Investigation of En route Metrics for Model Validation and Airspace Design Using the Total Airport and Airspace Modeler (TAAM)

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ABSTRACT
As part of an ongoing effort to evaluate and compare Air Traffic Management (ATM) modeling metrics, we simulated a region of congested airspace in the US National Airspace System (NAS) using the Total Airport and Airspace Modeler (TAAM), which is a high fidelity simulation model. TAAM output tables were used to estimate controller workload as a function of developing traffic flow and sector characteristics. In order to quantify the complexity of the sectors, we are evaluating a set of aggregate metrics that may reflect the sector characteristics and traffic patterns. An initial baseline study is described that estimated metrics such as movement and workload distributions of the existing airspace design. An analysis is conducted to assess the potential growth in the utilization of small aircraft on controller workload. This assessment should be of interest to simulation and airspace designers. It is also relevant to research on the projected growth of General Aviation (GA) activities on Air Traffic Control (ATC) workload.

INTRODUCTION
In each sector, the Air Traffic Controller (ATC) workload increases as a function of airspace complexity and traffic density. For different locations, the air traffic distribution varies based on the number of airports and their level of operations as well as the amount of crossing, ascending and descending traffic. As a result, controllers in each Air Route Traffic Control Center (ARTCC) encounter different workload levels. Simulating the whole NAS requires significant input file preparation, computational

speed and computer memory. On the other hand, ignoring sector specific controller workload constraints does not allow the simulation to be used to evaluate innovative new airspace designs such as those proposed by Zellweger, et. Al. [14]. These constraints need to be statistically represented in any new national network model. TAAM was used to simulate 162 sectors in 5 of the most congested ARTCCs in the North East region of the NAS. We are currently updating the aircraft flight profiles to be more representative of actual practice and comparing the results of the simulation to actual traffic statistics. Future work will continue to evaluate new aggregate metrics for new simulation models as part of our ongoing IV&V effort and evaluate innovative airspace designs designed to reduce controller workload restrictions.

Background
ATM chokepoints are areas in the airspace where there is a potential for many conflicts and the structure of aircraft flow patterns is complex. There are seven FAA identified chokepoints east of the Mississippi river as far north as Boston and as far south as Atlanta [1]. This region consists of the country's major population areas and busiest airports. Congestion at one chokepoint can propagate to the rest of the system and create delays at many airports. Figure 1 and 2 illustrate these national chokepoints and the respective ARTCCs.

As figure 2 shows, there are five ARTCCs that handle the guidance and control of the flights in these regions:

1. Washington Center (ZDC)
2. New York Center (ZNY)
3. Indiana Center (ZID)
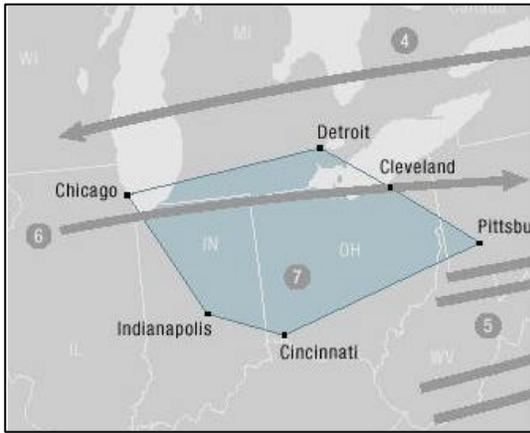4. Boston Center (ZBW)
5. Chicago Center (ZAU)

FIGURE 1. Representative of national choke points from FAA's Aviation Capacity Enhancement Plan (ACE Plan) 2001 [2].
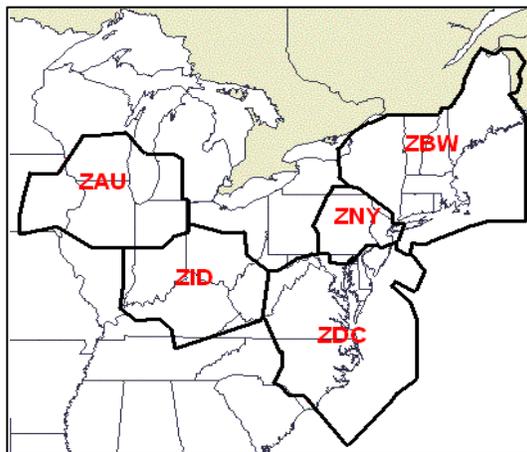

FIGURE 2. Five ARTCCs that are modeled in this study.

