ABSTRACT

Title of Thesis: RELATIONS AMONG ENROUTE AIR TRAFFIC,
CONTROLLER STAFFING AND SYSTEM PERFORMANCE

Sameer Datta Kamble, Masters of Science, 2005

Thesis directed by: Professor Paul M. Schonfeld
Department of Civil and Environmental Engineering

Relations are estimated among enroute air traffic, controller staffing and performance of controllers and ATC system. Controller staffing is found to increase at least linearly with air traffic in the US National Airspace System. Findings in literature review, FAA controller staffing models, FAA standards, and results of analyses support this finding.

Measures of controller performance, controller workload and models are developed to estimate relations between controller performance and air traffic in sectors and centers of the NAS. It is found that controller performance is not affected by air traffic congestion within sectors and centers. The estimated relations may be biased by factors such as spatial and temporal propagation of delays in the NAS, ATC procedures used to delay flights away from the source of airspace congestion, strategic and tactical planning performed by ATC system and different traffic management processes and programs implemented for traffic flow management in the NAS. There is a need to evaluate the performance of ATC system in managing air traffic and minimizing delays in the entire NAS.

It is found that a hyperbolic function is applicable for relating delays and enroute traffic volumes in the NAS. Monthly models estimated using monthly measures of delays and enroute traffic volumes perform better than daily models. Monthly models estimated for same calendar month of successive years show the best statistical fit. It appears that the enroute operational capacity of NAS can differ considerably for different months. Ground delays, taxi out delays, gate departure delays and airport departure delays used to reduce air delays due to enroute congestion are identified using the monthly and month-specific models.

RELATIONS AMONG ENROUTE AIR TRAFFIC, CONTROLLER STAFFING AND SYSTEM PERFORMANCE

by

Sameer Datta Kamble

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Advisory Committee:

Professor Paul M. Schonfeld, Chair
Professor Michael O. Ball
Assistant Professor Mark H. Lopez

Dedicated to my family in India

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CHAPTER I: INTRODUCTION

Problem statement:

As enroute air traffic increases and the NAS (National Airspace System) approaches its capacity, the delay and associated costs increase nonlinearly and steeply. There is a need to prepare for the air traffic growth in the system. The problems related to demand-capacity imbalance need to be anticipated and resources should be allocated in an efficient way.

There is a need to estimate relations among controller staffing, controller performance and enroute air traffic in the NAS. The capacity of enroute airspace sectors is limited by the number of aircraft which can be handled by controllers per unit time. Staffing in sectors is based on number of operations which can be handled by controllers per unit time and the difficulty involved in controlling those operations. Considering the future growth in enroute traffic, planning is needed to provide resources and training to meet the controller staffing needs of the future.

Adequate controller staffing and ATC resources should be provided to avoid degrading the NAS performance.

When a sector demand exceeds its capacity, workload increases for controllers in that sector and their performance may suffer. Hence, it is important to estimate the relations between performance of ATC system and enroute air traffic in sectors and centers of the

NAS. These relations evaluate the performance of the controllers and air traffic control (ATC) system.

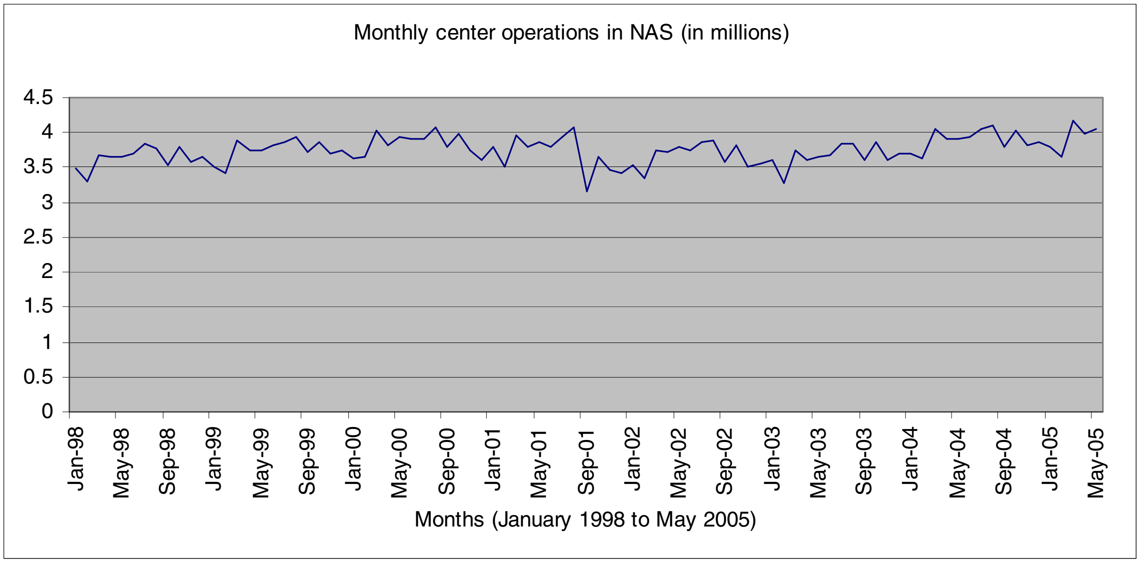

Figure 1.1 Time series trend of monthly traffic volumes (center operations) in NAS

Figure 1.1 shows the time series trend of monthly airspace traffic volumes in NAS (center operations in NAS) from January 1998 to May 2005.The period from January 1998 to September 2001 shows a steady increase in monthly center operations in NAS. The September 11, 2001 event impacted the air traffic operations in NAS. Hence, the period from September 2001 to February 2002 shows a sharp decline in enroute air traffic in NAS. However the period from February 2002 to May 2005 shows a gradual increase in the enroute NAS traffic.

In August 2004 the NAS handled 4.101 million center operations. This enroute traffic exceeded the August 2000 peak of 4.077 million center operations. In March 2005 the NAS handled 4.175 million center operations, the highest monthly enroute traffic ever recorded. This shows that the enroute air traffic is gradually increasing since September 11, 2001.

OPSNET (Air Traffic Operations Network) is the only database reports the number of operations delayed due to (center volume) enroute congestion. Figure 1.2 shows the time series trend of fraction of monthly center operations delayed due to enroute congestion in NAS.

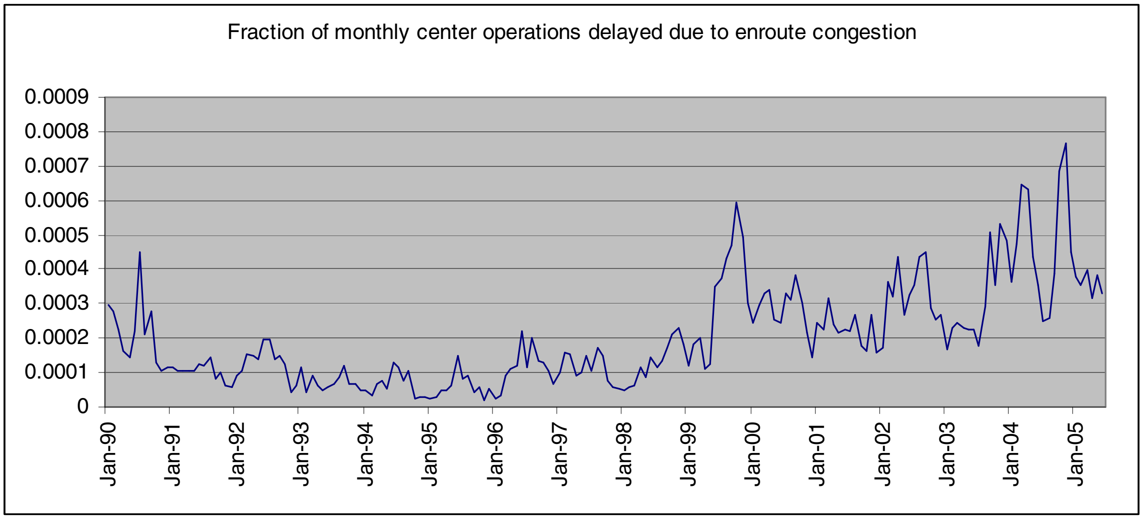

Figure 1.2 Time series trend of fraction of monthly center operations delayed due to enroute congestion in NAS.

The fraction of monthly center operations delayed due to enroute congestion increased from 0.0025 in January 96 to 0.033 in June 2005.

Figure 1.3 shows the time series trend of the percentage of monthly delayed operations in the NAS which are delayed by enroute congestion. This percentage increased from 0.319 in January 1996 to 2.79 in June 2005.

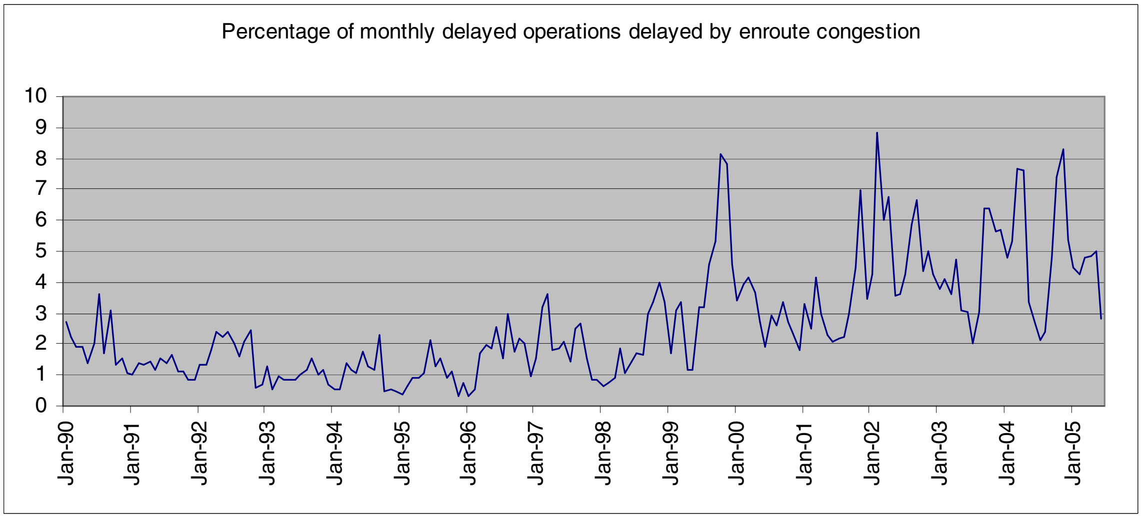

Figure 1.3 Time series trend of percentage of monthly delayed operations delayed due to enroute congestion in NAS.

Time series trends of the two graphs show that the percentage of operations delayed by enroute congestion, and the percentage of delayed operations delayed by enroute congestion is increasing in the NAS. Traffic volume in the NAS is causing an increase in delays and percentage of delays caused by enroute congestion. Hence it is important to explore the impact of further increases in enroute traffic on the ATC system performance. These relations must be estimated for individual sectors and centers, and for the entire NAS.

Objective:

The main objective of this study was to estimate statistically the relations among controller staffing, enroute traffic and ATC system performance. The following three relations were sought:

1. Relations between staffing of enroute air traffic controllers and enroute traffic. Such relations were estimated for individual sectors and centers, and for the entire NAS.
2. Relations between controller performance and air traffic in NAS sectors and centers.
3. Relations between ATC system performance and enroute traffic volumes in the NAS

Scope and methodology:

Since it is difficult to estimate strong relations between controller performance and air traffic within sectors and centers, such relations should also be estimated at an aggregate level for the entire NAS.

The literature was reviewed in order to assess previous research in the relevant areas. FAA standards on controller staffing, air traffic control procedures and data reporting requirements were also used to estimate the desired relations. Consultations with Air traffic controllers and other FAA personnel were helpful in providing:

1. Understanding of air traffic control procedures and ATC system operation in the NAS.
2. Data recorded by FAA, for use in this analysis.

Appropriate measures of controller staffing, NAS performance and enroute traffic were used to estimate these relations. For example controller staffing could be measured in terms of number of controllers, controller and NAS performance in terms of delays and enroute traffic in terms of operations. Individual differences may exist in the proposed metrics. For example controllers can be classified based on grade levels and operations can be classified into arrivals and departures. It was decided to use a simplified single metric to measure each variable. Based on the data available from FAA, models were developed for these relations, using statistical tools such as regression analyses and t tests. Appropriate time intervals and airspace components (sectors, centers or entire NAS) will be chosen for estimating the sought relations. Statistical tools like regression analyses and t tests will be used to estimate the relations.

It is possible that the relations among controller staffing, enroute traffic and ATC system performance could be biased by additional factors, such as improvement in ATC equipage which could affect the controller staffing and improve NAS performance. Hence care was needed in the data analysis and model development. Care was also needed in choosing data for centers, sectors and time periods. The feasible analyses were severely limited by the data available from FAA.

CHAPTER II: STRUCTURE OF THESIS

The following relations are estimated among enroute air traffic, controller staffing and ATC system performance in NAS

1. Relations between Enroute Air Traffic Controller Staffing and Enroute Air Traffic in the NAS
2. Relations between Controller Performance and Air Traffic in Sectors and Centers of the NAS
3. Relations between ATC System Performance and Enroute Air Traffic in the NAS

This thesis consists of nine chapters.

Chapter I: Introduction

Chapter II: Structure of thesis

Chapter III: Literature Review

Chapter IV: Relations between Enroute Air Traffic Controller Staffing and Enroute Air Traffic in the NAS

Chapter V: Relations between Controller Performance and Air Traffic in Sectors and Centers of the NAS

Chapter VI: Relations between ATC System Performance and Enroute Air Traffic in the NAS

Chapter VII: Conclusions

Chapter VIII: Recommendations for Future Work

Chapter IX: Unrealized analyses

The literature review performed to estimate three relations is contained in sections 3.1, 3.2 and 3.3 of chapter III.

Chapters IV, V and VI contain the methodology, analyses, results and interpretation of results for the three estimated relations.

The conclusions based on the three estimated relations are presented in sections 7.1, 7.2 and 7.3 of chapter VII.

Chapter IX discusses some analyses which were contemplated for estimating relations between ATC system performance and enroute traffic volumes in the NAS but not yet achieved, due to drawbacks of the NAS performance measures proposed in analyses which could bias the estimated relations and due to the unavailability of data.

An overview of the methodology employed to estimate the three relations is provided in section 3.4.

CHAPTER III: LITERATURE REVIEW

3.1. Relations between enroute air traffic controller staffing and enroute air traffic in the NAS.

The relation between staffing of enroute air traffic controllers and enroute air traffic in NAS sectors and centers was studied in section 3.1. The effect of improvement in equipage, job experience, individual performance and age on the workload and performance of enroute air traffic controllers (hereafter, referred to as controllers) are not considered as factors in the formulation of this relation.

3.1.1. US national airspace system and air traffic controller positions staffed for enroute sectors.

The US national airspace is divided into 21 air route traffic controller centers (ARTCC). For controller staffing purposes each center's airspace is subdivided into areas of specialization.

An area consists of 5 to 8 sectors which are generally grouped for specialization and operational purposes. Sector airspaces can be visualized as three-dimensional cubes, which have defined vertices and boundaries in space. The areas of specialization are equivalent in terms of operational workload and workload complexity. Controller workload in a sector is functionally divided into positions of radar controller (R controller), associate radar control (D controller) and hand-off controller. Rotational assignment of controllers is performed within each area of specialization.

Table 3.1 below shows the number of areas and sectors for 5 ARTCC`s in the NAS

LocID	Facility Name	State	Areas	Sectors
ZDC	Washington	VA	8	48
ZNY	New York	NY	6	30
ZJX	Jacksonville	FL	5	39
ZMA	Miami	FL	4	32
ZAB	Albuquerque	NM	5	38

Table 3.1 Number of areas and sectors in 5 ARTCC`s of NAS

3.1.2. Functional classification of enroute air traffic controller positions.

The authorized title for center air traffic controllers is provided in FAA(1999).The authorized title is given as "Air Traffic Control Specialist (Center)".

FAA (1999) provides a description of the functions performed by enroute air traffic controller positions.

i) To control enroute air traffic

ii) To provide approach control services and radar separation for IFR and VFR aircraft operating to and from non-approach controlled and non-controlled airports.

iii) To provide advisory services to pilots. These advisory services include information such as status of navigational aids, other traffic, weather and airport conditions, and status of restricted and military operating areas.

FAA (1997) classifies air route traffic controllers into “R-controller”, “D-controller” and “Tracker”. It also lists the functions for each category of controllers. “The R-controller communicates with aircraft pilots via radio frequencies and coordinates with other controllers within his/her facility and other facilities as situation dictates. The D-controller assists the R- controller by maintaining the flight progress bays, issuing clearances over the interphone and preplanning control activities. The D-controller reviews flight progress strips for new flights in conjunction with already existing flights to determine whether adequate separation will exist between aircraft. When the D-controller is not using the communication system s/he monitors the radio frequency of the R-controller. The Tracker assists the R-controller by monitoring the R-controllers radio frequency and scanning the PVD (Plan View Display) to identify and resolve potential conflicts.”

FAA (1997) study also lists the functions of the A-side or flight data position. The flight data position removes printed progress strips from printers, inserts them into holders, and distributes them to appropriate sectors for posting in the flight progress bays.

3.1.3. Current method used for controller staffing.

There are two methods used to staff controllers in sectors. The two methods have been discussed below.

Short term controller staffing:

The current staffing standards FAA (1997) for enroute air traffic controllers are developed using work measurement techniques (work sampling and time study). Work measurement techniques determine the actual time required by a controller to perform a standardized set of air traffic control functions or tasks within a fifteen minute interval. The staffing standard is developed as a mathematical model to estimate the number of persons required to perform a standardized set of air traffic control functions or tasks. The mathematical model contains equations composed of compiled work times required to perform air traffic control functions or tasks. FAA (1997) provides a staffing guide for the number of controllers required by function and the number of aircraft worked during a 15–minute interval. (Refer table 3.2)

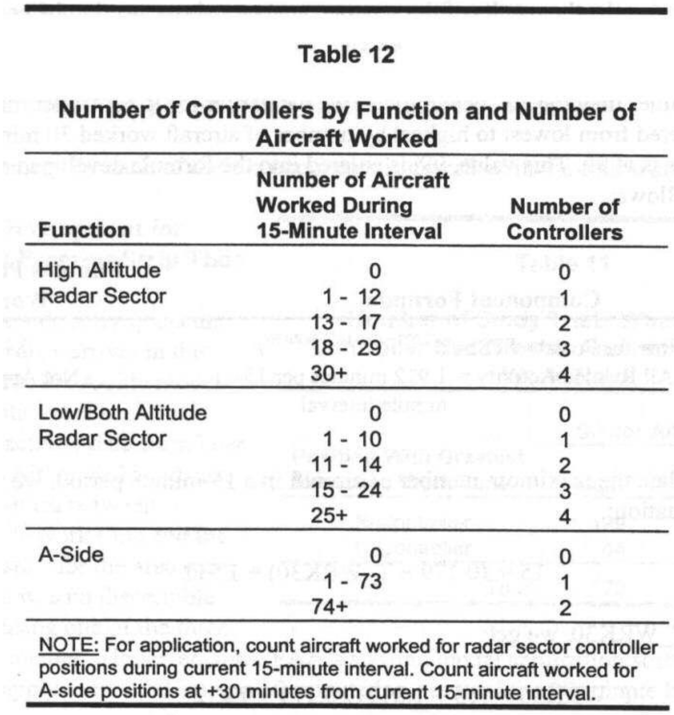

Table 12

Number of Controllers by Function and Number of Aircraft Worked

Function	Number of Aircraft Worked During 15-Minute Interval	Number of Controllers
High Altitude Radar Sector	0	0
	1 - 12	1
	13 - 17	2
	18 - 29	3
	30+	4
Low/Both Altitude Radar Sector	0	0
	1 - 10	1
	11 - 14	2
	15 - 24	3
	25+	4
A-Side	0	0
	1 - 73	1
	74+	2

NOTE: For application, count aircraft worked for radar sector controller positions during current 15-minute interval. Count aircraft worked for A-side positions at +30 minutes from current 15-minute interval.

Table 3.2 Number of controllers required to be staffed by function and number of aircraft worked

(Source: ARTCC Radar Sector Staffing Models, 1997)

However during a meeting[1] with air traffic controllers at the FAA Free Flight Office it was found that in practice the staffing of controllers and addition of controllers to sectors is not performed based on 15 minute radar controller staffing standards -FAA (1997). Instead facility managers and supervisors use their judgment and consider complexity to assign controllers to sectors subjected to different traffic levels.

[1] Meeting with Mr. Jeff Shearer, Mr. Ed Meyer, Mr. Dave Knorr and Mr. Antonio Rubiera at FAA Free Flight Office on 04/07/05.

Long term controller staffing:

FAA (1997)[2] and modified FAA (1991) controller staffing standards are used by FAA to predict future annual staffing requirements for ARTCC`s .APO forecasted annual center operations for future years and 15 minute radar controller staffing standards developed in FAA (1997) are used as inputs to estimate future controller staffing requirements for ARTCC`s. Long term staffing standards are used as a baseline for staffing controllers for days. In facilities managers support staffing based on the resources provided based on long term staffing standards. Managers could use overtime to meet the demand.

[2] Information provided by Mr. Elliott McLaughlin during meeting at FAA on 05/20/2005.Changes have been made to the FAA 1991 staffing model as explained by Mr. McLaughlin.

3.1.4. Relation between enroute air traffic, controller workload and ATC complexity

In this section the relation between enroute air traffic, controller workload and ATC complexity has been discussed.

3.1.4.1. ATC complexity and controller workload increases with enroute air traffic

FAA and other researchers have defined ATC (Air Traffic Control) complexity as a measure of difficulty in performing controller tasks (FAA (1995) and Grossberg (1989) as reported in FAA (1995)). Researchers have showed that a positive relation exists between ATC complexity and controller workload. Grossberg (1989) as reported in FAA (1995) has shown that ATC complexity affects the rate of increase of controller workload.

Characteristics of air traffic and sector airspace compose ATC complexity. Complexity factors related to characteristics of air traffic could be clustering of aircraft in the airspace Stein (1985) or number of intersecting flight paths, Mogford et al. (1993). Complexity factors related to sector airspace could be sector geometry, Buckley et al. (1983) or sector size, Mogford et al. (1993).

FAA (1995) explains that the interaction of a given level of traffic complexity with sector complexity creates overall ATC complexity. FAA (1995) also identifies traffic density as a component of ATC complexity. Buckley et al. (1983) reported that traffic density has a greater impact on system performance measures than sector geometry (airspace complexity). But, Buckley also reported that traffic density and sector geometry interact to effect system performance measures. On similar lines FAA (1985) reports that the interaction of air traffic characteristics (air traffic complexity) and physical characteristics of a sector (airspace complexity) generates overall ATC complexity and controller workload. It can be argued that traffic volume itself is the generator of ATC complexity and controller workload.

Researchers have found a positive relation among many air traffic complexity variables and controller workload. Using a simulation environment, Stein (1985) found a strong statistical correlation between controller workload (as measured by Air Traffic Workload Input Technique) and air traffic complexity variables. In Stein's simulation study, air traffic controllers predicted controller workload using Air Traffic Workload Input Technique. Some measures of the activity in the airspace were the variables aircraft count, frequency of minimum separation violations, average number of aircraft in a small block of airspace, and planned actions. Three levels of task load (low, moderate and high) were developed by varying selected system variables. Responses of controllers were obtained using ATWIT technique for different levels of task load. Study found that the controller's responses also reflected three levels of workload. A positive relationship was obtained between taskloads i.e. system variables and controller workload responses using ATWIT. It can be seen that the air traffic complexity factors used in Stein's (1985) study are generated by traffic volume itself.

It is proposed that an increase in traffic volume will increase air traffic complexity factors which in turn will increase the controller complexity and workload. Based on a review of ATC complexity literature, Pawlak et al. (1996) states that "an increase in amount of air traffic is related to an increase in complexity". Based on a thorough review of ATC complexity literature, Hilburn (2004) explains that traffic density in form of traffic count, density or load has been the single most widely analyzed variable for its influence on controller complexity and workload.

FAA (1999) also emphasizes the impact of traffic density on controller complexity and workload. It states that aircraft congestion has greatest impact on the difficulty and complexity of center controller positions. These complexity factors are present in different centers in varied combinations and intensity levels, and their impact becomes more pronounced with substantial increases in congestion of air traffic. Based on the airspace available, higher levels of air traffic congestion will cause more complex configurations of airspace to tackle more congested patterns of air traffic.

FAA (1999) explains that in congested control environment higher aircraft crossings, climbs and descents will occur in complex configurations of airspace. This will cause a need for increased precision and rapidness in controller's coordination and control actions, while he coordinates among the other members of bigger controller workforce. With an increase in air traffic in centers, higher coordination will be required among the controllers and the level of criticality involved in the controller's decisions and actions will increase. Optional plans available for the control and movement of aircraft will reduce. Under heavier levels of air traffic, the controllers will be subjected to continuing pressure to make rapid control decisions, and to communicate precisely and rapidly with pilots. Sustained air traffic levels will cause greater coordination problems and increase the congestion in airspace. Higher levels of continued traffic congestion experienced by a controller will demand higher performance from the controller in terms of his judgment, skills and his ability to make accurate decisions by rapidly reacting to extremely stressful work situations.

For developing an aggregate macroscopic relation between controller complexity (which generates controller workload) and traffic volume for the entire NAS the following hypothesis is proposed. It is proposed that for any sector or a group of sectors (centers) in the airspace, regardless of the physical characteristics of the sector (i.e. sector complexity) an increase in traffic volume will cause a proportional increase in controller complexity and workload.

3.1.4.2. Consideration of ATC complexity and controller workload which is not generated by traffic volume and its characteristics

There are researchers who have shown that traffic volume and its characteristics do not generate the overall controller complexity and workload in a sector. Sridhar et al. (1998) as reported in Yousefi et al. (2003) proposed that the real airspace complexity cannot be captured by considering only the number of aircraft passing through a sector .Based on his analysis, Yousefi et al. (2003) reported that less complex sectors were handling more aircraft in NAS.

Hilburn (2004) points out that researchers (Athenes et al. (2002), Mogford et al. (1995) and Kirwan et al. (2001)) have criticized traffic density for its inadequateness to capture some aspects of ATC complexity. Based on a literature review of controller workload studies, Majumdar et al. (2002) proposed that aircraft count is not a suitable measure of controller workload. Majumdar et al. (2002) propose that the following air traffic complexity factors cause controller workload- traffic mix, climbing-descending aircraft, aircraft speeds and horizontal and vertical separation standards.

ATC complexity consists of traffic complexity and airspace complexity. Based on literature review it was found that traffic volume causes traffic complexity. Traffic volume does not cause airspace complexity and the total ATC complexity. Airspace complexity varies across sectors in NAS. However for developing an aggregate macroscopic relation between traffic volume and ATC complexity for sectors and centers in NAS, it is proposed that airspace complexity could be held constant. Hence ATC complexity and controller workload will increase proportionally with an increase in traffic volume.

There are serious problems associated with the measurement of airspace complexityThis makes it difficult to measure the total ATC complexity. The problems associated with the measurement of total ATC complexity and controller workload for a sector or a group of sectors are explained in the next section.

3.1.5. Measurement of ATC complexity

In this section the difficulties in measurement of ATC complexity and the ATC Complexity metric developed and employed by FAA to measure ATC complexity have been discussed.

3.1.5.1. Difficulties in measurement of ATC complexity

The difficulties in measurement of ATC complexity are listed below:

i. Lack of consensus on a measure of ATC complexity and controller workload.

There is a lack of consensus on a measure of ATC complexity and controller workload in the literature. Researchers have developed different metrics using different approaches and validation techniques to measure ATC complexity and controller workload. Hilburn (2004) explains that no single metric can be used to measure all possible forms of ATC complexity present in airspace. On similar lines (Jorna (1991) as reported by Majumdar et al. (2002)) explains that controller workload has various definitions in literature and several researchers have developed different models to measure controller workload.

It is difficult to measure complexity of different sectors in NAS using a single complexity metric. Different airspaces have different types of complexity making it difficult for a single complexity metric to measure complexity at different airspaces Hilburn (2004). Hilburn provides examples of researches wherein the developed complexity metrics were developed or validated at only one specific site, (example Pawlak et al. (1996)) which questions the applicability of the developed metrics for other sectors or centers. Hilburn

(2004) also provides examples of research studies, in which the developed complexity metrics showed a variation in performance at different facilities.

ii. Difficulties in measuring complexity during development of FAA (1991) and FAA (1997) controller staffing standards.

FAA (1991)

FAA 1991 reported problems in measuring ATC complexity for individual sectors. During the preparation of FAA Staffing Standard for Air Route Traffic Control Centers, (FAA 1991), three complexity factors were identified and collected to study their effect on controller workload. Complexity factors in this study were defined as "variables that make one sector different or more complex than another". The three complexity factors collected for individual sectors were:

a) The number of navigational aids in a sector.

b) The number of airways in a sector.

c) The number of airway intersections in a sector.

During the model development process, a variation in time for controller work activities was observed between the results of staffing standard models and actual onsite observations. (Refer table 3.3)

The study team analyzed that no single complexity factor affected the controller work activities. However the combined effect of the complexity factors affected the controller work activities to some degree and could explain some amount of variation.

Model	Standard deviation (minutes)	
	Low altitude sectors	High altitude sectors
One controller model	2.21	Data not available
Two controller model	1.98	1.92

Table 3.3 Standard deviation of differences in controller work times between the staffing models and actual onsite observations

Since, only three complexity factors were considered for analysis, it is possible that the impact of other complexity factors not considered in the study could explain this unexplained variation.

FAA (1997)

During the development of FAA 1997 ARTCC staffing standards, no center or sector related ATC complexity was considered; instead measurement sites (centers) were selected from each of the four groups, which were stratified based on annual operations forecasted for fiscal year. The study team made an attempt to collect complexity data during their onsite visits. However, during the data collection phase, the study team estimated that the potential value of the collected data did not justify the amount of manual effort needed to collect the data and the data were not collected. The effect of complexity factors on controller workload was not studied in the FAA 1997 study.

3.1.5.2. ATC Complexity metric developed and employed by FAA

FAA has developed “Hourly Classification Index” to measure the difficulty and complexity levels of a center’s work situations FAA (1999). Center specific “Hourly Classification Indices” are used to assign ATC grade levels to controllers. ATC grade levels of controllers are used as a basis for deciding wages of controllers.

“Hourly Classification Index” increases with an increase in the values of the following metrics. These metrics measure traffic volume characteristics, and are used as intermediate inputs in the formula for estimating hourly classification index.

i) Weighted hourly count: Weighted hourly traffic count is used for estimating “Hourly Classification Index”. Formula for computing “weighted hourly count” assigns varying weights to different flight operations to reflect the complexity involved in performing activities related to those operations.

ii) Airspace density- Airspace density is a measure of the number of aircraft present per unit area in the facility’s airspace during an average hour of operation.

iii) Airspace usage- Airspace usage is defined as the total time in minutes for all aircraft in center’s airspace (during the average hour of busiest 1830 hours) divided by the average hourly sector operations.

It can be argued that the above traffic complexity characteristics incorporated in the HCI formula are driven by traffic volumes. With an increase in air traffic, the magnitudes and the intensity levels of the complexity factors will increase. This in turn will increase the values of HCI for centers. The formula for measuring HCI does consider other air traffic and sector related complexity characteristics like aircraft mix, proportion of domestic air traffic over water as compared to total domestic traffic, proportion of oceanic air traffic compared to total domestic air traffic, military operations and facility characteristics as intermediate inputs in the HCI formula.

Based on ATC complexity literature one could argue that the HCI does not capture all factors related to ATC complexity, which have been proposed and validated in the literature. The definition and development of HCI is suitable , since it is an macroscopic metric developed to measure complexity for centers and is vulnerable to the drawbacks of a macroscopic complexity metric explained in section 3.1.5.1.

HCI is operational since 1999 to date and is being efficiently used to assign grade levels to controllers and to decide their wages based on workload complexity. The efficient and successful operation of the HCI is a support to the hypothesis that complexity and workload can be measured in terms of air traffic volume and its characteristics.

3.1.6. Relation between air traffic operations and number of controllers staffed in sectors.

It is proposed that as the traffic volume (number of operations) handled by a center/sector increases the complexity and difficulty involved in performing the controller work activity (controller complexity) and controller workload increases. This will increase the controller task times for controlling same number of operations. The controller will spend more time for handling the same number of aircraft operations and will control fewer operations per unit time. This will warrant an increase in controller staffing per unit time in a sector as per 15 minute controller staffing standards FAA (1997).

The following findings from FAA (1997) support the proposed hypothesis.

i. Difference in controller task times for handling same number of operations

During the FAA (1997) staffing standard study, a series of data analyses was carried out to determine the statistically significant differences in the time measurement data attributable to differences among the eight centers participating in the study. During the analyses it was found that the amount of time spent by a controller or a staffing configuration at a center for the same number of total aircraft worked varied for different centers. The study team was unable to explain these differences.

These differences could possibly be explained by analyzing the annual operations forecasted for each center. The study team had classified the centers in the continental U.S. into four groups based on the annual operations forecasted for the fiscal year 1996. (Refer table 3.4).

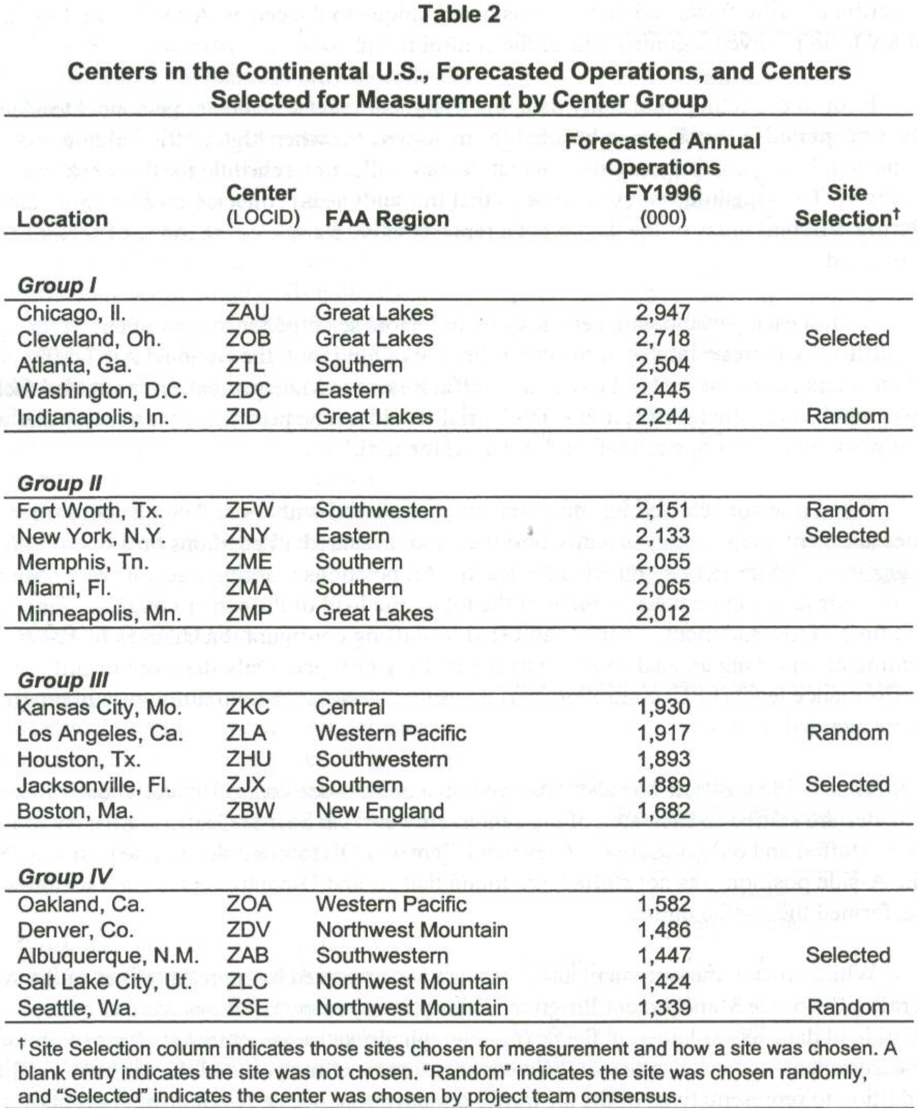

Table 2

Centers in the Continental U.S., Forecasted Operations, and Centers Selected for Measurement by Center Group

Location	**Center** (LOCID)	**FAA Region**	**Forecasted Annual Operations FY1996** (000)	**Site Selection†**
Group I				
Chicago, Il.	ZAU	Great Lakes	2,947	
Cleveland, Oh.	ZOB	Great Lakes	2,718	Selected
Atlanta, Ga.	ZTL	Southern	2,504	
Washington, D.C.	ZDC	Eastern	2,445	
Indianapolis, In.	ZID	Great Lakes	2,244	Random
Group II				
Fort Worth, Tx.	ZFW	Southwestern	2,151	Random
New York, N.Y.	ZNY	Eastern	2,133	Selected
Memphis, Tn.	ZME	Southern	2,055	
Miami, Fl.	ZMA	Southern	2,065	
Minneapolis, Mn.	ZMP	Great Lakes	2,012	
Group III				
Kansas City, Mo.	ZKC	Central	1,930	
Los Angeles, Ca.	ZLA	Western Pacific	1,917	Random
Houston, Tx.	ZHU	Southwestern	1,893	
Jacksonville, Fl.	ZJX	Southern	1,889	Selected
Boston, Ma.	ZBW	New England	1,682	
Group IV				
Oakland, Ca.	ZOA	Western Pacific	1,582	
Denver, Co.	ZDV	Northwest Mountain	1,486	
Albuquerque, N.M.	ZAB	Southwestern	1,447	Selected
Salt Lake City, Ut.	ZLC	Northwest Mountain	1,424	
Seattle, Wa.	ZSE	Northwest Mountain	1,339	Random

† Site Selection column indicates those sites chosen for measurement and how a site was chosen. A blank entry indicates the site was not chosen. "Random" indicates the site was chosen randomly, and "Selected" indicates the center was chosen by project team consensus.

Table 3.4 Centers in continental U.S., forecasted center operations, and centers selected for measurement by center group

(Source: ARTCC Radar Sector Staffing Models, 1997)

The eight measurement centers were chosen from these groups. Table 3.5 shows the statistically significant differences in the time measurement data attributable to differences among the eight centers.

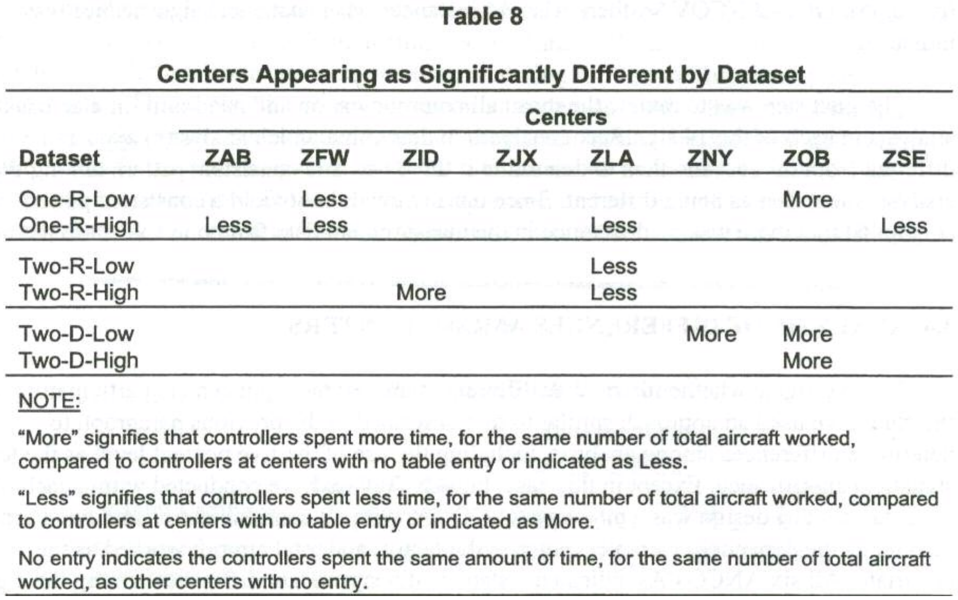

Table 8

Centers Appearing as Significantly Different by Dataset

	Centers							
Dataset	**ZAB**	**ZFW**	**ZID**	**ZJX**	**ZLA**	**ZNY**	**ZOB**	**ZSE**
One-R-Low		Less					More	
One-R-High	Less	Less			Less			Less
Two-R-Low					Less			
Two-R-High			More		Less			
Two-D-Low						More	More	
Two-D-High							More	

NOTE:

"More" signifies that controllers spent more time, for the same number of total aircraft worked, compared to controllers at centers with no table entry or indicated as Less.

"Less" signifies that controllers spent less time, for the same number of total aircraft worked, compared to controllers at centers with no table entry or indicated as More.

No entry indicates the controllers spent the same amount of time, for the same number of total aircraft worked, as other centers with no entry.

Table 3.5 Centers which appear significantly different by dataset

(Source: ARTCC Radar Sector Staffing Models, 1997)

Based on the above differences, it can be inferred that controllers at centers belonging to higher level groups (groups which have higher annual operations forecasted for the fiscal year 1996) spent more time for the same number of aircraft worked as compared to controllers at centers belonging to lower level groups. From tables 3.4 and 3.5 it can be observed that controllers at centers ZID and ZOB belonging to group I and center ZNY belonging to group II spent more time for the same number of total aircraft worked as compared to centers ZAB and ZSE belonging to group IV and center ZLA belonging to group III.

ii. Differential staffing requirement for low and high altitude sectors.

Results of FAA (1997) staffing standard study show that the activity time per aircraft for controllers assigned to low altitude sectors is higher than the activity time per aircraft (Refer table 3.6) for controllers assigned to high altitude sectors.

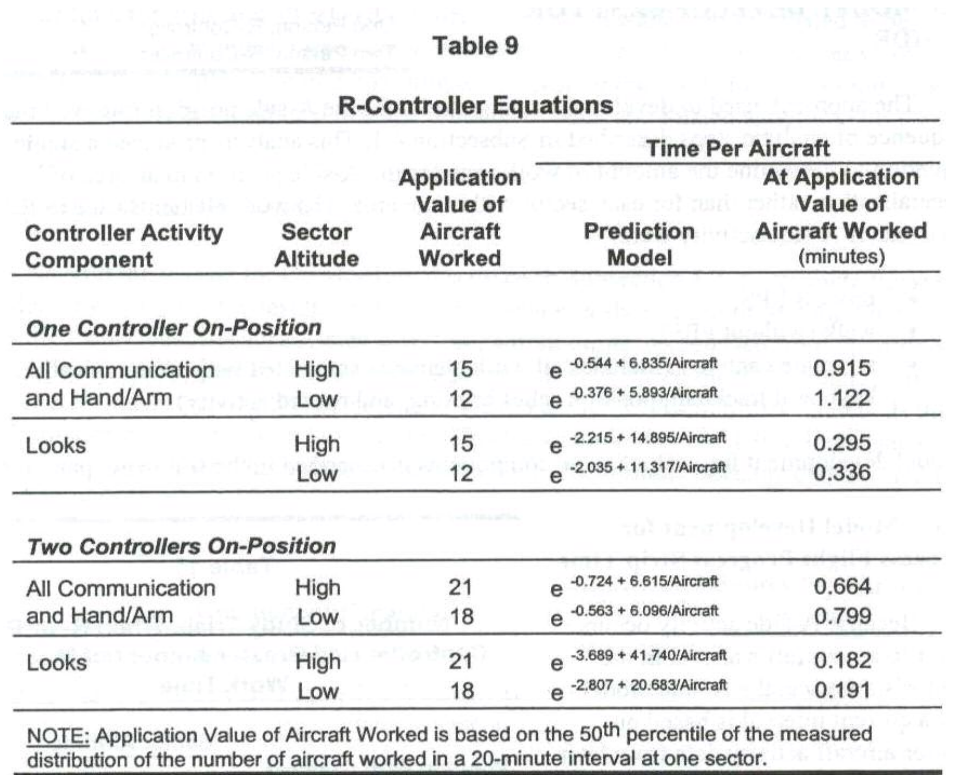

Table 9

R-Controller Equations

Controller Activity Component	Sector Altitude	Application Value of Aircraft Worked	Time Per Aircraft: Prediction Model	Time Per Aircraft: At Application Value of Aircraft Worked (minutes)
One Controller On-Position				
All Communication and Hand/Arm	High	15	$e^{-0.544 + 6.835/\text{Aircraft}}$	0.915
	Low	12	$e^{-0.376 + 5.893/\text{Aircraft}}$	1.122
Looks	High	15	$e^{-2.215 + 14.895/\text{Aircraft}}$	0.295
	Low	12	$e^{-2.035 + 11.317/\text{Aircraft}}$	0.336
Two Controllers On-Position				
All Communication and Hand/Arm	High	21	$e^{-0.724 + 6.615/\text{Aircraft}}$	0.664
	Low	18	$e^{-0.563 + 6.096/\text{Aircraft}}$	0.799
Looks	High	21	$e^{-3.689 + 41.740/\text{Aircraft}}$	0.182
	Low	18	$e^{-2.807 + 20.683/\text{Aircraft}}$	0.191

NOTE: Application Value of Aircraft Worked is based on the 50th percentile of the measured distribution of the number of aircraft worked in a 20-minute interval at one sector.

Table 3.6 R controller's work time per aircraft and number of aircraft worked per 15 minutes

(Source: ARTCC Radar Sector Staffing Models, 1997)

For single and two controller staffing configuration it can be seen that controllers assigned to low altitude sectors are able to control less aircraft operations per unit time as compared to controllers assigned to high altitude sectors. Refer table 3.7 below.

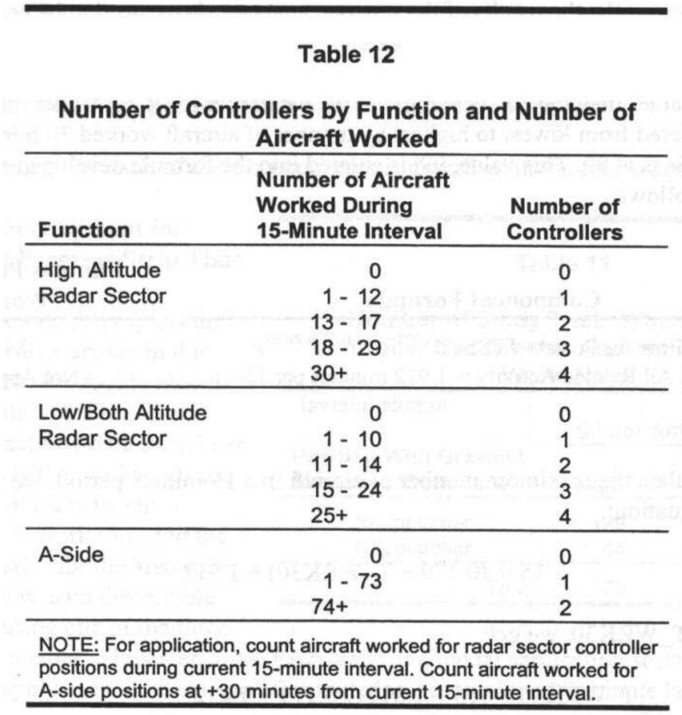

Table 12

Number of Controllers by Function and Number of Aircraft Worked

Function	Number of Aircraft Worked During 15-Minute Interval	Number of Controllers
High Altitude Radar Sector	0	0
	1 - 12	1
	13 - 17	2
	18 - 29	3
	30+	4
Low/Both Altitude Radar Sector	0	0
	1 - 10	1
	11 - 14	2
	15 - 24	3
	25+	4
A-Side	0	0
	1 - 73	1
	74+	2

NOTE: For application, count aircraft worked for radar sector controller positions during current 15-minute interval. Count aircraft worked for A-side positions at +30 minutes from current 15-minute interval.

Table 3.7 Number of controllers required to be staffed by function and number of aircraft worked

(Source: ARTCC Radar Sector Staffing Models, 1997)

It can be concluded that higher ATC complexity and higher traffic volumes in low altitude sectors make them more difficult and complex to control than high altitude sectors. This increases the workload for the controllers assigned to low altitude sectors. Hence controllers assigned to low altitude sectors can control less aircraft per unit time as compared to controllers in high altitude sectors. With increase in air traffic operations (considering the same distribution of operations in low and high altitude sectors) more controller staffing will be required in low altitude sectors compared to high altitude sectors for controlling same number of operations per unit time.

3.1.7. Factors affecting relation between controller staffing and enroute air traffic operations

Based on the literature review and results of FAA (1997) controller staffing standards it was found that the following factors affect relation between air traffic operations and staffing of controllers in sector and centers.

i. Diseconomies of staffing additional controllers to sectors.

In FAA (1997) a staffing guide for the number of controllers required by function and the number of aircraft worked during a 15 –minute interval is provided.

Table 3.6 shows thatfor a two controller staffing configuration (for both high and low altitude sectors) the R-controller's activity time per aircraft decreases with assistance from a D-controller as compared to the single R- controller staffing configuration. This decrease in activity time per aircraft for R controller is not proportional to the addition of a D controller to the sector.

For example the "All Communication and Hand/Arm" activity time per aircraft for high altitude sector decreases from 0.915 minutes to 0.664 minutes when the staffing of the sector is increased from a single controller to a two controller staffing configuration.

As a result, the increase in number of "total aircraft worked" by 2 controllers (R controller and D-controller) is not proportional to the "total aircraft worked" by 1 controller. (Refer table 3.2)

For example: In a high altitude radar sector, a single controller can handle a maximum of 12 aircraft in 15 minute interval. On addition of a controller to the sector, the two controller staffing configuration can only handle a total of 17 aircraft. This increase in the number of aircraft handled (5 aircraft) is not proportional to the addition of one controller to the sector. Similar argument can be made for relation between addition of third and fourth controller to a sector and the increase in operations handled by three and four controller staffing configurations.

Hence, based on the staffing standards, it can be seen that with an increase in air traffic operations, the assignment of additional controllers to the sectors will be more than proportional to the increase in aircraft operations in those sectors.

ii. Creation of additional NAS sectors through resectorisation

Hopkin (1982) proposed that the strategy of creating smaller sectors to reduce traffic volume and the workload of the controller cannot be justified when the coordination workload surpasses the reduction in workload due to creation of smaller sectors (As reported in FAA (1995)). On similar lines Jorna (1991) and Wickens et al. (1997) propose that a decrease in the size of the sector or an increase in the number of controllers is not a solution to the problem of high workload as it increases the communication and coordination between sectors and controllers.

Magill (1998) states that the traditional response of ATC system to the increased traffic demand has been to resectorize airspace and to assign more controllers in parallel to control the traffic. However this process cannot be continued for an indefinite period, because if the sectors become too small, the increased coordination between neighboring sectors will offset the benefits obtained from staffing more controllers in parallel.

