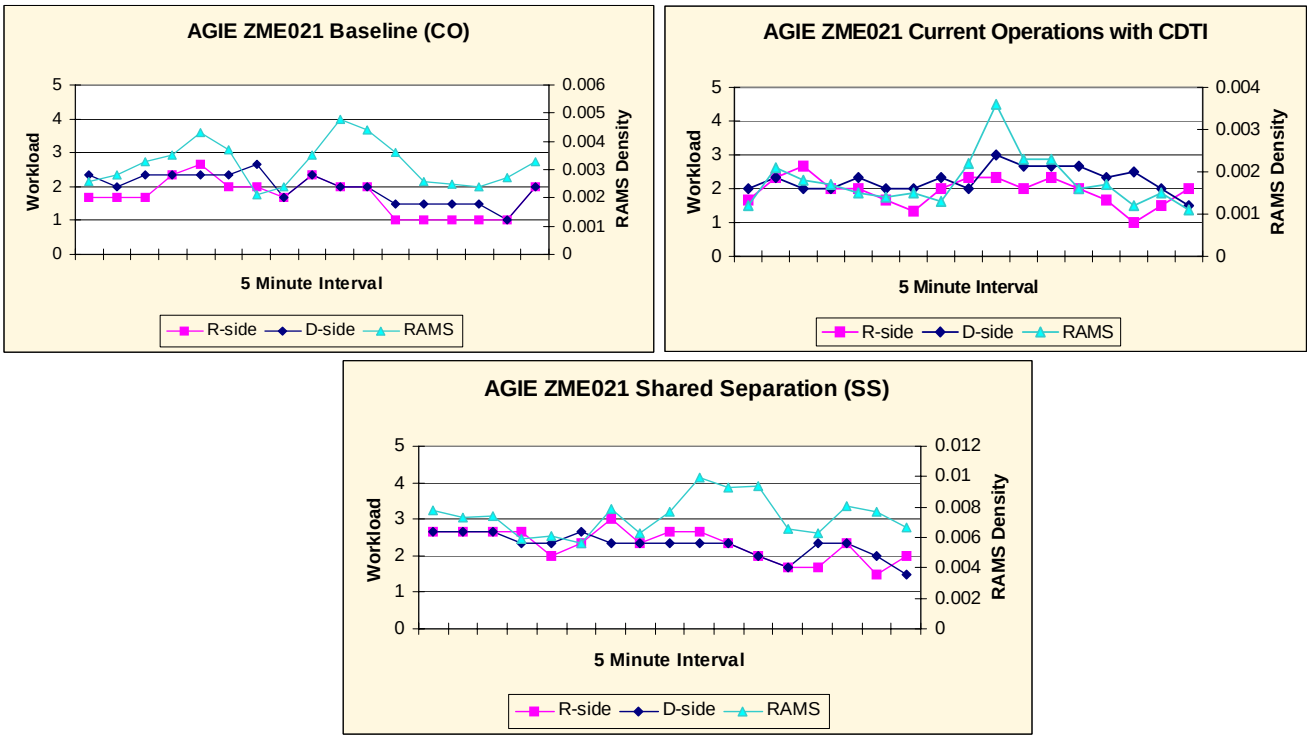

Figure 4. RAMS density output and mean subjective workload ratings for ZME021 baseline, CO:CDTI, and shared separation scenarios.