One of the most congested centers in the NAS is Washington Center. Currently, the arrival flows into Newark and LaGuardia Airports pass through narrow sectors located in the airspace of the Washington en route Center. These sectors can only accommodate a few aircraft in the holding patterns and the rest of the traffic has to be delayed before arriving to this area. This configuration creates congestion in neighboring sectors. In order to break the resulting gridlocks, the US Federal Aviation Administration (FAA) has proposed to swap the arrival flows for Newark and LaGuardia [1]. This change should increase the traffic flow to New York airports

from the Washington en route Center by balancing the traffic load. In the Chicago Center, existence of a large hub airport (O'Hare) and heavy crossing traffic creates major chokepoints. Similar situations apply to ZBW, ZNY, and ZID.

These ARTCC's control airspace over densely populated areas with a high level of socioeconomic activity. There are many small airports in these regions suitable for small aircraft operations. Figure 3 shows the 2,221 airports over the area of 1,000 n.m. around Washington DC. It is hypothesized that future growth in operations out of small airports would take place in the regions that are already experiencing capacity overload. This region was chosen for detailed simulation.
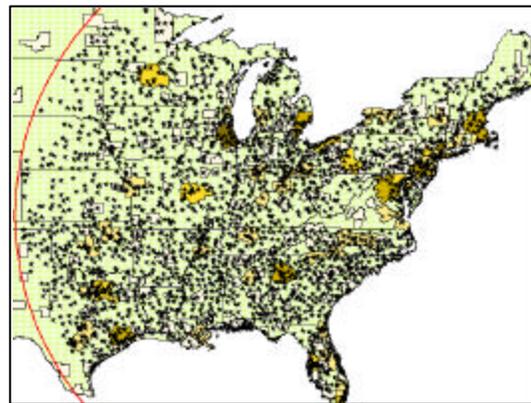

FIGURE 3. View of 1,000 n.m. around Virginia along with 2,221 public airports with the length of paved runway greater than 3,000 feet and the urban areas in yellow.

Future Small Aircraft Utilization
The NASA Small Aircraft Transportation System (SATS) research program is based upon the hypothesis that there will be a significant growth in the number of smaller aircraft, which will fly point-to-point, often to and from airports other than the 20 major airports in this region. Some evidence supporting this hypothesis comes from the rapid growth in:
1) Fractional ownership of business jets.
2) Air taxi services, possibly using planes like new small twin-engine jets being developed by Eclipse and Safire, both expected to sell under $1M.
3) Large growth of the regional jet (RJ) fleet [2].
It has been suggested that spreading the air transportation system to a network of small airports may relieve hub airport chokepoints and

break the gridlock of air traffic congestion [3]. However, without a significant change in the en route ATM system, a significant growth in the small aircraft traffic levels may result in a significant growth in ATC workload. Hence, the issue of controller workload could become a serious performance constraint for the entire system.

DEFINITIONS
Sector Characteristics
The NAS sectorization has not been designed based on a system-wide analytical methodology. Sector boundaries are drawn according to the controllers' visual understandings of traffic patterns and volumes. Through the years, both traffic patterns and volumes have changed significantly while most of the sectors are the same. Each sector, based on its characteristics, produces different workload levels for the same number of passing aircraft. Characteristics of a sector can be summarized based on the following:

▪ *Geometry of the sectors (polygonal or elongated):* In the polygonal shaped sectors, aircraft enter/leave the sector from different points at the controller's screen. In contrast, in elongated sectors, the traffic pattern is usually highly parallel and less complicated. It is proven that in the complex sectors, controllers use long-term memory to sketch the traffic pattern in their mind [5]. This increases the average workload per each aircraft.

▪ *Altitude:* Sectors are categorized into three types (low, high and ultra high). In each altitude range, the fleet mix varies and different aircraft types create different workload levels for the controllers.

▪ *Number of routes:* Usually sectors with more crossing routes have higher complexity and higher controller workload.

▪ *Number of route intersection:* Conflicts usually occur near the intersecting fixes. The controllers take more conflict resolution actions in sectors with more route intersections.

▪ *Number of neighboring sectors that feed/receive aircraft to/from the sector under study*: Having more neighboring sectors creates more controller-to-controller communication actions and hand offs.