Magill (1998) explains that the size of the sectors cannot be reduced below a minimum size. This is because in smaller sectors the controllers will not get adequate time or airspace to perform control actions. Coordination between sectors will become more complicated and delayed handoffs will degrade the consistency of the system. Andrews and Welch (1997) and Wickens et al. (1997) explain that decreasing sector size will reduce time spent per aircraft and will give less time to a controller to understand the situation. This in effect will increase workload. Mogford et al. (1993) has identified sector size as one of the factors, which affects decision making of the controllers.

FAA (1995) explains that creation of additional smaller sectors will increase the controller tasks of communication, handoffs and coordination among the sectors and controllers. FAA (1995) further reports that researchers have identified and measured the tasks of communication, handoffs and coordination as air traffic complexity factors, which increase the controller workload.

Grossberg (1989) as reported in FAA (1995), FAA order 7210.46, Mogford et al. (1993) and Schmidt (1976) have identified coordination as a complexity factor which increases controller workload.

Stein (1985) and Schmidt (1976) have identified handoff as a complexity factor which increases controller workload.

Soede et al. (1971) as reported in FAA (1995) has identified communication and Schmidt (1976) has identified point outs, structuring and bookkeeping events as complexity factors which increase controller workload.

It is proposed that with increasing air traffic operations and corresponding increase in controller workload, the number of controllers required per sector will eventually reach the maximum permissible number of controllers and the sectors will be divided. An increase in number of sectors in the NAS will cause a corresponding increase in the number of staffing of controllers. Creation of additional smaller sectors will increase the air traffic complexity and controller workload. This in turn will increase the time required by a controller to perform control tasks and warrant an increase in staffing of controllers as per FAA staffing standards

Figures 3.1 and 3.2 below show the number of static sectors and areas in NAS during period 2000 to 2004.

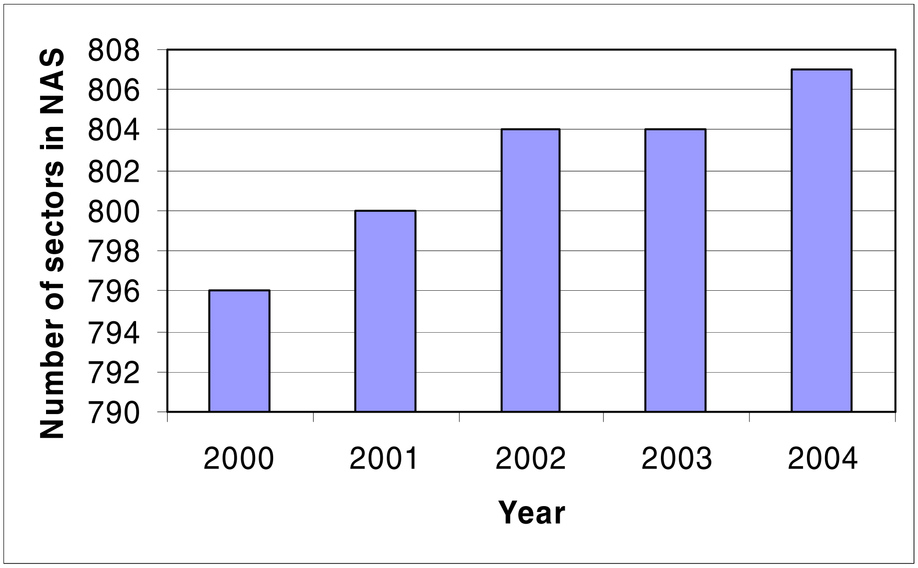

Figure 3.1 Annual increases in number of sectors in NAS

Data source: ATO office

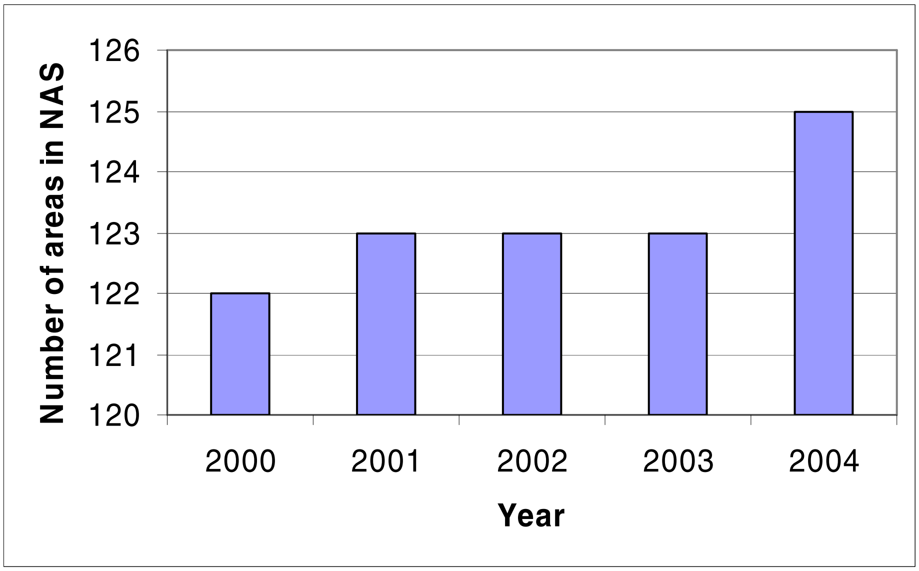

Figure 3.2 Annual increases in number of areas in NAS

Data source: ATO office

Number of areas and static sectors shown in graphs are annual metrics and these metrics show an increase over the years.

Dynamic resectorisation is currently being carried out for sectors in NAS. Depending on the amount of air traffic and the level of complexity of operations, two or more sectors are combined and managed by controllers at one work station. Several controller functions are also combined for performance by one controller during periods of low traffic volume in facilities FAA (1997). The dynamic resectorisation data was not available, since individual facilities record the data and the data are not sent to ATO office.

With an increase in enroute air traffic in NAS over the years, FAA has carried out airspace redesign by performing resectorisation and creating additional sectors to relieve air traffic congestion. From the above graphs it can be seen that there has been a small and gradual increase in number of sectors and areas in NAS.

iii. Assigning more sectors and functions to a controller during low traffic conditions.

With growth in air traffic operations during non peak periods, additional staffing of controllers will be required in the following scenarios.

1. FAA (1997) states that depending on the amount of air traffic and the level of complexity of operation two or more sectors can be combined and managed by controllers at one work station. During periods of low traffic volume in facilities, several controller functions are combined for performance by one controller.

As air traffic increases, more ATC staffing will be required in scenarios wherein two or more sectors have been combined and managed by controllers at one workstation and for sectors in which several controller functions are combined for performance by one controller.

2. Staffing of Flight data position:

FAA (1997) states that flight data positions are typically assigned as one per area. Since the peak workload for a flight data position can be distributed throughout periods of lighter workload, the effects of complexity and difficulty factors on workload are not to be considered. Hence, Flight data positions are staffed based on average staffing requirements (FAA 1997).

Increased air traffic operations in the areas to which flight data positions are assigned will have the following impacts on the staffing of these positions:

a. Flight data positions are not staffed during local hours of 12 a.m.-6a.m.i.e. the midnight shift (FAA (1997). With an increase in air traffic operations distributed throughout different time periods of the day, it will be required to staff this shift in the future.

b. There are some centers in which the A-side position is not staffed and the A-side duties are performed by the R and D controllers at each sector. Such staffing configurations were observed at the Seattle Center (ZSE) and the Cleveland Center (ZOB) during the FAA (1997) revalidation study. With growth in sector operations and an eventual increase in the work load for R and D controllers, A-side positions at such centers will need to be staffed.

Based on the above arguments, it is found that the staffing of flight data positions grows at least linearly with total aircraft activity count for an area.

3.1.8. Controller forecasting model developed by FAA for enroute air traffic center controllers

The current controller forecasting model uses FAA (1997) and modified FAA (1991)[3] staffing models to predict future annual controller staffing requirements. APO forecasted annual center operations, 15 minute controller staffing standards (developed in FAA (1997)) and 15 minute sector traffic count from Host Aircraft Management Execs (HAME) data are used as inputs to estimate future controller staffing requirements. The method used by FAA to predict future controller staffing requirements for center facilities is described below.

For 5th, 10th, 15th and 20th day of each month, 15 minute sector traffic count is obtained for all sectors of a center from the HAME database. HAME records 15 minute sector operations for all sectors of a center.

Using the FAA (1997), 15 minute controller staffing standard and using the 15 minute HAME traffic count, controllers are assigned to all sectors of a center for 24 hour period based on the type of sector i.e low or high, and based on the functional classification of controller i.e. R or D controller.

For each center facility, a linear regression is performed by relating center operations as the independent variable and the predicted number of controllers as the dependent variable. APO forecasted operations for a center are used as an input in the above regression model to compute the total number of controllers required in all sectors of the center. Hence for each facility, the annual staffing requirement corresponding to APO forecasted annual center operations is estimated from the above regression model.

When the linear regression staffing standard models were validated by FAA (FAA (1991) study) for each ARTCC facility by comparing the staffing standard calculations to the actual onboard staffing, accurate prediction results were obtained. Based on the linear regression employed in current controller forecasting model and validation results of the 1991 study the following relation is found between controller staffing and operations. It is found that controller staffing grows atleast linearly with air traffic operations.

During a meeting at FAA on 05/20/2005, Mr. Elliott McLaughlin indicated that managers in facilities need to support staffing based on resources provided by the current controller forecasting model. However managers could use overtime to meet the demand.

It was found that the current controller forecasting model has not been revalidated after its implementation. It is possible that the number of air traffic controllers required is greater than those predicted by the linear regression staffing model and a greater than linear relation exists between staffing of controllers and air traffic operations. Hence, there is a need to validate the current controller forecasting model. In analysis section the linearity assumption employed in the relation between actual air traffic operations and onboard staffing of controllers in centers is validated. Adequacy of controller staffing provided by current controller forecasting model was validated by comparing staffing standard predicted controller staffing with the actual on board staffing of controllers.

Order 1380.55, FAA (1998) states that the staffing standards for air route traffic control centers are updated at periodic intervals of 3 to 5 years. FAA (1997) ARTCC staffing standards guide has not been updated since 1997.

[3]Currently ATO is working on the expanded version of staffing standards. Types of sectors other than low and high altitude will be considered in the standards, since the implementation of RVSM impacts different stratums.

The FAA (1997) 15 minute radar controller staffing standards have been developed based on work load measurement technique (work sampling and time study) using 1997 data. Based on the findings in literature review it is proposed that with growth in air traffic operations, congestion effects will increase the complexity and difficulty involved in performing air traffic control activities. Time allowance for controller activities will increase. It is suggested that the "updated" staffing models, (staffing models used to staff controllers in a sector during a 15 minute period) will show a need to staff more controllers in a sector for the same aircraft count.

The adequacy of the 15 minute controller staffing model developed in FAA (1997) should be validated. Validation of the 15 minute controller staffing model was performed by ATO office (Mr. Elliott McLaughlin and his team) in a study entitled- "Trip Report Cleveland Air Traffic Control Facilities" in 2004. The study found that the number of controllers staffed onboard for 15 minute intervals based on the SISO data were greater than or equal to the required number of controllers predicted by FAA (1997) -15 minute controller staffing model.

The validation of FAA (1997) -15 minute controller staffing model was performed for one facility. It is proposed that the validation should be carried out at more facilities. It is further suggested that the 15 minute radar controller staffing standards -FAA (1997) should be revalidated by performing work sampling and time study to estimate if the time allowances for controller activities have increased. The sector operations controlled by different staffing configurations during a 15 minute period should be estimated in the revalidated (updated) staffing standards.

The sector operations controlled by different staffing configurations during a 15 minute period, based on the updated 15 minute standards should be compared with the original FAA 1997, 15 minute standards.

FAA staffing standards are used as a baseline for staffing controllers for days

[3] Changes have been made to the FAA 1991 staffing model as explained by Mr. Elliott McLaughlin during meeting at FAA on 05/20/2005.

3.1.9. Summary of literature review in section 3.1

Based on findings in literature, an aggregate macroscopic relation is proposed between operations and complexity for sectors and centers in NAS. It is proposed that air traffic complexity will increase with air traffic volume in sectors and centers in NAS. Airspace complexity has not been considered in the formulation of this relation. This is because of problems in measuring airspace complexity. Using HCI metric developed by FAA, it has been explained that traffic volume characteristics can be used to measure complexity and workload on controller.

A macroscopic relation is proposed between controller staffing and traffic volume in sectors and centers of NAS based on the following findings from literature review.

1. As the traffic volume handled by a center increases, the center specific complexity i.e. difficulty involved in performing controller work activity increases.

An increase in the traffic volume handled by a center causes an increase in center specific complexity. This increase in complexity causes an increase in the work time of center controller for controlling the same number of operations per unit time. As the traffic volume handled by center increases, the work time spent by a center controller for controlling the same number of center operations per unit time increases. With increase in total center operations, a center controller will be able to handle fewer operations per unit time. Hence more controllers will be required to handle the same air traffic operations per unit time in the center.

As the traffic volume handled by a center increases greater controller staffing will be required to handle the same air traffic operations per unit time in that center.

2. Linear regression employed in the controller forecasting model developed by FAA.

3. Other factors which support the proposed relation between controllers and operations are summarized below and have been discussed in detail in literature review.

i. Diseconomies of staffing additional controllers to sectors.

ii. Increase in no of sectors due to resectorisation

iii. Assignment of more sectors and functions to a controller in low traffic conditions.

iv. Differential staffing requirement for low and high altitude sectors:

v. Varying mix of operations.

FAA 1999 states that “Normally, an increase in air traffic indicates a proportionally larger staff of controllers”. Points 1 and 3 discussed above support the hypothesis that the number of air traffic controllers required is atleast equal to or greater than those predicted by the linear regression staffing models. Since these model equations are linear, it is found that controller staffing grows atleast linearly with air traffic operations. Factors like equipage, age and individual performance of controllers, which affect relation between controllers and workload are held constant. A linear or a greater than linear relation is proposed between the future air traffic operations in the NAS and the number of enroute air traffic controllers required

3.2. Relations between controller performance and air traffic in sectors and centers of the NAS

Relations between performance of controllers and air traffic in sectors and centers of NAS are studied in section 3.2.

3.2.1. Impact of air traffic congestion in sectors and centers

When workload exceeds the capacity of controllers staffed in a sector, controllers adopt varying strategies to regulate workload. In this section the strategies employed by the controllers to manage workload and their impact on the performance of controllers and air traffic control system have been studied.

Strategies used by controllers to handle workload caused by enroute sector congestion:

Researchers have proposed that controllers adopt varying strategies to regulate workload. Sperandio (1971) showed that under heavy traffic, controllers reduced the time spent processing each aircraft to achieve acceptable controller performance. Hence, the controller workload does not increase with air traffic volume. However the regulating strategy compromises on system performance measures like delay.

On similar lines Jorna (1991) discussed the validity of the statement “Controllers do not have control over their own workload”. Jorna explained that in the event of a high pace of incoming aircraft the controllers adopt the strategy of diverting them to holding areas. Jorna explains that such “parking” of aircraft represents one of the strategies available and used by a controller for active control of density of traffic which results in delays to the aircraft. Author further explains that these delays can be considered as a clear effect of the controller workload, which is translated by the controller into delays.

FAA (1997) reported a strong correlation (-0.627) between the time per aircraft for all communication and hand arm activities and the total aircraft worked by a controller. This means that as the total number of aircraft worked increases, total amount of time devoted to each aircraft during 20-minute study trial decreases. The report states that "It is assumed that when a controller is not actively communicating or performing a hand/arm activity they are scanning the PVD, workstation, and work area in general to detect potential conflicts and to maintain awareness of the situation. Therefore the work elements (look at plan view display, flight progress strips and look at other) are considered as standby tasks. When aircraft activity is low, these activity times are usually high since it fills the time available until other work is required, as the workload increases the amount of look only time decreases".

It can be concluded that the time spent by a controller in performing standby tasks of detecting potential conflicts and maintaining awareness of the situation could improve the system performance and reduce delays to flights being controlled by the controller.

Sperandio (1971) carried out an experimental study in an air traffic control tower to demonstrate how controllers adopt varying strategies to regulate workload. The controllers were asked to define the landing sequence of aircraft on a radar screen. The number of total aircraft and number of aircraft to be controlled were varied on a radar display. Data required for performing the task was given at the controllers request by an experimenter who recorded the order of requests as well as the control instructions given by a controller. The routing solutions chosen by the controller were also recorded.

Through statistical analysis of the landing sequences of aircraft, Sperandio found that the data required for controlling the first aircraft in a pattern of eight aircraft is same as the data required to define the total sequence in a pattern of only four aircraft. It was observed that the number of aircraft performance data required to define the landing sequence of aircraft decreases with increase in traffic. It was seen that under low traffic more data are required and data required decreases in a form of an inverted U curve.

Sperandio found that under low traffic controllers use direct approach strategy and ask for performance data to verify and achieve separation between aircraft. However under high traffic, the controllers resort to standardized routings which requires less performance data to be used. In standardized routings, firstly the aircraft head towards a given fix which is the stacking point where the holding pattern is performed and then aircraft head toward runway as per the standardized procedure which is familiar to the pilots. It was found that under heavy traffic, controllers reduced the time spent processing each aircraft. Sperandio further reported that in case of direct routing, performance data were required for almost 85% of the aircraft. However for standard routing, performance data were required for only 33% of the aircraft.

According to the author these results can be interpreted in the following way .In case of low traffic the controllers are unconstrained, and there are many solutions to the problem. However, there are very few optimal or the accurate solutions to the problem which the controllers attempt to find. Again, in case of heavy traffic there are many solutions to the problem but these solutions are constrained by airspace, and operator’s limitations, which narrows down the number of optimal solutions. Under heavy traffic controllers choose methods which require less analysis and information processing. The author explains that with increase in traffic levels, the controller reduces the number of variables to be processed. In low traffic, the controller takes into account higher amount of data. However, in high traffic, the controller takes into account only data necessary to perform the standardized routings. The author defines workload as a function of operating strategies adopted by the controller. The controller uses economical strategies when his workload capacity is reached.

Hence it is inferred that in case of low traffic the controllers attempt to find the most accurate or efficient solution which increases the system performance, i.e. decreases delays. But in case of high traffic, the workload of the controller increase due to the high amount of information processing required and also because of the limited solutions in the congested airspace. This forces the controllers to use substandard solutions which decrease the system performance i.e. increases delays. It was also observed that under heavy traffic the time devoted to process each aircraft decreases. The use of a standardized procedure indicates that the controller does not want to compromise safety by making active decisions under high traffic which could increase the possibility of errors.

Similar results were obtained by Coeterier (1971) in his experiment at Amsterdam airport to analyze the variation in strategies adopted by approach controllers to establish the landing sequence of aircraft under different maneuvering conditions. Two runways were considered 19R north which had a lot of maneuvering space and 01R south which had restricted maneuvering space. Considering only the inbound traffic for Schipol airport, seven traffic situations were considered by varying the number of planes, data such as distance to the gate, height and speed of airplanes, geographical position of planes.

The author explains that in the 19R runway situation the controller had a lot of maneuvering space. Due to the available flexibility for handling traffic in the current system, the controller had a great freedom to choose his strategy. Here the controller did not rely on "ready-made" procedures and made impromptu decisions to formulate his strategy for conflict solving and control. This required a great deal of attention and flexibility. On runway 01R, there was very little maneuvering space and in cases of conflict there were less possible solutions. Hence uniformity was observed between the strategies adopted by the controller because not much choice was observed amongst the strategies. Also planning has to be done at an earlier stage. Groups of airplanes consisting of more than 6 airplanes were handled in subgroups of two or three and a very high uniformity in strategy was observed among the controller subgroups.

The author analyzed these strategies which showed a high degree of uniformity, i.e. agreement among controllers. It could be suggested thatall these strategies have a direct effect on delay of traffic. Although the maneuvering restrictions in this case were due to the presence of restricted areas and airfield, similar maneuvering restrictions can be expected under conditions of airspace saturation due to heavy traffic. Hence it is proposed that similar strategies would be used by controllers under heavy traffic which would decrease system performance i.e. increase delays and reduce capacity.

Based on the above case studies it can be seen that under heavy workload conditions the controller might not work on delay reduction or airspace capacity optimization. Hence, it is suggested that system performance measure such as delay is a good measure of controller performance under workload.

A significant amount of research has been carried out to show that a positive relation exists between controller task performance and air traffic volume. In workload measurement experiments, effect of workload on controller performance has been studied. Controller task time and number of operational errors are some of the controller performance measures analyzed by the researchers. However the main problem in summarizing the results of these studies is that a variety of controller performance measures have been considered. It is proposed that some measure of system performance will be a better measure of controller performance under workload

During heavy traffic conditions in a sector, controllers reduce the time spent processing each aircraft to achieve acceptable controller performance in terms of aircraft handled per unit time. However the regulating strategy employed to manage controller workload affects the performance of the system.

3.2.2. Measures of controller performance and controller workload in sectors and centers

Relations are estimatedbetween controller performance and controller workload in sectors and centers of NAS. Measures of controller workload, measures of controller performance and models developed in literature which relate two measures have been studied in this section. Based on the literature review suitable measures of controller workload and performance are chosen and a model is proposed to estimate relation between two variables.

3.2.2.1. Measures of controller workload studied in literature

In U.S.A. and Europe, the capacity of an enroute sector in handling aircraft per unit time is limited by controller workload. Capacity of a sector is defined as the maximum number of aircraft per unit time which can be handled by controllers such that the controller workload limits are not exceeded. (Majumdar and Ochieng (2002) and FAA (1997)).

The FAA has developed staffing standard formulas for staffing controllers in a sector for 15 minute intervals based on the controller workload. In FAA (1997) controller workload is measured as "T_ worked". "T_WORKED is defined as number of aircraft in a sector during a 15 minute time interval and is calculated by summing number of aircraft in sector at the start of the trial with the total number of aircraft entering sector during the trial" FAA(1997).

Mills, S. H. (1998) proposed that measures of ATC activity- operations per unit time and flight seconds per unit time have limitations in measuring the true workload on controller. Hence Mills, S. H. (1998) developed Aircraft Activity Index as a measure of aircraft activity per unit time. Aircraft activity index is defined as:

Aircraft Activity Index =

$$\frac{\text{Flight Count}}{\text{Epoch Time}} \times \frac{\text{Control Time}}{\text{Epoch Time}}$$

Wherein epoch time is a period of time for which analysis of airspace activity is being performed. Control time is total flight minute activity which occurred during the considered epoch.

Consideration of ATC complexity in a measure of controller workload

FAA (1995) reports that Grossberg (1989) and Mogford et al. (1993) have measured climbing and descending aircraft flight paths and traffic respectively as complexity factors affecting controller workload. FAA (1999) lists mix of enroute and transitioning aircraft (aircraft climbing, and descending) as a factor, which could increase the complexity and difficulty level of workload in centers.

Majumdar, A., and Ochieng, W. Y. (2002) performed a regression analysis to determine factors which affect controller workload. They found that some of the variables related to aircraft profile data significantly affected controller workload. Variables measuring number and transit time of flights which entered or exited sectors in climb, cruise, descend or combination of climb-cruise, climb-cruise-descend, cruise–descend profiles were affecting controller workload.

Majumdar (a) reports that the traffic in a sector which is in cruise, ascend or descend profile impacts controller workload differently. He proposed the need to consider the interaction and quadratic effect of the cruise, ascend and descend traffic count in a sector for its impact on controller workload. Based on his statistical analysis he found that the following variable forms significantly affected controller workload

Square of traffic in cruise in a sector

Traffic in descend x traffic in cruise

Traffic in ascend x traffic in cruise

Traffic in descend x traffic in ascend

The above literature suggests a need to consider variables measuring mix of traffic in cruise and transition in a measure of controller workload.

3.2.2.2. Measures of controller performance studied in literature:

A variety of controller performance measures developed and analyzed in the literature were studied. Performance metrics were studied which measure the performance of controller under workload due to enroute congestion.

3.2.2.2.1. Operational error as a measure of controller performance:

Based on literature review it was found that operational errors committed by controllers are not suitable measures of controller performance under high workload. Researchers have found very weak relations between controller errors and controller workload and air traffic complexity.

Fowler (1980) reported that controllers adapt to peaks of heavy traffic but become prone to errors as traffic lightens. Hilburn (2001) reports that Breitler, Lesko and Kirk (1996) found very poor and almost no correlation between complexity and operational errors.

3.2.2.2.2. "Excess distance traveled by a flight" as a measure of controller performance

Bradford et al. (2000) evaluated the effectiveness of URET (User Request Evaluation Tool) for detecting and resolving conflicts between aircraft and between aircraft and airspace. They analyzed excess distances traveled by flights before and after implementation of URET (i.e. 1998 and 1999).

Howell et al. (2003) considered excess distance traveled by flights in a center as a measure of enroute inefficiency. Howell et al. (2003) considered delays related to enroute sector capacity constraints and flight path conflict avoidance as two of the five sources of "enroute inefficiency".

It is concluded that delays related to enroute sector capacity constraints and flight path conflicts are caused by traffic volumes in sector/center airspace. Hence excess distance is a suitable metric to study the effect of enroute congestion. Howell et al. (2003) and Bradford et al. (2000) have used the metric excess distance traveled by a flight. In both studies, excess distance was calculated as the difference between the actual flight path length in the center and the great circle route distance between the entry and exit points of the flight in that center.

Mullikin et al. (2000) proposed a measure of flight efficiency for an airspace. He proposed the metric as the average difference between the actual distance traversed by each flight in an airspace area and equivalent great circle distance, plus average number of maneuvers per flight calculated for all flights over a 24 hour period.

Suitability of "excess distance metric" for measuring workload due to enroute congestion

1. Bradford et al. (2000) explain that controllers impose extra distances on flights to resolve flight path conflicts. Krozel et al (2002) also reports that conflict detection and resolution by ATC causes flights to vectoring (aircraft follow zig zag path) or stretching of flight paths. During discussions with controllers, Howell et al. (2003) found that for enroute environment the most common method used for conflict resolution is vectoring as compared to speed control and vertical maneuvering. In the terminal area speed control and vertical maneuvering are more commonly used to resolve conflicts, where planes undergo changes in altitude and speed.

2. Howell et al. (2003) and Bradford et al. (2000) explain that flight times are affected by winds in enroute airspace .But wind causes less variation in excess distance traveled by flights.

Validity of "excess distance metric":

Bennett (2004) reports that wind optimal distance provides the most efficient trajectory for a flight. However there are problems in estimation of wind optimal distance. Bennett

(2004) performed an analysis to determine if great circle routes could be used as a substitute for wind optimal distance. Actual routes were compared with GCR routes by excluding 50 mile stretch from airports for flight data of two sample days. Excess time and distance of flights were compared for actual routes, great circle routes and wind optimal routes. It was found that GCR routes could be used as a good substitute for wind optimal routes.

Bradford et al. (2000) believe that GCR distance between entry and exit points if a flight in a center is a “reasonable measure of optimal distance.”

Drawbacks of “excess distance metric”:

Based on the literature review it was found that the “excess distance metric” had the following drawbacks.

i. Excess distance does not capture the speed restrictions imposed on aircrafts due to air traffic congestion (Bradford et al. (2000) and Howell et al. (2003)).

ii. Bradford et al. (2000) found that flights headed towards congested airports traveled greater excess distance compared flights headed to other destinations. After discussions with controllers the authors learned that all routes in a center cannot experience improvements in direct routings (i.e. reduction in excess distance traveled by a flight) because of implementation of URET. Based on their analysis of the ZID center the authors found that congestion in subsequent enroute centers and destination airports could restrict direct routings for the traffic flow in ZID.

Bradford et al. (2000) explain that flights with constraints imposed on them because of congestion in subsequent enroute centers and destination are not traveling under free flow conditions i.e. “true enroute environment” in the current center airspace. These constrained flights may not be given direct routings even when there is less congestion in the center airspace in which they are traveling. It is proposed that care should be taken in choosing the data for analyses, such that the chosen centers and time periods represent free flow traffic conditions.

3.2.2.2.3.. Time delay borne by a flight as a measure of controller performance

Schonfeld and Ying (2003) developed a model, which relates air traffic operations per unit time traversing an airspace and delay to the flights which traverse the airspace during the same time interval.

(Schonfeld and Luo, unpublished manuscript, 2003)

Schonfeld and Ying (2003) proposed the following queuing model for airspace “i”, time period “j” and constant “K”. Keeping all other factors constant, it is seen that the relation between airspace time delay and air traffic operations (sector demand) is quadratic with a second power.

$$airspace\ delay = \sum_i \sum_j \left(\frac{K * ((sector\ demand\ (\mathrm{i, j}))^2}{((avg\ sector\ capacity\ (\mathrm{i, j}) - sector\ demand\ (\mathrm{i, j}))} \right)$$

During discussions with controllers, Howell et al. (2003) found that speed control and vertical maneuvering are more commonly used to resolve conflicts in the terminal area where planes undergo changes in altitude and speed. There could be situations where speed control and vertical maneuvering could be performed to resolve potential conflicts in sectors and centers of enroute airspace. Conflicts in enroute airspace are caused by traffic volumes (airspace congestion). Speed restrictions are also imposed on aircraft due to congestion in sectors and centers in enroute airspace.

Hence enroute airspace congestion could cause speed control, speed restrictions and vertical maneuvering to be performed on flights in enroute sectors and centers. These controller actions cause time delays to aircraft. Excess distance does not capture time delays imposed on aircraft. Bradford et al. (2000) and Howell et al. (2003) explain that excess distance does not capture effects of speed restrictions imposed on aircrafts.

Controllers could use a variety of control procedures to manage enroute congestion. Brennan (2003) explains the tools used by controllers to delay flights.

1. Controllers could apply ‘vectoring’ on flights. Vectoring causes the flights to follow a zigzag pattern to reduce their effective speed”
2. Flights could be put into a circular holding pattern
3. Flights could be rerouted.

Advantages of time delay as a measure of controller performance

Control procedures like vectoring, holding flights in a circular pattern and rerouting flights increase the excess distance traveled by flights and impose time delays on flights. It could be argued that an increase in excess distance traveled by an aircraft in airspace will cause a corresponding increase in time delay to that aircraft.

Time delay is directly translatable into airline and air passenger costs.

This is one of the main advantages of time delay compared to excess distance traveled by flight.

Based on the above findings there is a need to consider time delays imposed on flights in sectors and centers of enroute airspace as a measure of controller performance under workload.

Depending upon the tools used by controllers, two forms of delays- excess distances and time delays are imposed on flights by the controllers due to enroute congestion.

3.2.2.3. Measurement of delays caused by sector and center congestion

In this section the suitability of simulation models to measure delays caused by sector and center congestion has been discussed. The need to use flight track data to measure delays caused by sector and center congestion has been explained.

i. Suitability of simulation models to measure delays caused by sector congestion

FAA (a) .NASPAC is a discrete event simulation model used to measure performance of the system for 80 busiest airports in US. NASPAC computes delay incurred by aircraft while they wait to use air traffic controller resources like arrival and departure fixes.

[4]NASPAC can provide us with airborne delays at various queues- arrival fix, departure fix, sector boundaries and enroute flow restrictions. DPAT is a discrete event simulation model used by MITRE which can also provide us with similar queues in airspace. DPAT and NASPAC can model the entire NAS.

FAA (a).NASPAC computes sector entry delay imposed on flights.

[5]NASPAC model holds flights at sector boundary if the simulation logic estimates that the MAP has been exceeded. The determining factors in gaining entrance to the busy sector depend on how busy the sector it is coming from is. The team has modeled 900 controlled sectors. In future model the flights will be separated by distance rather than time and speed adjustments as well as holding patterns will be deployed

In sections, 3.2.2.2.2 and 3.2.2.2.3 it was found that controllers impose time delays and excess distance delays on flights because of sector congestion. The simulation models have built-in assumptions to impose time delays on flights due to sector congestion which may or may not reflect the actual time delays imposed on flights. The simulation models are not built to model the excess distances traveled by flights due to airspace congestion. The simulation models cannot estimate excess distances traveled by flights due to sector congestion.

It was realized that DPAT and NASPAC were not suitable for estimating excess distances traveled or time delays borne by flights because of congestion in individual sectors and centers of NAS.

[4] Email correspondence with Mr. Daniel Citrenbaum, FAA

[5] Email correspondence with Mr. Douglas Bart, FAA

ii. The need to use flight track data to measure delays caused by sector and center congestion

It is concluded that actual recorded flight track data needs to be used to measure delays caused by sector and center congestion. Flight track data contains the following details of a flight: entry time, exit time in airspace, distance traveled in airspace, entry speed, exit speed in airspace and other details when the flights traverse sector and center airspaces. Using these data the measures of controller workload and controller performance (proposed in sections 5.1 and 5.2) can be calculated.

3.2.3. Model developed in literature to relate excess distances with congestion in centers

In this section the model developed in literature to relate excess distances with congestion in centers has been discussed.

Model developed by Howell et al. (2003):

Howell et al. (2003) classified sources of inefficiency in enroute airspace into five categories – delays related to enroute sector capacity limits, metering aircraft because of terminal congestion, conflict avoidance, routing aircraft around severe weather and static inefficiencies present in the current airspace route structure. Howell et al. (2003) considered delays related to enroute sector capacity constraints and conflict avoidance as a source of “enroute inefficiency”. It is proposed that both these enroute inefficiencies are caused by traffic congestion in sector/center airspace.

For understanding the relation between enroute inefficiency and traffic levels, Howell et al. (2003) considered excess distance traveled by flights in a center as a measure of enroute inefficiency.ETMS data for each of the 20 enroute air traffic centers for eight Wednesdays and Thursdays of March 2002 were used in the analyses.

Traffic activity in a center was computed as the total aircraft handled by a center during each 15 minute time interval. For each center, the maximum traffic activity during a 15 minute interval was set as a base, and the traffic activity during each 15 minute interval was expressed as a percentage of this 15 minute base. Excess distance was computed for each flight traveling in a center. Excess distance metric was computed for all flights in each of the 20 enroute centers for the considered time period.

Figure 3.3 shows the relation between normalized traffic activity during 15 minute interval and average excess distance for flights handled during 15 minute interval in a center, averaged over 20 enroute centers.

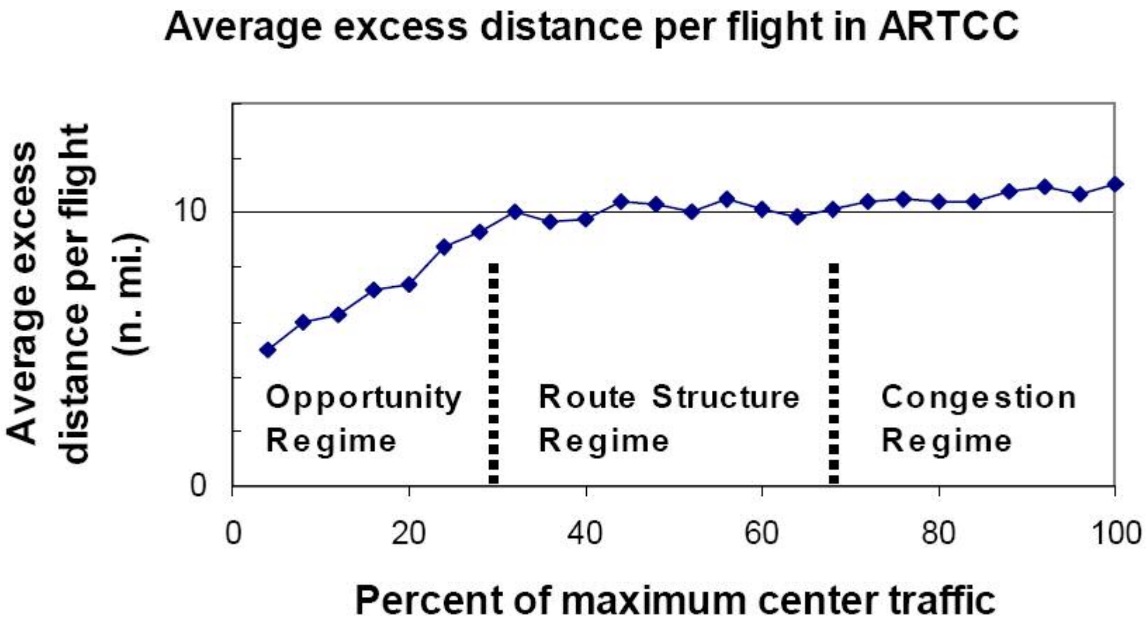

Figure 3.3 Relation between normalized traffic activity during 15 minute interval and average excess distance for flights handled during 15 minute interval in a center, averaged over 20 enroute centers (Howell et al. 2003).

The plot distribution was classified into three regimes–opportunity regime, route structure regime and congestion regime.

Opportunity regime:

In the opportunity regime the normalized traffic activity is between 0% to 30% of the peak traffic activity. Some flights get direct routings in this regime. Since these flights are not restricted to fly on airspace structure, excess distance traversed by those flights is reduced

Author explains that implementation of tools like URET which enable more direct routings will be effective in this region .These tools could reduce the excess distance in this regime and increase the traffic activity levels at which flights are restricted to stay on the route structure.

Congestion regime:

In the congestion regime the normalized traffic activity is greater than 70% of the peak traffic activity. In this regime, terminal capacity constraints, sector capacity constraints and conflict avoidance cause an increase in the average excess distance. Authors propose that tools which increase sector or terminal capacity (e.g. CPDLC, TMA, etc.) and tools which improve conflict resolution efficiency (e.g. URET) can reduce excess distance in this regime.

Center specific analysis was also performed using the same measures. Figure 3.4 shows the result of analysis performed for ZAB and ZAO centers.

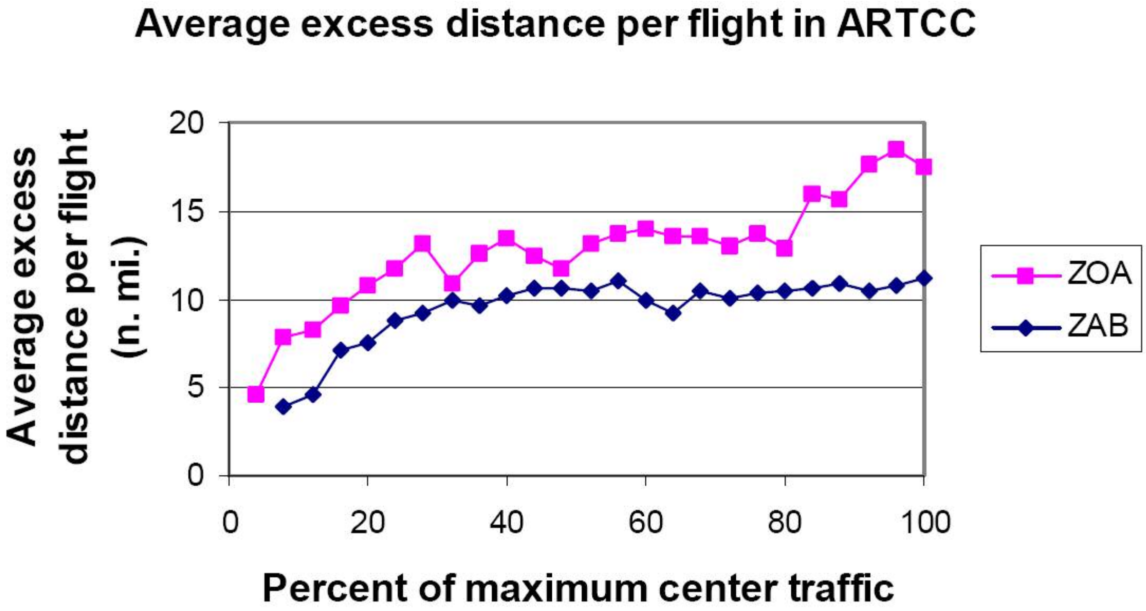

Figure 3.4 Relations between normalized traffic activity during 15 minute interval and average excess distance for flights handled during 15 minute interval in a center (Howell et al. 2003)

For each center average excess distance for all flights during a 15 minute interval was related to the normalized traffic activity corresponding to that 15 minute interval. Authors found that the relation between traffic levels and excess distance averaged over all centers did not show a significant increase in excess distance in congestion regime .However results for individual centers ZOA and ZAB showed an increase in excess distance in congestion regime. The levels of excess distance in the opportunity and route structure regimes was seen to be higher in ZOA compared to ZAB and a significant upturn was seen in excess distance in congestion regime of center ZOA.

Authors explain that ZOA center has higher traffic activity and greater proportion of arrivals and departures occur in ZOA centers airspace compared to ZAB. This causes the centers airspace to become complex and ZOA is more susceptible to cause excess distance delays to flights traveling in its airspace under high traffic levels (i.e. congestion regime).

3.2.4. Difficulties in estimating relations between flight delays/excess distances and congestion in sectors and centers.

The following difficulties were identified in estimating relations of time delays and excess distances with congestion in sectors and centers.

i. Factors affecting the time delays borne by flights and excess distances traveled by flights in airspace.

Howell et al. (2003) explain that flights could travel excess distances in airspace because of the following reasons. Flights could travel excess distances because of MIT restrictions imposed on aircraft because of terminal congestion, routing aircraft around severe weather and static inefficiencies present in the current airspace route structure. During discussions with controllers it was found that time delay could be imposed on flights because of the same reasons which are mentioned above. Airspace congestion in a specific airspace does not necessarily cause flights to travel excess distances or bear time delays in the same airspace.

[6]During discussions with controllers, it was revealed that time delays borne by aircraft and excess distances traveled by aircraft in airspace could be because of congestion in any of the successive airspaces on the route of the flight.

[6]Discussions with controllers at FAA office on 04/07/2005

Impact of terminal congestion on controller performance measure "excess distance"

Howell et al. (2003) explains that MIT restrictions are imposed in the enroute airspace (by aircraft metering) due to terminal congestion hundred of miles away. Bradford et al. 2000) also found that the metric "excess distance" was biased for data of ZID center. Authors found that the traffic in center ZID had constraints on northbound flows heading towards busy airports, Chicago, Detroit, Cleveland, Newark, JFK, and Philadelphia. These constraints affected the free traffic flow conditions in center ZID. It was found that MIT restrictions imposed on flows heading towards these airports could go back as far as 400 miles from the arrival airports. Bradford et al. (2000) found that flights headed towards congested airports traveled greater excess distance in the current center compared flights headed to other destinations. It is understood that all routes in a center cannot experience reduction in excess distance traveled by a flight because of less congestion in that center. Congestion in subsequent enroute centers and destination airports could cause the flights to travel greater excess distances in current center.

ii. Staffing of controllers in sectors and centers

a. Variation in number of controllers staffed in a sector or center could affect the performance of the controller team under same traffic levels. Understaffing of controllers in sectors during some periods could cause controller workload and this could increase the excess distance or time delays imposed on flights by controllers.

b. Effect of inadequate controller staffing during different levels of traffic activity could also bias the relation to be estimated.

iii. Characteristics and composition of traffic flow

Control procedures and tools used by controllers to maneuver flights in airspaces impose excess distances and time delays on flights .These control procedures could be employed not only because of congestion (workload) but also because of the characteristics and composition of traffic flow i.e. (fast aircraft behind slow) . This could cause bias in the proposed relation.

[7] During discussions with air traffic controllers it was found that excess distances and time delays imposed on aircraft due to characteristics and composition of traffic flow were too minor to affect the relations proposed in the analysis.

[7] Discussions with controllers at FAA office on 04/07/2005

3.2.5. Considerations in developing models to estimate relations between flight delays/excess distances and congestion in sectors and centers

Based on the literature review it was found that the following points should be considered while developing models to models to estimate relations between delays and airspace congestion.

i. The need to perform analyses for sectors

Total excess distance traveled by a flight in a center is the sum of excess distances in the individual sectors. Thus, varying congestion levels in individual sectors could affect the total excess distance through the center. Similar argument can be made for time delays borne by flights in a center. Hence the proposed analysis needs to be performed for centers and sectors.

ii. Care to be taken in choosing the data for airspaces and time periods

Data should be chosen such that the air traffic in the chosen center and sector airspaces and time periods is not delayed due to airspace congestion in successive centers on the path of the flights. The air traffic in the considered airspace should not be delayed due to terminal congestion, equipment failures, weather and runway capacity constraints. Flights should not be delayed in the considered airspaces due to upstream or downstream events.

3.3. Relations between ATC system performance and enroute air traffic in the National Airspace System (NAS)

Relations between ATC system performance and NAS enroute traffic are studied in section 3.3.

3.3.1. The need to consider entire NAS to estimate relations between delays and enroute traffic volumes by considering monthly and daily measures of delays and enroute traffic volumes in the NAS

In this section the need to consider entire NAS for estimating relations between delays and enroute traffic volumes by considering monthly and daily measures of NAS delays and NAS enroute traffic volumes has been discussed.

The enroute capacity of the NAS is not limited by the performance of controllers staffed in the sectors of NAS. Enroute airspace capacity is dependent on operational effectiveness of the different programs employed by the air traffic control system, performance of controllers and coordination among different air traffic control units.

Due to spatial and temporal propagation of delays in NAS, there is a need to estimate the performance of entire NAS. Due to temporal propagation of delays in NAS there is a need to estimate monthly and daily measures of delays and enroute traffic volumes. The performance of ATC system needs to be evaluated in reducing delays caused by enroute traffic volumes in the entire NAS.

The following four factors make it necessary to consider entire NAS for estimating relations between delays and enroute traffic volumes in NAS.

3.3.1.1. Strategic and tactical planning performed by ATC system and coordination among ATC units

The following paragraphs explain the role of ETMS (Enhanced Traffic Management System) and TMU (Traffic Management Unit) in managing air traffic in NAS.

Enhanced Traffic Management System (ETMS) is used for prediction on national and local scales of the traffic surges, gaps, and volume based on current and anticipated airborne aircraft (FAA b). Leiden and Green (2000) explain that Traffic Management Unit (TMU) predicts sector congestion in advance (an hour or more) using tools which give a perspective of flow of traffic entering a center from adjacent centers and traffic flow in sectors of a center. Coordination exists between the Traffic Management Unit and sectors to perform strategic planning for the sector. The specialist position in TMU develops solutions for efficient flow such that the capacity of sector is not exceeded. Reference website 1 explains that Traffic Management Specialists assess the predicted traffic flow into sectors and airports and employ least restrictive actions to ensure that traffic demand does not surpass capacity of the system.

Leiden and Green (2000) explain that the TMC (traffic management coordinator) position within TMU becomes active less than an hour before the strategic planning needs to be performed. TMCs are staffed to supervise the busiest streams of traffic in a center. TMC maintains efficiency of these streams by devising plans to fill gaps and merge streams.

TMC coordinates plans with the area supervisor. Area supervisor supervises a group of sectors within a center. Area supervisor then coordinates with the sector controllers. The objective is to develop an efficient and flawless merging of traffic such that the sector containing merge points does not get overloaded.

Inefficient functioning of air traffic flow management system can cause airspace and airport congestion and delays to flights. Hoffman and Voss (2000) report that Voss et al. (1997) has shown that inefficiencies in airspace could be caused by problems in airspace design and a mismatch of flow management procedures to traffic conditions. Airspace design becomes inefficient because of changes in air traffic patterns over time. Airspace congestion is caused by inefficient airspace design. ATFM (Air Traffic Flow Management System) manages and relieves airspace congestion. Authors explain that "An inefficient design is not cured by ATFM—the congestion is turned into ground delays". Howell et al. (2003) propose that static inefficiency in the current airspace route structure is a source of enroute inefficiency which causes flights to travel excess distances.

3.3.1.2. Time delays imposed on flights and excess distances traveled by flights because of airspace congestion could be borne by flights away from the source of airspace congestion

In this section the tools and techniques used by controllers to handle airspace congestion have been discussed. These tools and techniques impose delays on flights in airspaces away from the source of airspace congestion.

Tools used by controllers to handle airspace congestion

Based on the literature review it was found that congestion in enroute sectors, fixes and jet route segments are the most common sources of congestion in enroute airspace. Controllers could use a variety of control procedures to handle enroute congestion. Brennan (2003) explains the tools used by controllers to delay flights.

-Reduce ground speed of flight.

-Apply ‘vectoring,’ “flights follow a zigzag pattern to reduce the effective speed”

-Put flight into a circular holding pattern

-Reroute the flight.

Control procedures like vectoring, holding flights in a circular pattern and rerouting flights increase the excess distance traveled by flights. Flights which travel excess distances are delayed in time. It is concluded that time delay should be used to study the effect of airspace congestion. Time delays capture the effect of excess distances traveled by flights due to airspace congestion.

Techniques adopted by controllers and ATC system to handle sector congestion

Howell et al. (2003) explain that sector capacity (MAP) is used to perform enroute strategic planning. When MAP of a sector is exceeded, flights could be rerouted, or the departing aircraft are held on the ground. This method does not affect the flights, which are already traversing in the enroute airspace. Leiden and Green (2000) explain that rerouting of traffic, imposing MIT restrictions and ground holds are the most common solutions used to solve enroute congestion problems. The objective of these solutions is to maximize efficiency without exceeding sector capacity. Wanke et al. (2003) explain that traffic managers could use different methods among the ones discussed above to solve problems due to enroute sector congestion.

The three procedures discussed below to handle sector congestion are implemented when the sector demand exceeds MAP threshold of the sector. When the sector demand is less than the sector capacity, delays will not be imposed on flights traveling in that sector. Even in situations where sector demand has reached or exceeded sector capacity, delays will not be imposed on flights traveling in that sector. The procedures implemented to handle sector congestion will cause the flights to be delayed in other airspaces and in departure airports away from the source of airspace congestion.

i. Rerouting flights around congested airspace

Howell et al. (2003) explain that the sector capacity is defined by Monitor Alert Parameter (MAP) threshold. Enroute strategic planning is performed using MAP value of a sector. In event the sector capacity is exceeded the flights are rerouted around that sector. Wanke et al. (2003) also report that flights are rerouted around congested areas in the airspace.

Traffic management personnel from Cleveland center reported that in some cases alerts of sector exceeding capacity were given only fifteen seconds before sector capacity was predicted to exceed Leiden and Green (2000).In such situations flights are subjected to significant rerouting and delays to divert air traffic from the alerted red sector. During high traffic situations in a sector, the controller manages his workload by concentrating on communication and separation. It will not be practical to perform strategic planning in such situations.

Flights which are rerouted due to sector congestion may not be rerouted in the same sectors. Klopfenstein et al. (1999) ranked the centers and sectors by the frequency of rerouting of flights which had filed flight plan to fly over those airspaces. On analyzing data for 6 days of July 1999, authors found that more than 40% of the flights which had filed flight plan to fly over centers ZLA, ZMA, ZBW, ZFW, ZHU, ZJX, and ZSE were rerouted.

ii. Ground delays imposed on flights at departure airport

Howell et al. (2003) explain that flights could be delayed at the origin airport when the sector capacity is going to be exceeded. Studies of enroute delays conducted at FAA Command Center show that currently most of the sector capacity problems are solved by ground holding departing aircraft. This method does not affect the flights, which are already traversing in the enroute airspace. Wanke et al. (2003) report that sector congestion could cause ground delays and ground stops to be imposed on flights at departure airport.

iii. MIT restrictions imposed on flights

Wanke et al. (2003) report that sector congestion problems are solved by limiting access to airspace by imposition of miles-in-trail restrictions at the airspace boundary. Howell et al. 2003 explain that the use of MIT restrictions to tackle enroute congestion is frequent for flights departing from a major airport and taking a major jet route.