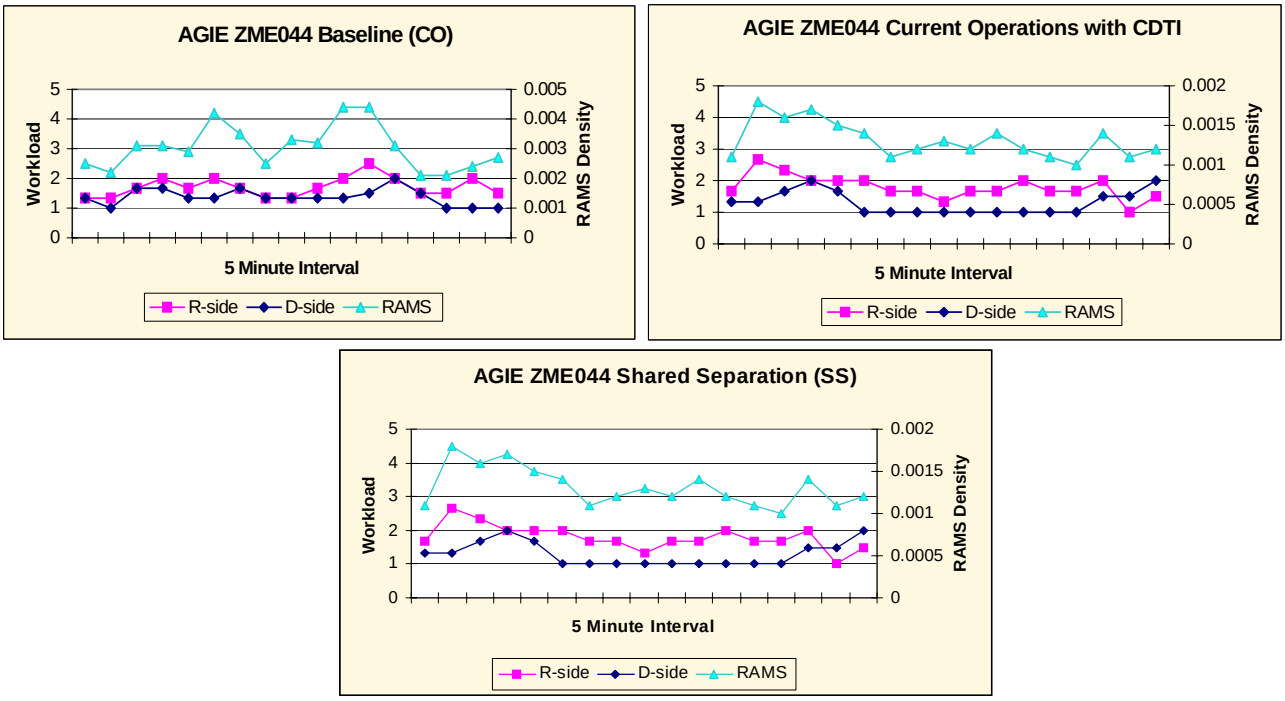

Figure 5. RAMS density output and mean subjective workload ratings for ZME044 baseline, CO:CDTI, and shared separation scenarios.

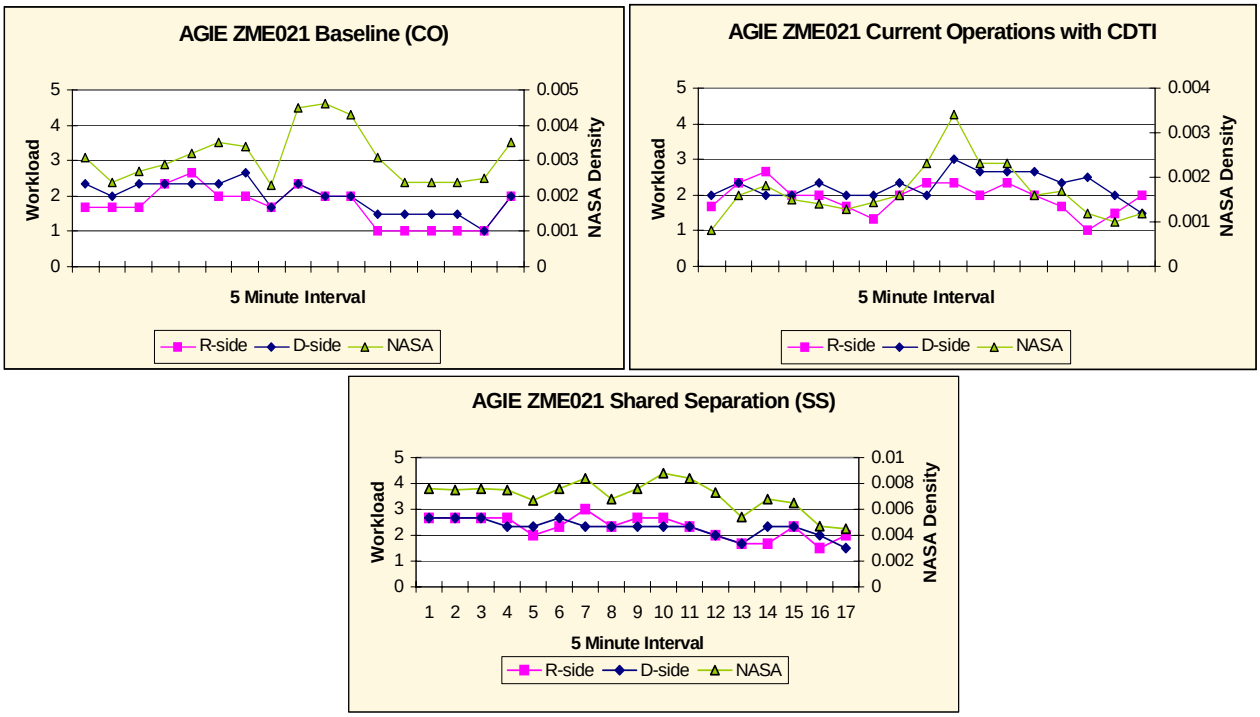

Figure 6. NASA density output and mean subjective workload ratings for ZME021 baseline, CO:CDTI, and shared separation scenarios.