▪ *Volume of the sector:* Larger sectors have more space to accommodate the aircraft without violating the minimum separation. On the other hand, the controller has to track more aircraft.

▪ *Special use airspace (SUA) in vicinity of the sector under study:* Flying around SUAs creates many restrictions. This interrupts the smoothness of aircraft flow.

▪ *Airport:* Airports are merging nodes in the network. There are more pilot-controller communication actions in vicinity of the airports. In addition, in the terminal area where aircraft descend or climb, controllers take many altitude change or vectoring actions.

Density, Congestion and Workload
In the context of this study, for each sector or volume of airspace, in any given time interval, "density" is the number of aircraft and "congestion" is the cumulative residence time of all aircraft passing through a sector.

▪ $Congestion = \dfrac{\sum_{i=1}^{n} T_i}{Sector}$ [minute/sector]

Where:
T_i = *Residence time for aircraft i in the sector.*
n = *Total number of aircraft passing through the sector during any given time interval.*

▪ *Density = Number of aircraft passing through a sector during any given time interval* [aircraft/sector]

Congestion is a function of sector shape, volume and complexity as well as the aircraft flow rate and pattern. It reflects the sector characteristics such as the length of crossing routes, sector shape, etc. In Figure 4, sector *a* and *b* have the same volume ($V_a = V_b$) and traffic flow rate (*three aircraft*) so density is the same while, because of the longer routes crossing the sector *b*, this sector has more residence time. In reality, neither of these metrics adequately estimates the level of controller activity.
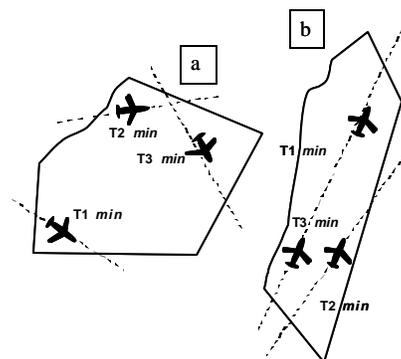

FIGURE 4. Illustration of Congestion vs. Density.
Mills 1998 introduced *Aircraft Activity Index (AAI)* as a new metric for ATC activity [6]. The AAI combines congestion and density to produce

a more informative metric than either measure provides when used alone.

$$AAI = \frac{Density}{Epoch\ Time} \times \frac{Congestion}{Epoch\ Time} [aircraft.minute/sect\ or]$$

Sector Complexity Index (CI)

In reality, aircraft in each sector, based on the sector complexity, create different workload levels that previous metrics fail to capture. A new metric, the complexity index (CI), for each sector is defined as the average workload per each aircraft. For a given time epoch:

$$CI = \frac{Total\ Workload}{Total\ Number\ of\ aircraft}$$

The CI is related to the average number and duration of coordination actions, level changes, handouts and other actions per each aircraft. Future airspace design and simulation models need to take a metric similar to this into consideration.

Workload Measurement

Controller workload is a confusing term and with a multitude of definitions, its measurement is not uniform [7]. Majumdar, 2001 [7] provides a comprehensive literature review in workload measurement. Similar to simulations of other systems containing human and machine interaction, simulating controller workload is a very challenging task. TAAM counts and records different actions that controllers take as well as the number of aircraft passing through each sector. The user can assign adjustment factors (F_{HM}, F_{CDR}, F_C, and F_{AC}) for each action, based on the action complexity and the level of workload that it creates for the controllers [8]. One way to adjust the factors is using the normalized time that each action requires. Our definition of workload is composed of four parameters:
1. Horizontal Movement Workload (WL$_{HM}$)
2. Conflict Detection and Resolution Workload (WL$_{CDR}$)
3. Coordination Workload (WL$_C$)
4. Altitude-Change Workload (WL$_{AC}$)

In each sector or group of sectors, the summation of these four parameters gives the total workload.

$$TotalWL = \sum_n WL_{HM} + WL_{CDR} + WL_C + WL_{AC}$$

Movement or basic workload (WL_{HM}) is determined by the number of aircraft in a sector (sector density) and the average flight time.

$$WL_{HM} = F_{HM} \times (N_{HM} \times T) \quad where:$$
$$F_{HM} = Adjustment\ factor\ for\ horizontal\ movement$$
$$N_{HM} = Number\ of\ aircraft\ passing\ through\ the\ sector$$
$$T = Average\ Flight\ Time$$