During discussions with controllers it was found that congestion in a sector, airspace fix or jetway in the enroute airspace could cause miles in trail restrictions to be imposed on flights which have filed flight plans to fly through the congested areas. The effect of MIT restrictions imposed on enroute flights could eventually reach the origin airports. In such cases, ground delays are imposed on flights supposed to fly on the effected airways. The entire process of propagation of delay from airspace to the departure airport takes take place over time and space.

Wanke et al. (2003) performed aggregate analysis of MIT restrictions recorded by ATCSCC (Herndon, VA). Analysis for entire NAS for period from 1/28/02 TO 2/01/02 was carried out. The geographic distribution of MIT restrictions showed that few MIT restrictions were used in Northwest ,Northeast (ZBW) and Southeast (ZJX and ZMA).ZOB and ZNY centers were subjected to most of the MIT`s.

3.3.1.3. Spatial and temporal propagation of delays in NAS

Inaccurate sector demand prediction could cause an increase in controller workload in the sector. Krozel et al. (2002) found that errors in prediction of sector count and sector entry time cause inaccurate sector demand prediction. Author studied found the following sources of error in prediction of sector count and sector entry time. Circular holding of flights causes entries in multiple sectors and enroute delay, which in turn causes sector entry time error. Conflict detection and resolution by ATC system causes vectoring (aircraft follow zig zag path) of flights or stretching of flight paths. Wanke et al. (2003) found that the predictions of sector demand were more affected by ground stops and ground delays programs compared to MIT restrictions. Ground stops, ground delay programs and MIT restrictions are Traffic Management processes used by ATC system to manage enroute congestion.

During interviews with traffic management personnel and center controllers, Leiden and Green (2000) found that in high traffic situations in a sector flights are subjected to significant rerouting and delays to divert air traffic from the alerted red sector. In such scenarios there is increased workload in the downstream sector, since the traffic levels expected for the downstream sector are not met. In some cases the red alerted sectors could travel from sector to sector along different directions in centers airspace.

Circular holding, vectoring and rerouting of flights are the control procedures used by controllers under heavy workload conditions in the sector. However these procedures could cause increased traffic activity in the neighboring sectors which are affected by implementation of these control procedures. If the traffic activity in the affected sectors is greater than the expected demand in those sectors, then controllers in the affected sectors will be subjected to workload. Controller workload in the affected sectors could cause the controllers to implement delay imposing strategies on flights. Hence there could be spatial propagation of delays in sectors of the airspace.

Brennan et al. (2003) explains that controllers impose delay on flights due to limited resource upstream from flight. Upstream congestion point on the path of the fight could be constrained arrival rate at airport, congested sector or severe weather in an area.

Klopfenstein et al. (1999) have shown that arrival fixes could cause departure delays and airborne delays to flights. Airborne delays could be caused by airborne circular holding. Congestion on jet route segment could cause departure delays.

Howell et al. (2003) report that the effects of terminal congestion can impact traffic hundred of miles before it enters the terminal area. Miles-In-Trail restrictions (MIT) imposed in the enroute airspace are a passback from the terminals. Flight paths of aircrafts entering an enroute center are metered by that center by imposing MIT restrictions. This MIT restriction is actually a "passback" from the center of the destination airport, and is employed as a metering strategy for flights entering that destination airport. MIT restrictions are imposed in the enroute airspace due to terminal congestion hundred of miles away. Wieland (2002) describes the magnitude of the spatial propagation of delays in NAS. He reports that a five to ten minute of an unplanned aircraft holding in NAS can affect an estimated 250 aircraft within 20 Seconds.

Brennan et al. (2003) explain that holding flights in airspace increases the demand at that airspace. This causes greater holding of flights and more delays to upstream flights. Cascade of the delay is so rapid that it moves out from the terminal area to over 1000 miles in 20 seconds. Delay caused by airborne holding at a specific location in airspace propagates rapidly in airspace. The delay at the original location also causes delays at later times to flights whose flight paths pass through the location where the delay occurred. Authors found that a delay causing event upstream on the route of the flight caused delays to flights even after the event had ended. Analysisperformed by Brennan et al. (2003) demonstrates temporal and spatial propagation of airborne delay through national airspace system for one day's worth of flights in NAS.

Hence it is seen that the delays caused by any source of enroute congestion i.e. congestion in sectors, fixes or jet route segments, could propagate over space and time. Brennan et al. (2003) considered both time and space axis in his analysis to study spatial and temporal propagation of delays caused by enroute congestion.

3.3.1.4. ATC programs implemented in NAS

The air traffic control system tries to maximize throughput and minimize delays in national airspace system using air traffic control procedures and programs. Bradford et al. (2000) states that "The NAS is a large, complex system that will continue to change and adapt to new infrastructure enhancement, technologies or procedures." The performance of national airspace system is affected by the effectiveness of different programs and procedures implemented by air traffic control system.

Numerous programs have been implemented by air traffic control system in NAS to handle congestion in airports and airspaces. A brief description of some of the programs currently implemented in the NAS to handle enroute congestion is provided.

1. Ground delay programs

a. EDCT (Expected Departure Clearance Times)

(FAA 2004) A GDP is a traffic management process implemented by the ATCSCC (Air Traffic Control System Command Center). Aircraft are held on ground to manage demand and capacity at a specific location by assigning arrival slots. GDP are used for traffic management and to limit airborne holding. The EDCT for flights are computed based on estimated time enroute and the arrival slot. It is important that the aircraft depart as close as possible to the EDCT. This ensures that the aircraft reach the impacted location on time. An equitable assignment of delays to all system users can be achieved by using GDPs.

During the meeting with controllers at FAA it was revealed that GDP is used for managing airport congestion but its use is extended for managing enroute congestion. GDP is only implemented at selected airports in NAS. Welch and Lloyd (2001) explains that ground holding aircraft can reduce airborne delay to flight, however the flight still lands behind the schedule time causing relative to schedule delays to flights

b. Ground Stops

(FAA 2004) Aircraft are asked to remain on the ground if they meet some specified criteria. This criterion could be airspace specific, airport specific or equipment specific. Normally ground stops GS`s could occur with little warning. GS is one of the most restrictive methods used for traffic management. Order explains that one of the objectives of using ground stops is to prevent the sectors from reaching their saturation levels.

2. Strategic Planning Team

(FAA c)The strategic planning team (SPT) is comprised of personnel at the ATCSCC, air route traffic control centers and selected terminal facilities. SPT discuss current and forecasted events and their impact on the system by scheduling telephone conferences approximately once every two hours.

3. Flow evaluation area (FEA) and flow constrained area (FCA)

(FAA c)The areas are three-dimensional volumes of airspace, along with flight filters and a time interval, which are used to identify flights. These areas are developed on an ad hoc basis. The purpose is to mange the aircraft in the airspace

4. National Route Program (NRP)

(FAA c) Using NRP, aircraft with level cruise flight above FL290 can request more optimal routes. Ref web site 2 explains that the NRP was initiated by FAA to “address the fuel and flight time concerns of the user community.”

5. Enroute sequencing program (ESP)

(FAA c)In this program a departure time is assigned to an aircraft which will facilitate integration of aircraft into the enroute stream.

6. National Airspace Redesign Program (NAR):

(FAA d) FAA has implemented the National Airspace Redesign program to increase the capacity and efficiency of the NAS. The NAR program has developed 21 strategic choke point actions for improving the air traffic system in the airspace between Boston, Chicago, and Washington, DC, which forms a congested triangle of airspace.

3.3.2. Models proposed in literature

For the present study, relations need to be estimated between delays and enroute air traffic in the entire NAS by considering daily and monthly measures of delays and enroute traffic volumes. A detailed literature review was carried out to understand the previous research performed on this subject. The following literature was reviewed:

1. Analytical models, deductive models and simulation models developed to study relations between NAS performance and enroute traffic volumes in the NAS, or to study either the NAS performance or enroute congestion.
2. Delay metrics developed by researchers to measure different forms of delays caused by enroute congestion in NAS.
3. Different measures of NAS performance developed by researchers.
4. Flight delay data recorded by FAA databases.

3.3.2.1. Use of simulation models to estimate relations between delays and enroute traffic volumes in NAS

Simulation models for NAS:

Numerous simulation models have been built to simulate US national airspace system or parts of the national airspace system. Simulation models can be used to estimate the proposed relation between enroute traffic volumes and delays caused by enroute congestion in entire NAS.

NASPAC (National Airspace System Performance Analysis Capability), LMINET, ACES (Airspace Concept Evaluation System) and DPAT (Detailed Policy Assessment Tool) are the models developed to simulate US national airspace system. LMINET is a queuing network model of the NAS developed by the Logistics Management Institute.

Simulation models have been developed to simulate national airspace system of other countries. Hoffman and Voss (2000) report that TAAM (Total Airport and Airspace Modeler) a large scale simulation model, has been used by NavCanada in Ottawa to simulate the entire Canadian airspace. RAMS (Reorganized ATC Mathematical Simulator) has been used to simulate approximately 1000 nautical miles square of airspace from Britain to Poland, north to Scandinavia and south to Italy by the Eurocontrol experimental centre in Bretigny-sur-Orge, France.

Drawbacks of using simulation models to estimate the relations

Hoffman and Voss (2000) explain some of the disadvantages of large scale simulation models. Authors report large scale simulation models are slow and expensive to build. It is difficult to model the intricacies of air traffic management facilities using these simulation models.

Bennett (2004) also explains some of the drawbacks of current queuing models use to model airspace systems. Author points out that the limitation on the capacity of TRACON (Terminal Radar Approach Control) facility is not considered in the simulation models. Airspace performance is not modeled for situations wherein airspace demand is less than capacity. The trajectories of flights in the models do not adapt to the conditions in the NAS. In reality tactical and strategic planning is performed by ATC system considering weather and congestion.

Zelinski et al. (2004) report that the ACES model (version 1.2) does not consider some key assumptions in simulating the NAS system. ACES model does not consider constraints on sector capacity and separation. The models can not simulate features like rerouting flights based on their flight plan and changes in enroute altitudes and cruise speeds of flights. The model can not simulate arrival terminal area and arrival surface delays. The modeld oes not cancel flights regardless of the delays borne by flights due to congestion and every flight is required to complete its flight plan. Flights are held at their gates in the event the airspace demand exceeds capacity. Hence departure delay imposed on flights is greater than surface or enroute delay.

Wieland (1997) discussed some of the drawbacks of DPAT model. He explains that DPAT lacks a detailed model for airports and cannot simulate gate assignments or taxiway movements

Current models developed to simulate US national airspace system are built on assumptions which do not reflect the current air traffic operating environment in NAS. Models cannot simulate the strategic and tactical planning performed by the ATC system to delay flights due to enroute airspace congestion, terminal congestion, weather and equipment failures. These simulation models do not model detailed aspects of the ATC facilities and airports. Due to these limitations of simulation models it was decided not to use simulation models to estimate the proposed relation between airspace congestion and delays caused by airspace congestion. Actual recorded data on the movement of flights in the NAS consisting of their transit times, distances traveled and delays were used to estimate the proposed relations.

Zelinski et al. 2004 reports results of 36 simulations of ACES which were run for 4 demand sets and 9 weather days. Based on results it was found that departure delay increased from approximately 0% to 30% (when considered as a percent of total delay) with an increase in demand and a decrease in capacity. Due to an increase in departure delay the takeoff surface delay decreased from 70% to 45% and enroute delay decreased from 36% to 21%.However these results could be biased because of the underlying assumptions on which the ACES model has been built.

3.3.2.2. Models proposed in literature

In this section studies have been discussed in which delays, enroute congestion and the relation between the two variables has been analyzed. An explanation has been provided as to why these studies cannot be used to estimate relations between delays and enroute congestion in NAS.

i. Models to estimate operational capacity of NAS

Wieland (2004) reports that Cocanower and Voss (1998) have modeled the instantaneous enroute capacity of airspace by applying the logistics equation to the ETMS data. Based on their analysis they estimated the maximum instantaneous enroute capacity of NAS to be 4212 flights in 1997. Wieland (2004) reports that Donohue (1999) developed a macro model to determine airspace capacity by considering wake vortex separation standards, air traffic controller workload, volume of airspace and other factors. Based on his model, he determined that in 1999 the system operated at approximately 61% of its maximum capacity. He also found that significant delays occur when the system starts operating above 50% of its capacity.

The above models determine the capacity of NAS and do not estimate a relation between airspace congestion and delays caused by airspace congestion.

ii. Comparison of airport throughput and airport capacity to identify problems of airspace congestion

Hoffman and Voss (2000) proposed a deductive approach to identify airspace capacity problems. Authors compared arrival and departure throughput at an airport with the runway capacity and scheduled demand at the same airport over a 24 hour period. Analysis was carried out for a day to reduce the impact of winds. Days chosen for the study were such that the airport operating conditions and weather conditions were good and no major equipment problems were reported on those days.

The authors compared schedule departure demand, departure runway capacity and actual departures at EWR (Newark International Airport) for one good weather day of October 1998.It was found that runway capacity for departures was underutilized although the scheduled departure demand exceeded the capacity several times during day. The authors explain that ATM system was limiting departure throughput because of airspace congestion and not because of runway congestion.

Authors found that runway capacity for arrivals was not underutilized for the scheduled arrival demand and low arrival throughputs were rarely seen. Author explains that flights arriving at that airport were not delayed in the airspace, since holding arrivals in airspace increases airspace congestion.

Congested airspace in the New York region was attributed as a cause for this demand capacity imbalance. Authors explain that EWR has lack of airspace for the organization and separation of arrival and departure flows and hence restrictions on departures were imposed at EWR.

This approach can only be used to identify airspace capacity problems in enroute sector feeding traffic flow to the airports. Welch and Lloyd (2001) also found that delays to flights caused at low airport throughputs were most often due to insufficient capacity in enroute sectors which are feeding the airport. This approach can not be used to relate delays with enroute airspace congestion in entire NAS.

iii. Relation between airborne delay and enroute congestion

Alj and Odoni (a) estimated a relation between airborne delay and enroute congestion. Authors performed an analysis of airborne delays by considering 618 directional origin destination pairs connecting 27 US airports for period from 1995 to 2000. Authors found that approximately 40% of airborne delay taken by a flight on an origin destination pair can be attributed to destination airport and remaining 60% of airborne delay can be attributed to airspace congestion. The analysis performed by Alj and Odoni (a) does not estimate total delays caused by enroute congestion. Ground delays caused by enroute congestion have not been considered in the analysis.

iv. Analysis of ground delays and ground stops:

Klopfenstein et al. (1999) analyzed ground stops and ground delay programs as inefficiencies in NAS. The locations, times and durations of these programs and their impact in terms of departure delays imposed on flights were studied.

Wanke et al. (2003) performed aggregate analysis of Ground stops and Ground delay programs recorded by ATCSCC (Herndon, VA). Analysis for entire NAS for period from 1/28/02 to 2/01/02 was carried out. The NE corridor was found to be imposing a larger number of GS`s. However it was found that no specific sector was imposing more GSs than other sectors and the use of GSs varied from one day to other. It was found that more GDPs were issued for certain airports. These airports were ATL, BOS, EWR, LAX, LGA, ORD, and SFO

In sections 3.3.1.2 - ii, 3.3.1.2 – iii and 3.3.1.4 it was found that delays due to enroute congestion could be imposed on ground or in the air. It is proposed to estimate relations between different forms of delays by phase of flight and enroute traffic in NAS. There is a need to estimate a measure of total delays caused by enroute congestion in NAS. These delays consist of delays borne by flights on ground and in air .i.e. the delays borne by flights during any phase of the flight. It is proposed to estimate relations between delays exclusively caused by enroute congestion and enroute congestion in NAS.

3.3.3. Queuing model developed by Wieland 2004 to estimate operational capacity of NAS using OPSNET data

Wieland (2004) determined the capacity of NAS by proposing a functional relationship between traffic volume and delays in NAS. He proposed a simple queuing relation between monthly operations handled by controllers in NAS and monthly total minutes of delays in NAS to estimate the operational capacity of NAS. OPSNET data were used in the analysis. Wieland (2004) states that considering the system capacity to be constant, an increase in traffic volume will cause an asymptotic increase in delays until traffic volume reaches the system capacity.

Monthly operations handled by controllers from January 2000 to December 2004 were related to corresponding total delay recorded in OPSNET using a simple queuing relation. The simple queuing functional form showed a 75 % correlation.

Despite of low explanatory power of the queuing model the author successfully validated his model by comparing results of the model to results of other studies. Author explains that he is confident of his results since the results are estimated from recorded data and not from simulation models.

Reasons for high variance in data

A simple queuing relation; between traffic volume and delays showed a correlation coefficient of 75% (R squared of 56.25%). Refer to figure 3.5 below.

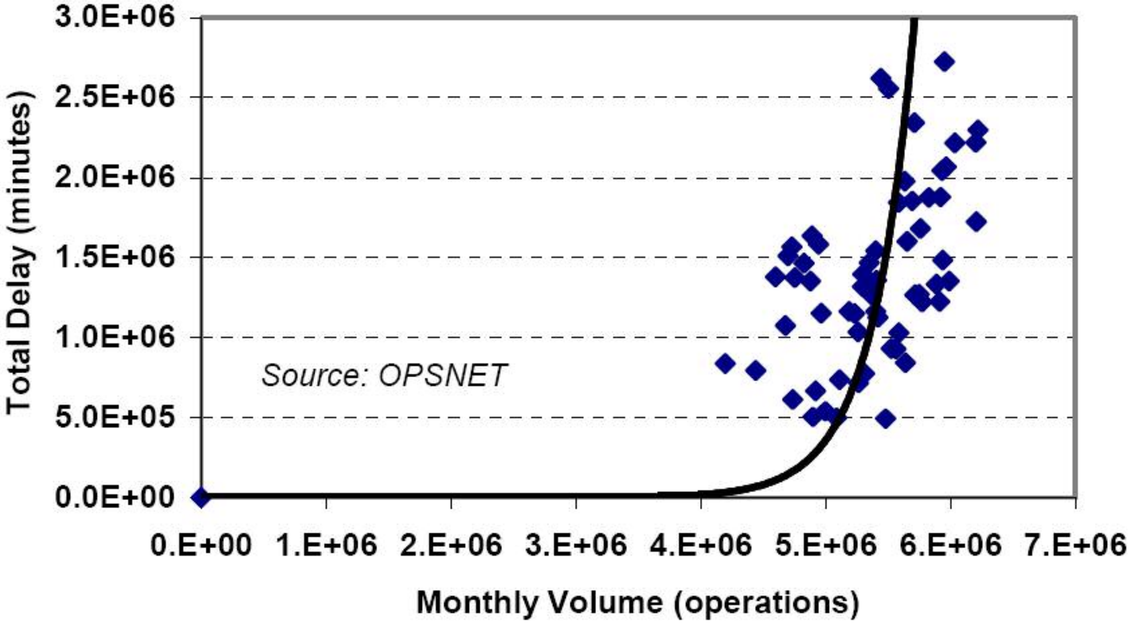

Figure 3.5 Relation between delays vs. NAS traffic volume from Wieland, 2004

Wieland (2004) provides an explanation for the low statistical power of the queuing model. He states that "from a statistical viewpoint, a queuing model of the NAS is not unreasonable, but the correlation is less than desirable due to high variance in the data". He further explains that in a queuing relation between capacity and delays, as the system capacity is reached the delays soar with small fluctuations in volume and the delays show very high variance.

The author uses three simple queuing curves to fit the delay volume data. Refer to figure 3.6 below.

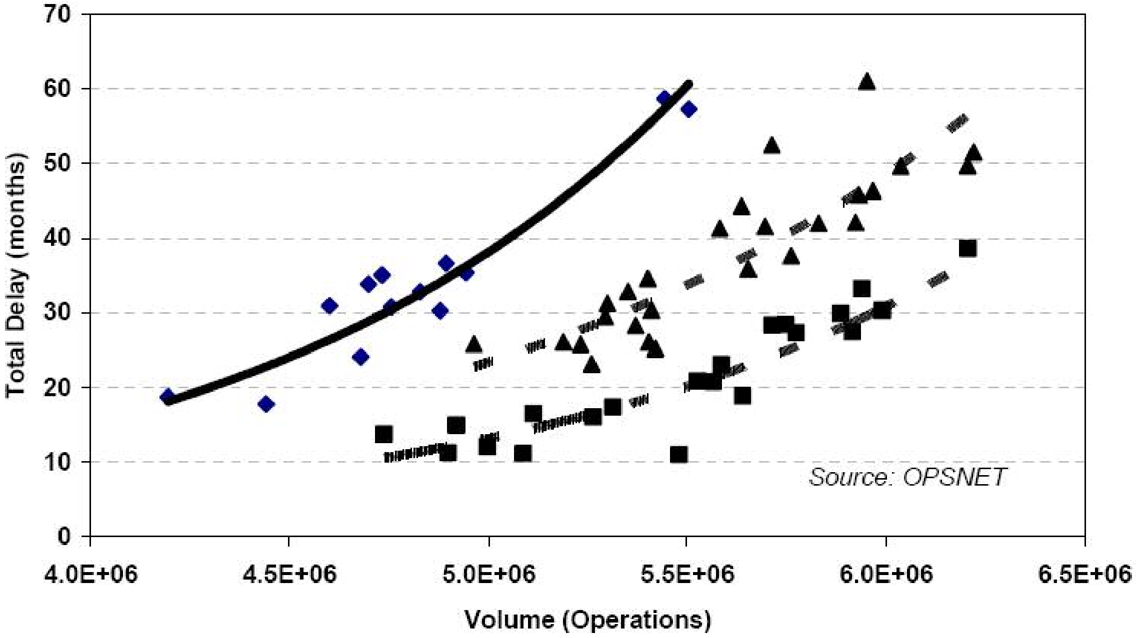

Figure 3.6 Relation between delays vs. NAS traffic volume plotted using three simple queuing curves from Wieland, 2004

The three curves showed a better correlation with the data .The correlation coefficients for the three curves ranged from 79 % to 89%. Author explains that the use of three queuing curves to fit the data provides a better explanation of the significant variation in the operations in NAS.

Factors affecting the proposed queuing relation

Wieland (2004) explains that the proposed relationship is valid only for the current state of the NAS. He explains that all other factors influencing the system capacity are held constant in his analysis. These factors include the airspace, airport, procedural restrictions and scheduling patterns i.e. mix of freight traffic and point – to – point and hub and spoke passenger traffic.

Author explains that the relation is sensitive to any capacity changes in NAS. Airlines could increase capacity of the system without increasing delays, by scheduling greater number of flights during midnight and 5:00 AM local time. Operations in the system are currently scheduled at times which are convenient for passengers and cargo transportation. Author also explains that the capacity is affected by winds, control procedures, pilot skills and controller workload.

Author proposes that as the system capacity is approached and delays increase in NAS, there will be adjustments in the behavior of the users of the system. These changes could include excessive cancellations of flights, schedule adjustments, more frequent use of off peak times, serving different airports, and changes in size of aircraft and service frequency. Author also expects regulatory changes like the current slot auctioning at LGA airport to occur in NAS. Author explains that FAA has currently implemented the Operational Evolution Plan to incrementally increase the capacity of the NAS. Author explains that this relation can not consider improvements planned for the future, or future changes resulting from a change of business practices adopted by the aviation service providers.

3.3.4. Selection of delay data to measure delays in NAS

Different forms of delays recorded by FAA, and drawbacks and suitability of different forms of delays (for performing the proposed analysis) have been discussed in this section.

3.3.4.1 Delay databases maintained by FAA

FAA Aviation Policy and Plans (APO) data system maintains three databases which record flight delay data. A brief description of the three databases is provided below:

Aviation System Performance Metrics (ASPM):

Delays are estimated by comparing flight times to carrier flight plans filed with the FAA or with the air carrier schedules from the Official Airline Guide (OAG) and carrier reservation systems.

Airline Service Quality Performance (ASQP):

Delays are estimated by comparing flight times to published carrier schedules (from OAG or carrier reservation systems).

Air Traffic Operations Network (OPSNET):

A detailed description of OPSNET database has been provided in section 3.3.5.

3.3.4.2 Drawbacks of data on delay relative to schedule:

ASQP and ASPM database estimate delays by comparing flight times to carrier schedule times. Based on the method used to estimate delays in the delay databases, two forms of delay data are available.

a) Relative to schedule delay data i.e. ASPM and ASQP database

b) OPSNET data

The suitability of both forms of data was studied to estimate relations between delays and enroute traffic volumes in NAS. Relative to schedule delay data are affected by the schedule padding performed by airlines. Relative to schedule delays are underestimated values of true delays in the system.

Alj and Odoni (a) found that airlines perform schedule adjustments in response to congestion in the system. True average delays were about 40% to 60% greater than average delays relative to schedule. Authors explain that ASQP data and relative to schedule delay are "poor indicators of true extent of air traffic delays" Alj and Odoni (a) found that on average actual gate-to-gate times were shorter compared to scheduled gate to gate times. Based on their analysis authors suggest that airlines can predict gate –to – gate times correctly, but are vulnerable to unpredictable departure times, which causes relative to schedule delays.

Willemain et al (2003) found that air carriers differed in their planning of the estimated enroute time of the flights. Some carriers were consistently different in their planning. He attributes a portion of this different to route planning. He found that the longest estimated enroute times were likely to be overestimations and the data gave the appearance of padding. All carriers showed same patterns in his analysis.

3.3.5. Suitability of OPSNET database for measuring traffic volumes and delays caused by enroute traffic volumes in the NAS

OPSNET database records delays imposed on IFR traffic due to different causes. OPSNET database only records delays which are greater than 15 minutes in duration. Delays imposed by cause excessive center volume (airspace congestion) are also recorded. Controllers in ATC facilities record these delays. (FAA circular 7210.55C). OPSNET database also records greater than 15 minute delays imposed by FAA ground delay programs.

FAA circular 7210.55C states that " Delays to Instrument Flight Rules (IFR) traffic of 15 minutes or more, which result from the ATC system detaining an aircraft at the gate, short of the runway, on the runway, on a taxiway, and/or in a holding configuration anywhere en route must be reported. Facilities should make a cumulative delay calculation when an aircraft is held at more than one fix within a facility. The IFR controlling facility must ensure delay reports are received and entered into OPSNET"

All air traffic facilities (except Flight Service Stations) report the traffic volume handled on the previous day in OPSNET database.

Currently the OPSNET database provides total number of delays, and total and average minutes of delays for days, months and years from January 1990 to date. OPSNET provides number of delays by category –departure/arrival/enroute/TMS; by class- air carrier/air taxi/general aviation/military and by cause - weather, excessive terminal volume, excessive center volume, equipment failure and runway capacity constraints.

OPSNET database also provides data on ground delays. OPSNET database provides number, total and average minutes of ground stop delays, EDCT delays and total ground delays for days, months and years from January 1990. OPSNET provides delay metrics for individual centers, airports and air traffic control facilities. OPSNET can provide aggregated delay metrics by region, service area and entire U.S.

Merits and drawbacks of OPSNET database have been discussed for measuring delays caused by enroute traffic volumes in the NAS.

3.3.5.1. Drawbacks of delay data from OPSNET database

1. OPSNET data recording is not automated. Controllers use their judgment to estimate the cumulative delay borne by an aircraft when the aircraft is held at more than one fix in a facility. Since controllers themselves record the delays there could be variation in the data recording techniques used by different controllers at different facilities. This variation in OPSNET data recording procedures could bias the OPSNET data.

Wieland (2004) explains that the procedures used for recording OPSNET data may be deficient. OIG 2001 found that manual recording of OPSNET data were causing problems of data accuracy and quality assurance (Wieland 2004) .OIG (2001) also reported that OPSNET data accuracy was not verified by putting any substantial efforts (Wieland 2004).

2. The greatest drawback of OPSNET is that it does not record delays which are less than 15 minutes in duration. A major proportion of delays borne by flights are less than 15 minutes in duration, which are currently not being recorded by OPSNET database.

3. OPSNET database records delays by five causes - weather, excessive terminal volume, excessive center volume, equipment failure and runway capacity constraints. OPSNET records only the number of delays by individual cause. OPSNET database does not record minutes of delays by individual cause-like enroute traffic volumes. OPSNET database records total minutes of delays by all causes in entire NAS. Hence the models are limited to analyzing the number of operations delayed by enroute traffic volume (center volume).

3.3.5.2 Merits of delay and traffic volume data from OPSNET database

1. The phenomenon of spatial and temporal propagation of delays in NAS has been discussed in section 3.3.1.3. The phenomenon of spatial and temporal propagation of delays makes it difficult to identify the cause of a flight delay which occurred at a specific time and location in NAS. It is difficult to distinguish delays caused by enroute congestion from delays by other causes. Bennett (2004) states that separation of enroute problems and terminal effects is difficult. OPSNET database is the only database which records caused by enroute traffic volumes (center volume). Controllers themselves identify the cause of the delays imposed on flights.

2. Relative to schedule delay data are an underestimation of the true delays in the system, since relative to schedule data are affected by schedule padding performed by airlines. Controllers in ATC facilities record delays in OPSNET database along with the cause of those delays. Delays by cause “center volume” recorded in OPSNET provide a true representation of delays caused by enroute traffic volumes in NAS.

Delays by cause “center volume” recorded in OPSNET database are not biased by the effect of schedule padding performed by airlines, wind, aircraft equipment and variation in routes flown by flights. Wieland (2004) also explains that OPSNET delays are not affected by airline schedule padding and perceptions of passengers.

3. Wieland (2004) explains that OPSNET database provides a very accurate representation of traffic volume. OPSNET records traffic volume comprising of flights which do not file flight plans with the ATC system and traffic which does not follow Instrument Flight Routes (IFR).

Wieland (2004) explains that most simulation studies of NAS can handle only air carrier, air taxi and IFR operating general aviation flights. Simulation studies can typically handle 40,000 to 60,000 flights per day. ETMS (Enhanced Traffic Management System) database records data of only those flights which file flight plans. ASPM database records data from large commercial planes operating at large airports. OAG record data of those flights for which passengers purchase tickets and a small sample of freight operations. On considering all the available data sources, OPSNET provides a complete record of air traffic volume.

4. OPSNET database records delays by four causes only. Wieland (2004) states that OPSNET does not record all delays caused by all sources for all flights operating in NAS. However he states that “Since OPSNET records only excessive delays, we need not worry about small “delay noise” that is generated by exogenous variables not correlated to volume”.

5. Alj and Odoni (a) explain that OPSNET database “severely underestimates delays”. However the authors explain that the airport rankings based on OPSNET delays were very similar to the airport ranking results based on the analysis of delays performed by authors. They suggest that OPSNET data can be useful for estimating relative extent of congestion at different airports.

Considering limitations and merits of OPSNET database it was decided to use OPSNET for the analysis proposed in section 6.5.1 and 6.5.2.1. The OPSNET database records only number of operations delayed because of enroute traffic volumes. Hence the analysis is strictly limited to analyzing the fraction of center operations delayed due to enroute congestion and fraction of delayed operations which are delayed due to enroute congestion. The proposed analysis has been explained in section 6.5.1.

3.4. Overview of Methodology

Based on the literature review, analyses and models are proposed to estimate three relations listed below.

1. Relation between controller staffing and enroute air traffic in NAS
2. Relations between controller performance and air traffic in sectors and centers of NAS
3. Relations between ATC system performance and enroute traffic volumes in the NAS

An overview of the methodology used to estimate the three relations is provided in sections 3.4.1, 3.4.2 and 3.4.3.

3.4.1 Relation between controller staffing and enroute air traffic in NAS

Based on the findings in the literature review it is found that a linear or more than linear relation is expected between controller staffing and enroute air traffic. In this section relations between controller staffing and enroute air traffic are explored. The following analyses are performed to estimate relations between controller staffing and enroute air traffic.

1. Relations between center operations and onboard controller staffing in NAS centers are determined.
2. Relations between enroute air traffic and factors that affect controller staffing are estimated.
3. Relations are estimated between number of dynamic sectors in a center and air traffic in the center.
4. The adequacy of current controller forecasting model in predicting controller staffing required for NAS centers was assessed.

Based on the available data from FAA, appropriate statistical analyses are employed to estimate the proposed relations. The relations are estimated for individual sectors and centers, and aggregate relations are also estimated for entire NAS.

3.4.2 Relations between controller performance and air traffic in sectors and centers of NAS

Based on the literature review measures of controller workload, measures of controller performance and models are developed in sections 5.1, 5.2 and 5.4 to estimate relations between controller performance and traffic volumes in sectors and centers of NAS.

In the literature review, it has been found that measures of controller performance (like delays incurred by flights or excess distances traveled by flights in airspace) could be affected by terminal congestion at destination airports, congestion in successive enroute centers on the path of the flight, weather and equipment failures. Hence care needs to be taken in choosing the data for airspaces and time periods so that flights in the considered data do not travel excess distances or bear time delays because of the causes mentioned above.

It is possible that the controller performance measures could be affected by congestion in successive centers/sectors on the route of the flights. Hence models are developed which relate controller performance in center/sector with congestion in successive center/sector on the path of the flight. A city pair analysis is also performed for all flights traveling between a specific city pair. Controller performance in any of the segments on the path of the flight along the city pair is related to congestion in all the successive segments on the route of the flight.

The performance of R controller staffing configuration and R & D controller staffing configuration (in a sector) is compared, in terms of managing the air traffic activity assigned to each staffing configuration. In literature review it was found that excessive traffic demand in a sector causes workload on the controllers and the performance of controllers could deteriorate because of workload.

3.4.3 Relations between ATC system performance and enroute traffic volumes in the NAS

Analyses are performed to estimate relations between delays and enroute traffic volumes in the NAS. Measures of enroute traffic volumes and measures of delays caused by enroute congestion are developed. Based on the literature, daily and monthly measures of delays and enroute traffic volumes are used to estimate proposed relations for the NAS. Appropriate functional forms are chosen to estimate the proposed relations.

Analyses are proposed to estimate relations between delays specifically caused by enroute congestion and enroute traffic volumes in entire NAS. Different forms of delays used to reduce air delays caused by enroute congestion are identified by performing the following analyses:

i. Relations are estimated between different forms of delays and NAS enroute traffic volumes.

ii. Trends in variation of different forms of delays are studied.

Models and analyses proposed to estimate relations between delays and enroute traffic volumes are discussed. The results of models and interpretation of the results are discussed.

CHAPTER IV: RELATIONS BETWEEN ENROUTE AIR TRAFFIC CONTROLLER STAFFING AND ENROUTE AIR TRAFFIC IN THE NAS

Three sets of analyses are performed to estimate relations between controller staffing and enroute traffic in NAS. In sets 4.1.1 and 4.1.2, relations are estimated between enroute air traffic and factors affecting controller staffing. In set 4.1.3, relations are estimated between center operations and onboard controller staffing in NAS centers. In set 4.1.5, relations are estimated between number of dynamic sectors in a center and air traffic in the center. With an increase in the number of dynamic sectors in a center, a corresponding increase in controller staffing will be required in that center.

In set 4.1.4, the adequacy of the current controller forecasting model in predicting staffing required for centers in NAS is assessed. Staffing predicted by the FAA model and onboard controller staffing (in centers) are compared.

The data and the method used to perform the analyses are discussed in section 4.1.

The results of the analyses and the interpretation of the results are discussed in section 4.2.

4.1. Proposed analysis

4.1.1. Relation between ATC complexity for centers and air traffic operations in centers.

4.1.2. Relation between air traffic operations and distribution of air traffic operations in centers during the peak 1830 hours and the second busiest 1830 hours of a 365 day period.

Relations are estimated between enroute air traffic and factors that affect controller staffing. The effect of increase in air traffic operations on factors which affect controller staffing is studied. In analyses 4.1.1. and 4.1.2, relations are estimated between enroute air traffic operations and the following factors:

-ATC complexity of the enroute air traffic control centers

-Growth in air traffic operations in centers during peak and off peak periods.

4.1.3. Relation between monthly onboard controller staffing in centers and monthly center operations

Relations are developed between monthly air traffic operations and monthly onboard number of controllers staffed in centers.

4.1.4. Validation of current controller forecasting model by comparing model predicted monthly staffing and actual on board monthly staffing of controllers

The current controller forecasting model is validated by comparing monthly predicted staffing and monthly onboard number of controllers staffed in centers.

4.1.5. Relation between number of dynamic sectors in a center and that center's air traffic operations

It is proposed to estimate relation between number of sectors in a center and the air traffic operations handled by the center. Dynamic resectorisation is currently being carried out for sectors in NAS. FAA (1997) explains that depending on the amount of air traffic and the level of complexity of operation two or more sectors are combined and managed by controllers at one work station. [1]Mr. McLaughlin from FAA explained that the combination of sectors in a center was done dynamically as the operations dictated and there was no way to track this information. The dynamic resectorisation data were not available, since individual facilities record the data and the data are not sent to ATO office. Hence this analysis could not be performed.

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[1] Information provided by Mr. Elliott McLaughlin during meeting at FAA on 05/20/2005

4.2. Analyses and results

4.2.1. Relation between ATC complexity for centers and air traffic operations in centers.

The Hourly Classification Index (HCI) developed by FAA, (FAA 1999) was used to study the effect of increases in air traffic operations in a center on the complexity and workload of the controllers staffed in those centers. Relations were developed between HCI`s and center operations for five chosen centers –ZMA (Miami FL ARTCC), ZJX (Jacksonville FL ARTCC), ZNY (New York NY ARTCC), ZDC (Leesburg VA ARTCC (DC)) and ZAB (Albuquerque NM ARTCC).

HCI`s are computed at the end of each calendar month of a year. HCI is computed for a rolling 365 day period ending at the end of each month.

Center air traffic operations corresponding to the 365 day rolling time period (used in computation of HCI) were used in the analysis.

Data source:

The ETAP(Enroute Traffic Analysis Program) is used to compute HCI for centers. The input data files used to estimate HCI, and the output files from the ETAP program were provided by Mr. Matt Dunne from FAA`s ATO-A/IT office. Monthly data from 08/2001 to 03/2004 were used in the analysis

Data organization and processing:

The raw output data were organized in the format required for analysis.

Data analysis:

Regression analyses were performed considering the air traffic operations during the 365 day period as the independent variable and the HCI for the corresponding 365 day period as the dependent variable. Different functional forms including power, exponential and linear forms were considered for the regression analysis.

Results:

Figures 4.1 to 4.5 show relations between HCI`s and center operations for five centers – ZMA, ZJX, ZNY, ZDC and ZAB.These relations are estimated using 365 day rolling time intervals.

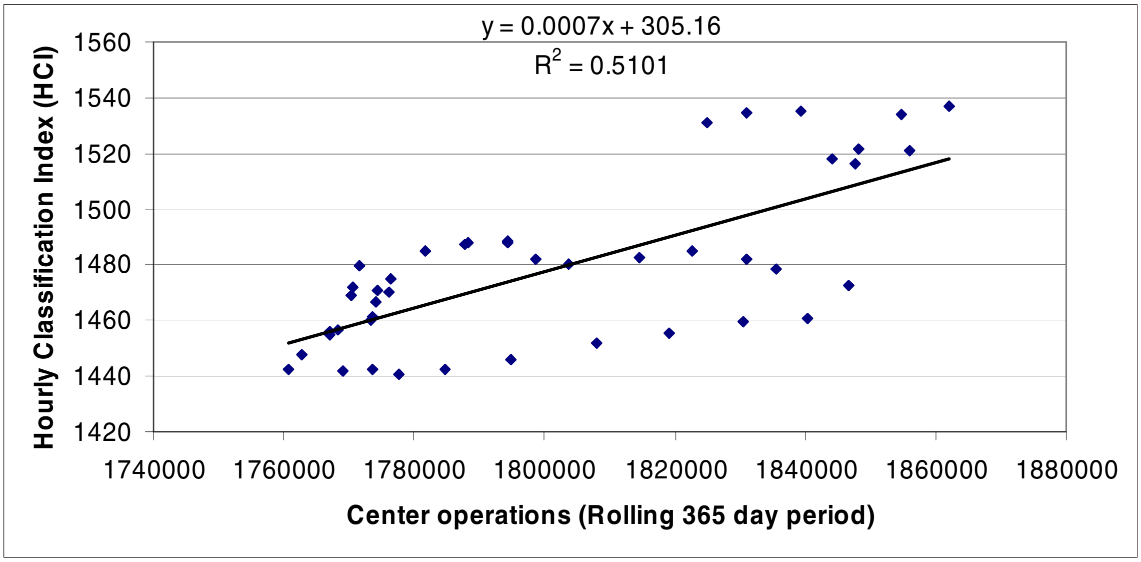

Figure 4.1 HCI vs. center operations (365 day rolling period) for the ZMA center

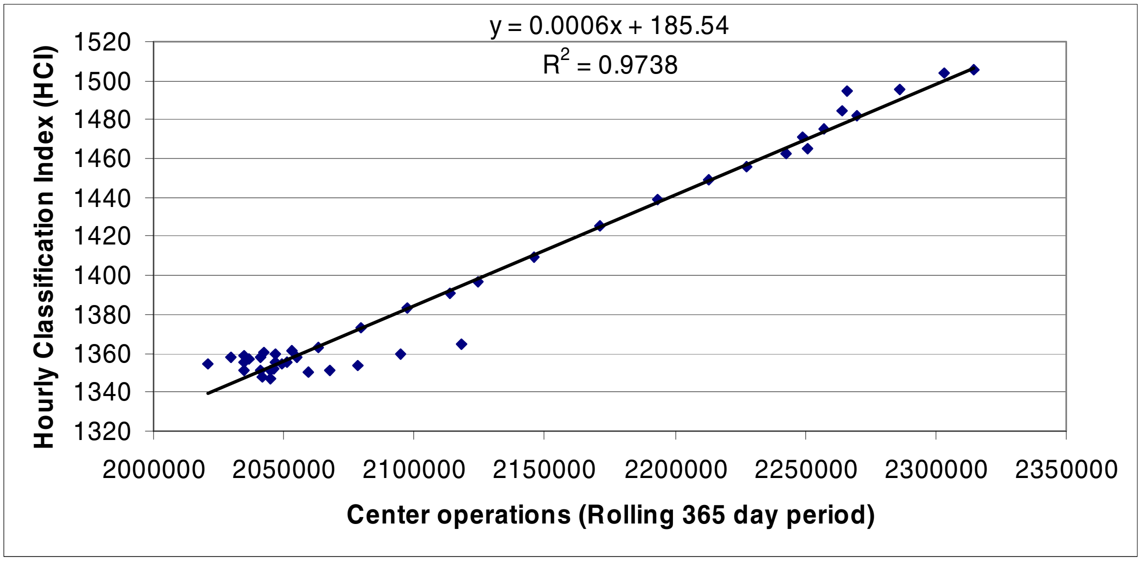

Figure 4.2 HCI vs. center operations (365 day rolling period) for the ZJX center

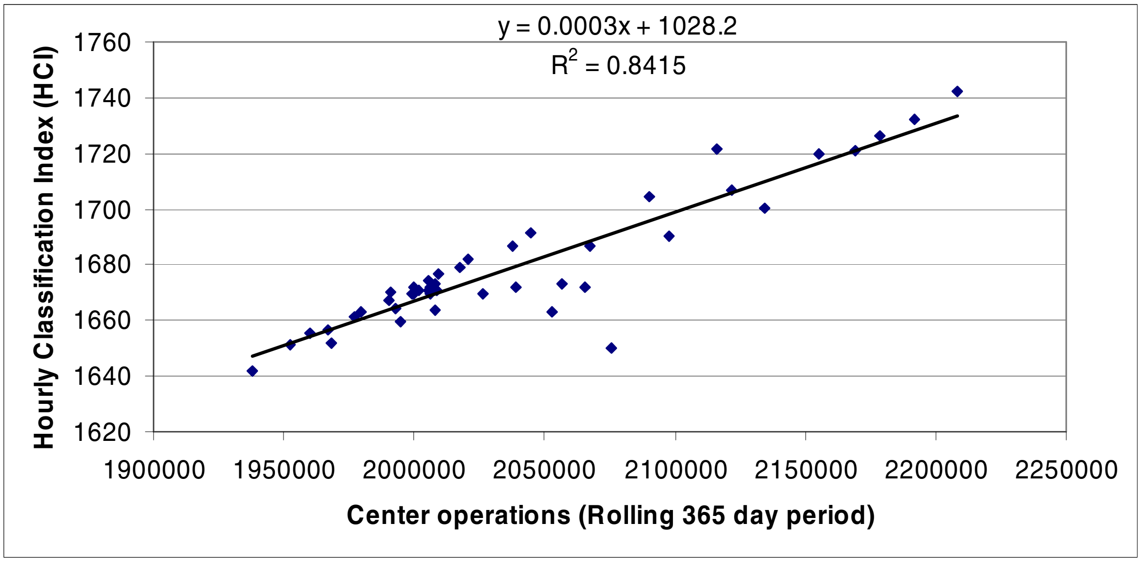

Figure 4.3 HCI vs. center operations (365 day rolling period) for the ZNY center

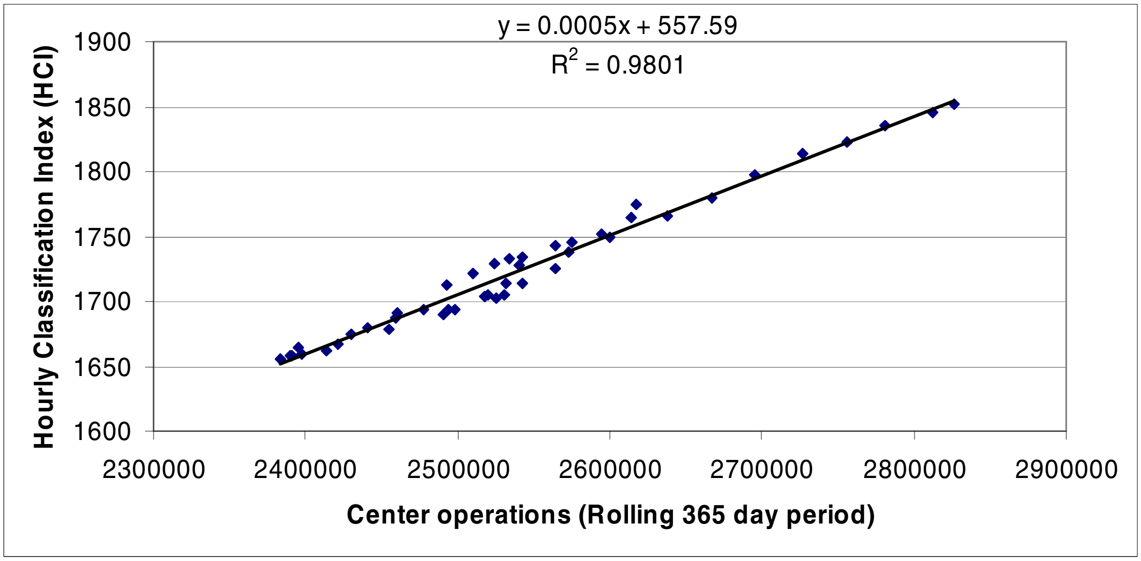

Figure 4.4 HCI vs. center operations (365 day rolling period) for the ZDC center

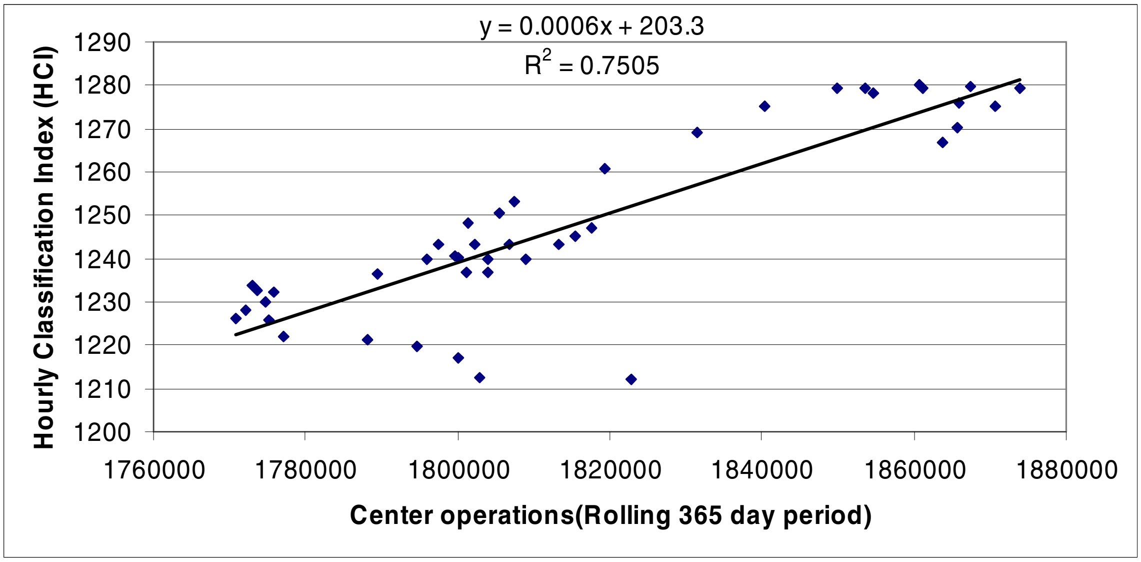

Figure 4.5 HCI vs. center operations (365 day rolling period) for the ZAB center

It was found that the linear form fitted the data very well for 4 centers except ZMA (Rsquared of 0.51). Linear regression models for ZDC and ZJX centers showed very high explanatory power with an Rsquared of greater than 95 %. Regression models for centers ZNY and ZAB showed good explanatory power with R squared values of 0.84 and 0.75 respectively.

HCI is currently used by FAA to assign ATC grade levels to controllers. ATC grade levels of controllers form a basis for determining controller wages. Based on the analysis results it can be stated that ATC controller grade levels and salaries increase proportionally (linearly) with NAS center operations. With increase in air traffic operations in NAS, higher grade level controllers with higher pay scales will be required to be staffed in sectors of NAS.

4.2.2. Relation between air traffic operations and distribution of air traffic operations in centers during the peak 1830 hours and the second busiest 1830 hours of a 365 day period.

Cav2/Cav1 is the ratio of total operations in the center during the second busiest 1830 hours and the busiest 1830 hours of a year (FAA 1999). ETAP program computes "Cav2/Cav1" as an intermediate input in the estimation of "HCI". Cav2, Cav1 and center operations are recorded for 365 day rolling time periods, which are used in computation of HCI.

We estimate relations between ratio of "Cav2/Cav1" and center operations for five chosen centers –ZMA, ZJX, ZNY, ZDC and ZAB.

Data analysis:

Regression analyses are performed considering center operations during 365 day period as the independent variable and the ratio of Cav2/Cav1 for the corresponding time period as the dependent variable. Different functional forms including power, exponential and linear forms were considered for the regression analysis.