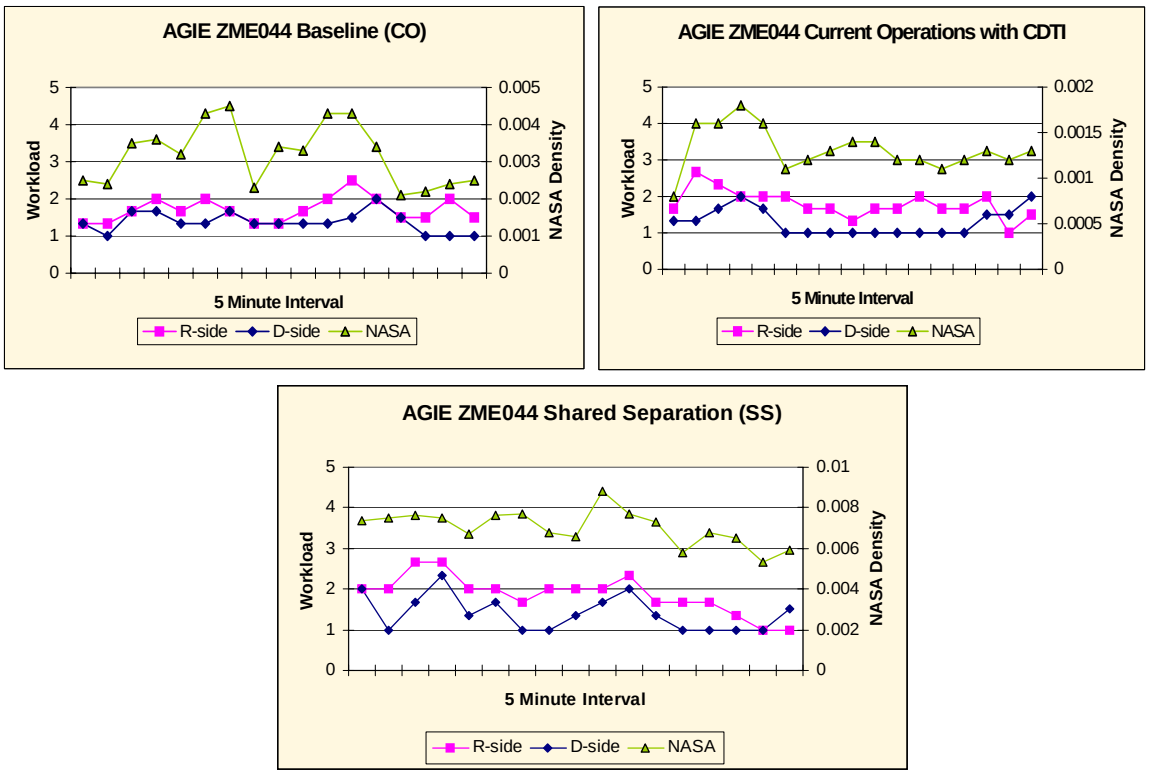

Figure 7. NASA density output and mean subjective workload ratings for ZME044 baseline, CO:CDTI, and shared separation scenarios.

CONCLUSIONS

The evaluation of the three density metrics described in this report suggest that the DD metric introduced by the FAA conforms more closely to the human performance data than the RAMS and NASA DD metrics. Although all DD metrics were determined to have significant positive correlations, the A/C D metric yielded the strongest relationship. Since this is a first attempted at evaluating DD metrics through the use of fast time modeling, it is recommended that these metrics and new sector complexity metrics that are being developed be evaluated. Since the AGIE HITL performance data is based on controller experience, cognitive processes, traffic complexity, and is regarded as a "soft" number additional comparisons between real time and fast time metrics are recommended. Over time, the quantification of sector complexity should be realized with repeated experimentation. Several new measures of sector complexity will be evaluated with the AGIE workload data described in this report in future studies.

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