The conflict workload (WL_{CDR}) is based on conflict detection using the type of conflict and the conflict severity. The conflict type is determined by the tracks of the aircraft (succeeding, crossing or opposite) and the flight phases (climbing, cruising, or descending). For each type it is possible to assign different adjustment factors F_{CDR}. The conflict severity is the percentage of available separation. For example if 100-120% or 80-100% of minimum separation is available. The closer aircraft are together, they create more workload for controllers. For each conflict severity, there is an associated adjustment factor defined as T_{CS}.

$$WL_{CDR} = F_{CDR} \times (T_{CT} \times N_{CDR}) \quad where:$$
$$F_{CDR} = Adjustment\ factor\ based\ on\ conflict\ type$$
$$T_{CS} = Conflict\ severity\ factor$$
$$N_{CDR} = Number\ of\ aircraft\ with\ this\ conflict\ type\ and\ severity$$

The coordination workload (WL_C) is determined by the type of coordination action including:
- Voice Call
- Clearance issue
- Inter facility transfer
- Silent transfer
- Intra facility transfer
- Tower transfer

For each of them there is a factor that reflects the complexity of that action.

$$WL_C = F_C \times N_{CA} \qquad \text{where :}$$

$F_C = Cordination\ action\ factor$

$N_C = Number\ of\ aircraft\ with\ this\ coordination\ action$

The altitude-change workload (WL_{AC}) is determined by the type of sector altitude clearance request for level off, commence climb and commence descent.

$$WL_{AC} = F_{AC} \times N_{AC} \qquad \text{where :}$$

$F_{AC} = Altitude\ c\ learance\ f\ actor$

$N_{AC} = Number\ of\ aircraft\ w\ ith\ this\ c\ learance$

The model counts each action, calculates workload parameters and finally reports the total workload.

SIMULATTION METHODOLOGY
Accuracy of an en route study is highly dependent on the level of detail in simulating the airspace structure, as well as the ability to process the model output. TAAM is a widely available, high fidelity, large scale and fast-time simulation model, designed to simulate very realistically, all possible aspects of the ATC, on the ground and in en route. It simulates the behavior of aircraft in all phases of flight, taking into consideration the instrument flight rules and the ATC procedures.

In each TAAM simulation, it is necessary to build number of large databases, which is a time consuming and data-collection intensive process. Due to TAAM's high fidelity, even a high performance workstation may require many hours to complete a large en route simulation and record the results.

Scenario Definition
The flying range for new small jets is in the order of 1,000 n.m. and they prefer to land in and take-off from runways longer than 3,000 feet. Based on this fact, the area of 1,000 n.m. centered on Washington DC is included in the simulation. This area contains the five identified congested ARTCCs and 2,221 public airports with a hard-paved runway measuring at least 3,000 feet in length. It was assumed that in the near future small aircraft may primarily tend to utilize airports equipped with any kind of instrument landing system, including Distance Measuring Equipment (DME), Localizer (LOC) or Instrument Landing System (ILS).

Accordingly, among all 2,221 public airports only those equipped with some kind of landing system were considered in the study. Table 1 and figure 5 outline the proposed airports. All large, medium, and small hub and non-hub primary airports in the US along with proposed small airports in the region of 1,000 n.m. around Virginia are taken into consideration. In addition, 72 non-US based airports are added to the airport database. This is required, due to the large number of international flights that operate out of the airports in the simulated area.

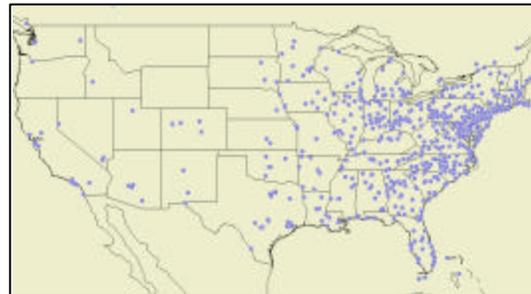| Airport Type	Number of Airports
Large hub	29
Medium hub	42
Small hub	70
Non-hub primary	272
Reliever, GA, and other commercial	182
International (Non-US based)	72
Total	667

TABLE 1. Airports considered in the study.

FIGURE 5. The 667 airports considered in the study.

The FAA operates 22 ARTCCs with 11 to 44 en route sectors each. These sectors, based on their altitude range, are categorized into low, high and ultra high. The commercial and GA operations range from small single-engine propeller aircraft flying in lower altitudes to wide-body jets that fly above 30,000 feet. In order to cover all these operations, all sectors for the simulated ARTCCs are included in the model. The number of simulated sectors in each ARTCC is shown in table 2.