Results:

Figures 4.6 to 4.10 show relations between ratio of "Cav2/Cav1" and center operations for five centers –ZMA, ZJX, ZNY, ZDC and ZAB. These relations are estimated using 365 day rolling time intervals.

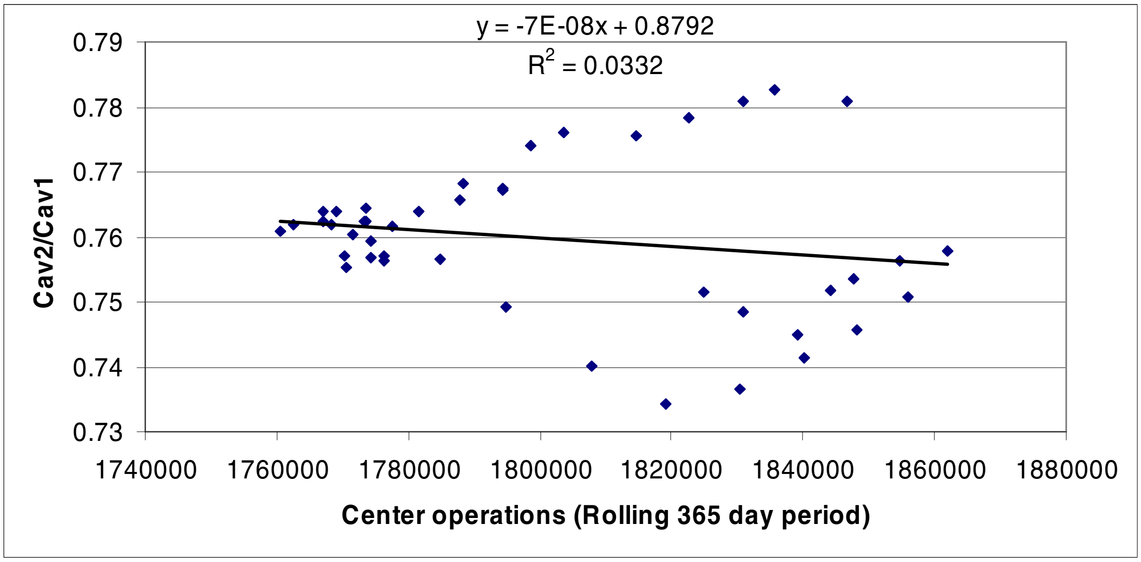

Figure 4.6 Cav2/Cav1 vs. center operations (365 day rolling period) for the ZMA center

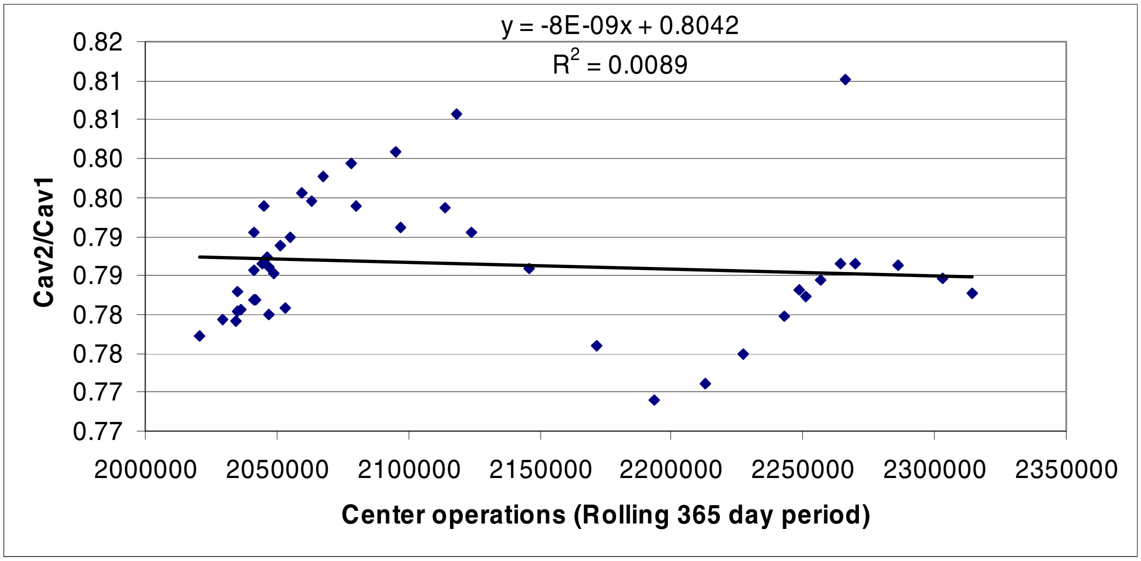

Figure 4.7 Cav2/Cav1 vs. center operations (365 day rolling period) for the ZJX center

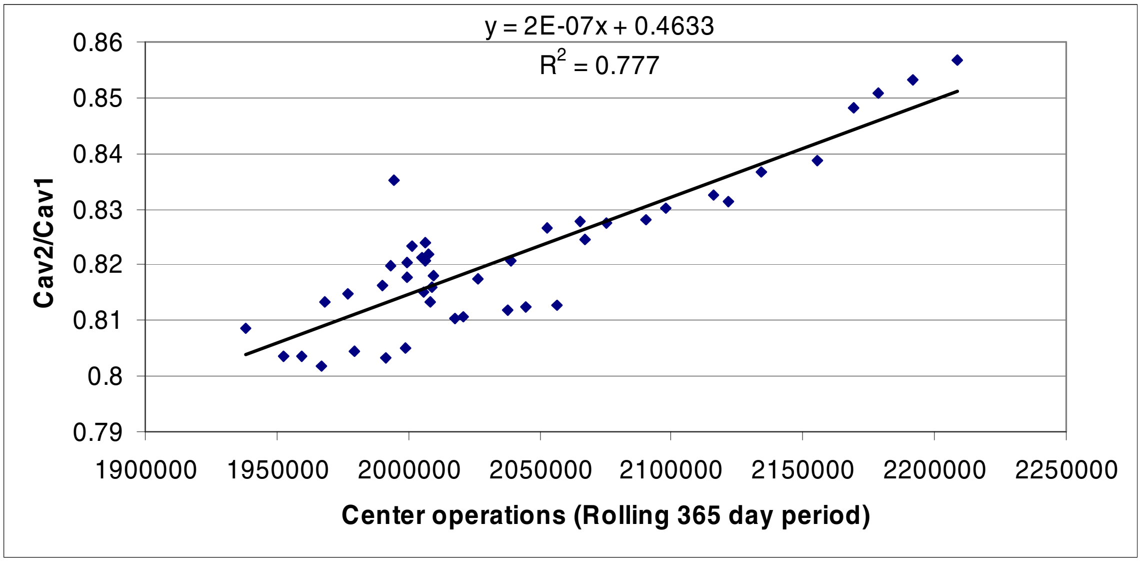

Figure 4.8 Cav2/Cav1 vs. center operations (365 day rolling period) for the ZNY center

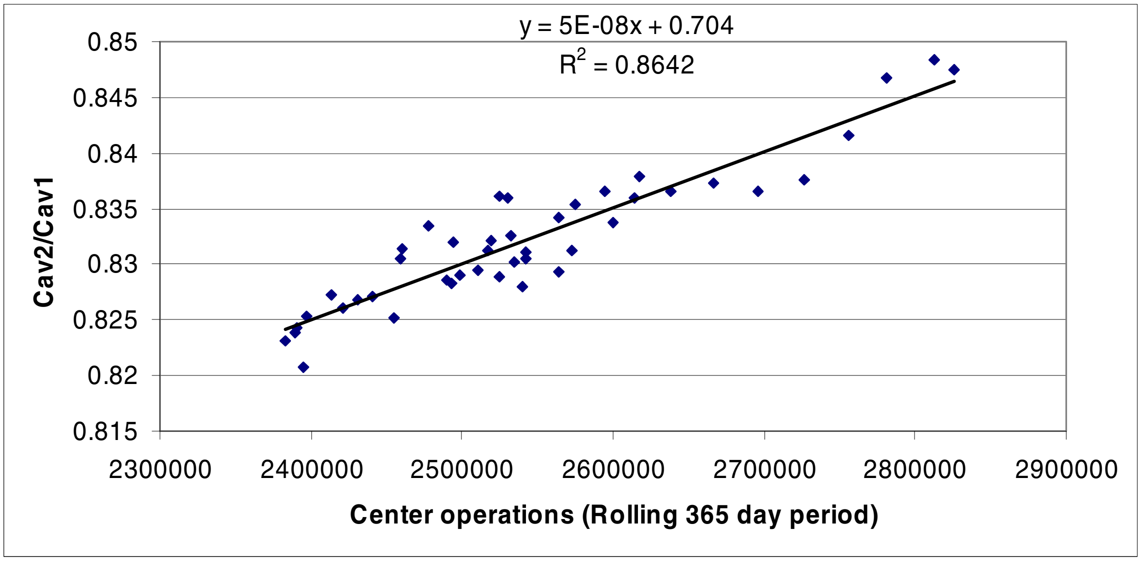

Figure 4.9 Cav2/Cav1 vs. center operations (365 day rolling period) for the ZDC center

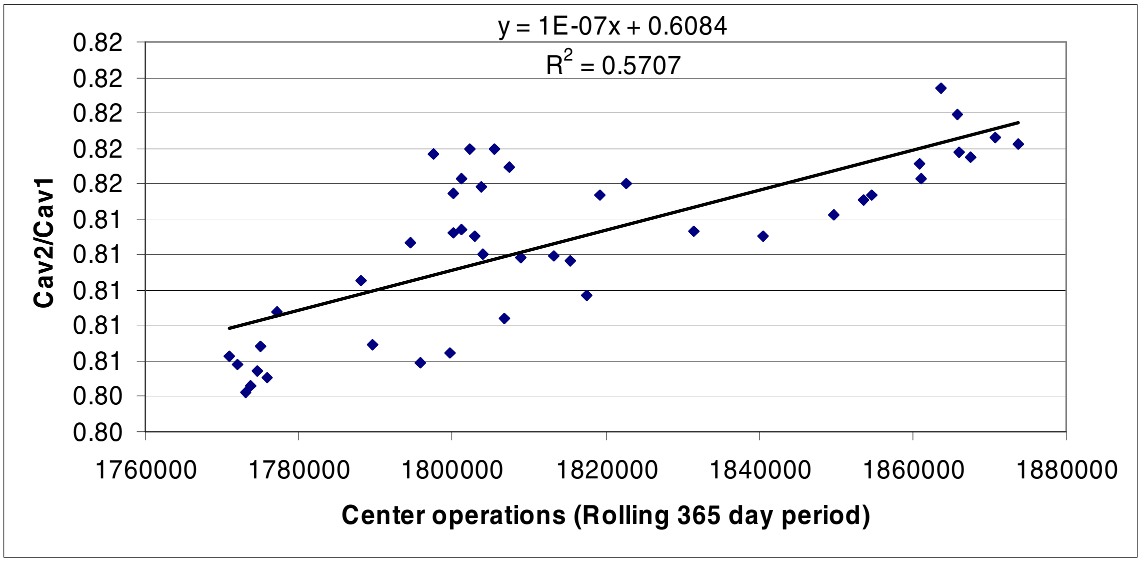

Figure 4.10 Cav2/Cav1 vs. center operations (365 day rolling period) for the ZAB center

It was found that the linear form fitted the data very well for centers ZDC (Rsquared of 0.8664) and ZNY (R squared of 0.78). A regression model for the ZAB center showed a low R squared value of 0.57. Regression models for ZMA and ZJX centers showed very low explanatory power with R squared values less than 0.01.

The growth in air traffic operations is getting uniformly distributed between peak and off peak periods in centers ZDC and ZNY. With increase in center operations during off peak periods, additional staffing of controllers and flight data positions will be required during off peak periods in centers like ZDC and ZNY. The effect of increase in off peak center operations on controller staffing has been discussed in section 3.1.7 of the literature review.

4.2.3. Relation between monthly onboard controller staffing in centers and monthly center operations

Data used in analysis:

[2]The data used in analysis sets 4.2.3 and 4.2.4 were provided by Mr. Elliott McLaughlin from FAA.

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[2] Data provided by Mr. Elliott McLaughlin during meeting at FAA on 05/20/2005

The following data are used in the analysis:

1. Annual enroute controller staffing standards for period 1999 to 2005.

These standards contain forecasted monthly air traffic controllers required in individual centers.

i. 2002 Air Traffic Enroute Staffing Standards for FY 2002

Produced: April 23, 2002

ii. 2003 Air Traffic Enroute Staffing Standards for FY 2003

Produced: March 19, 2003

iii. 2004 Air Traffic Enroute Staffing Standards for FY 2004

Produced: April 14, 2004

iv. 2005 Air Traffic Enroute Staffing Standards for FY 2005

Produced: April 14, 2004

2. The monthly center operations for 1999 – 2005, obtained from “The Air Traffic Activity Data System (ATADS)” website.

3. Data on monthly onboard number of controllers staffed in individual facilities for period 1999 to 2005.

4. Annual data for the number of areas and sectors in individual centers provided in staffing standards.

Results:

Figure 4.11 shows the relation between "monthly onboard controller staffing in all centers of NAS" and "monthly center operations in NAS". Monthly data from September 2001 to March 2005 are used for this analysis.

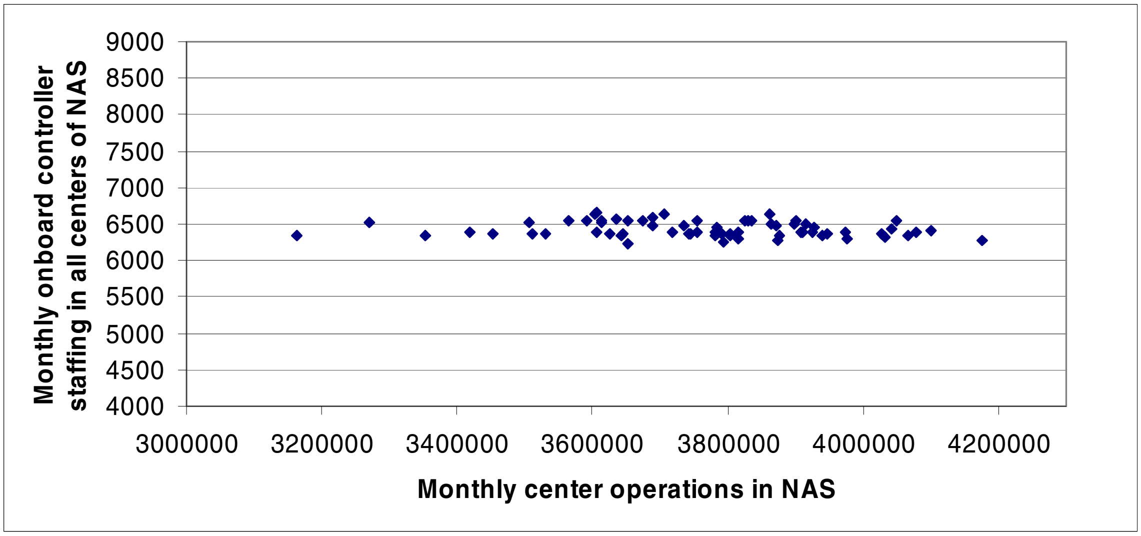

Figure 4.11 Monthly onboard controller staffing in all NAS centers vs. monthly center operations in NAS.

A linear relation was expected between operations and controllers required to be staffed in centers and sectors. However, the proposed relation was not found in the results in figure 4.11.

It is possible that the proposed linearity in the relation between controllers and operations could be observed at individual centers. Relations are estimated between "monthly onboard controller staffing" and "monthly center operations" for five individual centers – ZNY, ZMA, ZJX, ZDC and ZAB. Figures 4.12 to 4.16 show the relations between "monthly onboard controller staffing" and "monthly center operations" for the five centers.

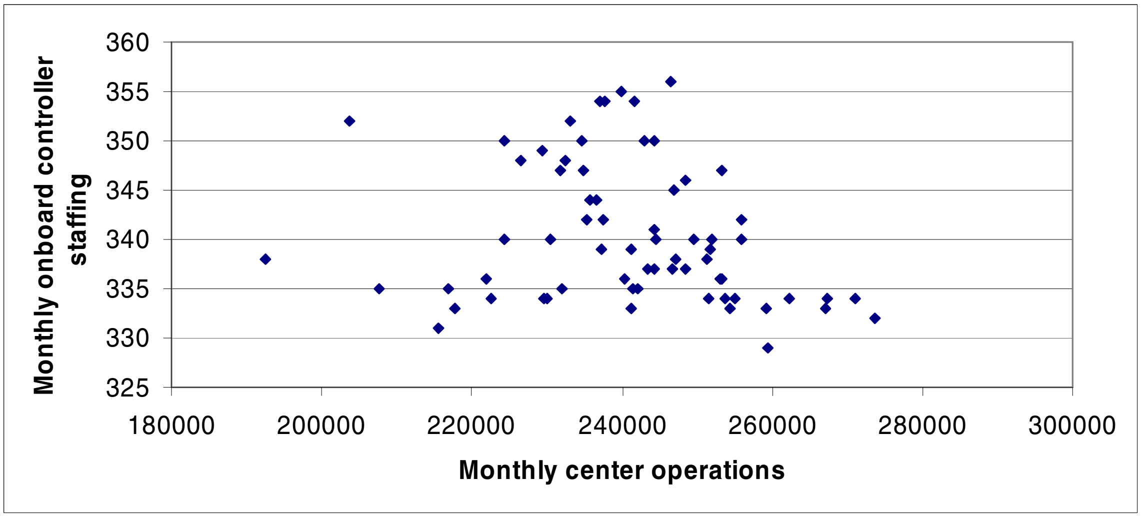

Figure 4.12 Monthly onboard controller staffing vs. monthly center operations for the ZNY center

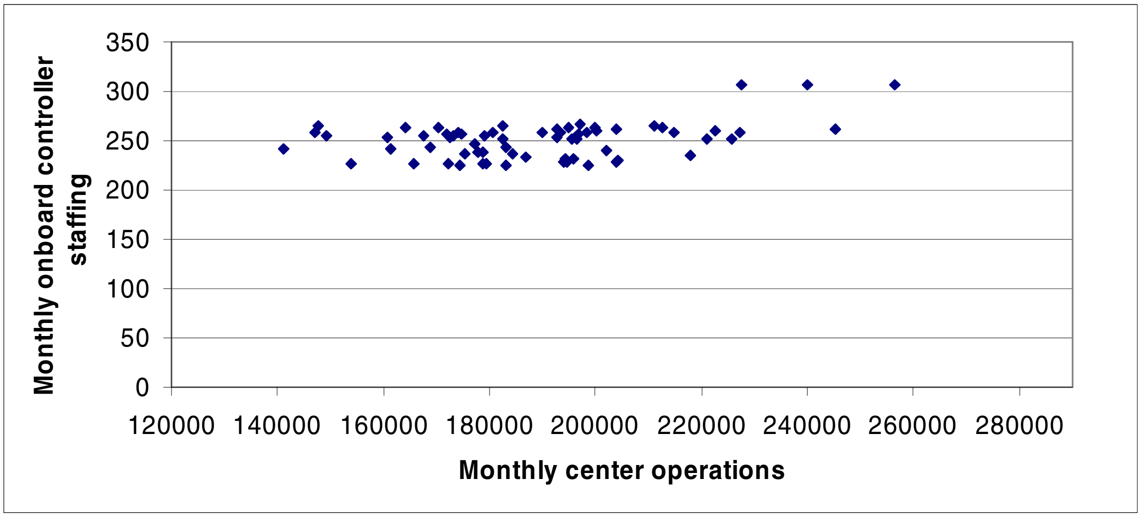

Figure 4.13 Monthly onboard controller staffing vs. monthly center operations for the ZMA center

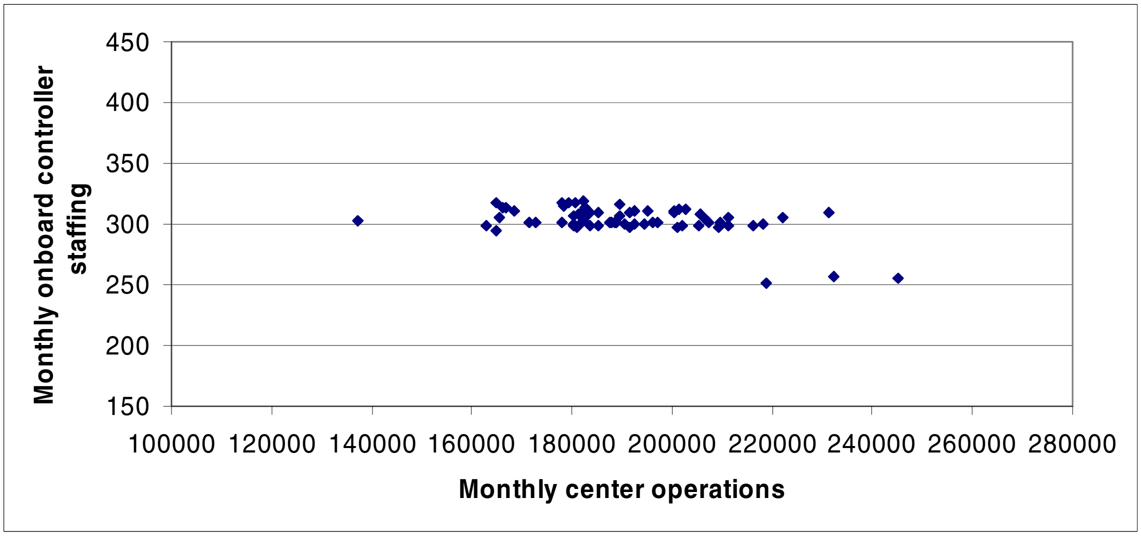

Figure 4.14 Monthly onboard controller staffing vs. monthly center operations for the ZJX center

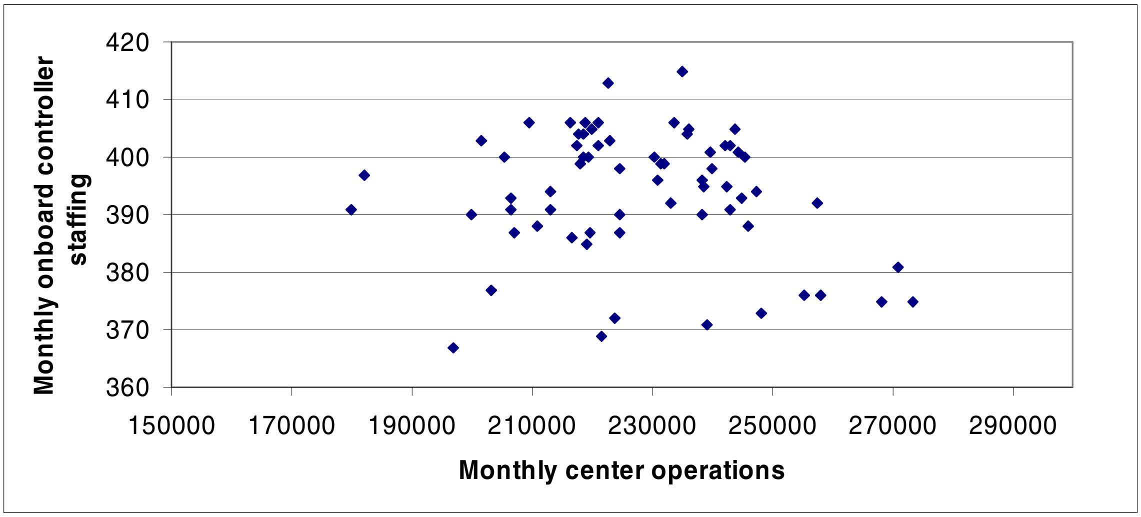

Figure 4.15 Monthly onboard controller staffing vs. monthly center operations for the ZDC center

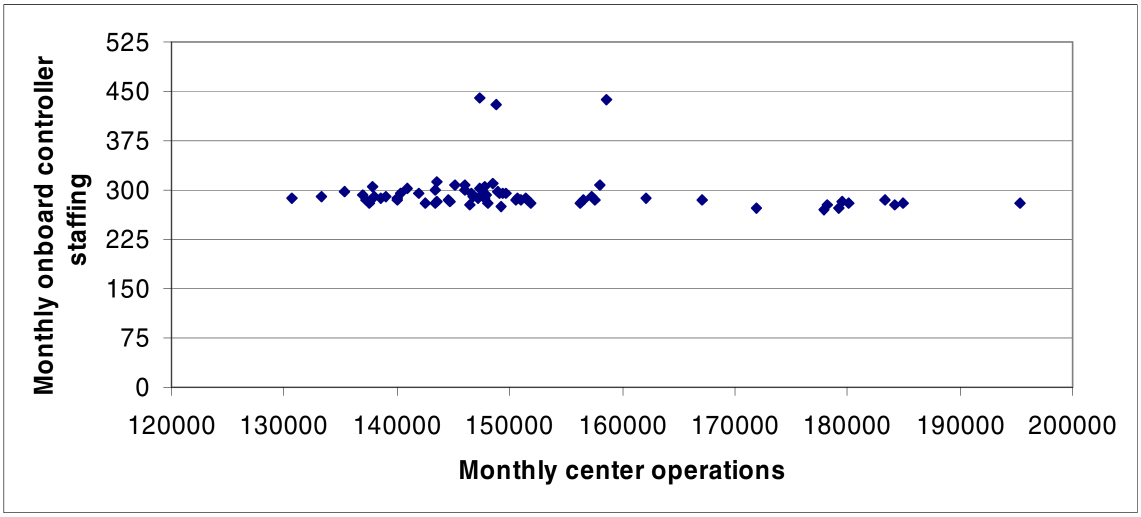

Figure 4.16 Monthly onboard controller staffing vs. monthly center operations for the ZAB center

The expected linearity in relation was not observed in the plots for individual centers, possibly due to the following reasons:

1. The variable “monthly onboard controller staffing” in individual facilities represents controllers who worked at a center facility in a month. An assumption is made that on average one controller works for a specific number of hours in a facility each month. However the validity of this assumption is subject to scrutiny. It is possible that controllers could work overtime, take leave and work for non uniform hours of shift.

2. Monthly onboard controllers in centers could be overstaffed for the monthly center operations they are subjected to control in a center.

3. The FAA controller forecasting model discussed in section 3.1.8 uses the variable “Monthly air traffic operations in centers” to staff controllers in centers. The same variable has been used in the above analysis. The variable “Monthly air traffic operations in centers” does not capture ATC complexity related to characteristics of operations. Controllers are staffed in sectors based on ATC complexity involved in controlling the sector operations.

Proposed improvements in analysis 4.2.3

It was realized that the variable “Monthly onboard number of controllers staffed in a center” does not capture the monthly controller work hours in a center. It was decided to use the variable “Monthly controller work hours worked by all controllers in a center” for the revised analysis.

SISO data were identified as a source. However great amount of processing is required to extract the data in the required format. Hence the proposed analyses are left for future studies. It is proposed to perform analysis 4.2.3 in the future using the SISO data.

4.2.4. Validation of current controller forecasting model by comparing model predicted monthly staffing and actual on board monthly staffing of controllers

Figure 4.17 shows the time series trend of the variables, "staffing standard forecasted monthly controller staffing in all centers of NAS" and "monthly onboard controller staffing in all centers of NAS".

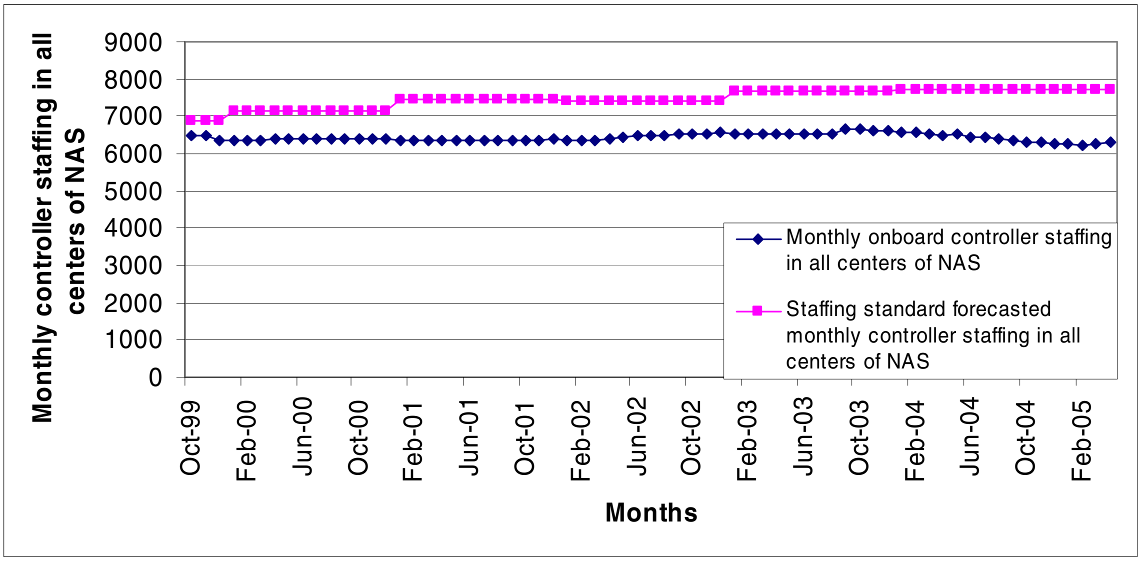

Figure 4.17 Time series trend of variables, staffing standard forecasted monthly controller staffing in all centers of NAS and monthly onboard controller staffing in all centers of NAS

Figure 4.18 shows the variables, “staffing standard forecasted monthly controller staffing in all centers of NAS” and “monthly onboard controller staffing in all centers of NAS” as a function of monthly center operations in NAS.

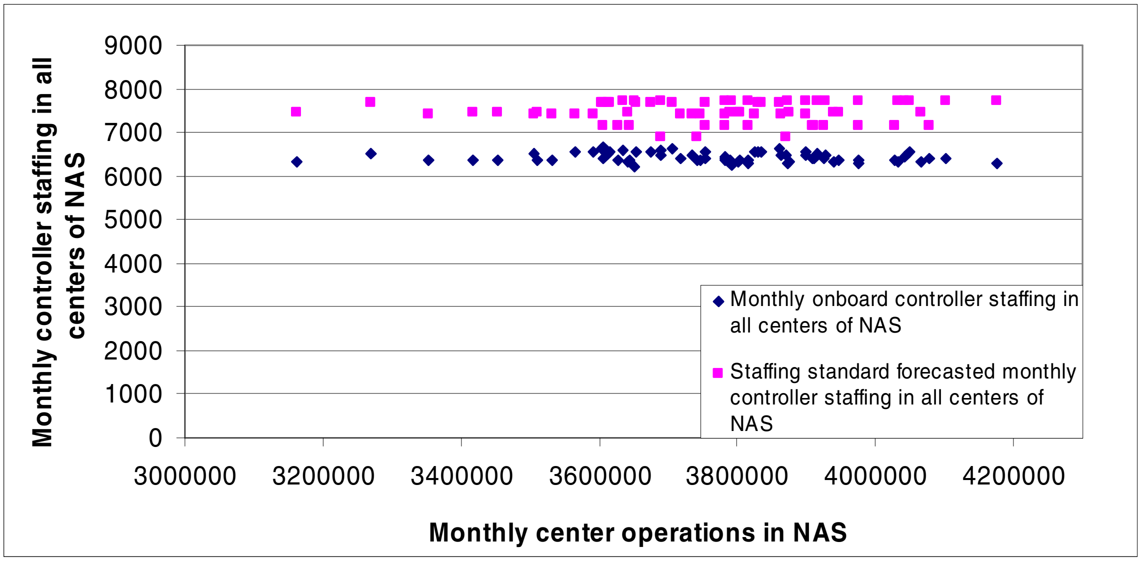

Figure 4.18 Staffing standard forecasted monthly controller staffing in all NAS centers and monthly onboard controller staffing in all NAS centers vs. monthly center operations in NAS.

Data for months from October 1999 to April 2005 were used for plotting figures 4.17 and 4.18.

In these figures it can be seen that the monthly controller staffing predicted by FAA model is greater than the actual onboard controller staffing for all months from October 1999 to April 2005.It can be concluded that the staffing standard provides adequate and greater than required monthly air traffic controllers in centers of NAS.

CHAPTER V: RELATIONS BETWEEN CONTROLLER PERFORMANCE AND AIR TRAFFIC IN SECTORS AND CENTERS OF THE NAS

Measures of controller workload and controller performance are developed in this section. Models are developed to estimate relations between controller workload and controller performance in NAS sectors and centers.

Care is taken in choosing data for NAS components (sectors and centers) and periods so that controller performance metrics are not affected by terminal congestion at destination airports, congestion in successive enroute centers along flight paths, weather and equipment failures.

There is a danger that controller performance measures could be affected by congestion in successive centers or sectors on the flight paths. Models are developed to estimate relations between controller performance in a center/sector and congestion in successive center/sector along the path of the flight. A city pair analysis is also performed for all flights appearing along a path linking a specific city pair. Controller performance in any of the segments on the path of the flight along the city pair is related to congestion in all the successive segments on the route of the flight.

In section 5.4 models are developed to estimate proposed relations. The models are estimated using regression analysis.

In section 5.4.4, the performance of R controller staffing configuration and R & D controller staffing configuration (in a sector) is compared, in terms of managing the air traffic activity assigned to each staffing configuration.

Measures of controller workload, controller performance, and models developed to estimate proposed relations are discussed in sections 5.1 to 5.4
The estimated models and the interpretation of results are discussed in sections 5.5 to 5.8.

NOTE: The division of US National Airspace System into centers and sectors has been explained in section 3.1.1. A center or a sector will be referred to as a NAS component.

5.1. Measures of air traffic activity (controller workload) in sectors and centers

“Flight-specific workload” is proposed below as a measure of controller workload for each flight traversing a center or a sector. “Flight-specific workload” is a measure of total flight activity seconds or total flight count handled by controllers in a NAS component (sector or center), while they are controlling one second of a flight under consideration.

“Flight-specific workload” is defined in two forms:
i. Seconds of flight activity handled by controller per second of considered flight.
ii. Flight operations handled by controller per second of considered flight.
Both measures of flight-specific workload are used below.

5.1.1. Suitability of metric "Flight-specific workload"

Howell et al 2003 uses total aircraft handled by a controller during a 15 minute interval as a measure of traffic per unit time. Normalized traffic activity for every 15 minute interval is related to average excess distance traveled by aircraft during that interval. Arguably, there could be bias in the relation between the two variables. In a given interval, excess distance traveled by a flight which enters/leaves the airspace in the last/first minute of the interval will not be affected by the congestion due to total number of flights in the airspace during that interval. The interarrival and departure distribution of flights may not be uniform for different intervals. This could bias the metric average excess distance traveled by flights during each time interval.

5.1.2. Computation of metric "Flight-specific workload"

i. In this section, flight-specific workload is computed in terms of seconds of flight activity handled by controller per unit time.

"Rolling time intervals" are specified for each flight. Considering the entry and exit times of a flight in airspace, traffic activity is computed only while the flight travels in the relevant airspace. The entry and exit times of the flight in the airspace denote the start and end times of the interval for that flight.

For each flight, traffic activity is considered only during the time when the flight traverses the airspace.

(Total flight Seconds)i,j denotes total flight activity seconds in the center or sector during time interval equal to duration of flight (i,j).

(i, j) denote entry and exit times of a flight in the airspace

Since different flights have different durations, the bias due to different intervals for different flights was eliminated as follows:

Flight-specific workload is denoted as “Avg flight secs”

“Avg flight secs”= (Total flight Seconds) i,j/ *[(observed duration of flight)i,j]*

Above variable represents seconds of flight activity handled by a controller while he controls each second of activity of flight (flight under consideration) in the sector or center. Hence, this is a measure of the workload on the controller.

(Total flight seconds)i,j induces workload on the controller and causes the undelayed transit time of the flight to extend to the observed transit time in the airspace. There is a need to consider the total aircraft seconds during the “undelayed transit time” of flight through the airspace which causes the “undelayed transit time” to extend to “observed transit time of flight” through the airspace.

Here an assumption is made that the aircraft activity present in the airspace during each minute of the undelayed transit time of the flight is approximately equal to the aircraft activity present in the airspace during each minute of the “observed transit time of flight”. The ETMS database does not estimate the planned duration of a flight (undelayed transit time) in a center or sector. Hence there is a need for the above assumption.

ii. In this section, flight-specific workload is computed in terms of flight operations handled by controller per unit time of the flight under consideration.

Flight-specific workload is denoted as “Avg flight count”

“Avg flight count”= (Total flight Operations) i,j/ *[(observed duration of flight)i,j]*

→Variable represents flight operations controlled by a controller while he controls each second of activity of flight (flight under consideration) in the airspace.

5.1.3. Incorporating ATC complexity in a measure of controller workload

In this section, ATC complexity factors which could be included in the measure of controller workload developed in section 5.1.2 are discussed.

i. Type of operation (arrival/departure/overflight)

In section 3.2.2.1 of the literature review it was found that traffic count and transit times of aircraft traversing airspace in climb/descend and cruise profiles affect controller workload significantly and differently.

The ETMS data used in the analysis do not provide details of flight profiles of operations -“climb”, “cruise”, “descend” and “climb-cruise-descent” flight profiles. Due to limitations of ETMS data, an approximation is made that operations with “climb”, “cruise”, “descend” and “climb-cruise-descent” flight profiles represent “departure”, “overflight”, “arrival” and “both” operations respectively. In the ETMS database “overflight” is a flight operation over an airspace and “both” denotes a flight operation which arrives and departs in the same airspace (center).

ii. Majumdar (a) showed that the interaction and quadratic effect of the cruise, ascent and descent traffic count in a sector affects the controller workload. In his analysis he considered the following variables and their functional forms:

$(\text{Traffic in cruise in a sector})^2$

Traffic in descend x traffic in cruise

Traffic in ascend x traffic in cruise

Traffic in descend x traffic in ascend

The above variables measuring the interaction and quadratic effect of cruise, ascend and descend traffic count are included in the proposed measure of controller workload. Due to limitations of ETMS data, variables measuring interaction and quadratic effect of arrival, departure, overflight and "both" operations are included in the proposed measure of controller workload.

5.2. Measures of controller performance in sectors and centers

5.2.1. Measures of controller performance proposed for analysis

Two measures of controller performance are proposed.

i. "Ratio of actual duration and GCR (Great Circle Route) distance of a flight" as a measure of controller performance:

ii. "Ratio of actual distance and GCR distance of a flight" as a measure of controller performance:

i. "Ratio of actual distance and GCR distance of a flight" as a measure of controller performance

Bradford et al. (2000), Howell et al. (2003) and Bennett (2004) defined excess distance traveled by a flight as the difference between actual distance traveled by the flight in the center and the GCR distance between the entry and exit points of the flight in the center.

The ratio of actual distance traveled by flight in the center and the great circle route distance between the entry and exit points of the flight in that center is proposed here as a measure of excess distance traversed by a flight in that center.

Suitability of metric “ratio of actual distance and GCR distance of a flight”

The excess distance metric proposed by Howell et al. (2003) is averaged for flights handled by the center during 15 minute intervals. Similarly excess distance metric proposed by Bradford et al. (2000) is averaged for flights in a center over a period of month. It is possible that the average value of excess distance (in an interval) could be biased for different time intervals. This bias could be caused by the variation in the length of actual flight paths traveled by the flights in the center during each interval.

ii. “Ratio of actual duration and GCR distance of a flight” as a measure of controller performance:

The ratio of actual duration of a flight in the center and the great circle route distance between the entry and exit points of the flight in that center is proposed as a measure of delay borne by a flight.

5.2.2. Consideration of operation type, user class of aircraft and physical class of aircraft in a measure of controller performance.

Based on the literature review it appears that arrival operations and operations which arrive and depart in the same airspace (center) are most susceptible to imposed restrictions due to terminal congestion at arrival airports. These restrictions could cause arrival and departure flights delays and excess distances even when the airspace they traverse is uncongested. Terminal congestion could bias the controller performance metrics for "arrival" and "both" operations. These controller performance metrics are developed to study the impact of airspace congestion on operations within the same airspace.

There is a need to analyze controller performance by considering each type of operation i.e. arrival, departure, overflight and "both". Dummy variables are introduced in regression models to study the performance of controllers in arrival, departure, overflight and "both" operations.

Aircraft belonging to different user class and physical class could have different speeds and could be controlled using different methods by the controller. This could bias the controller performance metrics for different user and physical class of aircraft. User class and physical class of aircraft are also considered as dummy variables in studying the performance of controllers with aircraft belonging to different user and physical classes.

The following dummy variables are included in regression models developed in sections 5.4.1 and 5.4.2

-Type of operations (arrival, departure, overflight and both.)

-User class of aircraft (air taxi, cargo, commercial, general aviation, military and other)

-Physical class of aircraft (piston, jet, turbo and other)

5.3. Data used for analyses

5.3.1. ETMS boundary crossing data for centers and sectors in NAS

Based on discussions with Mr. Daniel Citrenbaum, Ms. Nancy Stephens and Mr. Barry Davis, ETMS boundary crossing data for enroute centers and sectors were identified as appropriate for analysis. ETMS boundary crossing data for enroute centers and sectors was used for the analysis. The boundary crossing data record information on flights and airspaces (centers and sectors) as the flights cross the boundaries of the airspace. A spatial database engine tracks the flights as they cross the centers and sectors and calculates the following metrics for a 24 hour period. Data include domestic and international flight. (international arrivals, departures and overflights).

5.3.2. Details of ETMS boundary crossing data:

The ETMS boundary crossing data contain the following details:

Flight and aircraft details:

i. Call sign

ii. Aircraft type

iii. GMT departure date of the flight

iv. Arrival airport and departure airport

v. Flight identifier as created during ATA lab processing

vi. ETMS generated flight identifier or new identifier created during the ATA Lab enhancement process

vii. Flag identifying international flights

viii. Physical class of the aircraft

ix. User class of flight

Airspace (sector/center) details:

i. Name of the airspace through which the flight is crossing

ii. Actual distance of the flight through the airspace

iii. GMT time at which the flight crosses into and out of the airspace volume

iv. Time spent in the airspace volume

v. Great circle route distance between the in/out intersection

vi. Flag for international flights that fly over US controlled airspace

vii. Sequence number of boundary crossings for flights; determines order in which a flight crosses through each airspace volume

viii. Flag for determining if the flight flew NRP (National Route Program)

ix. Flag to determine whether flight departed, arrived or overflew the current airspace volume

x. Altitude at which the flight crosses into and out of the airspace volume

xi. Latitude where the flight crosses into and out of the airspace volume

xii. Longitude where the flight crosses into and out of the airspace volume

xiii. Velocity of the flight when it crosses into and out of the airspace volume

5.3.3. Period of data used in analyses:

Twenty-four-hour ETMS data for centers and sectors are used in the analysis. By using twenty-four-hour data the effect of winds on aircraft movements is minimized. Thus, the impact of wind on the controller performance metrics developed in section 5.2 is minimized.

5.4. Proposed models

The following models are proposed to estimate relations between controller performance and air traffic in NAS sectors and centers.

5.4.1. Relations between controller performance and controller workload for the same center/sector

In this analysis, relations are estimated between measures of controller workload and controller performance developed in sections 5.1 and 5.2. It is assumed that the excess distance and delay borne by a flight is due to traffic activity in the airspace while the flight is traversing it.

It is proposed here that the relation between "ratio of actual distance and GCR distance of a flight in airspace (sector/center)" and "flight-specific workload" is linear with a positive slope.

It is difficult to propose the precise relation between "ratio of actual duration and GCR distance of a flight in airspace (sector/center)" and "flight-specific workload". It is proposed that the relation between these two variables is non-linear. A simple queuing relation could also exist between the two variables. Three functional forms are considered for relating "ratio of actual duration and GCR distance traveled by flight in airspace (sector/center)" to "flight-specific workload". The three functional forms studied were power, exponential and linear.

Statistical analysis is performed to estimate relations between dependent and independent variables.

For 24 hour ETMS data, considering 15 -minute time intervals gives 96 sample data points. For performing statistical analysis more data points are required. Hence, sample data points need to be increased.

Controller workload measure "flight-specific workload" and controller performance measures are defined for each flight observation. Each flight observation is considered as a data point. One center in NAS handles an average of 8600 flights in 24 hours (Value is based on the ETMS data for 5 centers used in the analysis). The center data for 24 hour period gives us 8600 data points.

Time intervals used in analysis:

Rolling time intervals are specified for each flight observation. Entry and exit times of a flight in the airspace (sector/center) represent start and end points of time interval (i,j)considered for analysis of that flight.

(Where i = in_time of the flight in the airspace (sector/center)

j = out_time of the flight in the airspace (sector/center)

j-i = duration of flight in the center airspace (sector/center)

Dependent variables:

The following dependent variables are calculated for each flight:

Dependent variables for each flight observation with interval (i,j)	*Abbreviation*
(Actual distance /GCR distance)ij	Excess distance
(Actual duration/GCR distance)ij	Delay

Independent variables:

Based on the definition of "flight-specific workload" metric explained in section 5.1, the following independent variables are defined for each flight observation. These independent variables compose the construct of "flight-specific workload"

Independent variables are calculated for each flight observation from the ETMS boundary crossing data for the airspace (center/sector). The following intermediate variables are used to compute the independent variables.

{A, D, O and B denote arrival, departure, overflight and both operations; overflights fly over an airspace and "B" (both) denotes a flight which arrives and departs in the same airspace}

Variables for each flight observation with interval (i,j)	*Abbreviation*
(Seconds of activity of all types of operations) i,j	Flight seconds
(Seconds of activity of arrival operations) i,j	Flight seconds of A
(Seconds of activity of departure operations) i,j	Flight seconds of D
(Seconds of activity of over flight operations) i,j	Flight seconds of O

(Seconds of activity of both operations) i,j	Flight seconds of B

The above variables were also computed in terms of flight operations

The following independent variables are computed:

Independent variables for each flight observation with interval (i,j)	*Abbreviation*
[(Flight seconds)i,j/time interval (i,j)]	Avg flight secs
[(Flight seconds of A)i,j /time interval (i,j)]	Avg flight secs A
[(Flight seconds of D)i,j /time interval (i,j)]	Avg flight secs D
[(Flight seconds of O)i,j /time interval (i,j)]	Avg flight secs O
[(Flight seconds of A)i,j /time interval (i,j)]2	
[(Flight seconds of D)i,j /time interval (i,j)]2	Squared avg flight secs D
[(Flight seconds of O)i,j /time interval (i,j)]2	Squared avg flight secs O
[(Flight seconds of A)i,j /time interval (i,j) * (Flight seconds of O)i,j /time interval (i,j)]	Product A*O flight secs
[(Flight seconds of D)i,j /time interval (i,j) * (Flight seconds of O)i,j /time interval (i,j)]	Product D*O flight secs
[(Flight seconds of A)i,j /time interval (i,j) * (Flight seconds of D)i,j /time interval (i,j)]	Product A*D flight secs
[Dummy variable indicating type of operation arrival, departure, overflight, both]	A/D/O/B
[Dummy variable indicating user class of a/c; commercial/GA/air taxi]	C/G/T
[Dummy variable indicating physical class of a/c; piston/jet/turbo]	P/J/T

The above independent variables were also computed in terms of flight operations.

Functional forms used in analyses:

The following functional forms were used for relating dependent and independent variables.

Model with dependent variable	*Functional form*
(Actual distance /GCR distance) i,j	Linear
(Actual duration/GCR distance)i,j	Linear/second power/exponential

Statistical analyses:

Regression analyses were performed for the following models:

a) Models with dependent variable "ratio of actual distance and GCR distance of flight"

Models 1.1. to 1.4: Controller workload is measured in terms of flight activity seconds in these models.

Dependent variable	(Actual distance /GCR distance) i,j			
Independent variables	Model 1.1	Model 1.2	Model 1.3	Model 1.4
Avg flight secs	P	P	P	P
Avg flight secs A		P	P	P
Avg flight secs D		P	P	P
Avg flight secs O		P	P	P
Product A *O flight secs			P	P
Product D *O flight secs			P	P
Product A *D flight secs			P	P
Squared avg flight secs O				P
Arr/Dep/Over/Both	P	P	P	P
Comm./GA/Air taxi	P/#	P/#	P/#	P/#
Piston/Jet/Turbo	#/P	#/P	#/P	#/P

P denotes variable present in the model

The same model was estimated twice by alternately dropping either of the two variables denoted by "#". This was done to avoid correlation between the two dummy variables.

Models 2.1. to 2.4: Controller workload is measured in terms of flight operations in these models.

Dependent variable	(Actual distance /GCR distance) i,j			
Independent variables	Model 2.1	Model 2.2	Model 2.3	Model 2.4
Avg flight count	P	P	P	P
Avg flight count A		P	P	P
Avg flight count D		P	P	P
Avg flight count O		P	P	P
Product A *O flight count			P	P
Product D *O flight count			P	P
Product A *D flight count			P	P
Squared avg flight count O				P
Arr/Dep/Over/Both	P	P	P	P
Comm./GA/Air taxi	P/#	P/#	P/#	P/#
Piston/Jet/Turbo	#/P	#/P	#/P	#/P

b) Models with dependent variable "ratio of actual duration and GCR distance of a flight"

Models 3.1 to 3.6: Controller workload is measured in terms of flight activity seconds in these models.

Dependent variable	(Actual duration /GCR distance) i,j					
Independent variables	Model 3.1	Model 3.2	Model 3.3	Model 3.4	Model 3.5	Model 3.6
Avg flight secs	P	P	P	P		
Squared avg flight secs			P	P		
Exp(avg flight secs)					P	P
Avg flight secs A		P		P		
Avg flight secs D		P		P		
Avg flight secs O		P		P		
Squared avg flight secs A				P		
Squared avg flight secs D				P		
Squared avg flight secs O				P		
Exp(avg flight secs A)						P
Exp(avg flight secs D)						P
Exp(avg flight secs O)						P
Arr/Dep/Over/Both	P	P	P	P	P	P
Comm./GA/Air taxi	P/#	P/#	P/#	P/#	P/#	P/#
Piston/Jet/Turbo	#/P	#/P	#/P	#/P	#/P	#/P

P denotes variable present in the model

Models 4.1 to 4.6: Controller workload is measured in terms of flight operations in these models.

Dependent variable	(Actual duration /GCR distance) i,j					
Independent variables	Model 4.1	Model 4.2	Model 4.3	Model 4.4	Model 4.5	Model 4.6
Avg flight count	P	P	P	P		
Squared avg flight count			P	P		
Exp(avg flight count)					P	P
Avg flight count A		P		P		
Avg flight count D		P		P		
Avg flight count O		P		P		
Squared avg flight count A				P		
Squared avg flight count D				P		
Squared avg flight count O				P		
Exp(avg flight count A)						P
Exp(avg flight count D)						P
Exp(avg flight count O)						P
Arr/Dep/Over/Both	P	P	P	P	P	P
Comm./GA/Air taxi	P/#	P/#	P/#	P/#	P/#	P/#
Piston/Jet/Turbo	#/P	#/P	#/P	#/P	#/P	#/P

P denotes variable present in the model

5.4.2. Effect of congestion in successive center/sector on flight path

The difficulties in estimating relations between controller performance metrics and controller workload in sectors and centers have been explained in section 3.2.4. It is possible that traffic in the successive airspace on the flight path could increase distances or delays for flights in the current airspace.

Hence an analysis was proposed to relate air traffic activity in the successive airspace and the excess distances traveled and delays borne by flights in the current airspace. The following variables were used.

Dependent variables:

The following dependent variables were computed for each flight:

Dependent variables for interval (i,j)	*Abbreviation*
(Actual distance /GCR distance)i,j	Excess distance
(Actual duration/GCR distance)ij	Delay

(i,j) denote the entry and exit times of flights in the considered airspace.

The time interval (i,j) defines the duration of the flight in the airspace under consideration. Traffic activity in the successive airspace on the flight path is computed for time interval (i,j).

Independent variables:

{A, D, O and B denote arrival, departure, overflight and both operations; overflights pass through an airspace while “B” denotes a flight which arrives and departs in the same airspace}

Variables for each flight observation with interval (i,j)	*Abbreviation*
(Seconds of activity of all types of operations in successive airspace) i,j	Flight seconds in successive airspace

(i,j) denote the entry and exit times of flight in the current airspace.

Independent variables for each flight observation with interval (i,j)	*Abbreviation*
[(Flight seconds in successive airspace)i,j/time interval (i,j)]	Avg flight secs in successive airspace
[(Flight seconds in successive airspace)i,j /time interval (i,j)] 2	Squared avg flight secs in successive airspace
exp[(Flight seconds in successive airspace)i,j/time interval (i,j)]	Exp avg flight secs in successive airspace
[Dummy variable indicating type of operation arrival, departure, overflight, both]	A/D/O/B
[Dummy variable indicating user class of a/c; commercial/GA/air taxi]	C/G/T
[Dummy variable indicating physical class of a/c; piston/jet/turbo]	P/J/T

The above independent variables were also computed in terms of flight operations.

Functional forms used in analyses:

The following functional forms were used for relating dependent and independent variables.

Model with dependent variable	*Functional form*
(Actual distance /GCR distance) i,j	Linear
(Actual duration/GCR distance) i,j	Linear/second power/exponential

Statistical analyses:

Statistical analyses are performed for the following models.

a) Models with dependent variable "ratio of actual distance and GCR distance of a flight"

Models 5.1. and 5.2: Controller workload is measured in terms of flight activity seconds in these models.

Dependent variable	(Actual distance /GCR distance) i,j	
Independent variable	Model 5.1	Model 5.2
Avg flight secs in successive airspace	P	P
Arr/Dep/Over/Both		P
Comm./GA/Air taxi		P/#
Piston/Jet/Turbo		#/P

P denotes variable present in the model

Models 6.1. and 6.2: Controller workload is measured in terms of flight operations in these models.

Dependent variable	(Actual distance /GCR distance) i,j	
Independent variable	Model 6.1	Model 6.2
Avg flight count in successive airspace	P	P
Arr/Dep/Over/Both		P
Comm./GA/Air taxi		P/#
Piston/Jet/Turbo		#/P

P denotes variable present in the model

b) Models with dependent variable "ratio of actual duration and GCR distance of a flight"

Models 7.1 to 7.6: Controller workload is measured in terms of flight activity seconds in these models.

Dependent variable	(Actual duration/GCR distance) i,j					
Independent variable	7.1	7.2	7.3	7.4	7.5	7.6
Avg flight secs in successive airspace	P	P	P	P		
Squared avg flight secs in successive airspace			P	P		
Exp avg flight secs in successive airspace					P	P
Arr/Dep/Over/Both		P		P		P
Comm./GA/Air taxi		P/#		P/#		P/#
Piston/Jet/Turbo		#/P		#/P		#/P

P denotes variable present in the model

Models 8.1 to 8.6: Controller workload is measured in terms of flight operations in these models.

Dependent variable	(Actual duration/GCR distance) i,j					
Independent variable	8.1	8.2	8.3	8.4	8.5	8.6
Avg flight count in successive airspace	P	P	P	P		
Squared avg flight count in successive airspace			P	P		
Exp avg flight count in successive airspace					P	P
Arr/Dep/Over/Both		P		P		P
Comm./GA/Air taxi		P/#		P/#		P/#
Piston/Jet/Turbo		#/P		#/P		#/P

P denotes variable present in the model

5.4.3. Analysis of flights traveling between a city pair

In sections 3.2.4 and 3.2.5, it is discussed that traffic in any of the NAS components on the flight path could impose excess distances or delays to the subject flight in any of the previous NAS components.

An analysis is proposed to relate air traffic activity in any of the NAS components on the route of the flight with the excess distances and delays borne by flights in preceding NAS components. The following procedure was used to compute the dependent and independent variables.

Let us assume that all flights between a specific city pair traverse the same three centers on their route in the same sequence. Time interval (i,j,k) is specified for each flight. For a subject flight (i,j,k) denotes entry and exit times of a flight in airspace k. Thus, for a subject flight, time interval (i,j,2) denotes its entry and exit times in the second center on its flight path.

The excess distances and delays borne by flights in the first center airspace are related with controller workload in the second and third center airspace on the flight path. Similarly, excess distances and delays borne by flights in the second center airspace are related to controller workload in the third center airspace on the flight path.

For time interval (i,j,1), controller workload is computed in the second and third centers on the flight path. Similarly, for time interval (i,j,2) controller workload is computed in the third center on the flight path.

Dependent variable for each flight with interval (i,j,k):

(i,j) denote entry and exit times of flight in center "k" on the flight path.

Dependent variables for interval (i,j,k)	*Abbreviation*
(Actual distance /GCR distance)i,j,1	Excess distance traversed by flight in first center on flight path
(Actual distance /GCR distance)i,j,2	Excess distance traversed by flight in second center on flight path
(Actual distance /GCR distance)i,j,3	Excess distance traversed by flight in third center on flight path
(Actual duration/GCR distance)i,j,1	Delay borne by flight in the first center on flight path
(Actual duration/GCR distance)i,j,2	Delay borne by flight in the second center on flight path
(Actual duration/GCR distance)i,j,3	Delay borne by flight in the third center on flight path

For time interval (i,j,1), (i.e. the interval when the flight is traversing the first center), the controller workload in second and third centers on the flight path is denoted by CW (i,j,1,2) and CW (i,j,1,3) respectively. Similarly for interval (i,j,2) , (i.e. the interval when the flight is traversing the second center) the controller workload in the third center on the flight path is denoted by CW (i,j,2,3).

Controller workload is measured by the independent variables. Controller workload is denoted as "independent variable (i,j,k,l)".

Independent variables:

Variables for each flight observation with interval (i,j,k,l)	*Abbreviation*
(Seconds of activity of all type of operations in center “l”) i,j,k,l	Flight seconds in center “l”

(i,j) denote the entry and exit times of flight in airspace “k”.

Independent variables for each flight observation	*Abbreviation*
[(Flight seconds in airspace “1”)i,j/time interval (i,j,k)]	Avg flight secs in center “l”
[(Flight seconds in airspace “l”)i,j /time interval (i,j,k)] 2	Squared avg flight secs in center “l”
exp[(Flight seconds in airspace “l”)i,j/time interval (i,j,k)]	Exp avg flight secs in center “l”

The above independent variables were also computed in terms of flight operations.

Functional forms used in analyses:

The following functional forms were used for relating dependent and independent variables.

Model with dependent variable	*Functional form*
(Actual distance /GCR distance)	Linear
(Actual duration/GCR distance)	Linear/Second power/exponential

Statistical analyses:

Regression analyses were performed for the following models:

a) Models with dependent variable “ratio of actual distance and GCR distance of a flight”

Models 9.1 and 9.2: Controller workload is measured in terms of flight activity seconds in these models.

Model 9.1:

Dependent variable	(Actual distance /GCR distance) i,j,1
Independent variable	Model 9.1
Avg flight secs in center "2"	P
Avg flight secs in center "3"	P

P denotes variable present in the model

Model 9.2:

Dependent variable	(Actual distance /GCR distance) i,j,2
Independent variable	Model 9.2
Avg flight secs in center "3"	P

P denotes variable present in the model

Models 10.1 and 10.2: Controller workload is measured in terms of flight operations in these models.

Model 10.1:

Dependent variable	(Actual distance /GCR distance) i,j,1
Independent variable	Model 9.1
Avg flight count in center “2”	P
Avg flight count in center “3”	P

P denotes variable present in the model

Model 10.2:

Dependent variable	(Actual distance /GCR distance) i,j,2
Independent variable	Model 10.1
Avg flight count in center “3”	P

P denotes variable present in the model

b. Models with dependent variable "ratio of actual duration and GCR distance of a flight"

Models 11.1 to 11.6: Controller workload is measured in terms of flight activity seconds.

Models 11.1 to 11.3:

Dependent variable	(Actual duration/GCR distance) i,j,1		
Independent variable	Model 11.1	Model 11.2	Model 11.3
Avg flight secs in center "2"	P	P	
Avg flight secs in center "3"	P	P	
Squared avg flight secs in center "2"		P	
Squared avg flight secs in center "3"		P	
Exp avg flight secs in center "2"			P
Exp avg flight secs in center "3"			P

P denotes variable present in the model

Models 11.4 to 11.6:

Dependent variable	(Actual duration/GCR distance) i,j,2		
Independent variable	Model 11.4	Model 11.5	Model 11.6
Avg flight secs in center "3"	P	P	
Squared avg flight secs in center "3"		P	
Exp avg flight secs in center "3"			P

Models 12.1 to12.6: Controller workload is measured in terms of flight operations in these models.

Models 12.1 to12.3:

Dependent variable	(Actual duration/GCR distance) i,j,1		
Independent variable	Model 12.1	Model 12.2	Model 12.3
Avg flight count in center “2”	P	P	
Avg flight count in center “3”	P	P	
Squared avg flight count in center “2”		P	
Squared avg flight count in center “3”		P	
Exp avg flight count in center “2”			P
Exp avg flight count in center “3”			P

P denotes variable present in the model

Models 12.4 to12.6:

Dependent variable	(Actual duration/GCR distance) i,j,2		
Independent variable	Model 12.4	Model 12.5	Model 12.6
Avg flight count in center “3”	P	P	
Squared avg flight count in center “2”		P	
Exp avg flight count in center “2”			P

5.4.4. Performance comparison of R and R & D controller staffing configurations in a sector

Facility managers and supervisors use their judgment and consider complexity for assigning an additional D controller to a sector. Hence the traffic demand at which a D controller is added to a sector could be different for different sectors. The traffic activity and corresponding controller workload subjected to the two controller staffing configurations (R controller staffing configuration and R and D controller staffing configuration) is different.

In the literature review it is found that controllers could impose delays and excess distances on flights due to workload. It is estimated whether the air traffic activity imposed on the two controller staffing configurations causes either of them to impose delays or excess distances on flights. The performance of the two staffing configurations is compared in managing the air traffic activity assigned to them.

The two measures of controller performance developed in section 5.2.1 were used to study the performance of each controller staffing configuration. Those two controller performance metrics are:

i. “Ratio of actual distance and GCR distance of a flight in a sector” for each flight controlled by a specific staffing configuration.

ii. “Ratio of actual duration and GCR distance of a flight in a sector” for each flight controlled by a specific staffing configuration.

Data used for analysis

SISO data (Sign in Sign out data)

A sector can be staffed with the following configurations:

1. R controller staffing configuration
2. R controller and D controller (Hand off controller) staffing configuration
3. R controller, D controller and A controller staffing configuration

The SISO database records the start and end times of the shift of each controller who works at a specific position (R, D or A).

The controllers manually enter the start and end times of their work shifts.

The start and end times of shifts are recorded to the second. The SISO information is recorded for all NAS centers.

The SISO database also records the initials of the controller who enters the data.

Data source

The SISO data were provided by Mr. Matt Dunne, Manager of National Offload Program at the ATO-A/IT Office.

Boundary crossing data for flights

The boundary crossing data from section 5.5 are used in this analysis. Data for four sectors (ZDC04, ZJX68, ZNY39 and ZMA20) are used. SISO data are used for the same sectors and periods which correspond to the boundary crossing data.

Analyses:

For each of the four sectors, the twenty-four-hour SISO data are matched to the corresponding twenty-four-hour boundary crossing data. [1]SISO data and boundary crossing data for all sectors are recorded in GMT (ZULU) times.

[1] SISO data for all centers are recorded based on GMT (ZULU) times. Mr. Matt Dunne provided this information by email.

The following procedure was performed for each of the four sectors:

1. The periods of the day during which the R or R and D controller staffing configuration worked in a sector were determined. These periods were determined using SISO data.

2. Flights were classified into two bins depending on whether the flight was controlled by an R or an "R and D" controller staffing configuration. Flights were sorted into bins

based on the “m_time” of the flight. The “m_time of a flight is calculated in the following way.

Let “a” and “b” denote the entry and exit times of a flight in a sector. The “m_time” of a flight is computed as a + (b-a)/2. The “m_time” is calculated as the midpoint of the duration of the flight in the sector’s airspace.

Flights traversing the sector’s airspace during the 24 hour period are sorted into two bins based on “m_time” of the flights. By using “m_time” to classify flights, only those flights are considered which are present in the sector for maximum duration during the period when the sector was controlled by an R or an R & D staffing configuration.

3. The average values of the controller performance metrics are computed for each bin. The average values in the two bins are compared. Unpaired unequal t tests are used to compare the average values.

Analyses and interpretation of results

5.5. Selection of centers and sectors and details of data used.

5.5.1. Data used for analysis

Twenty-four-hour ETMS boundary crossing data for the chosen centers and sectors is used in the analyses.

Selection of centers

Five centers were chosen from 21 enroute air traffic control centers. The fraction of center operations delayed due to center congestion was used as the criterion for choosing centers which are most susceptible to delays caused by enroute congestion.

The fraction of center operations delayed due to center congestion is computed for 21 centers from the OPSNET database. The values are computed for individual months from January to March 2005 and for entire period from January to March 2005.The centers with the highest fraction for the considered periods were chosen for analyses. These are:

1. ZNY (New York NY ARTCC)
2. ZMA (Miami FL ARTCC)
3. ZAB (Albuquerque NM ARTCC)
4. ZJX (Jacksonville FL ARTCC)
5. ZDC (Leesburg VA ARTCC (DC))

Selection of dates for five chosen centers

A specific date was chosen for each of the 5 centers. The date was chosen between 01/01/2005 and 04/22/2005. As discussed in section 3.2.5 the data for centers and sectors were chosen based on the following considerations:

1. The center handled maximum operations on the chosen date

2. Flights in the considered centers were not delayed due to terminal congestion, equipment failures and weather on the chosen date. Data on traffic operations and delays (greater than 15 minute period delays) were obtained from OPSNET database.

Data for centers and dates listed in table 5.1 were chosen for analyses

Table 5.1

Center	*Date*	*Operations handled during 24 hour period*
ZNY	3/11/2005	9418
ZMA	1/3/2005	8727
ZAB	3/24/2005	5879
ZJX	2/7/2005	9117
ZDC	3/29/2005	9682

Selection of sectors and dates

One sector was chosen from each of the four centers (ZDC, ZJX, ZNY and ZMA).The sector which handled maximum operations among all sectors in a center was chosen. Data for the sector were taken for the same date as its center.

Data for sectors and dates listed in table 5.2 were chosen for analyses

Table 5.2

Sector	*Date*
Sector ZDC04	03/29/2005
Sector ZJX 68	2/7/2005
Sector ZNY 39	3/11/2005
Sector ZMA 20	1/3/2005

5.5.2. Additional data used for analysis:

The analysis for following sectors and centers was conducted with data for the following dates. The centers and sectors did not handle maximum traffic on the dates listed below. However flights traversing the centers and sectors on the chosen dates were not delayed due to terminal congestion, congestion in other enroute centers, equipment failures and weather.

Data for centers and dates listed in table 5.3 were used for analyses

Table 5.3

Center	*Date*
US Dom ZDC	04/15/2003
US Dom ZLA	04/15/2003
US Dom ZNY	04/15/2003

Data for sectors and dates listed in table 5.4 were used for analyses

Table 5.4

Sectors of center US Dom ZDC	*Date*
Sector ZDC03	01/15/2005
Sector ZDC 04	01/15/2005
Sector ZDCDI	01/15/2005

5.5.3. ETMS data used in the analysis:

Twenty-four-hour ETMS boundary crossing data were obtained for the chosen centers and sectors.

Corrections in ETMS data

There were errors in data which were identified based on specifications in ETMS data dictionary. Flight observations which had the following errors were eliminated from the data.

1. Those with entry and exit speeds in airspace (center or sector) greater than 15 nmi/min
2. Those with duration of zero seconds in a sector or center.

On average, for each center, 5% of the 24 hour data (individual flight observations) had errors.

Drawbacks of the ETMS data:

ETMS database records information only for those flights which file flight plans with the ATC system. Military flights are excluded.

5.6. Data processing tools and statistical softwares used for performing analyses

The following data processing tools and statistical software are used in the analyses.

Calculation of dependent and independent variables for the models

The following procedure was adopted for computing dependent and independent variables for each flight observation of each dataset. Macros were developed in Microsoft Excel to compute the independent variables from 24 hour ETMS data. On average the macro took 6 hours of processing time to compute independent variables for 5000 flight observations. All the data processing and formatting was performed using Microsoft Excel.

Statistical softwares used for analysis

Intercooled Stata 7.0 was used as a statistical analysis tool

The formatted data comprising dependent and independent variables were entered as input in the Stata program.

5.7. Analyses and results

Relations are sought between controller performance and controller workload for the same airspace (center or sector) in model 5.4.1.

Flights could travel excess distances or bear delays in airspace because of congestion in any of the successive airspace on the route of the flight. Hence there is a need to analyze models developed in sections 5.4.2 and 5.4.3.

In section 5.7.2, relations are estimated between excess distances and delays to flights in the subject airspace, and congestion in successive airspace.

In section 5.7.3, relations are estimated between excess distances and delays borne by flights in the current airspace, and congestion in any of the successive centers or sectors on the flight path.

The explanatory power of the models is determined by holding other factors constant.

5.7.1. Estimating relation between controller workload and controller performance for the same airspace.

a. Analysis for centers

Models 1.1 to 1.4, 2.1 to 2.4, 3.1 to 3.6 and 4.1 to 4.6 were analyzed for the following centers to estimate relations between controller workload and controller performance in the center airspace.

Center	*Date*
US Dom ZNY	3/11/2005
US Dom ZMA	1/3/2005
US Dom ZAB	3/24/2005
US Dom ZDC	4/15/2003
US Dom ZLA	4/15/2003
US Dom ZNY	4/15/2003

Statistical Analysis:

Multivariate regression analyses were performed for the models using data for above centers. None of the models showed statistically significant results even at 10% level of significance.

Heteroscedasticity:

Results of regression analyses were checked for heteroscedasticity by using "hettest" command in Stata. Multivariate regression analyses were also conducted using robust standard errors. Robust standard errors correct the standard errors for heteroscedasticity. The presence of heteroscedasticity was not detected in any of the models.

Multicollinearity:

Regression models were developed considering only the independent variables to see if there is any correlation among the independent variables. None of the regression models showed good explanatory power. These regression models showed that the independent variables were not statistically correlated with each other. Considering the effect captured by each independent variable, it may be concluded that the independent variables are not correlated with each other.

Scatter plots

Statistical analysis showed that the models had no explanatory power. Scatter plots were developed considering following dependent and independent variables to understand the relation between the variables.

Dependent variables:

i. Ratio of actual distance and GCR distance of flight

ii. Ratio of actual duration and GCR distance of flight

Independent variables:

1. Avg flight secs

2. Avg flight count

Results for center USDom-ZDC (4/15/2003)

Results of models 1.1 to 1.4 and 2.1 to 2.4:

Figures 5.1 and 5.2 show relations between excess distance traveled by a flight in center and the following flight-specific workload metrics for the same center:

1. Avg flight secs

2. Avg flight count

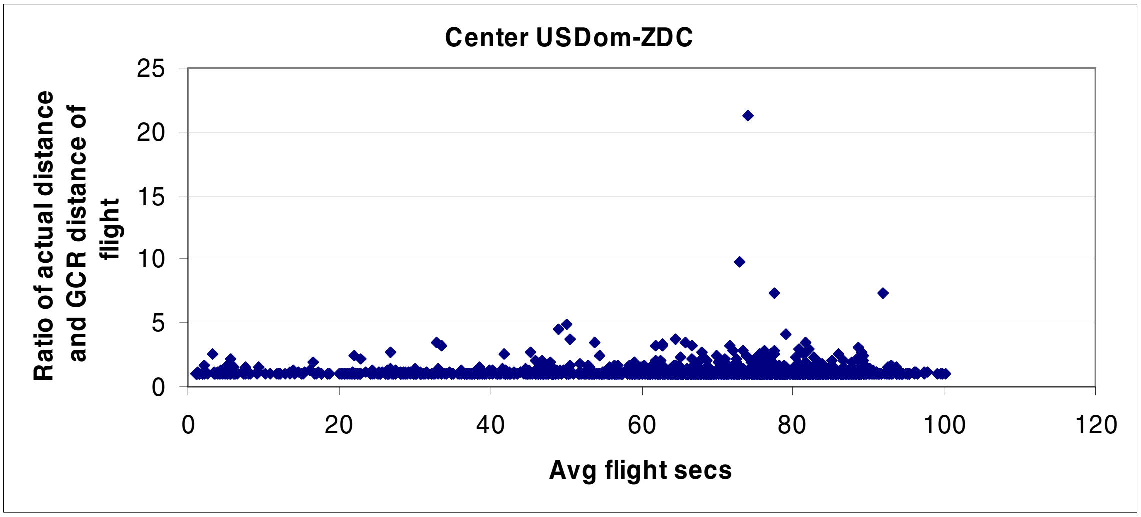

Figure 5.1 Ratio of actual distance and GCR distance of flight vs. avg flight secs for center US Dom ZDC

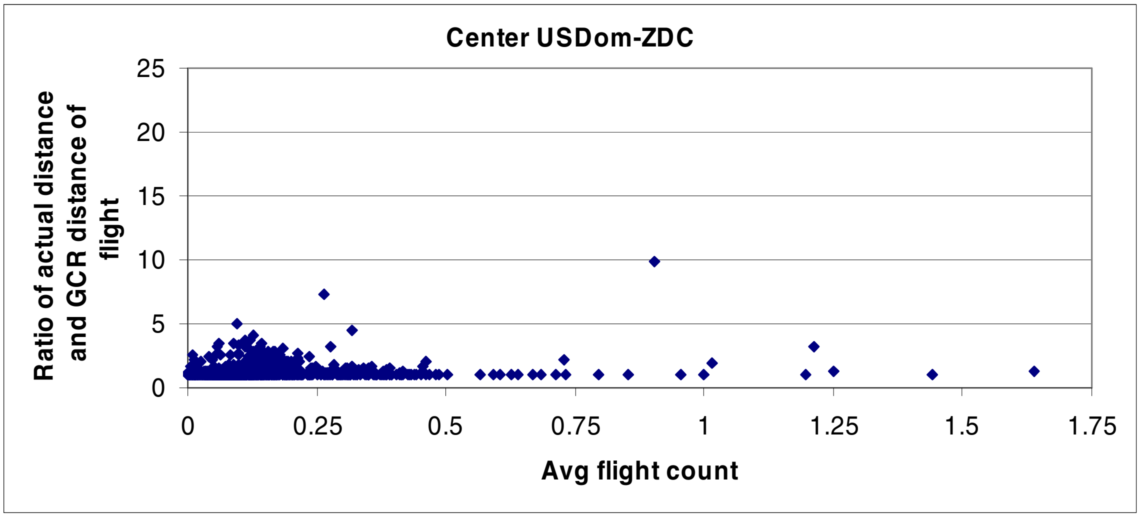

Figure 5.2 Ratio of actual distance and GCR distance of flight vs. avg flight count for center US Dom ZDC

Figures 5.3 and 5.4 show relations between the same variables shown in figures 5.1 and 5.2. In this case the relations are shown for selected operations which are selected in the following way.

Operations with the same aircraft type, physical class, user class and type of operation (arrival, departure, overflight or both) are considered. For center US Dom ZDC, operations belonging to following categories are shown in figures 5.3 and 5.4

Aircraft	E145
Physical class	Jet
User class	Air taxi
Operation	Overflight

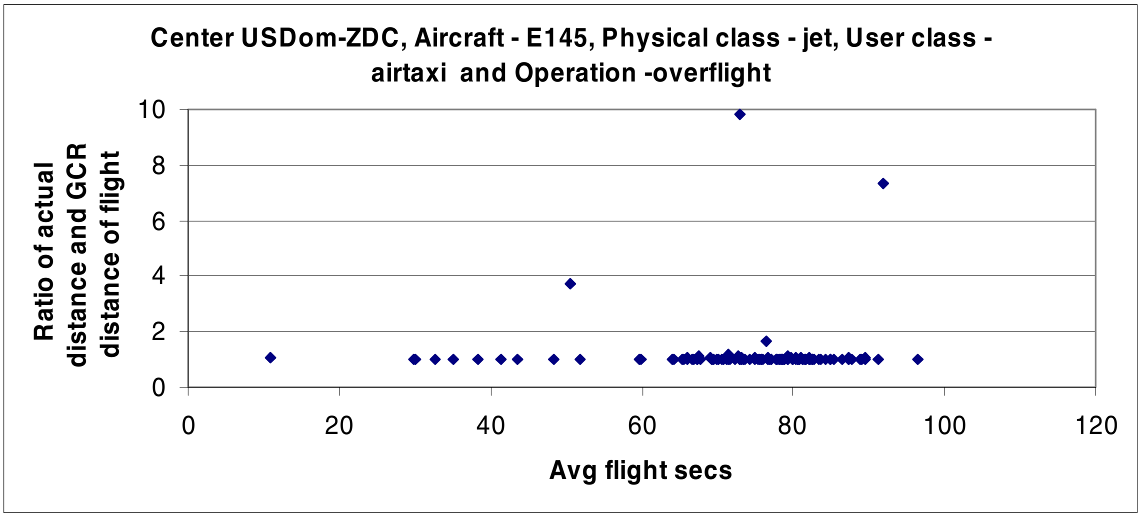

Figure 5.3 Ratio of actual distance and GCR distance of flight vs. avg flight secs (for selected operations of center US Dom ZDC)

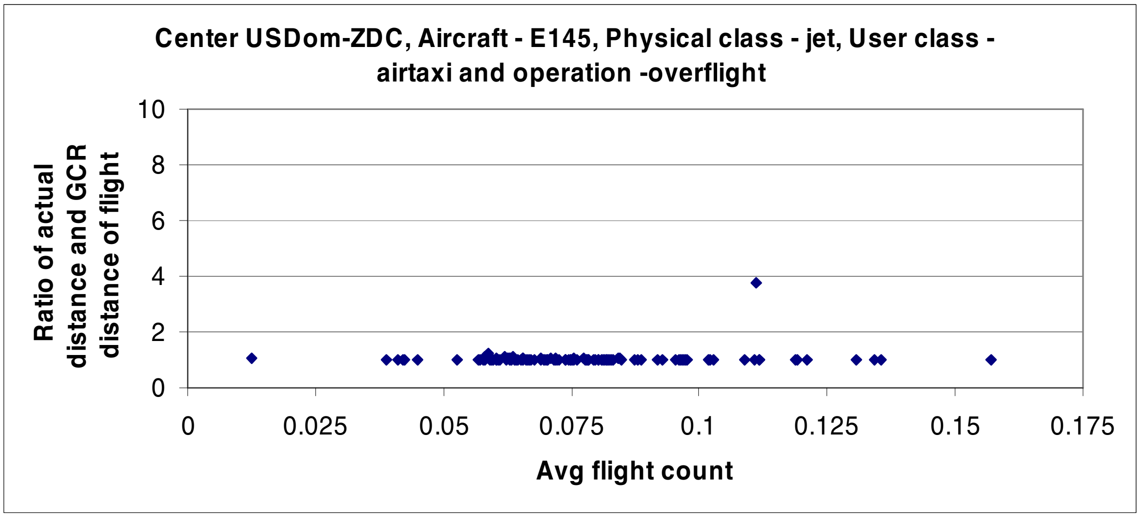

Figure 5.4 Ratio of actual distance and GCR distance of flight vs. avg flight count (for selected operations of center US Dom ZDC)

Results of models 3.1 to 3.6 and 4.1 to 4.6:

Figures 5.5 and 5.6 show relations between delay borne by a flight in center and the following flight-specific workload metrics for the same center:

1. Flight-specific workload (in seconds)

2. Flight-specific workload (in operations)

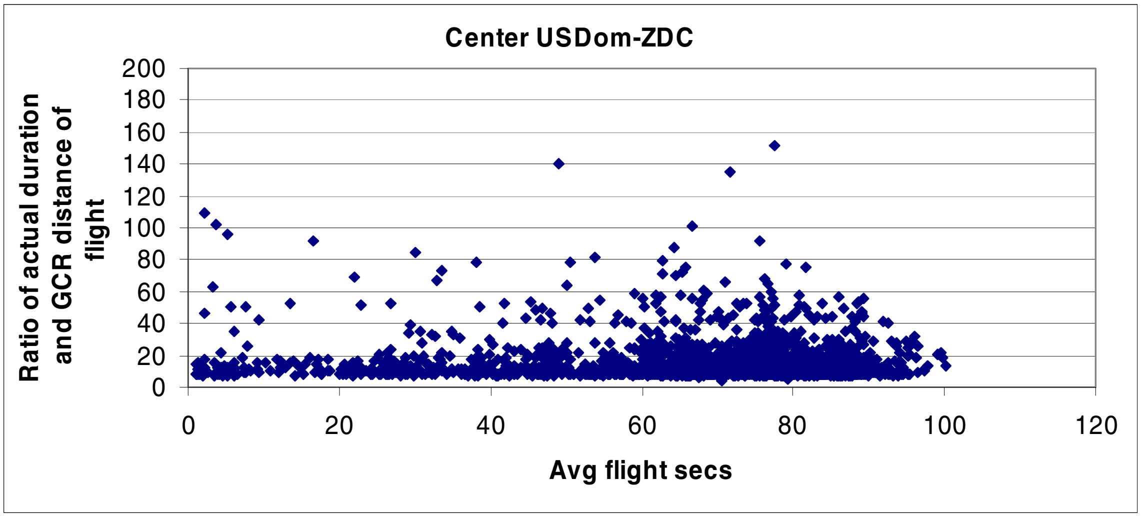

Figure 5.5 Ratio of actual duration and GCR distance of flight vs. avg flight secs for center US Dom ZDC

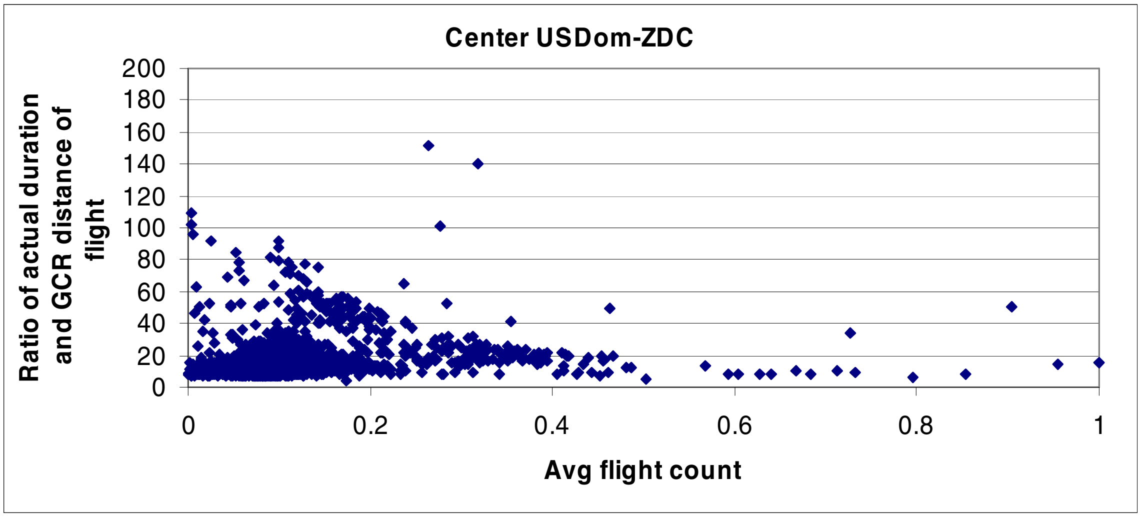

Figure 5.6 Ratio of actual duration and GCR distance of flight vs. avg flight count for center US Dom ZDC

Figures 5.7 and 5.8 show relations between the same variables shown in figures 5.5 and 5.6. In this case the relations are shown for selected operations which are selected in the following way.

Operations with the same aircraft type, physical class, user class and type of operation (arrival, departure, overflight or both) are considered. For center US Dom ZDC, operations belonging to following categories are shown in figures 5.7 and 5.8

Aircraft	E145
Physical class	Jet
User class	Air taxi
Operation	Overflight

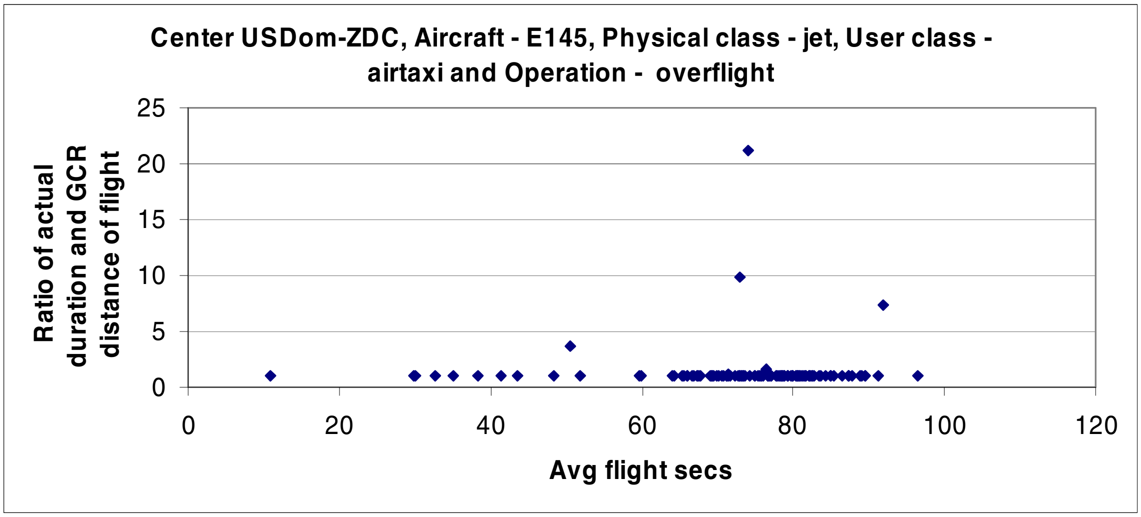

Figure 5.7 Ratio of actual duration and GCR distance of flight vs. avg flight secs (for selected operations of center US Dom ZDC)

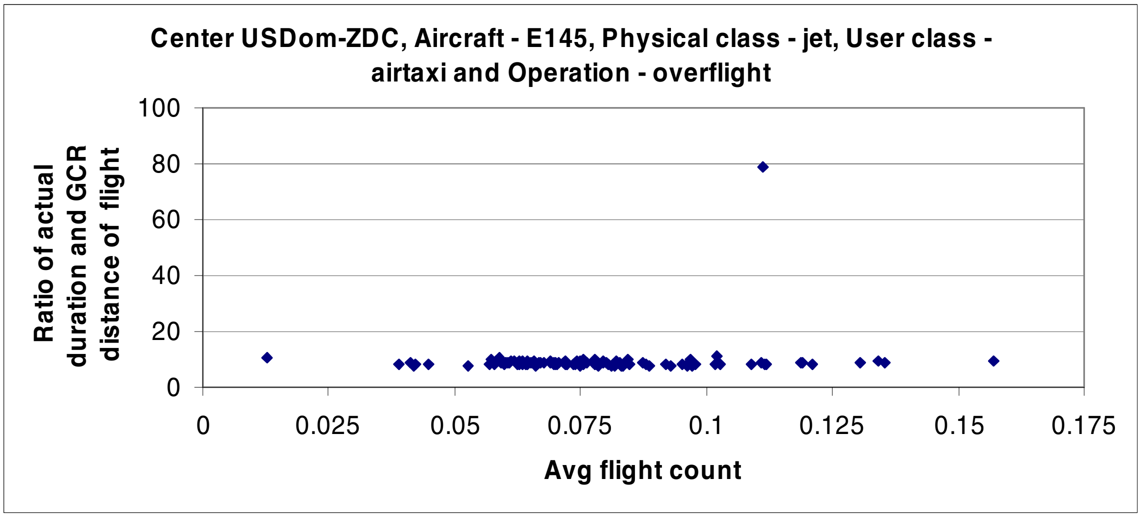

Figure 5.8 Ratio of actual duration and GCR distance of flight vs. avg flight count (for selected operations of center US Dom ZDC)

The literature review revealed that “arrival” and ‘both” types of operation may have restrictions imposed on them due to terminal congestion at arrival airports. This could bias the dependent variables. Scatter plots were also developed by considering only overflights or departure flights. However based on the trend seen in scatter plots, neither of the dependent variables is affected by the considered independent variables. The plot is almost flat in all cases.

b. Analysis for sectors

Total excess distance traveled and total delay borne by a flight in a center is the sum of excess distances in the individual sectors. Thus, varying congestion levels in individual sectors could affect the total excess distance through the center. Models 1.1 to 1.4, 2.1 to 2.4, 3.1 to 3.6 and 4.1 to 4.6 developed in section 5.4.1 were analyzed for the following sectors.

Sector	Date
Sector ZDC03	01/15/2005
Sector ZDC 04	01/15/2005
Sector ZDCDI	01/15/2005
Sector ZNY 39	3/11/2005
Sector ZMA 20	1/3/2005
Sector ZDC04	03/29/2005

Statistical Analysis:

Multivariate regression analyses were performed for models 1.1 and 1.2 considering the data for the above sectors. None of the models showed statistically significant results even at the 10% significance level. Statistical tests did not find heteroscedasticity or multicollinearity in the models developed for the above sectors.

Scatter plots

Scatter plots were developed considering the same dependent and independent variables which were considered for centers. Scatter plots were developed by considering only overflights and departure flights. Scatter plots showed no relation between the following dependent and independent variables.

Dependent variables:

i. Ratio of actual distance and GCR distance of flight

ii. Ratio of actual duration and GCR distance of flight

Independent variables:

1. Avg flight secs
2. Avg flight count

Results for sector ZDCDI (01/15/2005)

Results of models 1.1 to 1.4 and 2.1 to 2.4:

Figures 5.9 and 5.10 show relations between excess distance traveled by a flight in sector and the following flight-specific workload metrics for the same sector:

1. Avg flight secs
2. Avg flight count

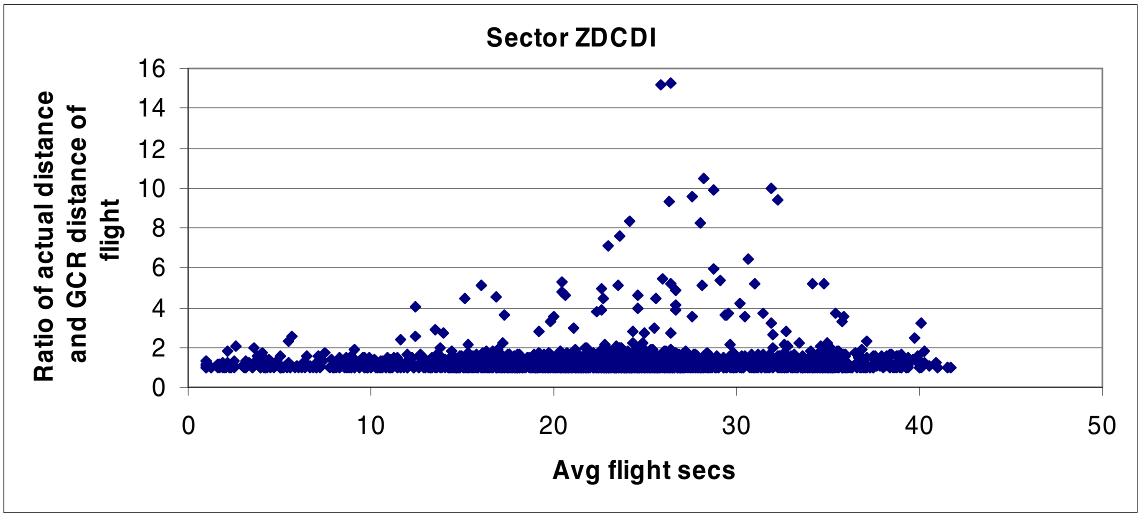

Figure 5.9 Ratio of actual distance and GCR distance of flight vs. avg flight secs for sector ZDCDI

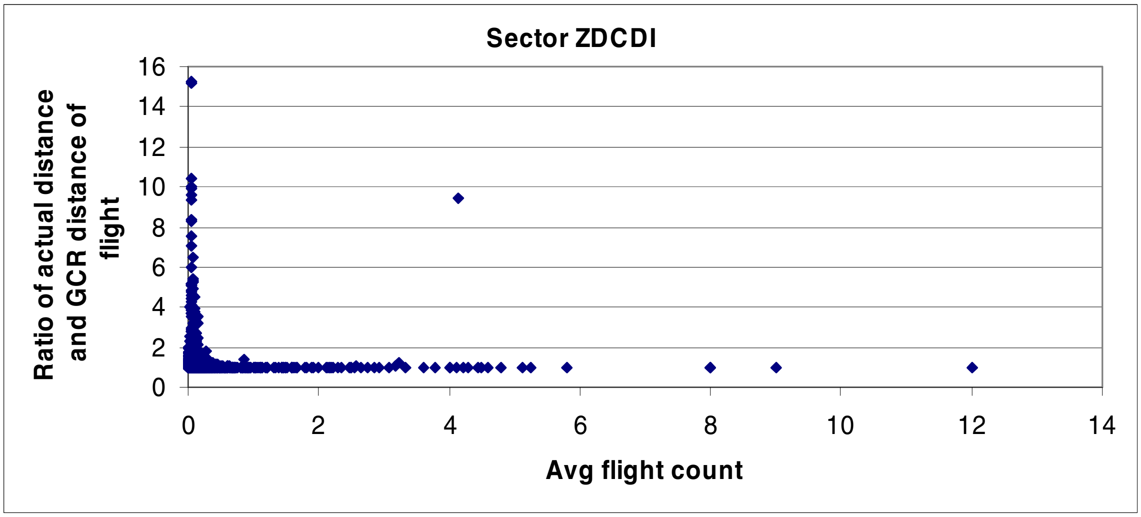

Figure 5.10 Ratio of actual distance and GCR distance of flight vs. avg flight count for sector ZDCDI

Figures 5.11 and 5.12 show relations between the same variables shown in figures 5.9 and 5.10. In this case the relations are shown for selected operations which are selected in the following way.

Operations with the same aircraft type, physical class, user class and type of operation (arrival, departure, overflight or both) are considered. For sector ZDCDI, operations belonging to following categories are shown in figures 5.11 and 5.12.

Aircraft	CRJ2
Physical class	Jet
User class	Commercial
Operation	Arrival operation

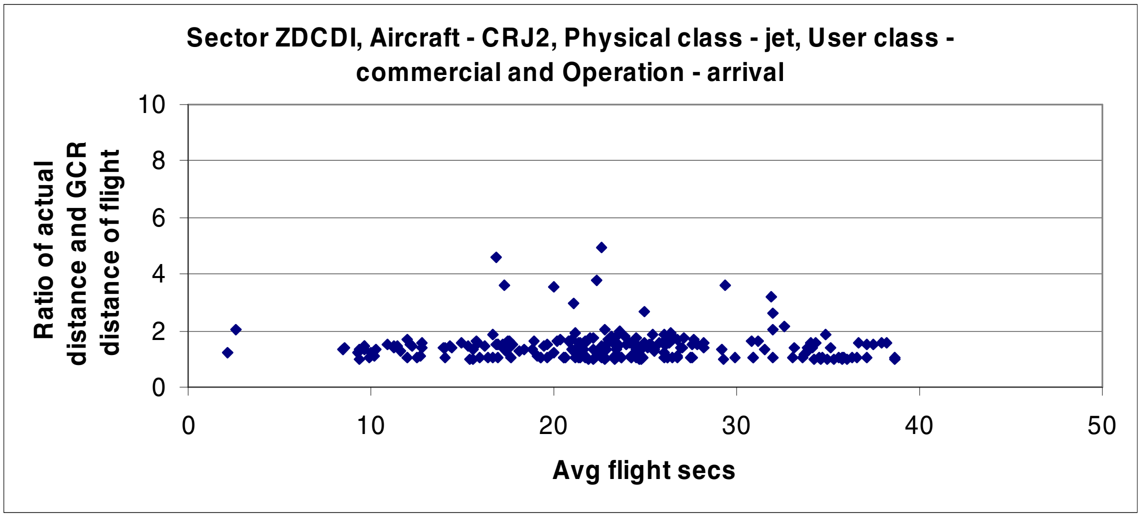

Figure 5.11 Ratio of actual distance and GCR distance of flight vs. avg flight secs (for selected operations of sector ZDCDI)

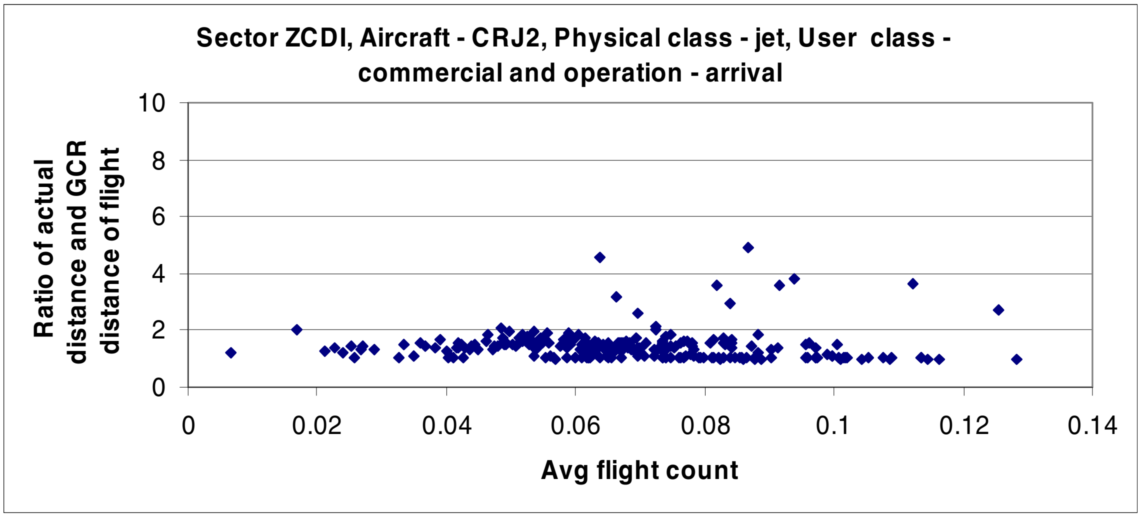

Figure 5.12 Ratio of actual distance and GCR distance of flight vs. avg flight count (for selected operations of sector ZDCDI)

Results of models 3.1 to 3.6 and 4.1 to 4.6:

Figures 5.13 and 5.14 show relations between delay borne by a flight in sector and the following flight-specific workload metrics for the same sector:

1. Flight-specific workload (in seconds)

2. Flight-specific workload (in operations)

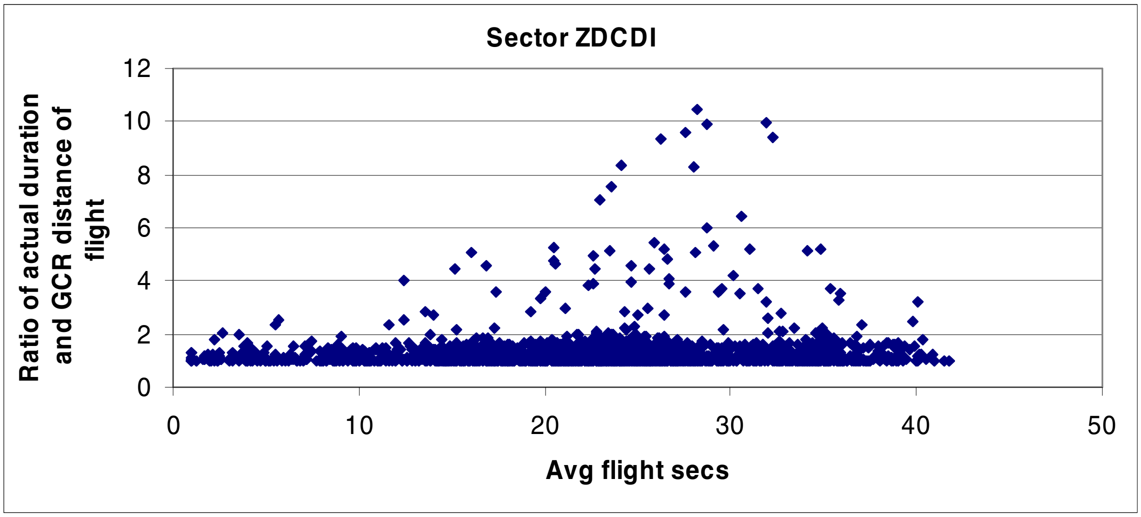

Figure 5.13 Ratio of actual duration and GCR distance of flight vs. avg flight secs for sector ZDCDI

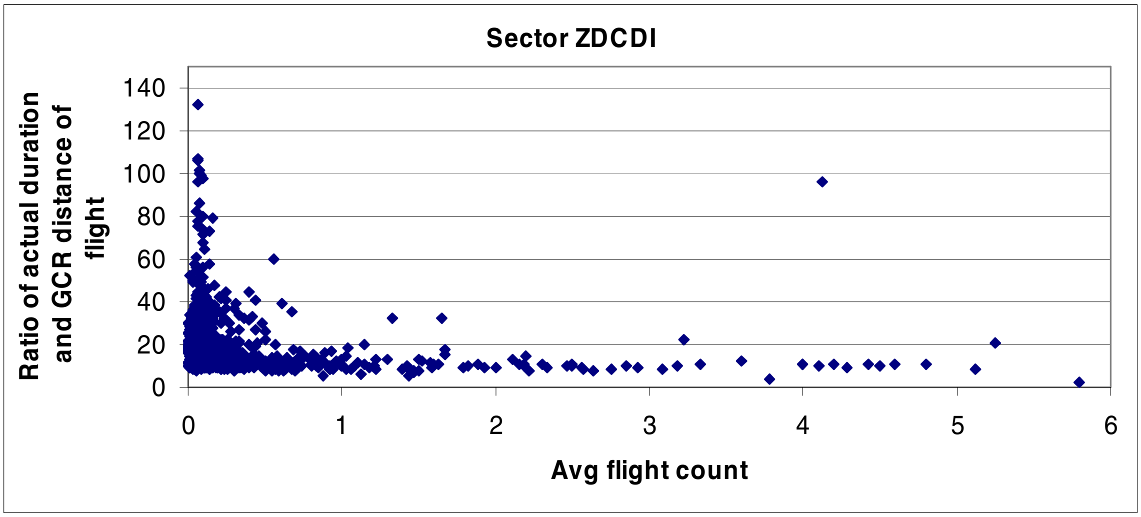

Figure 5.14 Ratio of actual duration and GCR distance of flight vs. avg flight count for sector ZDCDI

Figures 5.15 and 5.16 show relations between the same variables shown in figures 5.13 and 5.14. In this case the relations are shown for selected operations which are selected in the following way.