ARTCC	Number of Sectors
ZDC	43
ZNY	25
ZID	34
ZBW	19
ZAU	41

TABLE 2. Number of Simulated Sectors.

The flight schedule is the backbone of any large-scale en route study. In order to conduct the baseline study, it was important to use the most inclusive flight database. In the US, there are two main sources of traffic data available:

- The Enhanced Traffic Management System (ETMS): reports only Instrument Flight Rules (IFR) operations for both commercial and GA operations. Also Flight Explorer (Developed by Dimension International Inc.) that provides same data as ETMS in real time.
- The Official Airline Guide (OAG): provides only scheduled airline operations.

In our study, we used the commercial flight data from the Flight Explorer database. Since none of these databases provides an inclusive GA schedule, a separate effort was conducted to generate the existing and potential future GA flights. GA operations are generated based on census socioeconomic activities for communities in vicinity of the airports. Based on distance distribution, the operations are then distributed by time-of-day to construct a full timetable. Table 3 summarizes the number of flights used in the course of one full day.

Market segment	Number of daily flights
▪ Non-GA including Commercial, GA and Cargo (IFR) extracted from the Flight Explorer	22764
▪ General Aviation traffic (IFR and VFR) generated based on Logistics Management Institute (LMI) Gravity Model	7051
Total	29815

TABLE 3. Number of daily flights used in the baseline scenario.

The altitude assignments are calculated by TAAM, based on the aircraft characteristics and origin and destination (OD) distances. For GA operations, three representative aircraft types were selected and their characteristics are included in the TAAM default data aircraft characteristics module. Table 3 shows the aircraft classifications, number of daily operations and proposed aircraft types.

Acft Classification	Op./Day	Acft type
Single-engine IFR	349	Bonanza 36
Single-engine VFR	3481	Bonanza 36
Multi-engine VFR	899	King Air B200
Multi-engine piston IFR	633	King Air B200
Multi-engine turbo IFR	653	King Air B200
Jet IFR	1037	Citation 500
Total	7051	

TABEL 4. Break down of generated GA flights, along with their representative aircraft types.

We assumed aircraft fly great circle between OD and used direct routes in the study. The process of GA traffic generation is a long discussion and we did not present details of the analysis in this paper. For more information please refer to [9].

RESULTS

As outlined in figure 6, the aircraft movement and workload levels are not uniformly distributed among different ARTCCs. Two large hub airports (Chicago O'Hare and Midway) are located in the Chicago Center (ZAU) and this center is in the midway of the NE-to-SW operations. As a result, although ZAU is a comparatively small center, it accommodates a large portion of the overall traffic. At a more detailed level, the same distribution is shown for low, high, and ultra high sectors in figures 7 and 8. Except for ZID that does not contain any large airport, the low altitude airspace is predicted by TAAM to be more congested.

For different ARTCCs, the amount of workload increase due to the growth in GA operations is illustrated in figure 9. The horizontal axis is percentage of increase in the daily GA operations from the baseline and the vertical axis is the computed workload during one day. Note that the workload is predicted to increase more rapidly in ZDC and ZNY as the amount of small aircraft activity increases. Running the model for more than 100% cloned GA flights required an excessive amount of computer memory and an extremely fast processor that was beyond our capabilities. It can be hypothesized that further increases in GA workload would grow

exponentially beyond a doubling in air traffic. However, due to the existing in trail separation restrictions, there is a maximum number of aircraft that each sector can accommodate. After the sector reaches to its maximum capacity, if the aircraft flow continues to grow, aircraft would be delayed in the preceding sectors all the way to the origin airports. At some point in the number of GA flights, delays should start to grow exponentially and the system would become practically locked. This limit can be defined as the ultimate capacity of the system to handle growth in GA operations.

Figure 10 outlines the 50 most complex sectors and their daily movement. Although not rigorous, overall, more dense sectors are those with less complexity. Intuitively it can be interpreted as a good design (less complex sectors are capable to accommodate more aircraft without exceeding the controller workload thresholds). Figure 11 illustrates the histogram of CI for 162 simulated sectors. The large variation of CI depicts the non-uniformity in sector design. This non-uniformity might be the cause of under utilization of existing airspace. It needs to be investigated whether a good sector design balances the airspace complexity or aircraft density among different sectors.