Operations with the same aircraft type, physical class, user class and type of operation (arrival, departure, overflight or both) are considered. For sector ZDCDI, operations belonging to following categories are shown in figures 5.15 and 5.16.

Aircraft	CRJ2
Physical class	Jet
User class	Commercial
Operation	Arrival operation

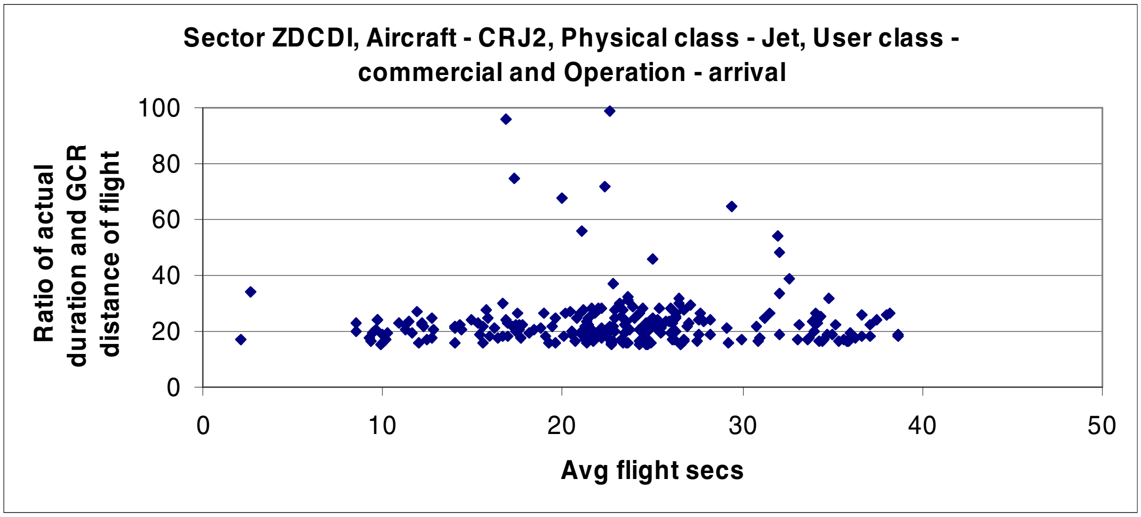

Figure 5.15 Ratio of actual duration and GCR distance of flight vs. avg flight secs (for selected operations of sector US Dom ZDCDI)

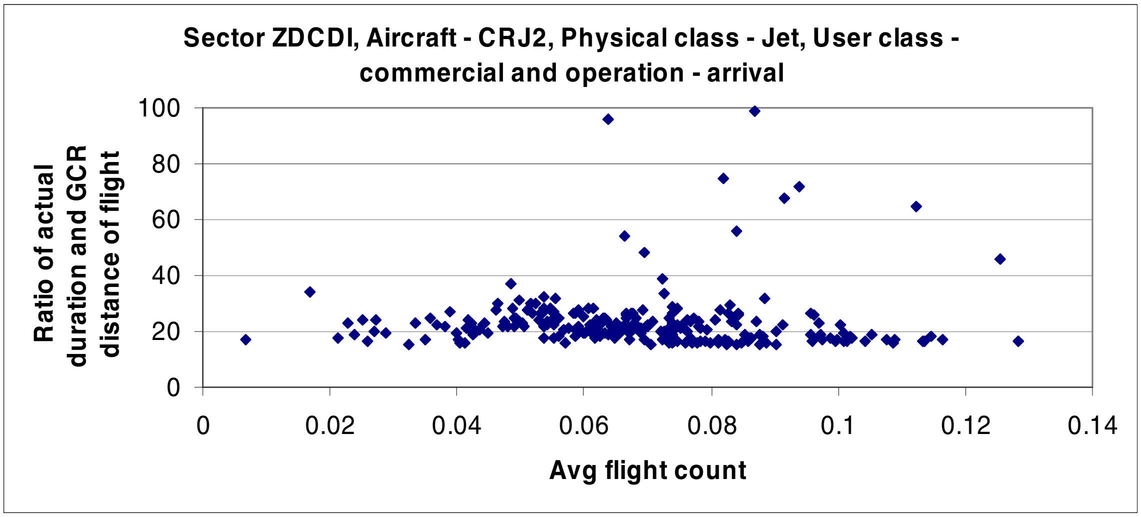

Figure 5.16 Ratio of actual duration and GCR distance of flight vs. avg flight count (for selected operations of sector US Dom ZDCDI)

c. t tests to estimate difference in values of controller performance metrics under different levels of traffic activity in the airspace.

For the models estimated in section 5.7.1, scatter plots between dependent variable and independent variables were flat and showed no relation. Two tailed t tests were conducted for some of the models to determine if the value of dependent variables "ratio of actual distance and GCR distance of flight" and "ratio of actual duration and GCR distance of flight" was equal under different levels of traffic activity.

For the considered model, the data were divided into two sets by considering the median of data for variable "avg flight secs" or "avg flight count" as the break point between two data sets. Two tailed unequal, unpaired t tests were conducted to determine if the average value of dependent variable was equal in both the data sets.

Two tailed t tests showed that there was no statistical difference in the values of excess distances traveled and delays borne by flights under different levels of traffic activity. Most of the models which were analyzed for t tests gave same results for t tests. Results in the models were statistically significant at 5 % significance level.

5.7.2. Effect of congestion in successive airspace on the path of the flight

In the center and sector analysis of model 5.4.1 in section 5.7.1, flights were not delayed in any airspace (center/sector) due to congestion in that airspace.

Models 5.1, 5.2; 6.1, 6.2; 7.1to 7.6 and 8.1 to 8.6 were analyzed, to estimate relation between excess distances traveled and delays borne by flights in an airspace and air traffic activity in the successive airspace on the path of the flight. Data for the following centers and sectors were used in the analyses.

Flights which traveled consecutively through the US Dom ZDC and US Dom ZBW centers were considered in the data set for center analysis.

Center	*Successive center*	*Date*
US Dom ZDC	US Dom ZBW	04/15/2003

Similarly flights which traveled consecutively through the ZDC004 and ZDC 003 sectors were considered in the data set for sector analysis.

Sector	*Successive sector*	*Date*
ZDC04	ZDC03	01/15/2005

Statistical Analysis:

The data for the above centers and sectors were used to perform multivariate regression analyses for models in section 5.4.2. None of the models showed statistically significant results even at 10% level of significance. Statistical tests did not show the presence of heteroscedasticity or multicollinearity in the models.

Scatter plots

Scatter plots were developed between the following dependent and independent variables.

Dependent variables:

i. Ratio of actual distance and GCR distance of flight in airspace

ii. Ratio of actual duration and GCR distance of flight in airspace

Independent variables:

1. Avg flight secs in successive airspace (center/sector)
2. Avg flight count in successive airspace (center/sector)

a. Results for centers

Results of models 5.1, 5.2, 6.1 and 6.2

Figures 5.17 and 5.18 show relations between excess distance traveled by a flight in center US Dom ZDC and the following flight-specific workload metrics for center US Dom ZBW

1. Avg flight secs
2. Avg flight count

In this case relations are shown for selected operations which are selected in the following way.

Operations with the same aircraft type, physical class, user class and type of operation (arrival, departure, overflight or both) are considered. Operations belonging to following categories are shown in figures 5.17 and 5.18

Aircraft	E145
Physical class	Jet
User class	Air taxi
Operation	Overflight

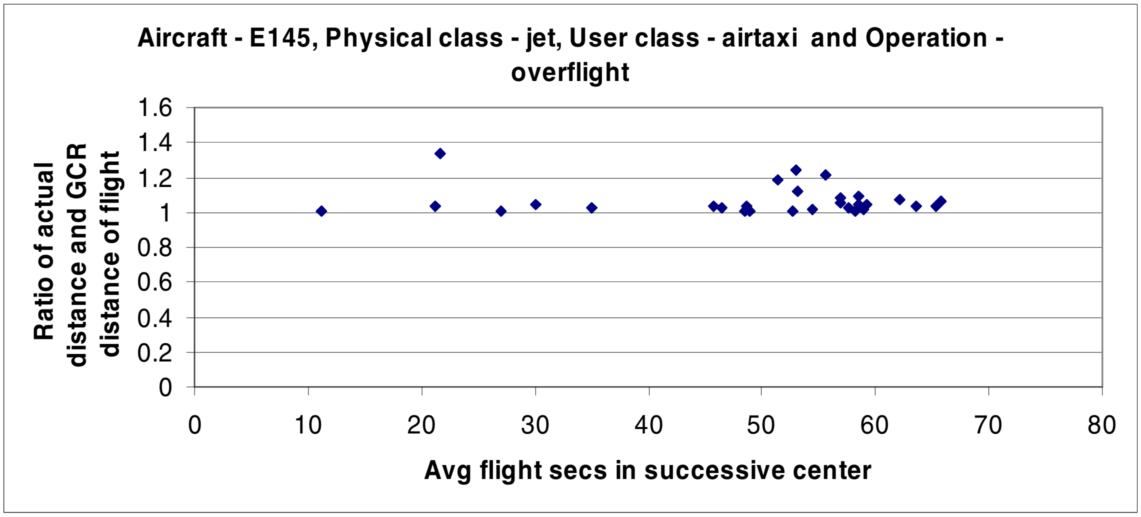

Figure 5.17 Ratio of actual distance and GCR distance of flight in center US Dom ZDC vs. avg flight secs for center US Dom ZBW (for selected operations)

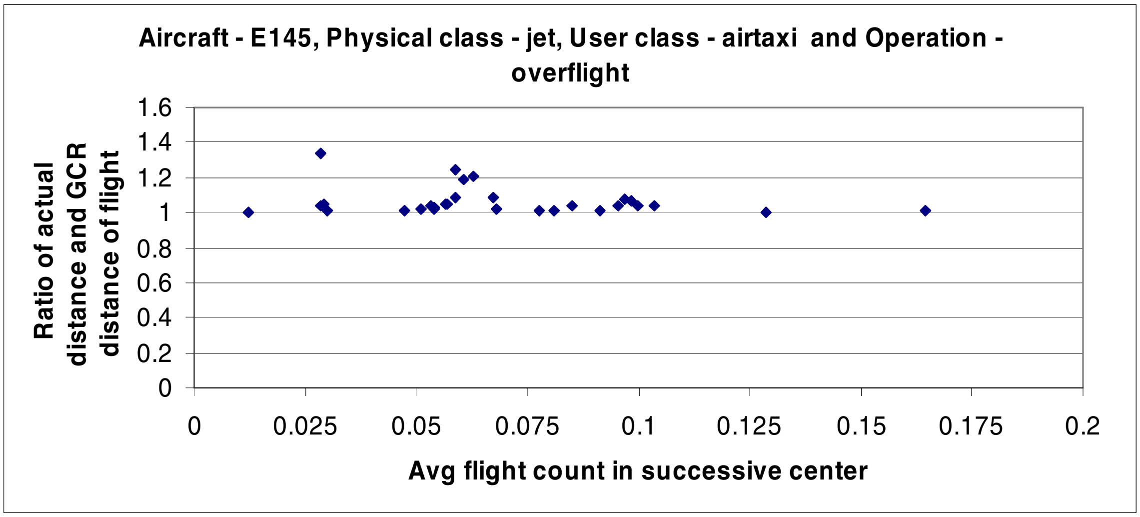

Figure 5.18 Ratio of actual distance and GCR distance of flight in center US Dom ZDC vs. avg flight count for center US Dom ZBW (for selected operations)

Results of models 7.1 to 7.6 and 8.1 to 8.6

Figures 5.19 and 5.20 show relations between delay borne by a flight in center US Dom ZDC and the following flight-specific workload metrics for center US Dom ZBW.

1. Avg flight secs

2. Avg flight count

In this case relations are shown for selected operations which are selected in the following way.

Operations with the same aircraft type, physical class, user class and type of operation (arrival, departure, overflight or both) are considered. Operations belonging to following categories are shown in figures 5.19 and 5.20.

Aircraft	E145
Physical class	Jet
User class	Air taxi
Operation	Overflight

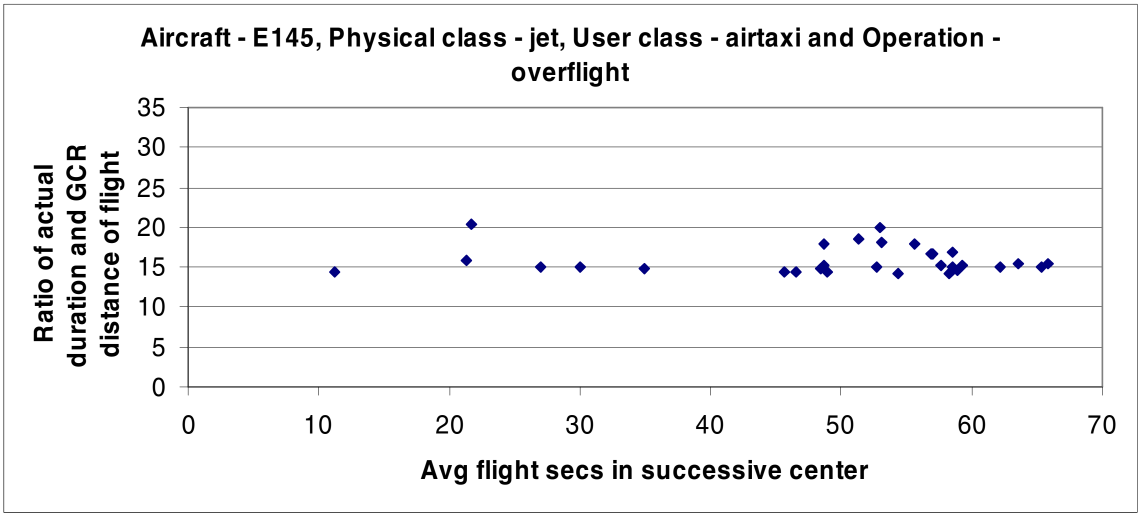

Figure 5.19 Ratio of actual duration and GCR distance of flight in center US Dom ZDC vs. avg flight secs for center US Dom ZBW (for selected operations)

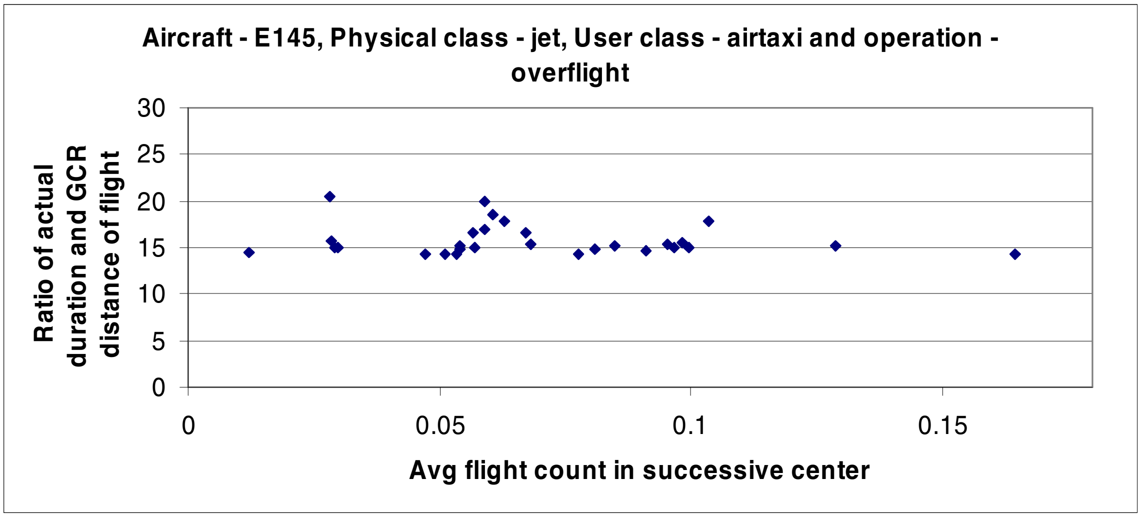

Figure 5.20 Ratio of actual duration and GCR distance of flight in center US Dom ZDC vs. avg flight count for center US Dom ZBW (for selected operations)

b. Results for sectors

Results of models 5.1, 5.2, 6.1 and 6.2

Figures 5.21 and 5.22 show relations between excess distance traveled by a flight in sector ZDC04 and the following flight-specific workload metrics for sector ZDC03

1. Avg flight secs
2. Avg flight count

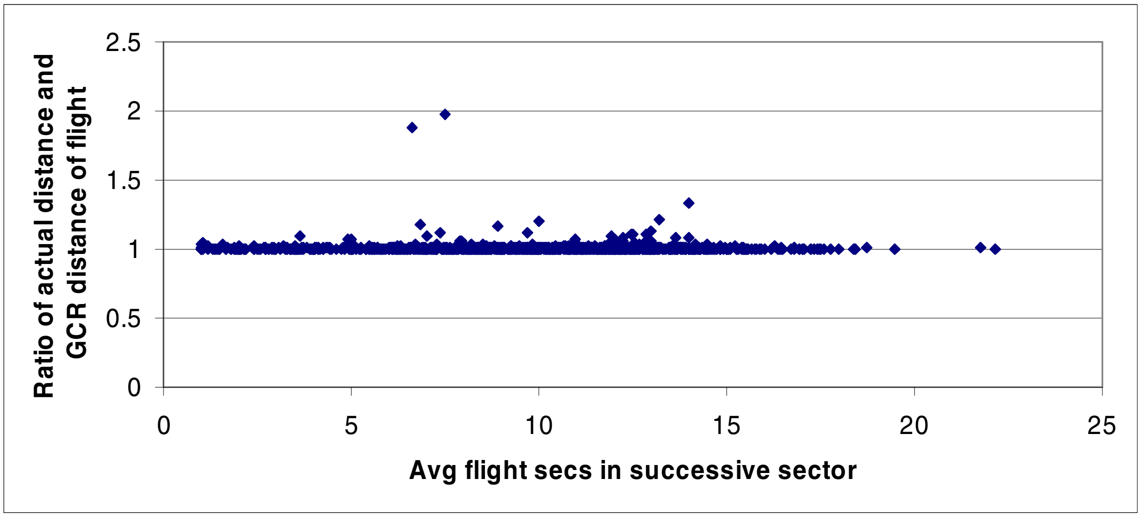

Figure 5.21 Ratio of actual distance and GCR distance of flight in sector ZDC04 vs. avg flight secs for sector ZDC03

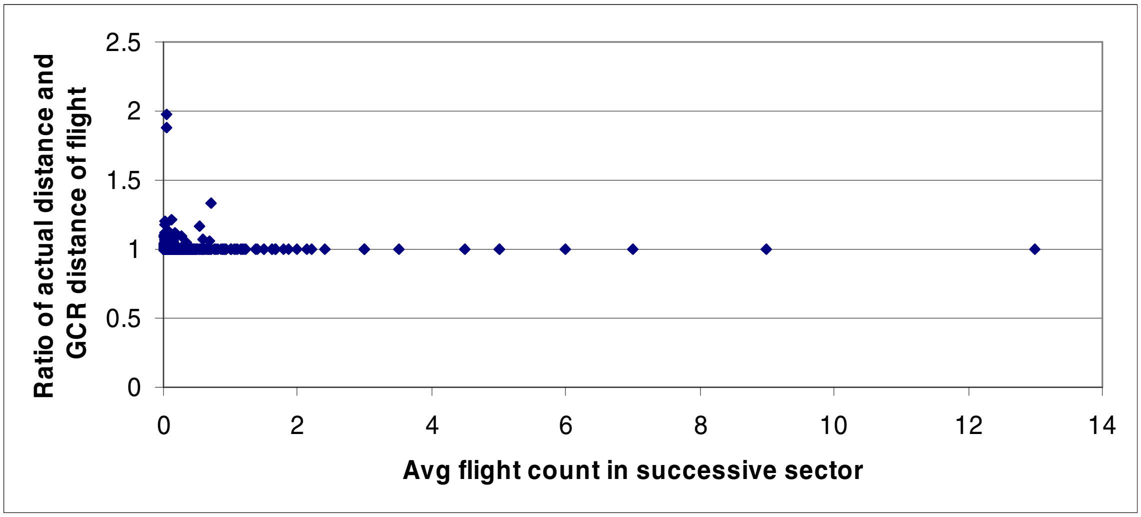

Figure 5.22 Ratio of actual distance and GCR distance of flight in sector ZDC04 vs. avg flight count for sector ZDC03

Figures 5.23 and 5.24 show relations between the same variables shown in figures 5.39 and 5.40. In this case the relations are shown for selected operations which are selected in the following way.

Operations with the same aircraft type, physical class, user class and type of operation (arrival, departure, overflight or both) are considered .Operations belonging to following categories are shown in figures 5.23 and 5.24

Aircraft	B737
Physical class	Jet
User class	Commercial
Operation	Overflight

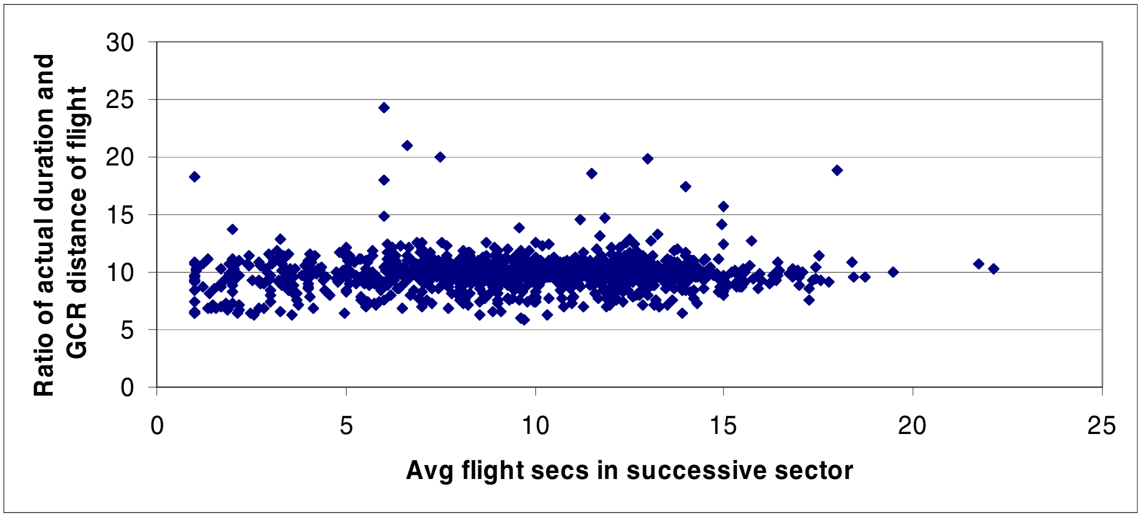

Figure 5.23 Ratio of actual duration and GCR distance of flight in sector ZDC04 vs. avg flight secs for sector ZDC03

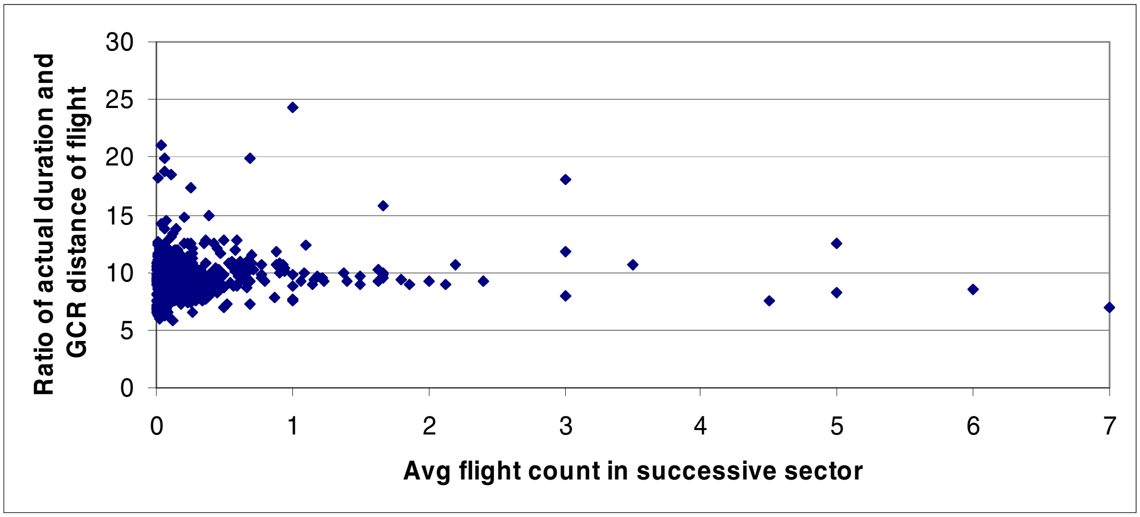

Figure 5.24 Ratio of actual duration and GCR distance of flight in sector ZDC04 vs. avg flight count for sector ZDC03

Results of models 7.1 to 7.6 and 8.1 to 8.6

Figures 5.25 and 5.26 show relations between delay borne by a flight in sector ZDC04 and the following flight-specific workload metrics for sector ZDC03

1. Avg flight secs, and 2. Avg flight count

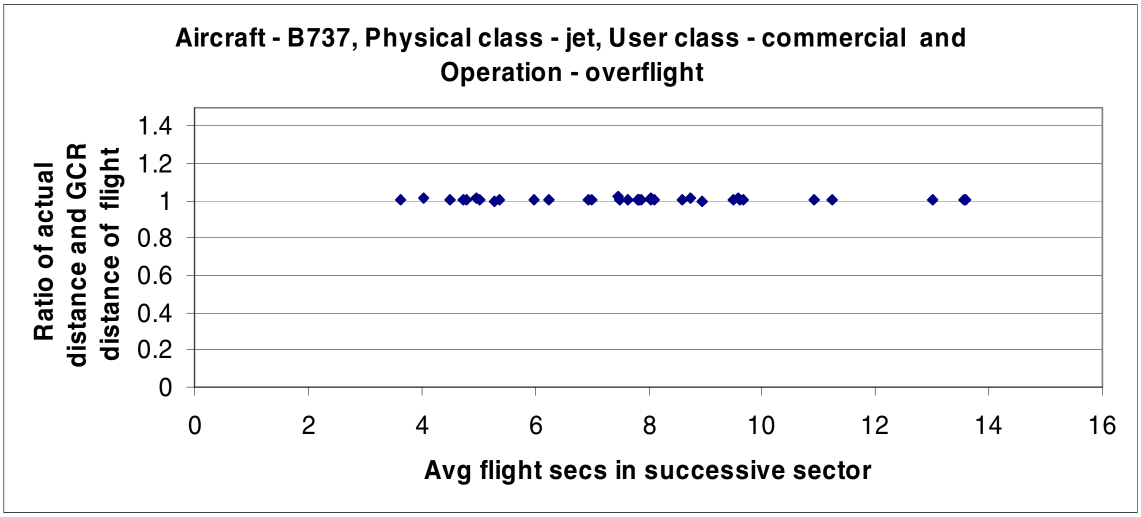

Figure 5.25 Ratio of actual distance and GCR distance of flight in sector ZDC04 vs. avg flight secs for sector ZDC03 (for selected operations)

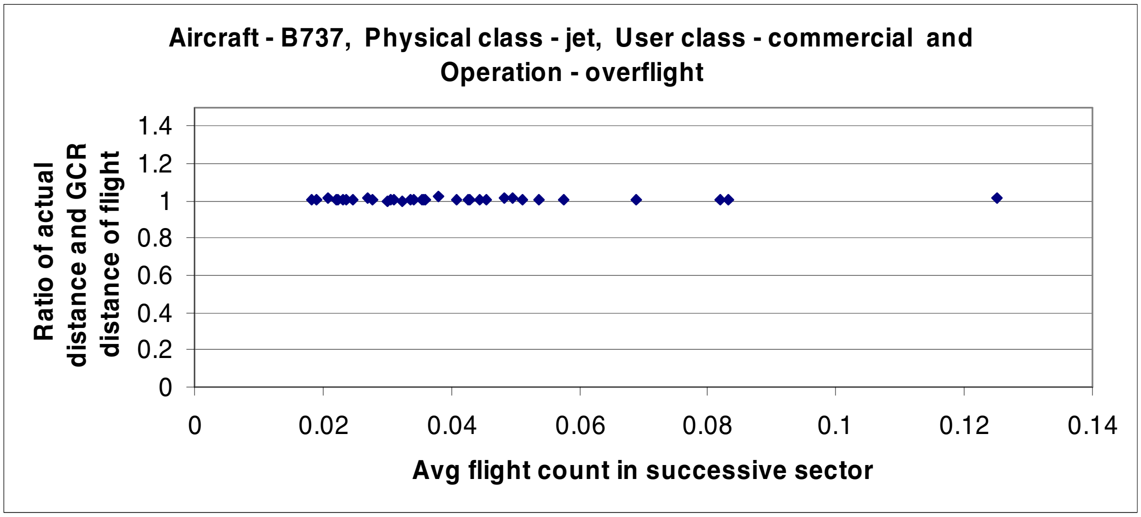

Figure 5.26 Ratio of actual distance and GCR distance of flight in sector ZDC04 vs. avg flight count for sector ZDC03 (for selected operations)

Figures 5.27 and 5.28 show relations between the same variables shown in figures 5.25 and 5.26. In this case the relations are shown for selected operations which are selected in the following way.

Operations with the same aircraft type, physical class, user class and type of operation (arrival, departure, overflight or both) are considered .Operations belonging to following categories are shown in figures 5.27 and 5.28.

Aircraft	B737
Physical class	Jet
User class	Commercial
Operation	Overflight

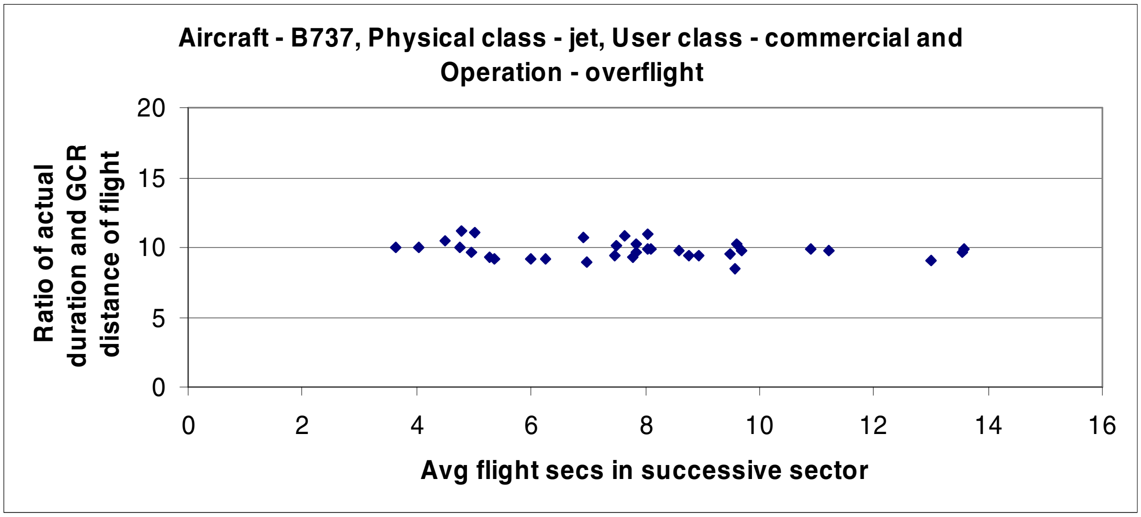

Figure 5.27 Ratio of actual duration and GCR distance of flight in sector ZDC04 vs. avg flight secs for sector ZDC03 (for selected operations)

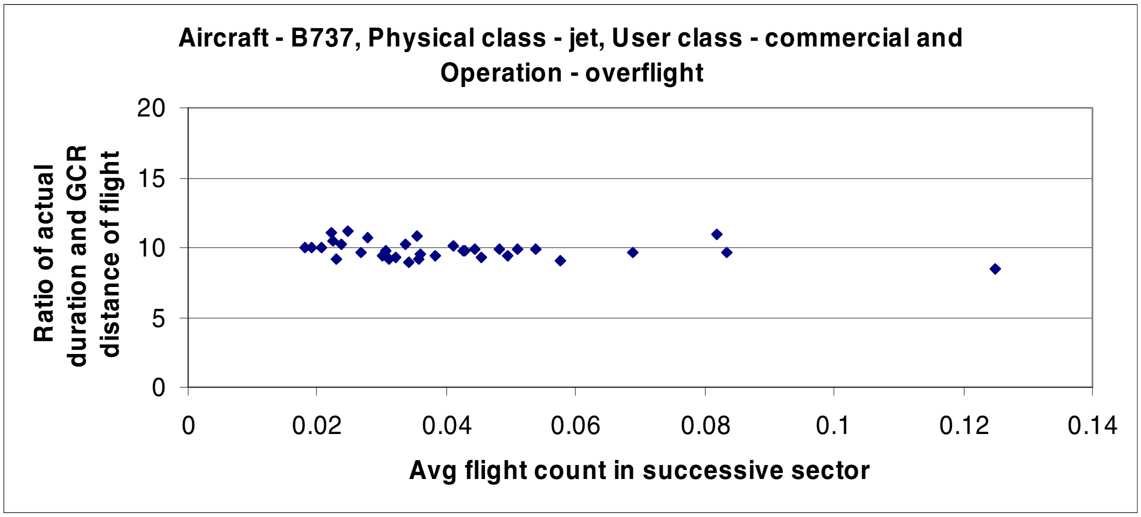

Figure 5.28 Ratio of actual duration and GCR distance of flight in sector ZDC04 vs. avg flight count for sector ZDC03 (for selected operations)

5.7.3. Analysis of flights traveling between a city pair:

Analysis in section 5.7.2 showed that there was no relation between excess distances traveled and delays borne by flights in an airspace and air traffic activity in the successive airspace on the path of the flight.

It is possible that excess distance delays and delays borne by flights in a center could be caused by congestion in any of the successive centers on the path of the flight. Using models 5.1, 5.2, 6.1, 6.2, 7.1 to 7.6 and 8.1 to 8.6, relations are estimated between delays borne by flights and excess distances traveled by flights in any of the centers on the path of the flight and congestion in successive centers on the route of the flight.

Analyses were conducted for all flights traveling from Dallas/Fort Worth International Airport (DFW) to Chicago O'Hare International Airport (ORD) on 04/15/2003.

Statistical analysis of model 3.1 can be performed only for those flights, which fly through the same centers along their flight path, and all flights fly the centers or sectors in the same sequence.

The data considered for flights traveling from DFW to ORD airport showed that 65 flights flew from DFW to ORD on 04/15/2003. However only 20 flights flew through three common centers in the same sequence. The 20 flights chosen for the analysis flew centers US Dom-ZFW, US Dom-ZKC and US Dom-ZAU in the same sequence.

Statistical Analysis:

Multivariate regression analyses were performed for models 3.1 and 3.2 considering data for 20 flights. None of the models showed statistically significant results even at 10% level of significance. Statistical tests did not show the presence of heteroscedasticity or multicollinearity in the models.

In table 5.5, numbers are assigned to three centers, based on sequence in which 20 flights traversed three centers while traveling from DFW to ORD on 04/15/2003.

Table 5.5

Center Number	Center Name
Center 1	US Dom ZFW
Center 2	US Dom ZKC
Center 3	US Dom ZAU

Scatter plots

Scatter plots were developed considering dependent variables and the flight-specific workload metrics in the models. Scatter plots showed no relation between dependent variables and independent variables.

Results of model 9.1:

Figures 5.29 and 5.30 show relations between excess distance traveled by a flight in center 1 and flight-specific workload (in seconds) in centers 2 and 3 respectively.

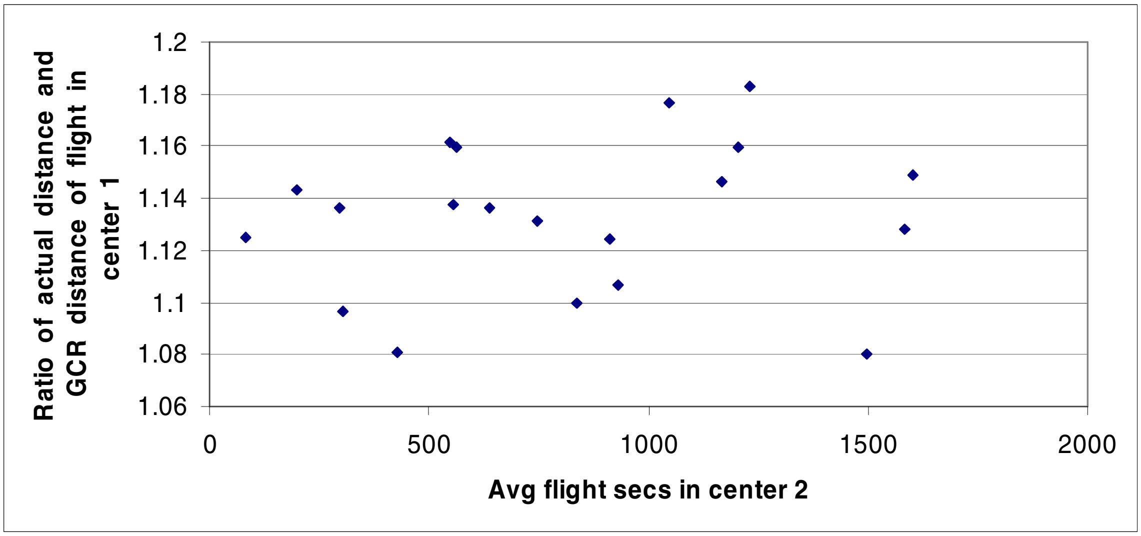

Figure 5.29 Ratio of actual distance and GCR distance of flight in center 1 vs. flight-specific workload (in seconds) in center 2

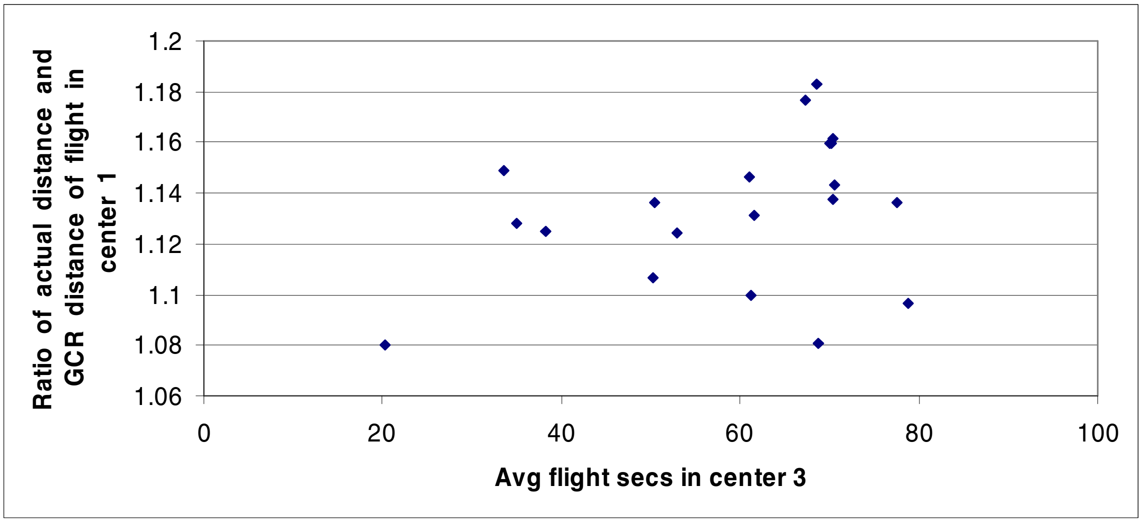

Figure 5.30 Ratio of actual distance and GCR distance of flight in center 1 vs. flight-specific workload (in seconds) in center 3

Results of model 10.1:

Figures 5.31 and 5.32 show relations between excess distance traveled by a flight in center 1 and flight-specific workload (in operations) in centers 2 and 3 respectively.

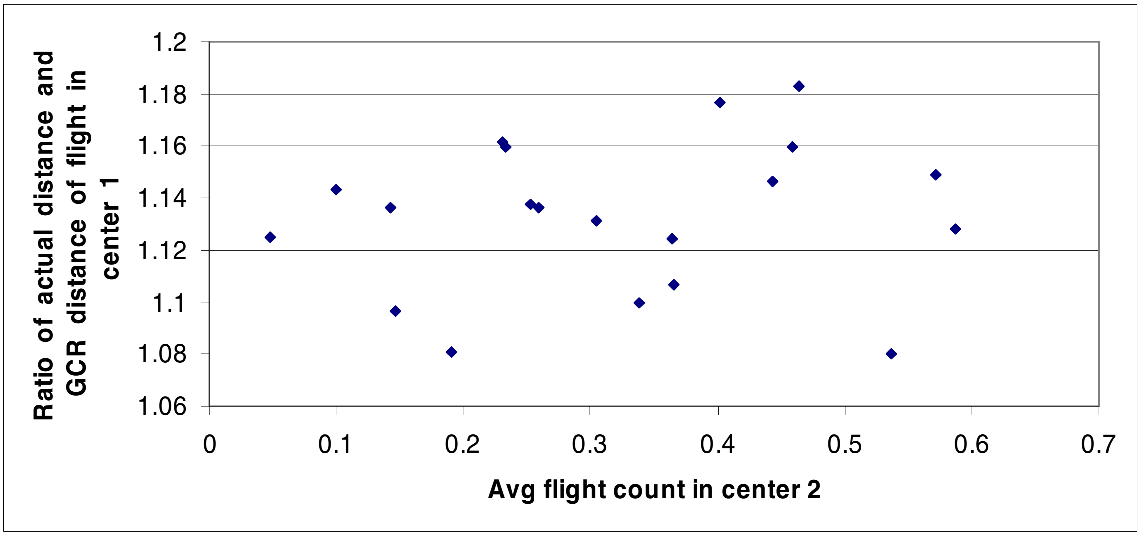

Figure 5.31 Ratio of actual distance and GCR distance of flight in center 1 vs. flight-specific workload (in operations) in center 2

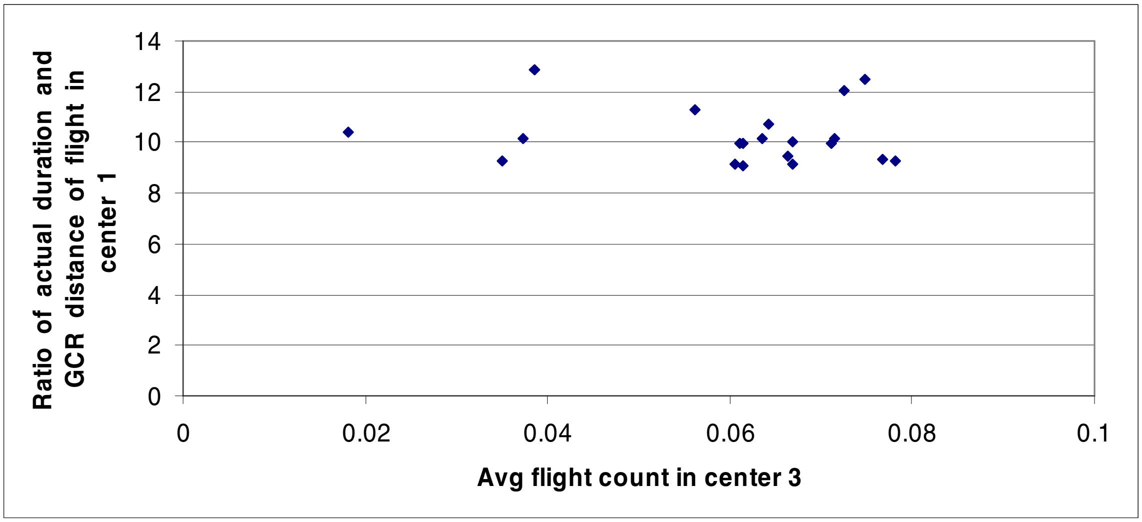

Figure 5.32 Ratio of actual distance and GCR distance of flight in center 1 vs. flight-specific workload (in operations) in center 3

Results of model 9.2:

Figure 5.33 shows relations between excess distance traveled by a flight in center 2 and flight-specific workload (in seconds) in center 3.

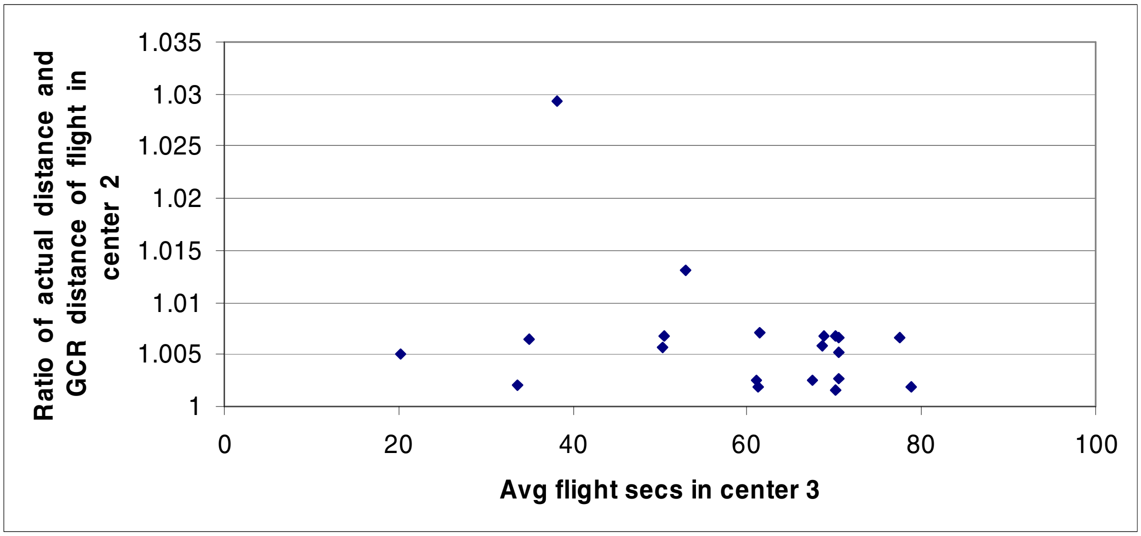

Figure 5.33 Ratio of actual distance and GCR distance of flight in center 2 vs. flight-specific workload (in seconds) in center 3

Results of model 10.2:

Figure 5.34 show relations between excess distance traveled by a flight in center 2 and flight-specific workload (in operations) in center 3.

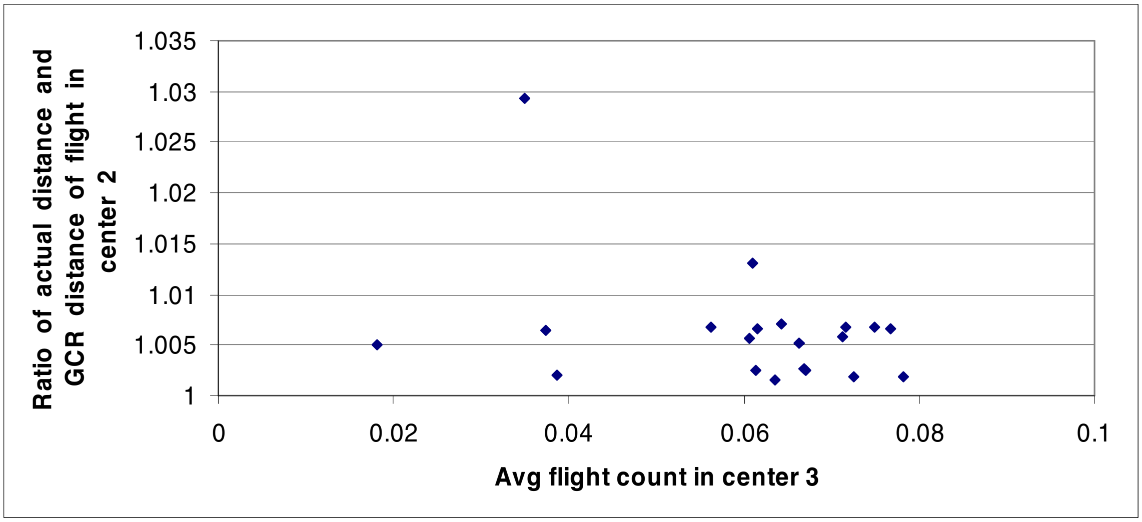

Figure 5.34 Ratio of actual distance and GCR distance of flight in center 2 vs. flight-specific workload (in operations) in center 3

Results of models 11.1 to 11.3:

Figures 5.35 and 5.36 show relations between delay borne by a flight in center 1 and flight-specific workload (in seconds) in centers 2 and 3 respectively.

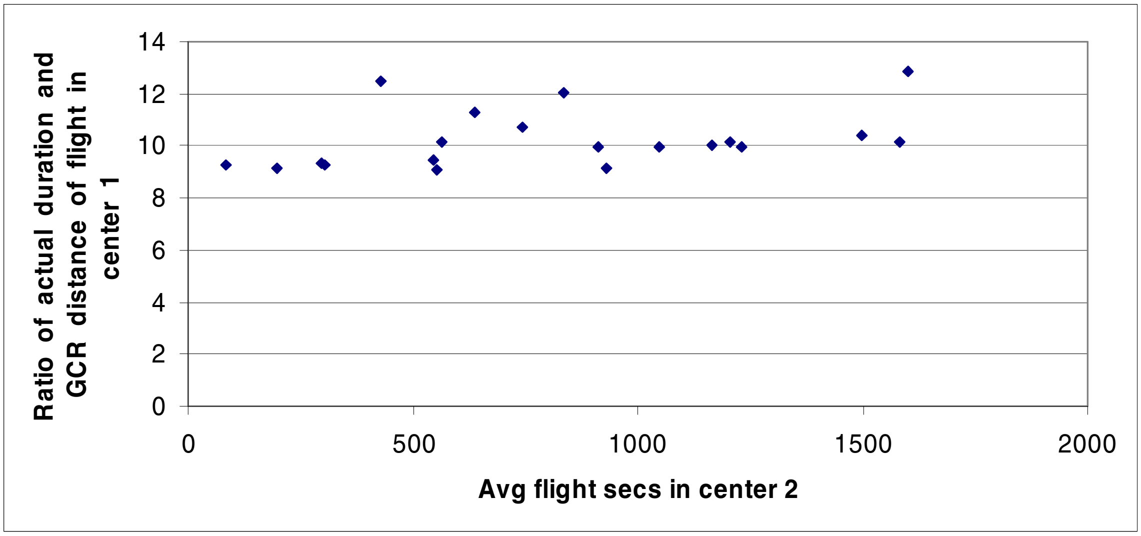

Figure 5.35 Ratio of actual duration and GCR distance of flight in center 1 vs. flight-specific workload (in seconds) in center 2

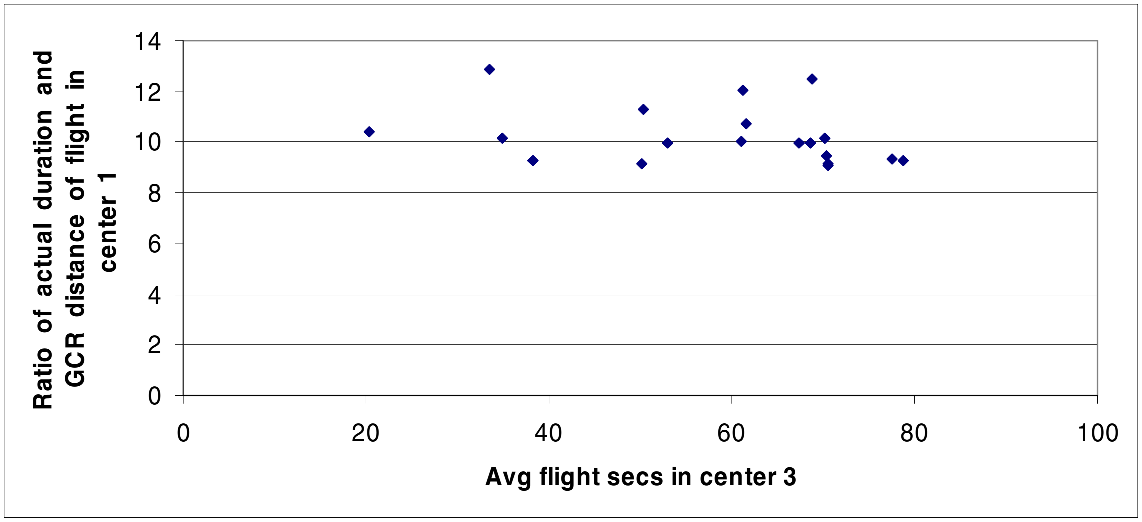

Figure 5.36 Ratio of actual duration and GCR distance of flight in center 1 vs. flight-specific workload (in seconds) in center 3

Results of models 12.1 to 12.3:

Figures 5.37 and 5.38 show relations between delay borne by a flight in center 1 and flight-specific workload (in operations) in centers 2 and 3 respectively.

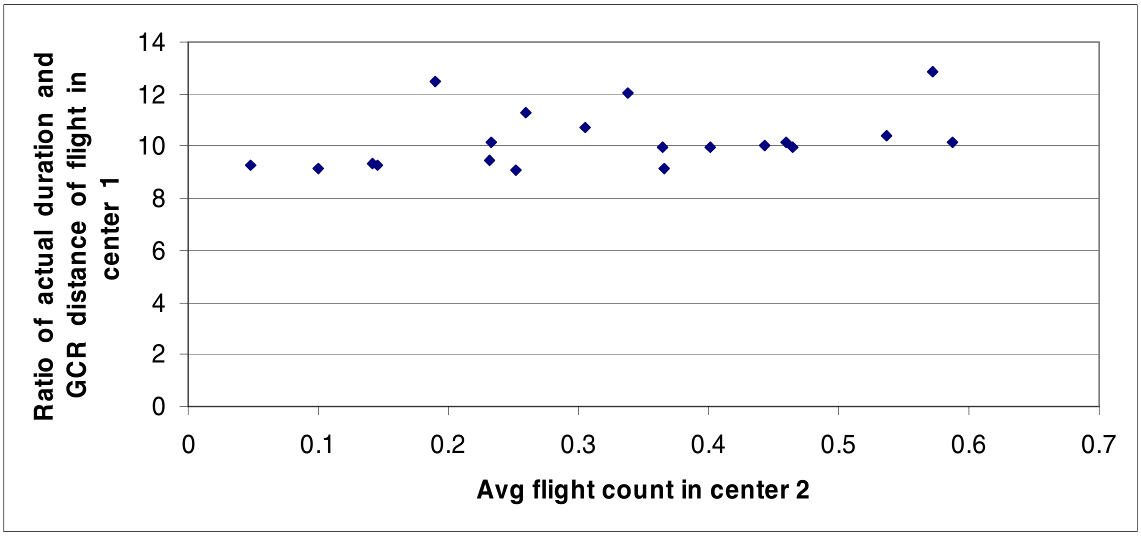

Figure 5.37 Ratio of actual duration and GCR distance of flight in center 1 vs. flight-specific workload (in operations) in center 2

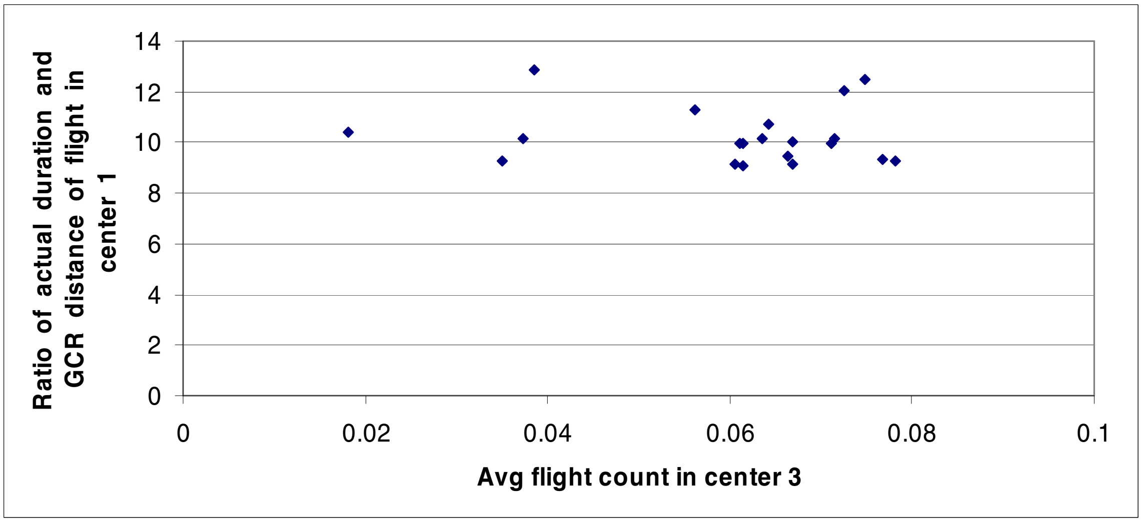

Figure 5.38 Ratio of actual duration and GCR distance of flight in center 1 vs. flight-specific workload (in operations) in center 3

Results of models 11.4 to 11.6:

Figure 5.39 shows relations between delay borne by flight in center 2 and flight-specific workload (in seconds) in center 3.

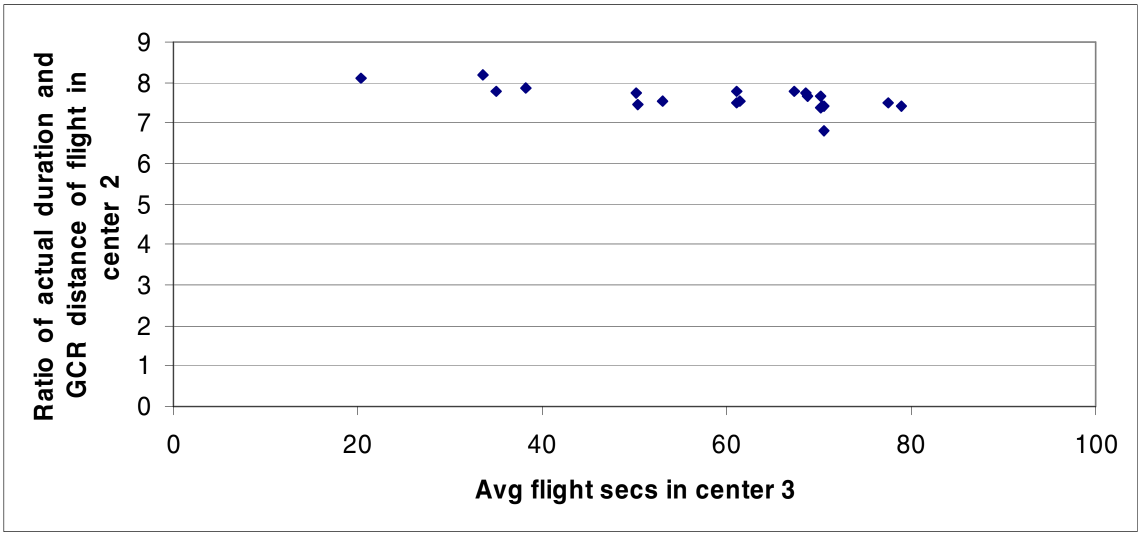

Figure 5.39 Ratio of actual duration and GCR distance of flight in center 2 vs. flight-specific workload (in seconds) in center 3

Results of models 12.4 to 12.6:

Figure 5.40 shows relations between delay borne by a flight in center 2 and flight-specific workload (in operations) in center 3.

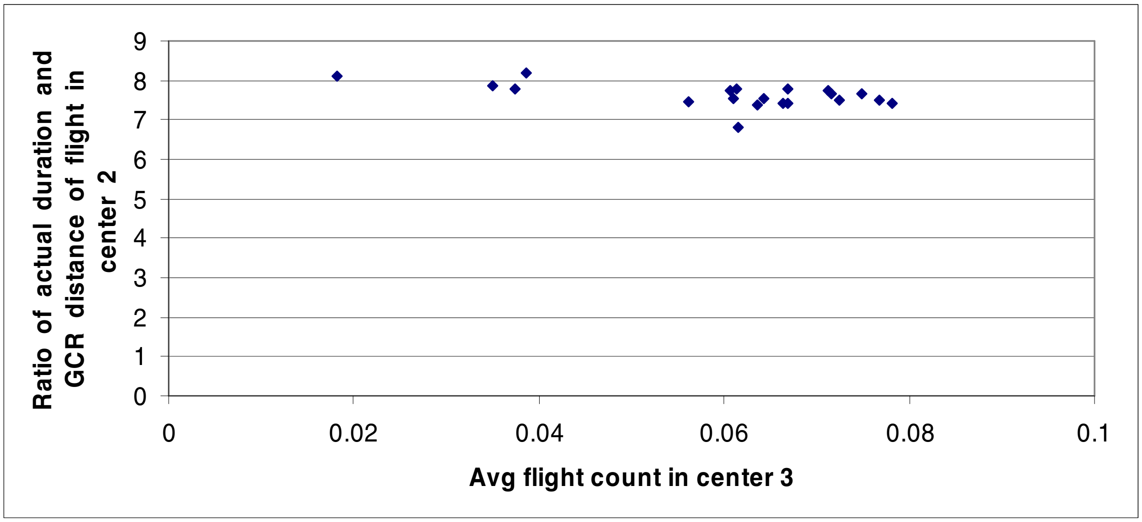

Figure 5.40 Ratio of actual duration and GCR distance of flight in center 2 vs. flight-specific workload (in operations) in center 3

These analyses cannot be performed for sectors, since detailed ETMS data are not recorded for sectors.

Result of models estimated in section 5.7

Common result for models 5.4.1 and 5.4.2:

The following common result was seen for models 5.4.1 and 5.4.2

In regression models with dependent variable "ratio of actual duration and GCR distance of flight", dummy variables representing type of operations (arrival/departure/overflight and both) were statistically significant in some models. This could be because of the different speeds at which arrival, departure and overflight operations travel in the airspace.

Statistical relation was not seen between entry and exit speed of aircraft in the centers and the following variables:

i. Dummy variables representing type of operation (arrival/departure/overflight and both operation).

ii. Dummy variable representing aircraft types.

It is possible that different types of operations have restrictions imposed on them because of terminal and airport congestion at arrival airports or congestion in the upstream enroute centers on the route of the flights.

5.7.4. Comparing the performance of R controller staffing configuration with R & D controller staffing configuration in a sector.

In this analysis four sectors and days were chosen based on considerations discussed in sections 3.2.4 and 3.2.5. The boundary crossing data for four sectors used in section 5.7 were used in this analysis. SISO data for the same sectors and periods were used.

Analyses were performed for the four sectors and periods listed in table 5.6 below:

Table 5.6

Sectors of center US Dom ZDC	*Date*
Sector ZDC04	03/29/2005
Sector ZJX 68	2/7/2005
Sector ZNY 39	3/11/2005
Sector ZMA 20	1/3/2005

For the four sectors, twenty-four-hour SISO data were matched to the corresponding twenty-four-hour boundary crossing data.

An examination of the SISO data for four centers showed that the R controller staffing configuration and R and D controller staffing configuration were the two staffing configurations staffed in sectors of those centers.

Flights were classified into the two bins depending on whether the flight was controlled by an R controller staffing configuration, or an "R and D" controller staffing configuration. Flights were sorted into bins based on the "m_time" of the flight. The calculation of "m_time" has been explained in section 5.4.4.

The average values of the controller performance metrics are computed for each bin. Average values in the two bins were compared using unpaired unequal t tests. The two measures of controller performance listed below were used to study the performance of each controller staffing configuration.

The two controller performance metrics along with their abbreviations used to perform statistical analyses are listed in table 5.7.

Table 5.7

Controller performance metric	Abbreviation	
	R controller staffing configuration	R and D controller staffing configuration
Ratio of actual distance and GCR distance for each flight controlled by a staffing configuration.	rdist	rddist
Ratio of actual duration and GCR distance for each flight controlled by a staffing configuration.	rdelay	rddelay

Results:

The performance of the two staffing configurations in a sector was compared in terms of managing the air traffic activity assigned to each staffing configuration.

In section 3.2.4 it has been discussed that excess distances traveled by flights in a sector and delays borne by flights in a sector could be due to a variety of reasons other than controller workload caused by air traffic. The care to be taken while choosing the sectors and periods for the sector data has been discussed in section 3.2.5. Based on those considerations, sector data were chosen for four sectors used in this analysis

It is assumed that flights in the four chosen sectors traveled excess distances and incurred delays only because of workload on controllers staffed in those sectors. Based on this assumption results have been discussed.

The results of two tailed t tests for the two sectors are shown in tables 5.8 and 5.9.

Results for sector ZDC04 are shown in table 5.8

```
. ttest  rddist= rdist, unpaired unequal

Two-sample t test with unequal variances

------------------------------------------------------------------------------
Variable |     Obs        Mean    Std. Err.   Std. Dev.   [95% Conf. Interval]
---------+--------------------------------------------------------------------
rddist   |     351    1.011593    .0029405      .05509    1.005809    1.017376
 rdist   |     844    1.038807    .0314269    .9130055    .9771224    1.100491
---------+--------------------------------------------------------------------
combined |    1195    1.030813    .0222119    .7678381    .9872345    1.074392
---------+--------------------------------------------------------------------
    diff |           -.027214    .0315642               -.0891661    .0347382
------------------------------------------------------------------------------
Satterthwaite's degrees of freedom:  857.666

                Ho: mean(rddist) - mean(rdist) = diff = 0

     Ha: diff < 0               Ha: diff ~= 0              Ha: diff > 0
       t =  -0.8622              t =  -0.8622              t =  -0.8622
   P < t =   0.1944          P > |t| =   0.3888          P > t =   0.8056

. ttest  rddelay= rdelay, unpaired unequal

Two-sample t test with unequal variances

------------------------------------------------------------------------------
Variable |     Obs        Mean    Std. Err.   Std. Dev.   [95% Conf. Interval]
---------+--------------------------------------------------------------------
rddelay  |     351    8.513875    .0682927    1.279463    8.379559     8.64819
rdelay   |     844    8.916538    .2660606    7.729506    8.394319    9.438757
---------+--------------------------------------------------------------------
combined |    1195    8.798266    .1890197    6.534178    8.427419    9.169114
---------+--------------------------------------------------------------------
    diff |          -.4026637    .2746855               -.9417256    .1363983
------------------------------------------------------------------------------
Satterthwaite's degrees of freedom:  947.832

        Ho: mean(rddelay) - mean(rdelay) = diff = 0

     Ha: diff < 0               Ha: diff ~= 0              Ha: diff > 0
       t =  -1.4659              t =  -1.4659              t =  -1.4659
   P < t =   0.0715          P > |t| =   0.1430          P > t =   0.9285
```

Table 5.8 Results of two tailed t tests for sector ZDC04

Results for sector ZJX 68 are shown in table 5.9

```
. ttest  rddelay= rdelay, unpaired unequal

Two-sample t test with unequal variances

------------------------------------------------------------------------------
Variable |     Obs        Mean    Std. Err.   Std. Dev.   [95% Conf. Interval]
---------+--------------------------------------------------------------------
rddelay  |     720     9.23086    .2332915    6.259869    8.772846    9.688874
rdelay   |     335    9.054794    .1138595    2.083971    8.830822    9.278766
---------+--------------------------------------------------------------------
combined |    1055    9.174953    .1632437    5.302279    8.854633    9.495272
---------+--------------------------------------------------------------------
    diff |            .1760657    .2595938               -.3333564    .6854878
------------------------------------------------------------------------------
Satterthwaite's degrees of freedom:  982.341

            Ho: mean(rddelay) - mean(rdelay) = diff = 0

     Ha: diff < 0               Ha: diff ~= 0              Ha: diff > 0
       t =   0.6782               t =   0.6782              t =   0.6782
   P < t =   0.7511          P > |t| =   0.4978          P > t =   0.2489

. ttest  rddist= rdist, unpaired unequal

Two-sample t test with unequal variances

------------------------------------------------------------------------------
Variable |     Obs        Mean    Std. Err.   Std. Dev.   [95% Conf. Interval]
---------+--------------------------------------------------------------------
rddist   |     720     1.00443    .0006322    .0169636    1.003189    1.005671
rdist    |     335    1.005208    .0006607    .0120937    1.003908    1.006508
---------+--------------------------------------------------------------------
combined |    1055    1.004677    .0004797    .0155814    1.003736    1.005618
---------+--------------------------------------------------------------------
    diff |           -.0007781    .0009145               -.0025729    .0010166
------------------------------------------------------------------------------
Satterthwaite's degrees of freedom:  882.042

        Ho: mean(rddist) - mean(rdist) = diff = 0

     Ha: diff < 0               Ha: diff ~= 0              Ha: diff > 0
       t =  -0.8509               t =  -0.8509              t =  -0.8509
   P < t =   0.1975          P > |t| =   0.3950          P > t =   0.8025
```

Table 5.9 Results of two tailed t tests for sector ZJX 68

Results of t tests showed that the average values of controller performance metrics for both the controller staffing configurations (bins) were equal for sector ZDC04 and sector ZJX 68.

The performance of the two different controller staffing configurations was equal in sectors ZDC04 and ZJX 68.

Results for sectors ZNY39 and ZMA20:

Results for sector ZNY39:

Table 5.10 shows result of two tailed t tests for sector ZNY39. For sector ZNY39, the controller performance metric “rddelay” was greater than “rdelay”.

```
. ttest  rdelay=  rddelay, unpaired unequal

Two-sample t test with unequal variances

------------------------------------------------------------------------------
Variable |     Obs        Mean    Std. Err.   Std. Dev.   [95% Conf. Interval]
---------+--------------------------------------------------------------------
rdelay   |     803    9.940184    .0717295    2.032617    9.799384    10.08098
rddelay  |     304    10.22881    .1244418    2.169718    9.983927    10.47369
---------+--------------------------------------------------------------------
combined |    1107    10.01944     .062341    2.074186    9.897124    10.14176
---------+--------------------------------------------------------------------
    diff |           -.2886233    .1436346               -.5708034   -.0064432
------------------------------------------------------------------------------
Satterthwaite's degrees of freedom:  516.259

            Ho: mean(rdelay) - mean(rddelay) = diff = 0

     Ha: diff < 0               Ha: diff ~= 0              Ha: diff > 0
       t =  -2.0094                t =  -2.0094              t =  -2.0094
   P < t =   0.0225          P > |t| =   0.0450          P > t =   0.9775

. ttest  rdist= rddist, unpaired unequal

Two-sample t test with unequal variances

------------------------------------------------------------------------------
Variable |     Obs        Mean    Std. Err.   Std. Dev.   [95% Conf. Interval]
---------+--------------------------------------------------------------------
rdist    |     803    1.014778     .001098    .0311139    1.012622    1.016933
rddist   |     304    1.017654    .0017074    .0297703    1.014295    1.021014
---------+--------------------------------------------------------------------
combined |    1107    1.015568    .0009246    .0307643    1.013753    1.017382
---------+--------------------------------------------------------------------
    diff |           -.0028768      .00203               -.0068641    .0011104
------------------------------------------------------------------------------
Satterthwaite's degrees of freedom:   568.67

        Ho: mean(rdist) - mean(rddist) = diff = 0

     Ha: diff < 0               Ha: diff ~= 0              Ha: diff > 0
       t =  -1.4172                t =  -1.4172              t =  -1.4172
   P < t =   0.0785          P > |t| =   0.1570          P > t =   0.9215
```

Table 5.10 Results of two tailed t tests for sector ZNY39

The t test results for sector ZNY39 were statistically significant at 5% level of significance.

This means that the R and D controller staffing configuration imposed higher delays on flights compared to R controller staffing configuration.

Sector ZMA20:

Table 5.11 shows result of two tailed t tests for sector ZMA 20.For sector ZMA20, the controller performance metric “rdist” was greater than ‘rddist”. The controller performance metric “rdelay” was greater than “rddelay”.

```
. ttest  rdist=rddist, unpaired unequal

Two-sample t test with unequal variances

------------------------------------------------------------------------------
Variable |     Obs        Mean    Std. Err.   Std. Dev.   [95% Conf. Interval]
---------+--------------------------------------------------------------------
rdist    |      96    1.145994     .043897    .4301007    1.058848    1.233141
rddist   |     874    1.025223    .0027088    .0800803    1.019906    1.030539
---------+--------------------------------------------------------------------
combined |     970    1.037175    .0050986    .1587938     1.02717    1.047181
---------+--------------------------------------------------------------------
    diff |            .1207717    .0439805                 .033468    .2080754
------------------------------------------------------------------------------
Satterthwaite's degrees of freedom:  95.7247

        Ho: mean(rdist) - mean(rddist) = diff = 0

     Ha: diff < 0               Ha: diff ~= 0              Ha: diff > 0
       t =   2.7460               t =   2.7460               t =   2.7460
   P < t =   0.9964          P > |t| =   0.0072          P > t =   0.0036

. ttest  rdelay= rddelay, unpaired unequal

Two-sample t test with unequal variances

------------------------------------------------------------------------------
Variable |     Obs        Mean    Std. Err.   Std. Dev.   [95% Conf. Interval]
---------+--------------------------------------------------------------------
rdelay   |      96     13.2395    .6261178    6.134677     11.9965     14.4825
rddelay  |     874    11.36218    .1450935    4.289469    11.07741    11.64696
---------+--------------------------------------------------------------------
combined |     970    11.54798    .1456621     4.53662    11.26213    11.83383
---------+--------------------------------------------------------------------
    diff |            1.877318    .6427096                .6030057    3.151629
------------------------------------------------------------------------------
Satterthwaite's degrees of freedom:  105.444

        Ho: mean(rdelay) - mean(rddelay) = diff = 0

     Ha: diff < 0               Ha: diff ~= 0              Ha: diff > 0
       t =   2.9209               t =   2.9209               t =   2.9209
   P < t =   0.9979          P > |t| =   0.0043          P > t =   0.0021
```

Table 5.11 Results of two tailed t tests for sector ZMA 20

The t test results were statistically significant at 5% level of significance.

The above results show that the R controller staffing configuration imposed higher delays and distance delays on flights compared to R and D controller staffing configurations.

In sector ZNY39, the R and D controller staffing configuration performed poorly compared to R controller staffing configuration for one controller performance metric.
In sector ZMA20, the R controller staffing configuration performed poorly compared to R and D controller staffing configuration for both the controller performance metrics.

For sectors ZNY39 and ZMA20 it was found that the performance of the two different controller staffing configurations was not equal and no specific staffing configuration performed better than the other.

The facility managers and supervisors use their judgment and consider complexity to assign an additional D controller to a sector. The traffic activity and corresponding controller workload subjected to the two controller staffing configurations is different.

In two out of the four considered sectors, performance of the two different staffing configurations is not equal in managing the air traffic activity assigned to them. It could be concluded that the current method of staffing additional “D” controller to a sector could be inadequate for some sectors in NAS.

5.8. Comparison of results of models estimated in section 5.7 with results of Howell et al. (2003)

Results of models estimated in section 5.7 are compared with relation between traffic activity and average excess distance for flights per unit time proposed by Howell et al 2003.

Figure 3.3 shows relation between normalized traffic activity during 15 minute interval and average excess distance for flights handled during 15 minute interval in a center, averaged over 20 enroute centers.

Based on the scatter plots developed for models in section 5.7.1, it can be proposed that current traffic levels in sectors and centers of NAS can be categorized into "route structure regime". Howell et. al. (2003) explain that traffic levels in the airspace are such that flights are restricted to stay on route structure, but extensive maneuvering is not required to control traffic flow.

Howell at al 2003 propose that the normalized traffic activity is between 30% to 70% of the peak traffic activity in route structure regime. Excess distance traversed by flights in this regime is almost constant. The author proposes implementation of tools or initiatives (e.g. RVSM, RNP, choke point initiatives, airspace redesign, dynamic resectorisation, etc.) for improvement in this regime. These tools can reduce the inefficiency in the airspace structure and lower the "plateau value" of excess distance.

CHAPTER VI: RELATIONS BETWEEN ATC SYSTEM PERFORMANCE AND ENROUTE AIR TRAFFIC IN THE NAS

6.1 Organization of chapter

This chapter has been divided into nine sections. A summary of contents in each section has been provided below:

Sections 6.2 and 6.3:

Four analyses have been proposed to estimate relations between ATC system performance and enroute traffic volume in the NAS. Due to the drawbacks of NAS performance measures proposed in analyses and difficulties in performing the analyses, there is a need to use recorded delay as a measure of system performance. It is proposed to extend the NAS model developed by Wieland 2004 to estimate relations between delays and enroute traffic volume in the NAS.

Section 6.4:

In section 6.4 the measures of delays and enroute traffic volume in NAS have been developed. The need to estimate relations for entire NAS by considering daily and monthly measures of time delays and enroute traffic volume has been explained. The need to develop month-specific models (models for same calendar months of a year) and the functional forms used to estimate relations have been explained.

Section 6.5:

Using the recorded delay data available from FAA databases measures of enroute traffic volume and measures of different forms of delays have been developed. Daily and monthly measures of delays have been developed.

Monthly models are developed to estimate relations between monthly delay metrics and monthly enroute traffic volume. Similarly daily models are developed to estimate relations between daily delay metrics and daily enroute traffic volume. The statistical analyses used to estimate the models have been discussed.

Two types of models have been developed. Models developed to estimate relations between delays specifically caused by enroute congestion and enroute traffic volume in NAS.

Models developed to estimate relations between different forms of delays and enroute traffic volume in NAS. Types of delays used to reduce air delays caused by enroute airspace congestion are identified by performing the following analyses:

Relations are estimated between different types of delays and enroute traffic volume in NAS. Analyses are proposed to study time series trend of different forms of delays, and trend in variation of delays with increase in enroute traffic volume

Sections 6.6 to 6.7

Results of models and analyses proposed in section 6.5 have been discussed.

Sections 6.8 and 6.9

Results obtained in sections 6.6 and 6.7 are interpreted.

Based on the results a relation is proposed between delays and enroute traffic volume in the NAS .The reasons for the low explanatory power of the monthly and month-specific models which estimate relations between delays and demand have been discussed. Drawbacks of the month-specific models and drawbacks of the delay data used to perform analyses have been discussed.

6.2. Difficulties in estimating relations between ATC system performance and enroute traffic volume in the NAS.

Based on the literature review, four analyses were proposed to estimate relations between NAS performance measures and enroute traffic volume in the NAS. The four proposed analyses are listed below and have been discussed in detail in the appendix:

1.1. Analysis proposed to estimate relations between flight times and enroute traffic volume in the NAS.

1.2. Analysis proposed to estimate relations between excess distances traveled by flights and traffic volume in the NAS.

1.3. Sector MAP values were used to measure NAS performance, for estimating relations between NAS performance and enroute traffic volume in the NAS.

1.4. Enroute delays caused by Traffic Management processes were used as measures of NAS performance, for estimating relations between NAS performance and enroute traffic volume in the NAS.

Analyses 1.1 and 1.2 could not be pursued further because of the bias caused by factors which affected relations between NAS performance measures (flight times and excess distances traveled by flights) and enroute traffic volume. Analyses 1.1 and 1.2 and their drawbacks have been discussed in the appendix. Analyses 1.3 and 1.4 could not be performed due to unavailability of required data.

6.3. Analyses proposed to estimate relations between recorded flight delays and enroute traffic volume in the NAS.

Due to the drawbacks of the analyses and NAS performance measures proposed in section 6.2, it was decided to use recorded delays as measures of ATC system performance in the NAS. Recorded delay data are used to estimate relations between delays and enroute traffic volume in NAS. In previous studies, models were developed which relate delays and air traffic in the entire NAS. Wieland 2004 has proposed a model which relates delays with air traffic volume in entire NAS. It is proposed to extend Wieland`s model to estimate relations between delays and enroute traffic volume in the NAS. In section 6.4 the proposed extension to Wieland`s model has been discussed.

6.4. Proposed extension toWieland`s model

In this section, analyses are proposed to estimate relations between delays caused by enroute congestion and enroute traffic volume in the NAS.

6.4.1. Measureof enroute traffic volume in entire NAS:

Enroute traffic volume is measured as center operations per day or center operations per month in all centers of NAS.

6.4.2. Measure of delays caused by enroute congestion:

Delay is measured in terms of average minutes of delay per day or average minutes of delay per month caused by enroute congestion in NAS. Delay is also measured in terms of operations delayed per day or operations delayed per month due to enroute congestion in NAS.

6.4.3. The need to estimate relations for entire NAS by considering daily and monthly measures of delays and enroute traffic volume.

The need to consider delays as a measure of performance of NAS

Delays borne by flights are used as a measure of performance of NAS. Delays can capture the effect of excess distances traveled by flights due to enroute congestion. The advantages of delays over the “excess distance metric” are discussed in section 3.2.2.2.

Researchers have performed a variety of analyses on different types of delays. Mueller and Chatterji (2002) studied the distribution of departure and arrival delays. They found that departure delay fitted Poisson distribution and enroute and arrival delay fitted the normal distribution. Delays can be classified into different types based on the phase of the flight i.e. arrival delays, departure delays, taxi delays, gate delays, enroute delays. Ground delays and ground stops are “Traffic Management processes”. Ground delays (EDCT) and ground stops delay flights at the departure airport.

It was found in the literature review that researchers have estimated relations between different forms of delays and airport and terminal congestion. Few studies have been conducted on delays caused by enroute congestion or to estimate relations between delays and enroute traffic volume.

The need to estimate relations for the entire NAS by considering daily and monthly measures of delays and enroute traffic volume has been explained.

The need to estimate relations for entire NAS

The following factors make it necessary to estimate the relations for entire NAS:

1. The effect of spatial and temporal propagation of delays in NAS has been discussed in section 3.3.1. Airspace congestion can cause delays to be imposed on aircraft in airspace or in airports. By analyzing the entire NAS, those delays caused by enroute congestion which propagate to different regions of the national airspace system can be captured.

2. Strategic and tactical planning is performed by the ATC system for entire NAS. Coordination exists among different ATC units in NAS. Programs implemented by the ATC system are implemented after considering the entire NAS. These factors make it necessary to evaluate the performance of the ATC system in reducing delays in entire NAS. All the above points have been discussed in detail in section 3.3.1of literature review.

3. Tools and techniques used by controllers to handle airspace congestion could cause delays to flights hundreds of miles away from the source of airspace congestion. This point has been discussed in detail in section 3.3.1.

The need to consider daily and monthly measures of delays and enroute traffic volume

It is necessary to estimate relations using monthly and daily measures of delays and enroute traffic volume in NAS, for the following reasons:

1. Due to temporal propagation of delays, delays which occur in a specific period could be caused by airspace congestion in previous periods. A day or month is considered as the period for measuring delay. Average minutes of delay per day or average minutes of delay per month is treated as one data point for statistical analysis.

Similarly operations delayed per day or operations delayed per month is considered as a data point for statistical analysis. A day or month is a sufficient period to capture the entire delay caused by an airspace congestion event which occurred at any instant during the period. The phenomenon of temporal propagation of delays in NAS has been discussed in section 3.3.1.

2. Hoffman and Voss (2000) considered monthly averages for arrival delay, departure delay, average taxi out time and enroute time as indicators of airspace or airport congestion. They explain that airline schedules in US change approximately once every month, and hence monthly averages are used for developing metrics. The authors studied the time series trend of these metrics.

6.4.4. The need to develop "Month-specific models"

Adverse weather conditions in the national airspace decrease the operational capacity of the airspace. Month-specific weather effects could affect the monthly operational capacity of the national airspace. Operational capacity of the national airspace could be different for each calendar month of the year.

Air traffic demand in the NAS varies for different calendar months of the year. ATC system implements different programs in NAS during specific calendar months of the year. These programs are implemented to increase efficiency of the NAS and to reduce delays in the system.

Development of month-specific models:

Relations are estimated between delays caused by enroute congestion and enroute traffic volume by considering monthly data point for the same calendar month of all years. Twelve datasets are constructed for twelve months of a calendar year in the following way. In a dataset, each data point represents the same "calendar" month of all years from 1990 to 2005. The dataset for January consists of all January's from 1990 to 2005. Twelve data sets are constructed for twelve calendar months of the year.

6.4.5. Functional forms used to estimate relations

Wieland (2004) estimated a relation between monthly traffic volume in NAS and monthly total minutes of delays in NAS. Monthly operations handled by controllers from January 2000 to December 2004 were related to corresponding total monthly minutes of delays recorded in OPSNET. A simple queuing relation, delay = demand/(capacity-demand) was used to relate the two variables.

Wieland (2004) explains that considering the system capacity to be constant, an increase in traffic volume will cause an asymptotic increase in delays until traffic volume reaches the system capacity. He further explains that in a queuing relation between capacity and delays, as the system capacity is reached the delays soar with small fluctuations in volume.

A hyperbolic function Y = X/ (A-B*X) is used to relate delays caused by enroute congestion with the enroute traffic volume in the NAS.

The hyperbolic function is reasonable in representing a congested system whose service times increase very steeply as capacity is approached.

Zelinski et al. (2004) reports results of 36 simulations of ACES which were run for 4 demand sets and 9 weather days. The results generated by ACES, for delays in NAS were analyzed. The analysis of delays and demand in NAS showed that quadratic relations fitted the data with low and random residuals. These results support the hypothesis that a non linear relation exists between delays and demand in NAS.

The following functional forms were used to estimate relations between delays and enroute traffic volume in NAS

1. Hyperbolic functional form

Y = X/ (A-BX)

2. Power relation

Y = A * X^B

6.5. Proposed analyses (Extension to Wieland`s model (Wieland 2004))

Analyses proposed in this section are extension to Wieland`s model from Wieland (2004) Wieland (2004) has considered total minutes of delays in NAS to estimate relations between delays and air traffic in NAS. Wieland (2004) has considered delays due to all causes. Enroute traffic volume is measured as center operations in all centers of NAS.

Two analyses are proposed to estimate relations between delays and enroute traffic volume. 1. In section 6.5.1, delays specifically caused by enroute congestion are used. OPSNET records delays due to enroute traffic volume imposed on flights on the ground (at the departure airport) or in the enroute airspace.

2. In sections 6.5.2 and 6.5.3, different forms of delays are identified (delays by different phase of flight – arrival delays, enroute delays, departure delays, gate delays and taxi delays) which are used to reduce air delays caused by enroute airspace congestion. Based on the literature review, forms of delays are identified which are used to reduce air delays caused by enroute airspace congestion. Relations are estimated between different forms of delays and enroute traffic volume to confirm if the delay types found in literature are used to reduce air delays caused by enroute airspace congestion.

6.5.1. Analysis performed using delays specifically caused by enroute congestion which are recorded by OPSNET database as delays by cause "center volume"

OPSNET database records delays by five causes - weather, terminal volume (terminal congestion), center volume (center congestion), equipment failures and runway capacity constraints. OPSNET records only the number of delays by individual cause. OPSNET database does not record minutes of delays by individual cause like center volume. The OPSNET database provides number of operations delayed due to five causes for days, months and years from January 1990.

Measures of delays caused by “enroute congestion”

The advantages of using traffic volume and delay data recorded by OPSNET compared to other databases have been explained in section 3.3.5. of literature review. The most important reason for using OPSNET data are that OPSNET is the only database which provides data on delays due to center congestion.

The OPSNET database only provides number of operations delayed due to center congestion. The number of operations delayed due to center congestion can be related with enroute traffic volume. Two delay metrics are defined to measure delays caused by enroute congestion.

1. “Fraction of center operations in NAS which are delayed due to enroute congestion”.
2. “Fraction of delayed operations delayed by enroute congestion”

1. “Fraction of center operations in NAS which are delayed due to enroute congestion”.

The above metric is computed as the ratio of number of operations delayed due to enroute congestion and center operations in NAS.

2. “Fraction of delayed operations delayed by enroute congestion”

The above metric is computed as the ratio of number of operations delayed by enroute congestion and the number of operations delayed by all causes. This metric is computed for entire NAS.

Both metrics are computed as monthly delay metrics for all months from 1990 to 2005. These metrics are also computed as daily delay metrics for days from April 2004 to April 2005.

Measure of enroute traffic volume:

Enroute traffic volume is measured as total center operations in all centers of NAS.

Statistical analysis:

Regression analysis is performed to estimate relations between delay metrics and enroute traffic volume in the NAS. The two delay metrics listed below are used to develop models 1.1 and 1.2 and models 2.1 to 2.4

1. “Fraction of center operations in NAS which are delayed due to enroute congestion”.
2. “Fraction of delayed operations delayed by enroute congestion”.

Monthly and daily models are developed by estimating relations between daily delay metric and daily center operations in NAS and monthly delay metric and monthly center operations in NAS. The following models are estimated by considering daily or monthly metrics and data for specified periods.

Monthly models

Period from 1990 to 2005 is considered for developing these models.

Monthly delay metrics and monthly center operations are considered as data points. Regression analysis is performed for the following data sets.

Model 1.1 Data for period: 1990 to 2005

Model 1.2 Twelve datasets are constructed for twelve months of a calendar year in the following way. In a dataset, data points represent the same "calendar" month of all years from 1990 to 2005. The dataset for January consists of all January's from 1990 to 2005. Twelve data sets are constructed for twelve calendar months. Data from 1990 to 2005 is used for estimating these models. Hence forth model 1.2 will be referred to as month-specific model.

Daily models

Period from 04/2004 to 04/ 2005 is considered for developing these models.

Daily delay metric and daily center operations are considered as data points. Regression analysis is performed for the following data sets.

Model 2.1. Data for period: 04/ 01/2004 to 04/30/2005.

Model 2.2. Data for period: 01/01/2005 to 04/30/2005.

Model 2.3. Data for individual months from 04/2004 to 04/2005

Model 2.4. Twelve datasets are constructed for twelve months of a calendar year in the following way. In a dataset, data points represent days of the same "calendar" month of

2004 and 2005. The dataset for January consists of all days of January 2004 and January 2005. Twelve data sets are constructed for twelve calendar months. Data from 04/2004 to 04/2005 is used for estimating these models.

6.5.2. Analyses performed using different forms of delays used to reduce air delays caused by enroute congestion

Forms of delays used to reduce air delays caused by enroute congestion

In section 3.3.1 of literature review it was found that when sector capacity (MAP) is exceeded flights could be ground delayed at departure airport by using ground holds or ground stops. In the same section it is discussed how the effect of MIT restrictions imposed on flights in airspace due to airspace congestion could reach the origin airport and cause flights to be ground delayed.

During a meeting with controllers at FAA, controllers told that enroute airspace congestion could cause different types of delays to be imposed on flights at the origin airport. Controllers explained that taxi out delays and departure delays could be imposed on flights because of enroute airspace congestion. Based on the literature review and discussions with controllers, it was found that the following types of delays could be imposed on flights because of enroute airspace congestion:

1. Ground delays
2. Taxi out delay
3. Departure delays

In this analysis relations are estimated between different types of delays (which could be used to reduce air delays caused by enroute airspace congestion) and enroute traffic volume. Databases are identified which provide data on different types of delays. Based on the data provided by databases monthly and daily delay metrics are developed for different types of delays. Regression analysis is performed to estimate relations between delay metrics and enroute traffic volume.

6.5.2.1. Analysis of average ground delay and number of operations delayed by category-arrival, departure and enroute

Delays recorded by OPSNET database:

The following types of delays are recorded by OPSNET database.

<u>Ground delays</u>

OPSNET database provides data on ground stop delays and EDCT delays.

OPSNET database provides number and average minutes of ground stop delays and EDCT delays. OPSNET computes ground delay as the sum of ground stop delays and EDCT delays. Average ground delay is computed as ground delay minutes divided by total operations ground delayed. Analysis is performed using average minutes of ground delay. OPSNET provides average minutes of ground delay for days, months and years from January 1990.

<u>Number of operations delayed by category- departure/enroute and arrival</u>

OPSNET database records number of delayed operations belonging to each category – departure, enroute and arrival. OPSNET database does not record minutes of delay by individual category- departure, enroute and arrival .The OPSNET database provides number of delayed operations belonging to each category for days, months and years from January 1990.

The following data are available for delays belonging to departure, enroute and arrival categories.

1. Number of operations departure delayed
2. Number of operations delayed enroute
3. Number of operations arrival delayed

Hence the models are limited to analyzing the number of delayed operations belonging to departure, enroute and arrival categories.

Three delay metrics are defined for delays belonging to arrival, departure and enroute categories.

1. “Fraction of center operations which are departure delayed”.
2. “Fraction of center operations which are delayed enroute”.
3. “Fraction of center operations which are arrival delayed”.

The above 3 metrics are computed as the ratio of delayed operations belonging to each category (arrival, enroute and departure) and center operations in NAS.

Delay metrics developed from OPSNET database:

The four metrics listed below are developed from the delay data provided by OPSNET database.

1. Average minutes of ground delay

2. “Fraction of center operations which are departure delayed”.
3. “Fraction of center operations which are delayed enroute”.
4. “Fraction of center operations which are arrival delayed”.

These four delay metrics are computed as monthly metrics for all months from 1990 to 2005. These metrics are also computed as daily metrics for days from May 2004 to May 2005.

Measure of enroute traffic volume:

Enroute traffic volume is measured as total center operations in all centers of NAS.

Statistical analysis:

Regression analysis is carried out to estimate relations between delay metrics and enroute traffic volume in the NAS. The four delay metrics listed below are used to develop models 1.1 and 1.2 and models 2.1 to 2.4.

1. Average minutes of ground delay.
2. “Fraction of center operations which are arrival delayed”.
3. “Fraction of center operations which are departure delayed”.
4. “Fraction of center operations which are delayed enroute”.

Monthly and daily models are developed by estimating relations between daily delay metric and daily center operations in NAS and monthly delay metric and monthly center operations in NAS. The following models are estimated by considering daily or monthly metrics and data for specified periods.

Monthly models:

Period from 1990 to 2005 is considered for developing these models.

Monthly delay metrics and monthly center operations are considered as data points. Regression analysis is performed for the following data sets.

Model 1.1. Data for period: 01/1990 to 04/2005

Month-specific model 1.2. Twelve datasets are constructed for twelve months of a calendar year in the following way.In a dataset, data points represent the same “calendar” month of all years from 1990 to 2005. The dataset for January consists of all January’s from 1990 to 2005. Twelve data sets are constructed for twelve calendar months. Data from 01/1990 to 04/2005 is used for estimating these models.

Daily models:

Daily delay metric and daily center operations are considered as data points.

Models 2.1 to 2.4 (described in section 6.5.1) are estimated using the four delay metrics developed in this section.

6.5.2.2. Analysis of average minutes of delay by category- airport departure delay, gate departure delay, taxi- in/out delay, airborne delay, block delay and gate arrival delay

Delays recorded by ASPM database:

The following forms of delays are recorded by ASPM database.

Relative to schedule delays and relative to flight plan delays

ASPM database can compute delays by two procedures. ASPM database can compute delays by comparing actual flight times to scheduled flight times, and by comparing actual flight times to filed flight plan times. ASPM database can provide same type of delay in two formats:

i) Relative to schedule delay
ii) Relative to flight plan delay

In section 3.3.5.2, drawbacks of relative to schedule delay data have been discussed. For this analysis it was decided to use relative to flight plan delays. Relative to schedule delays were compared with relative to flight plan delays for the same type of delay (average daily delay and average monthly delay). It was found that relative to schedule delays were greater than relative to flight plan delays. However both delays followed the same time series trend.

Different types of delays recorded by ASPM database

ASPM database provides average time delays for days, months and years from January 1998.ASPM database provides data for the following types of delays. Definitions of different types of delays are provided below. These definitions are taken from ASPM database.

1. Average gate departure delay

Average gate departure delay is the difference between the actual gate out time and the filed flight plan gate out time

2. Average taxi out delay

Average taxi out delay is the difference between taxi out time minus unimpeded taxi out time.

3. Average airport departure delay

Average airport departure delay is an estimated delay derived from the actual wheels off time minus the flight plan gate out time less the unimpeded taxi out time.

4. Average airborne delay

Average airborne delay is the actual airborne time less the flight plan estimated time enroute (estimated enroute time of the flight filed in the flight plan).

5. Average taxi in delay

Average taxi in delay is calculated as actual taxi in time minus unimpeded taxi in time. Taxi in delays may occur when a gate is not available for an arriving aircraft.

6. Average block delay

Average block delay is calculated as actual gate-to-gate time minus scheduled gate-to-gate.

7. Average gate arrival delay

Average gate arrival delay is the difference between the actual gate in time and the flight plan gate in time.

Delay metrics developed from ASPM database:

The seven delay metrics which were extracted from ASPM database are listed below:

1. Average gate departure delay
2. Average taxi out delay
3. Average airport departure delay
4. Average airborne delay
5. Average taxi in delay
6. Average block delay
7. Average gate arrival delay

The above metrics are obtained as monthly metrics for all months from 1998 to 2005. These metrics are also obtained as daily metrics for days from May 2004 to May 2005

Measure of enroute traffic volume:

Enroute traffic volume is measured as total center operations in all centers of NAS.

Statistical analysis:

Regression analysis is carried out to estimate relations between delay metrics and enroute traffic volume in the NAS. The seven delay metrics listed below are used to develop models 1.1 and 1.2 and models 2.1 to 2.4

1. Average gate departure delay
2. Average taxi out delay
3. Average airport departure delay
4. Average airborne delay

5. Average taxi in delay
6. Average block delay
7. Average gate arrival delay

Monthly and daily models are developed by estimating relations between daily delay metrics and daily center operations in NAS and monthly delay metrics and monthly center operations in NAS. The following models are estimated by considering daily or monthly metrics and data for specified periods.

Monthly models:

Period from 01/1998 to 04/2005 was considered for developing these models.

Monthly delay metrics and monthly center operations are considered as data points. Regression analysis is performed for the following data sets.

Model 1.1. Data for period: 01/1998 to 04/2005

Month-specific model 1.2. Twelve datasets are constructed for twelve months of a calendar year in the following way. In a dataset, data points represent the same "calendar" month of all years from 1998 to 2005. The dataset for January consists of all January's from 1998 to 2005. Twelve data sets are constructed for twelve calendar months. Data from 01/1998 to 04/2005 is used for estimating these models.

Daily models:

Daily delay metric and daily center operations are considered as data points.

Models 2.1 to 2.4 (described in section 6.5.1) are estimated using the seven delay metrics developed in this section.

6.5.3. Trends in the variation of different delay types

In this analysis the variation in different types of delays over time and with increase in enroute traffic volume is studied. The following delay metrics (delays by category) were obtained as monthly metrics for all months from 01/1998 to 05/2005 from ASPM database.

1. Average gate departure delay
2. Average taxi out delay
3. Average airport departure delay
4. Average airborne delay
5. Average taxi in delay
6. Average block delay
7. Average gate arrival delay

The above seven delay metrics are used in this analysis. Enroute traffic volume is measured as monthly operations in allcenters of NAS.

Two plots were developed to study variation in trend of seven delay metrics.

1. Time series trend of monthly delay metrics for period: 01/1998 to 05/2005.
2. Variation in monthly delay metrics with increase in monthly enroute traffic volume in the NAS. Period from 01/1998 to 05/2005 was considered for this analysis.

6.6. Analyses and results

In sections 6.5.1 and 6.5.2, monthly, month-specific and daily models are developed for estimating relations between delays and enroute traffic volume in NAS. These models are analyzed using regression analyses. WinSTAT the Statistics Add-In for Microsoft ® Excel is used for performing the regression analyses. Results of models and analyses proposed in section 6.5 are discussed in section 6.7.

6.7. Results

6.7.1. Estimating relations between delays caused by enroute congestion and enroute traffic volume in the NAS

The two delay metrics listed below were considered as dependent variables in the regression models.

1. “Fraction of center operations in NAS which are delayed due to enroute congestion”.
2. “Fraction of delayed operations delayed due to enroute congestion”

Monthly models

Period from 1990 to 2005 was considered for developing these models.

Monthly delay metric and monthly center operations are considered as data points. Regression analyses were performed for the following data sets.

Model 1.1 Data for period: 1990 to 2005

A total of fifteen datasets were constructed by dropping each subsequent year from1990.For example the second dataset consisted of data from 1991 to 2005 and the fifteenth dataset consisted of data from 2004 to 2005. Regression analyses were carried out for fifteen datasets.

1. Results for delay metric "Fraction of center operations in NAS which are delayed due to enroute congestion".

The best statistical fit was obtained for the following data.

Data for period: 01/1994 to 04/2005

Figure 6.1 shows relation between fraction of center operations delayed due to enroute congestion and monthly center operations in NAS.