The result of the attempt to formulate functional relationship between workload and Aircraft Activity Index (AAI) is outlined in figures 12. For individual sectors, the future workload levels can be calculated using the regression function.
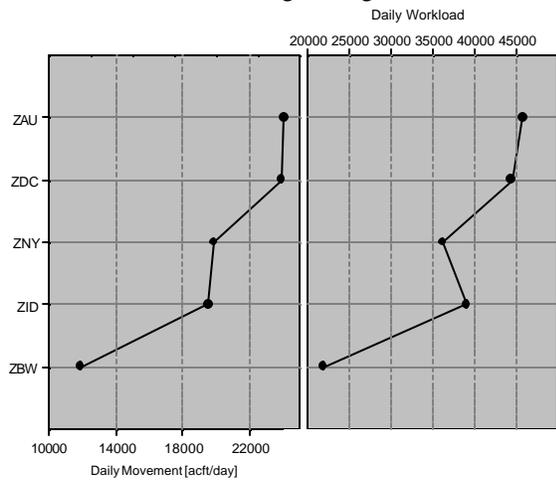
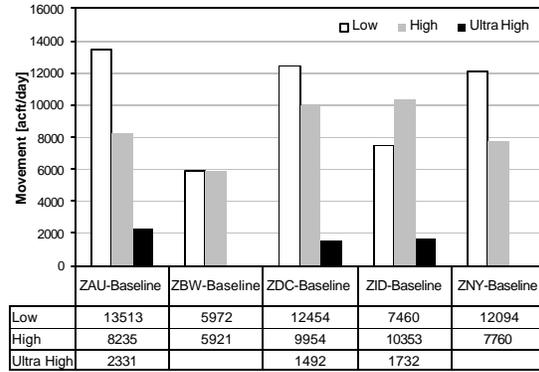**FIGURE 6. Movement and Workload distribution for the North East ARTCCs (base case).**

	ZAU-Baseline	ZBW-Baseline	ZDC-Baseline	ZID-Baseline	ZNY-Baseline
Low	13513	5972	12454	7460	12094
High	8235	5921	9954	10353	7760
Ultra High	2331		1492	1732	

FIGURE 7. Daily Movement distributions for the low, high and ultra high sectors in the North East ARTCCs.

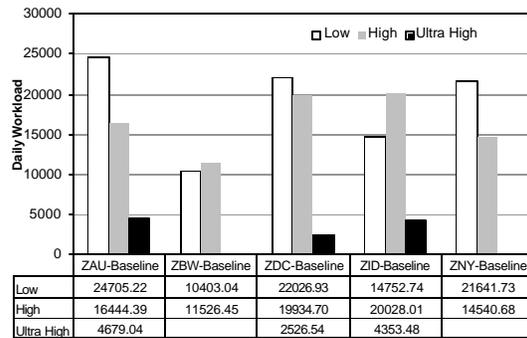|	ZAU-Baseline	ZBW-Baseline	ZDC-Baseline	ZID-Baseline	ZNY-Baseline
Low	24705.22	10403.04	22026.93	14752.74	21641.73
High	16444.39	11526.45	19934.70	20028.01	14540.68
Ultra High	4679.04		2526.54	4353.48	

FIGURE 8. Daily Workload distributions for the low, high and ultra high sectors in the North East ARTCCs.
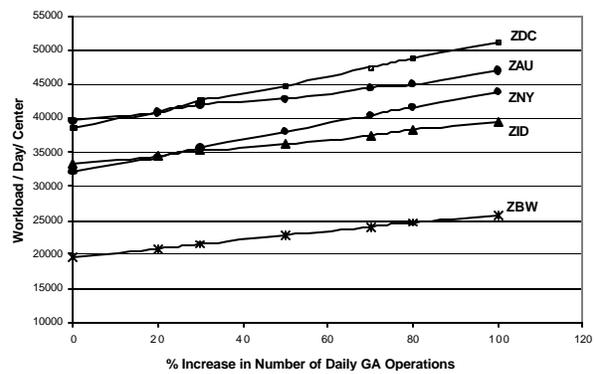
FIGURE 9. Percentage of growth in daily GA operations from the baseline vs. daily workload for different ARTCCs.
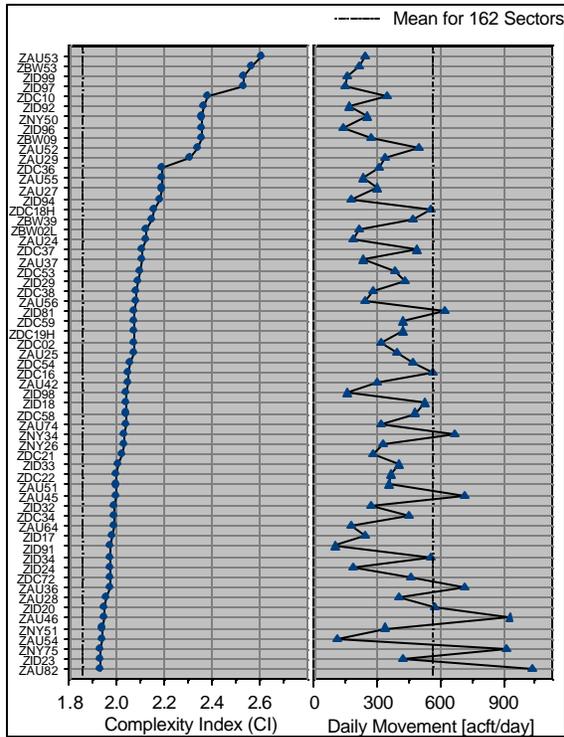
FIGURE 10. The Sector Complexity Index (CI) and Daily Movement for the 50 most complex sectors.
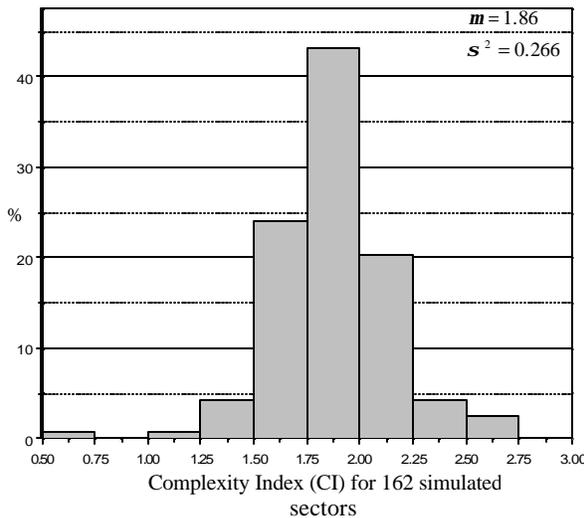

FIGURE 11. Histogram of the Complexity Index (CI) for 162 simulated sectors in the NE corridor.
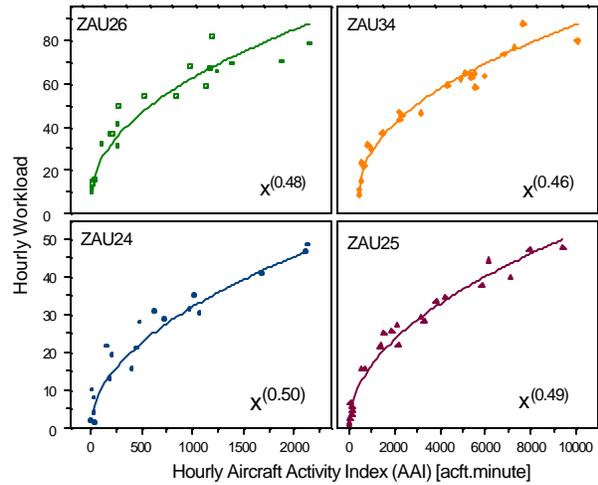

FIGURE 12. Power regression for the Aircraft Activity Index (AAI) vs. Workload for sample sectors in the ZAU Center.

OBSERVATIONS AND FUTURE WORK

The National Airspace System is facing capacity constraints due to the growth in demand for air travel in all market segments. Potential future trends in the small aircraft utilization and the growth in operation of small airports may present new challenges in the ATM. Major changes in the ATM procedures may be necessary to address the issue of controller workload. The use of new technology in Communication, Navigation and Surveillance (CNS) of the small aircraft to enable the pilots for self-separation could be utilized to reduce the controller workload.

Designing sectors with more uniform complexities might be a solution to avoid ATC workload constraints. Also, allocating certain altitude ranges for free flight, specifically for aircraft equipped with the advanced CNS equipment should result to decrease in overall workload.

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AUTHURE BIOGRAPHIES

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