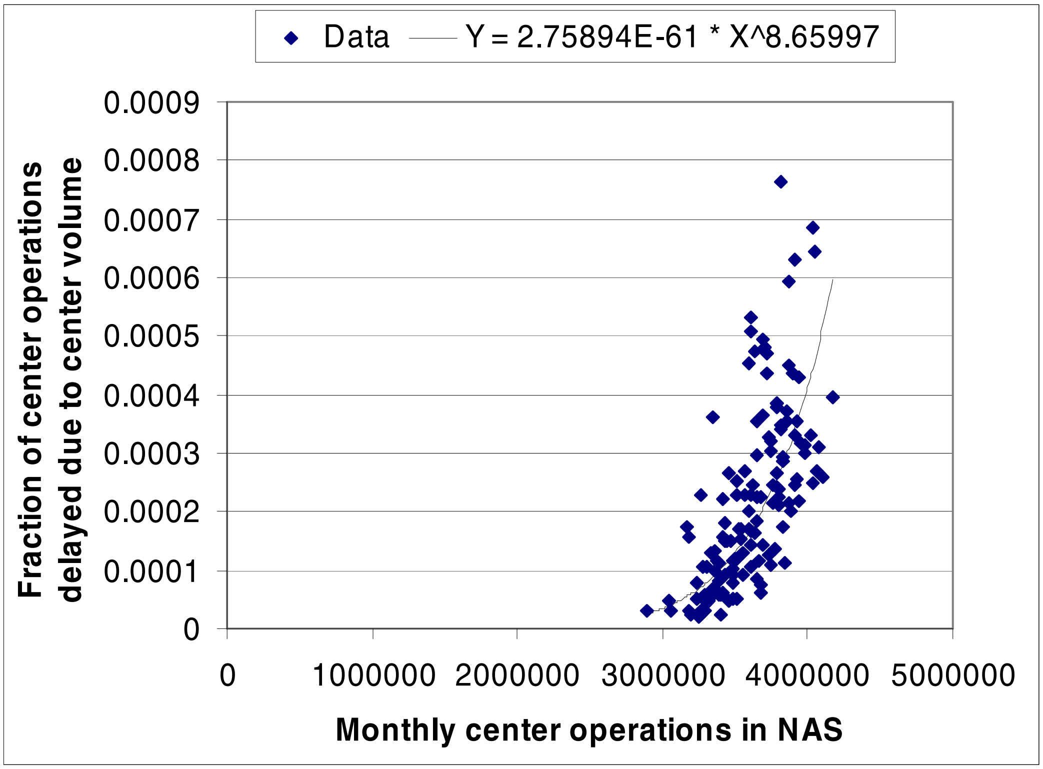

Figure 6.1 Fraction of center operations delayed due to center volume vs. monthly center operations in NAS

Results of regression analyses are shown in table 6.1 below:

Table 6.1

X-Variable:	Monthly center operations in NAS			
Y-Variable:	Fraction of center operations delayed due to center volume			
	N	**A**	**B**	**R-Square**
Y = A * X^B	136	2.759E-61	8.660	0.543
Y = X / (A + B*X)	136	3.123E+11	-78039.687	0.448

2. Results for delay metric "Fraction of delayed operations delayed due to enroute congestion".

The best statistical fit was obtained for the following data.

Data for period: 01/1993 to 06/2005

Figure 6.2 shows relation between fraction of delayed operations delayed due to enroute congestion and monthly center operations in NAS.

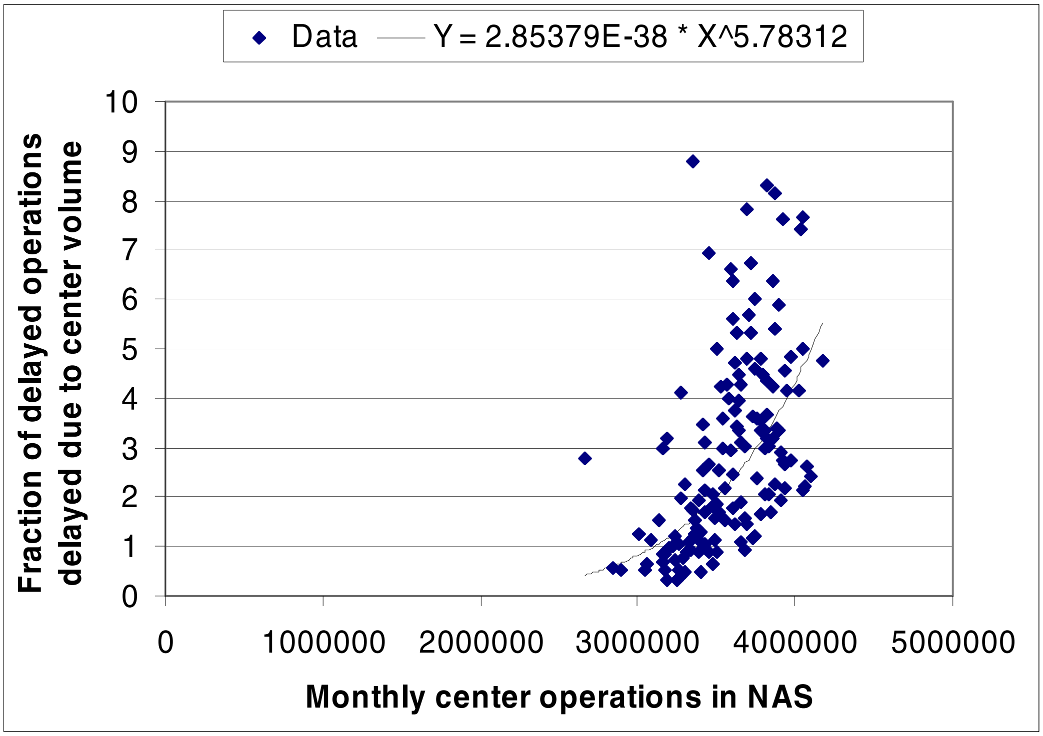

Figure 6.2 Fraction of delayed operations delayed due to center volume vs. monthly center operations in NAS

Results of regression analyses are shown in table 6.2 below

Table 6.2

X-Variable:	Monthly center operations in NAS			
Y-Variable:	Fraction of delayed operations delayed due to enroute congestion			
	N	**A**	**B**	**R-Square**
Y = A * X^B	150	2.854E-38	5.783	0.380
Y = X / (A + B*X)	150	1.399E+07	-3.323	0.340

Month-specific models:

Model 1.2 Data for period: 01/1990 to 06/2005.

Twelve datasets are constructed for twelve months of a calendar year in the following way. In a dataset, each data point represents the same "calendar" month of all years from 1990 to 2005. The dataset for January consists of all January's from 1990 to 2005. Twelve data sets are constructed for twelve calendar months.

Eleven subsets are constructed for each calendar month. Eleven subsets were constructed from the dataset of each calendar month. Subsets were constructed by dropping each subsequent year from1990.For example the second subset for January consisted of all January's from 1991 to 2005 and the eleventh subset for January consisted of all January's from 2000 to 2005.

Regression analyses were carried out for a total of 132 subsets which were developed from 12 datasets for 12 calendar months. For each calendar month, eleven subsets were analyzed. For each month, a subset was found which showed the highest R squared value for the model. R squared value is considered as a goodness of fit.

1. Results for delay metric "Fraction of center operations in NAS delayed due to enroute congestion".

Relation between fraction of center operations delayed due to enroute congestion and monthly center operations in NAS is estimated

Table 6.3 shows results of regression analyses for month-specific models for delay metric “Fraction of center operations in NAS delayed due to enroute congestion".

R squared values are reported.

Table 6.3

Month	**Years**	**Y = A * X^B**	**Years**	**Y = X / (A - B*X)**
January	95 to 05	0.85	95 to 05	0.78
February	94 to 05	0.70	94 to 05	0.66
March	94 to 05	0.72	94 to 05	0.60
April	93 to 05	0.71	93 to 05	0.72
May	93 to 05	0.83	93 to 05	0.85
June	93 to 04	0.70	93 to 04	0.65
July	93 to 05	0.67	93 to 05	0.76
August	93 to 05	0.67	93 to 05	0.70
September	99 to 05	0.68	99 to 05	0.79
October	94 to 05	0.83	95 to 05	0.75
November	94 to 05	0.74	94 to 05	0.56
December	93 to 05	0.76	93 to 05	0.63

The best statistical fit was obtained for the following data:

Month-specific model for May showed the best statistical fit. Data were considered for period from 1993 to 2005.

Figure 6.3 shows result of month-specific model for delay metric "Fraction of center operations in NAS delayed due to enroute congestion" for May.

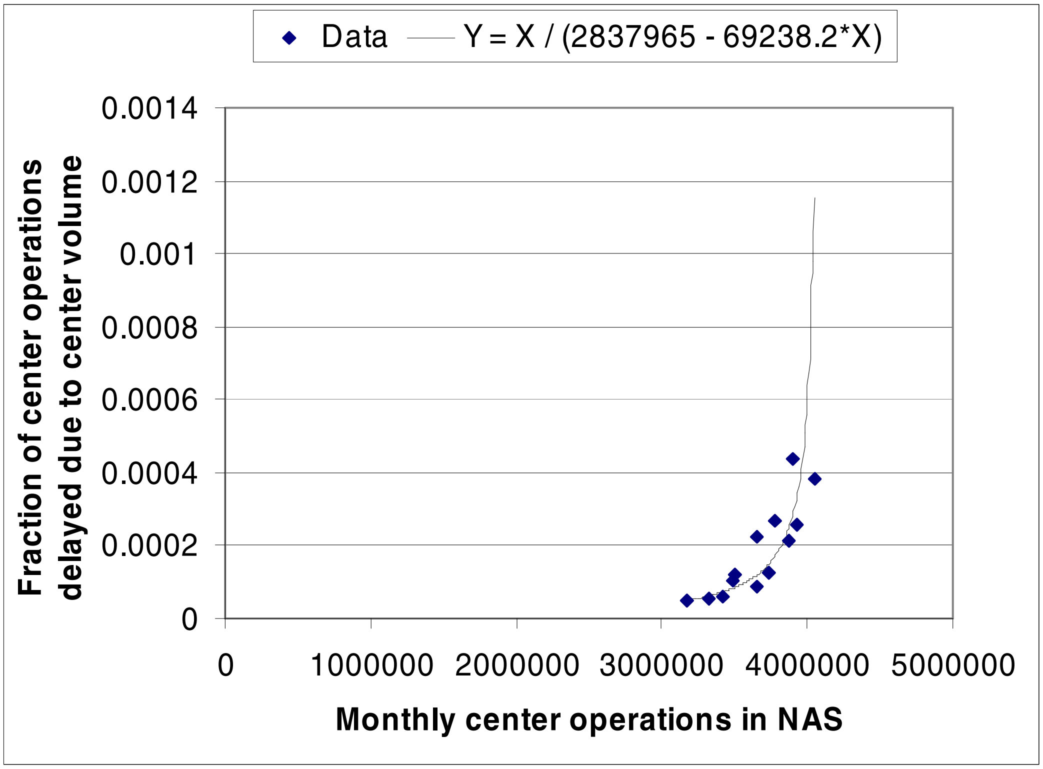

Figure 6.3 Fraction of center operations delayed due to center volume vs. monthly center operations in NAS (Month-specific model for May)

Results of regression analyses are shown in table 6.4 below

Table 6.4

X-Variable:	Monthly center operations in NAS			
Y-Variable:	Fraction of center operations delayed due to enroute congestion			
	N	**A**	**B**	**R-Square**
Y = A * X^B	13	9.925E-66	9.321	0.825
Y = X / (A + B*X)	13	2.838E+11	-69238.235	0.852

2. Results for delay metric "Fraction of delayed operations delayed due to enroute congestion".

Relation between fraction of delayed operations delayed due to enroute congestion and monthly center operations in NAS is estimated.

Table 6.5 shows results of regression analyses for month-specific models for delay metric "Fraction of delayed operations delayed due to enroute congestion".

R squared values are reported.

Table 6.5

Month	**Years**	**Y = A * X^B**	**Years**	**Y = X / (A - B*X)**
January	94 to 05	0.74	95 to 05	0.74
February	93 to 05	0.58	93 to 05	0.65
March	93 to 05	0.61	93 to 05	0.54
April	93 to 05	0.60	93 to 05	0.64
May	93 to 05	0.63	93 to 05	0.63
June	-	-	-	-
July	93 to 05	0.63	93 to 05	0.77
August	93 to 05	0.35	93 to 05	0.47
September	91 to 05	0.55	91 to 05	0.45
October	93 to 05	0.68	95 to 05	0.62
November	92 to 05	0.58	94 to 05	0.50
December	93 to 05	0.72	93 to 05	0.68

Month-specific model for month of June showed very poor explanatory power.

The best statistical fit was obtained for the following data.

Month-specific model for July showed the best statistical fit. Data were considered for period from 1993 to 2005.

Figure 6.4 shows result of month-specific model for delay metric “Fraction of delayed operations delayed due to enroute congestion” for July

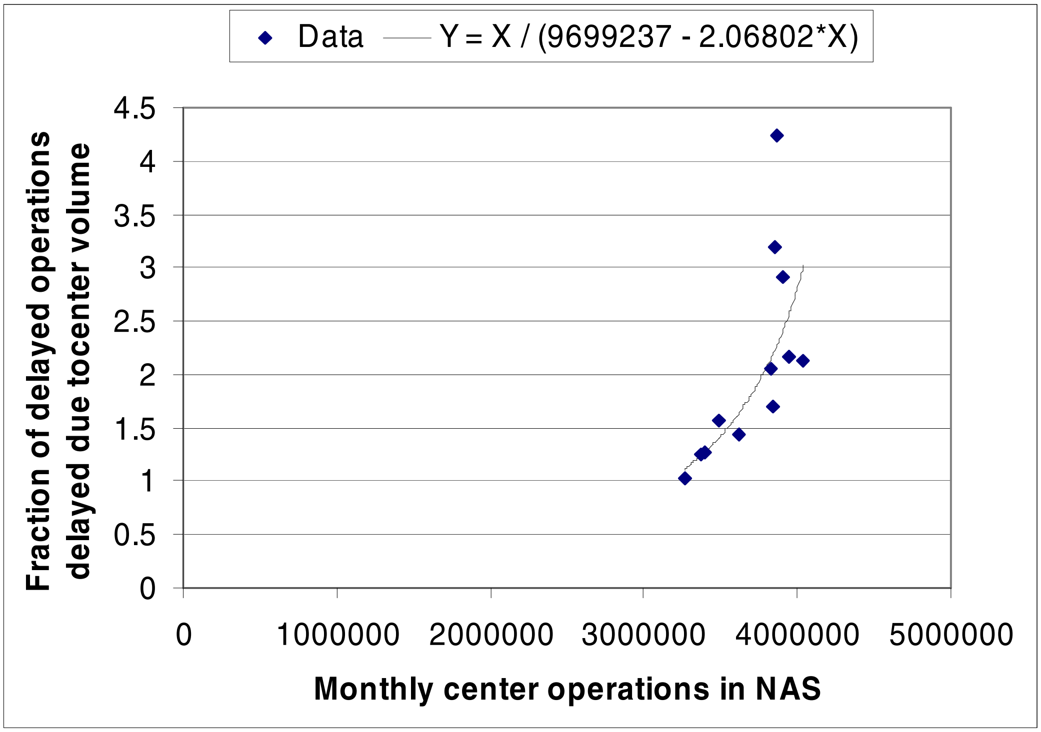

Figure 6.4 Fraction of delayed operations delayed due to center volume vs. monthly center operations in NAS (Month-specific model for July)

Results of regression analyses are shown in table 6.6 below

Table 6.6

X-Variable:	Monthly center operations in NAS			
Y-Variable:	Fraction of delayed operations delayed due to center volume			
	N	**A**	**B**	**R-Square**
Y = A * X^B	12	7.665E-31	4.628	0.625
Y = X / (A + B*X)	12	9.699E+06	-2.068	0.770

<u>Daily models:</u>

Models 2.1 to 2.4

Period from 04/2004 to 04/2005 was considered for developing these models.

Daily delay metric and daily center operations are considered as data points. Regression analyses were performed for the following data sets.

Model 2.1. Data for period: 04/ 01/2004 to 04/30/2005.

Model 2.2. Data for period: 01/01/2005 to 04/30/2005.

Model 2.3. Data for individual months from 04/2004 to 04/2005

Model 2.4. Twelve datasets were constructed for twelve months of a calendar year in the following way. In a dataset, data points represent days of the same “calendar” month of 2004 and 2005. The dataset for January consists of all days of January 2004 and January 2005. Twelve data sets were constructed for twelve calendar months. Data from 04/2004 to 04/2005 is used for estimating these models.

The above models were estimated by considering the two delay metrics as dependent variables. Regression analyses were carried out for all the models. All the models showed poor explanatory power. All the models had R squared values less than 0.4.

6.7.2. Estimating relations between different forms of delays (used to reduce air delays caused by enroute airspace congestion) and enroute traffic volume in the NAS

6.7.2.1. Analysis of average ground delay and number of operations delayed by category-arrival, departure and enroute

The four delay metrics listed below are considered as dependent variables in the regression models.

1. Average minutes of ground delay
2. "Fraction of center operations in NAS which are departure delayed".
3. "Fraction of center operations in NAS which are delayed enroute".
4. "Fraction of center operations in NAS which are arrival delayed".

Monthly models:

Period from 1990 to 2005 was considered for developing these models.

Monthly delay metric and monthly center operations are considered as data points. Regression analyses were performed for the following data sets.

Model 1.1 Data for period from 01/1990 to 04/2005

A total of fifteen datasets were constructed by dropping each subsequent year from1990. For example the second dataset consisted of data from 1991 to 2005 and the fifteenth dataset consisted of data from 2004 to 2005. Regression analyses were carried out for fifteen datasets.

1. Results for delay metric "Average minutes of ground delay".

The best statistical fit was obtained for the following data.

Data for period: 01/1990 to 04/2005

Figure 6.5 shows relation between average ground delay and monthly center operations in NAS.

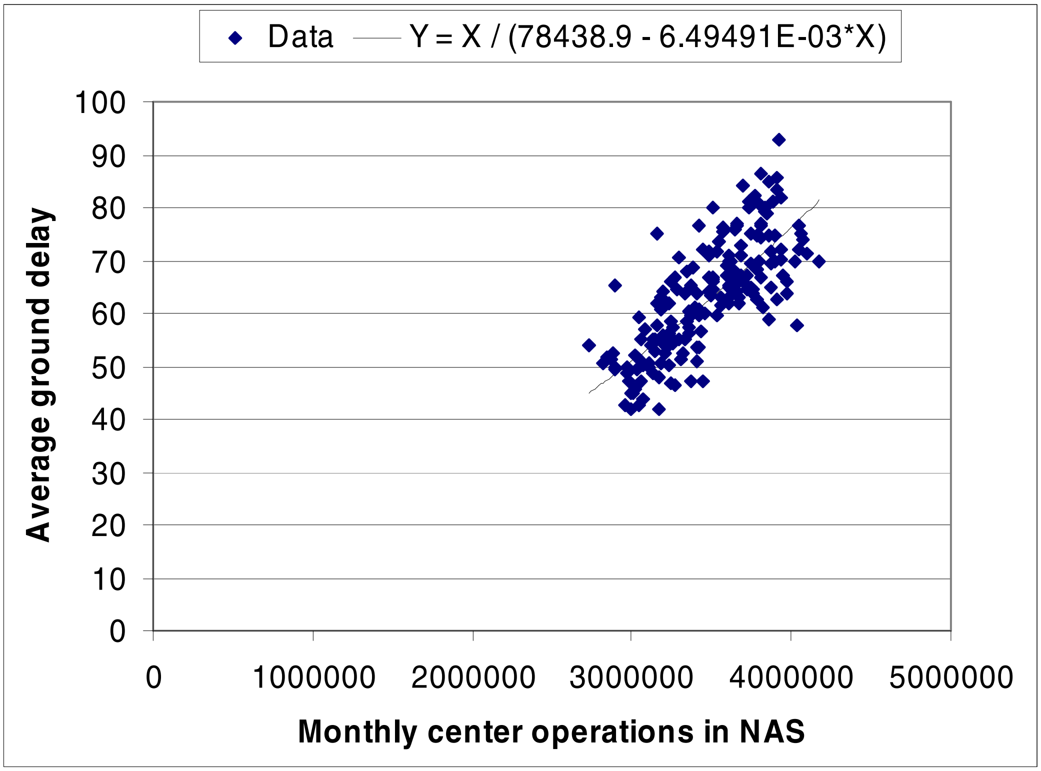

Figure 6.5 Average ground delay vs. monthly center operations in NAS

Results of regression analyses are shown in table 6.7 below

Table 6.7

X-Variable:	Monthly center operations in NAS			
Y-Variable:	Average ground delay			
	N	**A**	**B**	**R-Square**
Y = A * X^B	184	5.915E-08	1.380	0.579
Y = X / (A + B*X)	184	7.844E+04	-0.006	0.579

2. Results for delay metric "Fraction of center operations which are departure delayed".

The best statistical fit was obtained for the following data.

Data for period: 01/1995 to 04/2005

Figure 6.6 shows relation between fraction of center operations which are departure delayed and monthly center operations in NAS.

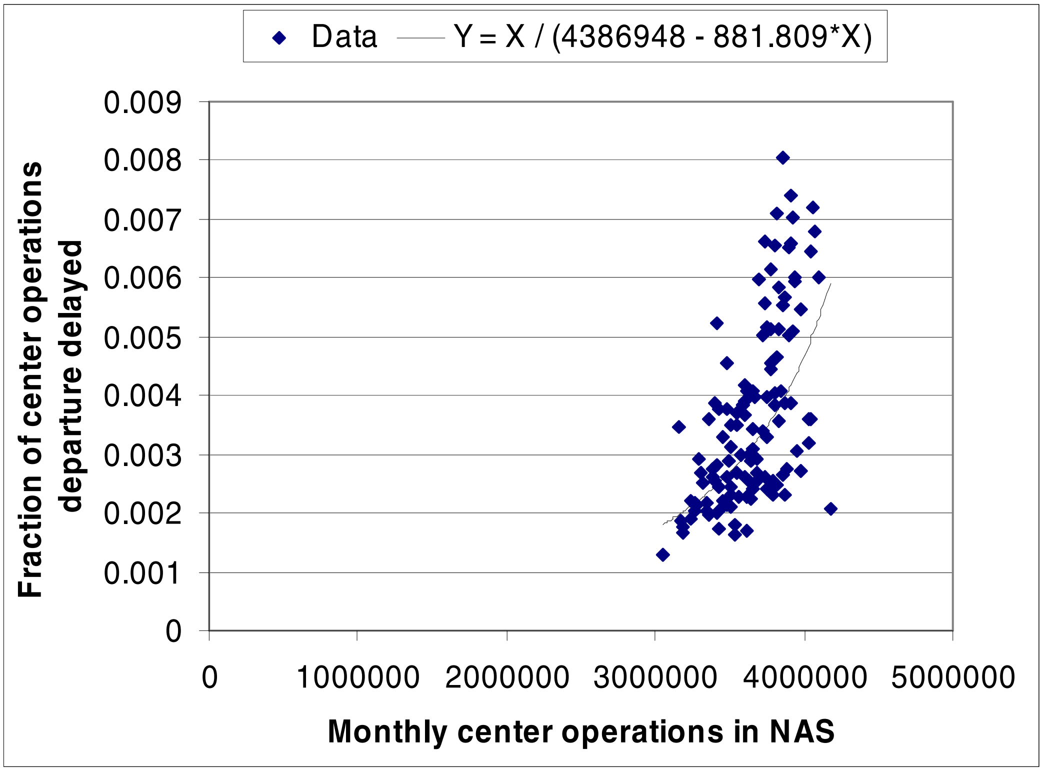

Figure 6.6 Fraction of center operations departure delayed vs. monthly center operations in NAS

Results of regression analyses are shown in table 6.8 below

Table 6.8

X-Variable:	Monthly center operations in NAS			
Y-Variable:	Fraction of center operations departure delayed			
	N	**A**	**B**	**R-Square**
Y = A * X^B	124	1.784E-28	3.852	0.379
Y = X / (A + B*X)	124	4.387E+09	-881.810	0.390

3. Results for delay metric “Fraction of center operations which are delayed enroute”

4. Results for delay metric “Fraction of center operations which are arrival delayed”.

Model 1.1 was estimated by considering the above delay metrics as dependent variables. Regression analyses were carried out for all the models. All the models showed poor explanatory power. All the models had R squared values less than 0.4.

Month-specific models:

Model 1.2 Data for period: 1990 to 2005

Twelve datasets were constructed for twelve months of a calendar year in the following way. In a dataset, each data point represents the same “calendar” month of all years from 1990 to 2005. The dataset for January consists of all January’s from 1990 to 2005. Twelve data sets were constructed for twelve calendar months. Regression analyses were carried out for 12 datasets.

1. Results for delay metric “Average ground delay”.

Data from 01/1990 to 04/2005 is used for estimating month-specificmodels for delay metric “Average ground delay”.

Relation between average ground delay and monthly center operations in NAS is estimated.

Table 6.9 shows results of regression analyses for month-specific models for average ground delay.

R squared values are reported.

Table 6.9

Period: 01/ 90 to 04/05	**Y = A * X^B**	**Y = X / (A - B*X)**
January	0.62	0.64
February	0.52	0.52
March	0.62	0.61
April	0.55	0.55
May	0.74	0.75
June	0.76	0.77
July	0.82	0.82
August	0.69	0.70
September	0.48	0.49
October	0.64	0.69
November	0.68	0.67
December	0.71	0.72

The best statistical fit was obtained for the following data:

Month-specific model for July showed the best statistical fit. Data were considered for period from 01/1990 to 04/2005

Figure 6.7 shows result of month-specific model for delay metric “Average ground delay” for July

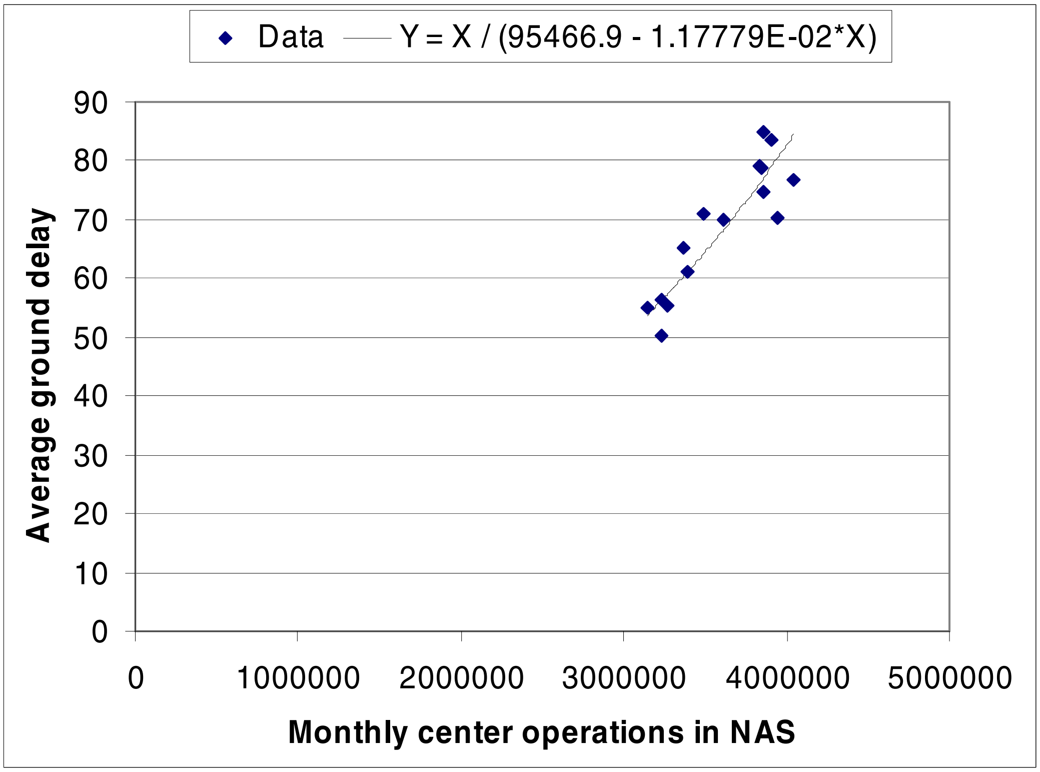

Figure 6.7 Average ground delay vs. monthly center operations in NAS (Month-specific model for July)

Results of regression analyses are shown in table 6.10 below

Table 6.10

X-Variable:	Monthly center operations in NAS			
Y-Variable:	Average ground delay			
	N	**A**	**B**	**R-Square**
Y = A * X^B	15	2.532E-10	1.744	0.819
Y = X / (A + B*X)	15	9.547E+04	-0.012	0.823

2. Results for delay metric “Fraction of center operations which are departure delayed”.

Data from 01/1994 to 04/2005 is used for estimating month-specificmodels for delay metric “Fraction of center operations which are departure delayed”.

Relation between fraction of center operations which are departure delayed and monthly center operations in NAS is estimated.

Table 6.11 shows results of regression analyses for month-specific models for delay metric "fraction of center operations which are departure delayed"

Table 6.11 (R squared values are reported.)

Period: 01/ 94 to 04/ 05	**Y =A * X^B**	**Y = X / (A - B*X)**
January	0.10	0.08
February	0.62	0.62
March	0.52	0.56
April	0.34	0.34
May	0.80	0.87
June	0.62	0.56
July	0.33	0.33
August	0.89	0.90
September	0.67	0.65
October	0.52	0.55
November	0.41	0.43
December	0.64	0.67

Month-specific models for the month of January, April and July showed very poor explanatory power. These models had R squared values less than 0.4.

The best statistical fit was obtained for the following data.

Month-specific model for August showed the best statistical fit. Data were considered for period from 01/1994 to 04/2005.

Figure 6.8 shows result of month-specific model for delay metric "Fraction of center operations which are departure delayed" for August.

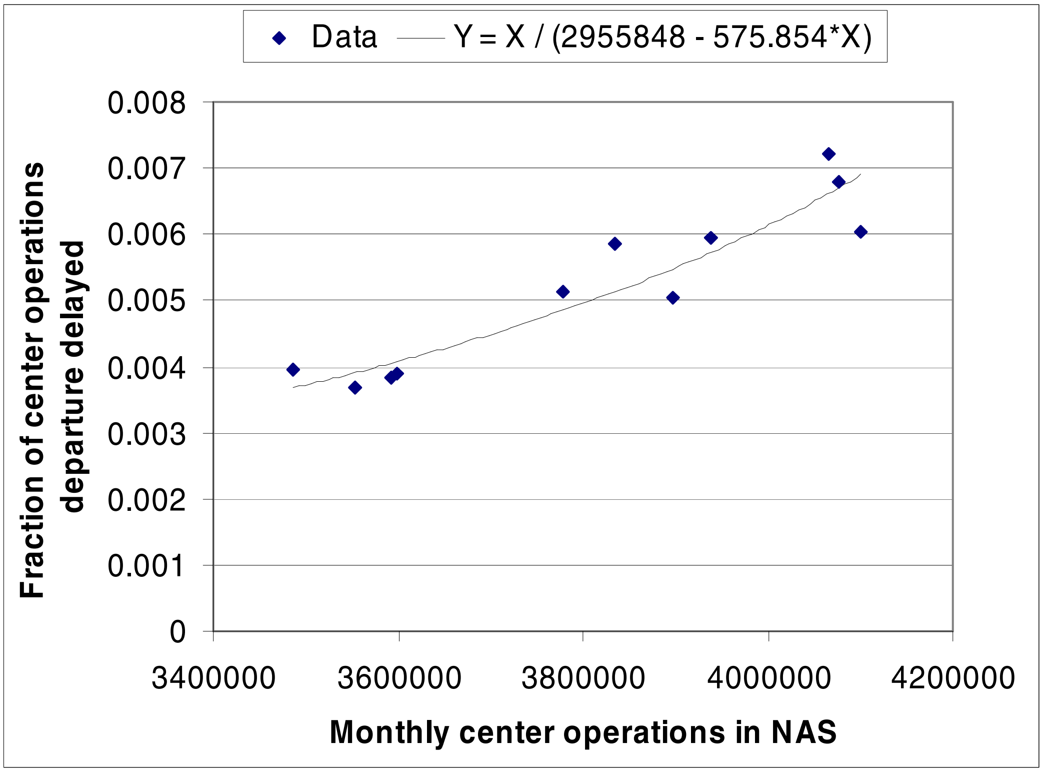

Figure 6.8 Fraction of center operations departure delayed vs. monthly center operations in NAS (Month-specific model for August)

Results of regression analyses are shown in table 6.12 below

Table 6.12

X-Variable:	Monthly center operations in NAS			
Y-Variable:	Fraction of departure delayed center operations			
	N	**A**	**B**	**R-Square**
Y = A * X^B	11	2.084E-28	3.858	0.890
Y = X / (A + B*X)	11	2.956E+09	-575.855	0.895

3. Results for delay metric "Fraction of center operations which are delayed enroute"

4. Results for delay metric "Fraction of center operations which are arrival delayed"

Model 1.2 was estimated by considering the above delay metrics as dependent variables. Regression analyses were carried out for all the models. All the models showed poor explanatory power. All the models had R squared values less than 0.4.

Daily models:

Models 2.1 to 2.4

The daily metrics used to develop these models and the period considered to develop data sets are exactly the same as the ones used to develop daily models in section 6.7.1. The above models were estimated by considering the four delay metrics as the dependent variables. Regression analyses were carried out for all the models. All the models showed poor explanatory power. All the models had R squared values less than 0.4.

6.7.2.2. Analysis of average minutes of delay by category- airport departure delay, gate departure delay, taxi- in/out delay, airborne delay, block delay and gate arrival delay

The seven delay metrics listed below are considered as dependent variables in the regression models.

1. Average gate departure delay
2. Average taxi out delay
3. Average airport departure delay
4. Average airborne delay
5. Average taxi in delay
6. Average block delay
7. Average gate arrival delay

Monthly models:

Period from 01/1998 to 04/2005 was considered for developing these models.

Monthly delay metric and monthly center operations are considered as data points. Regression analysis is performed for the following data sets.

Model 1.1

A total of seven datasets were constructed by dropping each subsequent year from1998. For example the second dataset consisted of data from 1999 to 2005 and the seventh dataset consisted of data from 2004 to 2005. Regression analyses were carried out for seven datasets.

1. to 7. Results for seven delay metrics

Model 1.1 was estimated by considering the seven delay metrics as dependent variables. Regression analyses were carried out for all the models. All the models showed poor explanatory power. All the models had R squared values less than 0.4.

Month-specific models:

Model 1.2

Twelve datasets were constructed for twelve months of a calendar year in the following way. In a dataset, each data point represents the same "calendar" month of all years from 1998 to 2005. The dataset for January consists of all January's from 1998 to 2005. Twelve data sets were constructed for twelve calendar months. Regression analyses were carried out for 12 datasets.

1. Results for delay metric "Average gate departure delay".

Relation between average "average gate departure delay" and monthly center operations in NAS is estimated.

Regression analyses were carried out for all the models. All the month-specific models showed poor explanatory power except the month of November.

The best statistical fit was obtained for the following data:

Month-specific model for November showed the best statistical fit. Data were considered for period from 01/1998 to 04/2005.

Figure 6.9 shows result of month-specific model for delay metric "Average gate departure delay" for November

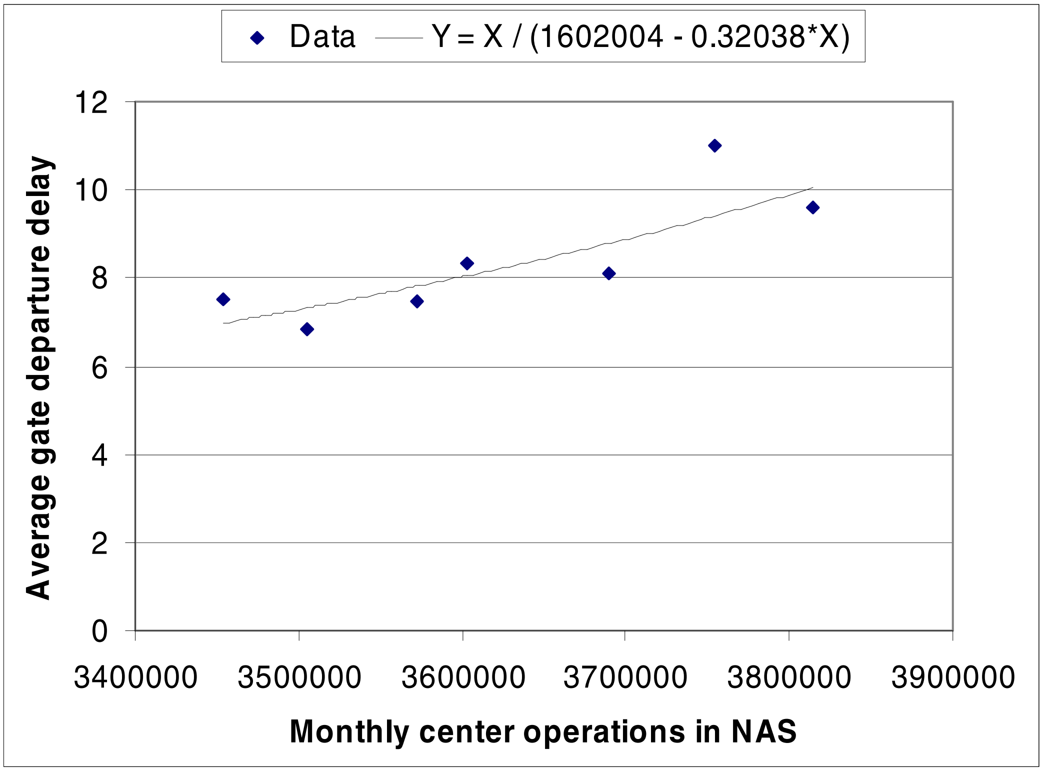

Figure 6.9 Average gate departure delay vs. monthly center operations in NAS (Month-specific model for November)

Results of regression analyses are shown in table 6.13 below

Table 6.13

X-Variable:	Monthly center operations in NAS			
Y-Variable:	Average gate departure delay			
	N	**A**	**B**	**R-Square**
Y = A * X^B	7	1.513E-24	3.772	0.700
Y = X / (A + B*X)	7	1.602E+06	-0.320	0.715

2. Results for delay metric “Average taxi out delay”.

Data from 01/1998 to 04/2005 is used for estimating these month-specific models.

Relation between average taxi out delay and monthly center operations in NAS is estimated.

Table 6.14 shows results of regression analyses for month-specific models for delay metric “Average taxi out delay".

R squared values are reported.

Table 6.14

Period: 01/98 to 04/05	**Y = A * X^B**	**Y = X / (A - B*X)**
January	0.64	0.64
February	0.23	0.24
March	0.71	0.69
April	0.52	0.52
May	0.52	0.54
June	0.94	0.94
July	0.30	0.27
August	0.70	0.69
September	0.38	0.35
October	0.88	0.88
November	0.48	0.47
December	0.25	0.29

Month-specific models for the month of February, July, September and December showed very poor explanatory power. These models had R squared values less than 0.4.

The best statistical fit was obtained for the following data.

Month-specific model for June showed the best statistical fit. Data were considered for period from 01/1998 to 04/2005.

Figure 6.10 shows result of month-specificmodel for delay metric “Average taxi out delay” for June

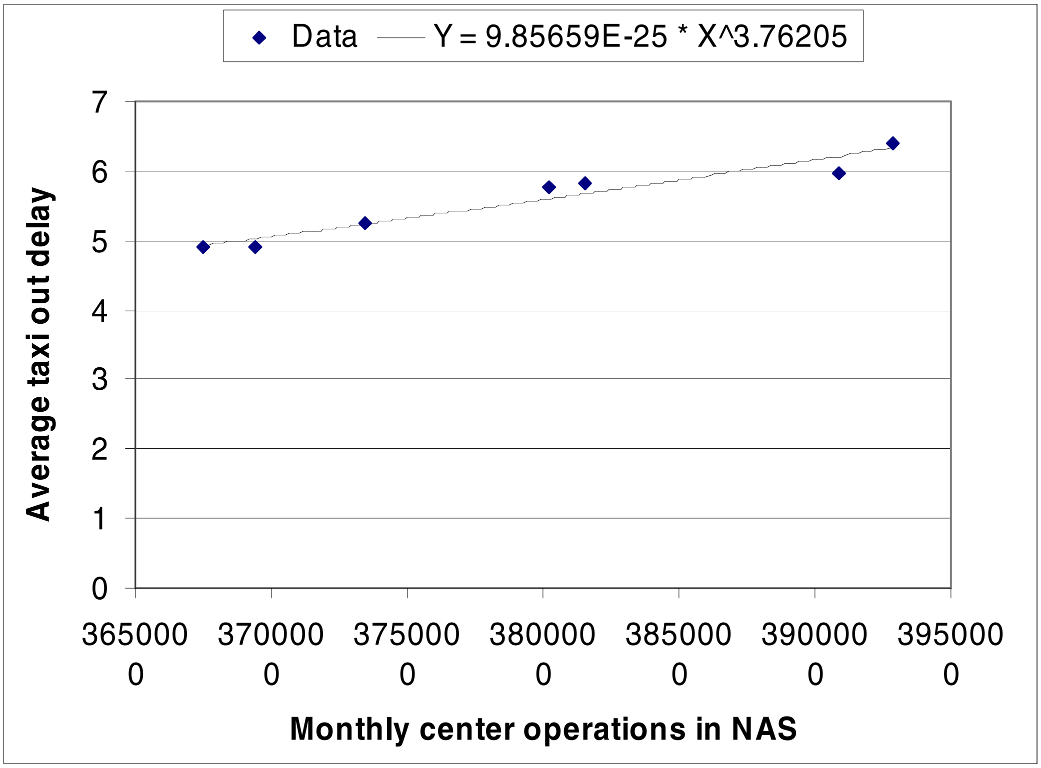

Figure 6.10 Average taxi out delay vs. monthly center operations in NAS (Month-specific model for June)

Results of regression analyses are shown in table 6.15 below

Table 6.15

X-Variable:	Monthly center operations in NAS			
Y-Variable:	Average taxi out delay			
	N	**A**	**B**	**R-Square**
Y = A * X^B	7	9.857E-25	3.762	0.944
Y = X / (A + B*X)	7	2.588E+06	-0.502	0.941

3. Results for delay metric "Average airport departure delay".

Data from 01/1998 to 04/2005 is used for estimating these month-specific models.

Relation between average airport departure delay and monthly center operations in NAS is estimated.

Table 6.16 shows results of regression analyses for month-specific models for delay metric "Average airport departure delay".

R squared values are reported.

Table 6.16

Period: 01/98 to 04/05	**Y = A * X^B**	**Y = X / (A - B*X)**
June	0.62	0.59
August	0.46	0.43
October	0.47	0.45
November	0.71	0.72

Month-specific models for all other months except above months showed very poor explanatory power. These models had R squared values less than 0.4.

The best statistical fit was obtained for the following data.

Month-specific model for November showed the best statistical fit. Data were considered for period from 01/1998 to 04/2005. Results of the model are tabulated below.

Figure 6.11 shows result of month-specific model for delay metric "Average airport departure delay" for November

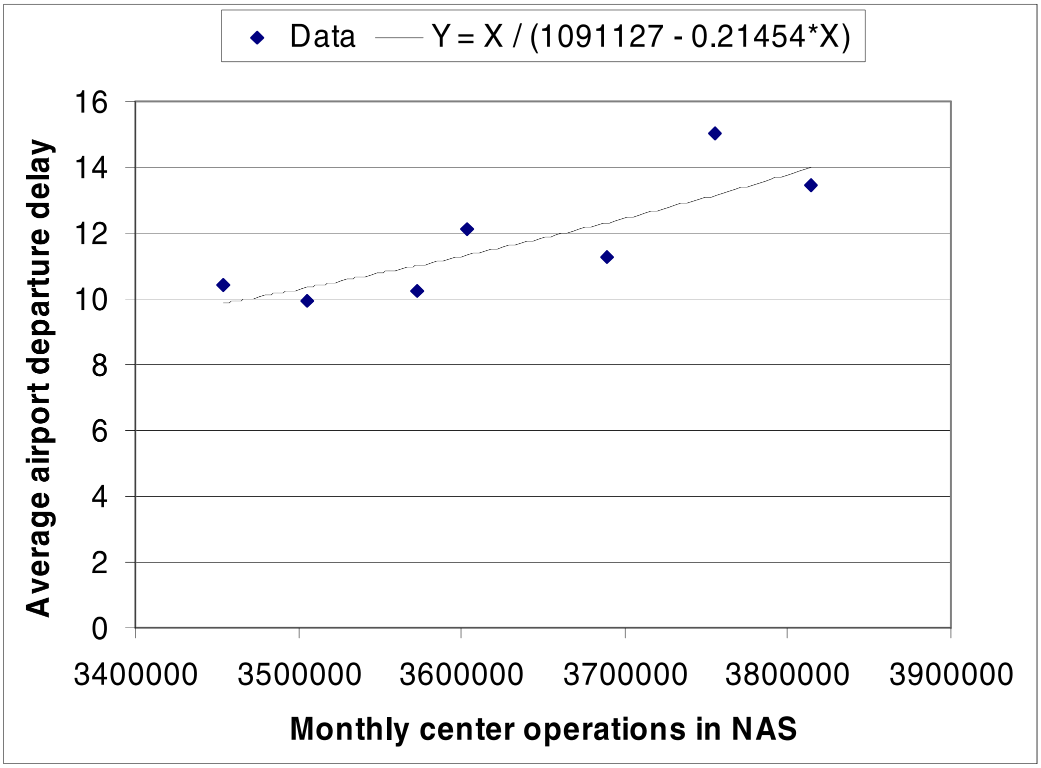

Figure 6.11 Average airport departure delay vs. monthly center operations in NAS (Month-specific model for November)

Results of regression analyses are shown in table 6.17 below

Table 6.17

X-Variable:	Monthly center operations in NAS			
Y-Variable:	Average airport departure delay			
	N	**A**	**B**	**R-Square**
Y = A * X^B	7	2.926E-23	3.598	0.708
Y = X / (A + B*X)	7	1.091E+06	-0.215	0.721

4. Results for delay metric "Average block delay".

Data from 01/1998 to 04/2005 is used for estimating these month-specific models.

Relation between average block delay and monthly center operations in NAS is estimated.

Table 6.18 shows results of regression analyses for month-specific models for delay metric "Average block delay".

R squared values are reported.

Table 6.18

Period: 01/98 to 04/05	**Y = A * X^B**	**Y = X / (A - B*X)**
September	0.54	0.55
October	0.93	0.90
December	0.41	0.43

Month-specific models for all other months except above months showed very poor explanatory power. These models had R squared values less than 0.4.

The best statistical fit was obtained for the following data.

Month-specific model for December showed the best statistical fit. Data were considered for period from 01/1998 to 04/2005. Results of the model are tabulated below.

Figure 6.12 shows result of month-specificmodel for delay metric "Average block delay" for December.

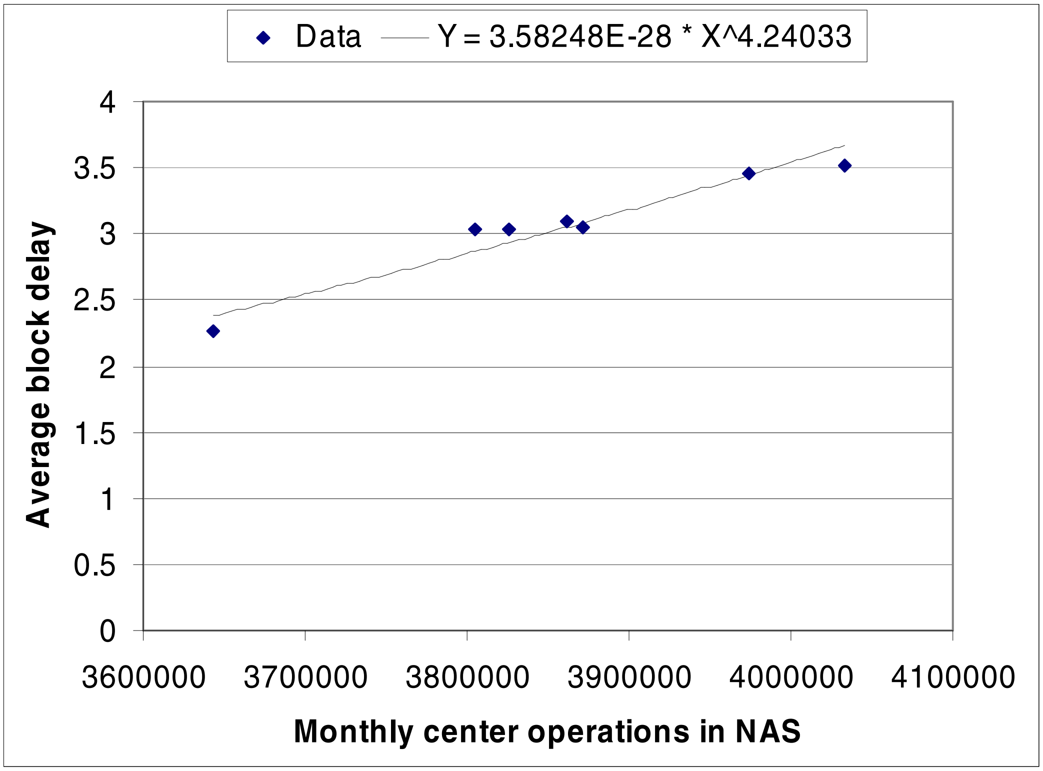

Figure 6.12 Average block delay vs. monthly center operations in NAS (Month-specific model for December)

Results of regression analyses are shown in table 6.19 below

Table 6.19

X-Variable:	Monthly center operations in NAS			
Y-Variable:	Average block delay			
	N	**A**	**B**	**R-Square**
Y = A * X^B	7	3.582E-28	4.240	0.925
Y = X / (A + B*X)	7	5.794E+06	-1.170	0.901

5. Results for delay metric "Average airborne delay"

6. Results for delay metric "Average taxi in delay"

7. Results for delay metric "Average gate arrival delay"

Model 1.2 was estimated by considering the above delay metrics as dependent variables. Regression analyses were carried out for all the models. All the models showed poor explanatory power. All the models had R squared values less than 0.4.

<u>Daily models:</u>

Models 2.1 to 2.4

The daily metrics used to develop these models and the period considered to develop data sets are exactly the same as the ones used to develop daily models in section 6.7.1.

The above models were estimated by considering the four delay metrics as the dependent variables. Regression analyses were carried out for all the models. All the models showed poor explanatory power. All the models had R squared values less than 0.4.

6.7.3. Trend analyses of different types of delays

The trends in variation of different types of delays over time and with increase in enroute traffic volume were studied. The following delay metrics (by category) were obtained as monthly metrics for all months from 01/1998 to 05/2005 from ASPM database. The delay metrics are extracted as “delays relative to flight plan” from the ASPM database.

1. Average gate departure delay
2. Average taxi out delay
3. Average airport departure delay
4. Average airborne delay
5. Average taxi in delay
6. Average block delay
7. Average gate arrival delay

The above seven delay metrics are used in this analysis. Enroute traffic volume is measured as monthly operations in all centers of NAS.

Two plots were developed to study variation in trend of the seven delay metrics.

1. Time series trend of variation in monthly delay metrics for period: 01/1998 to 05/2005.
2. Variation in monthly delay metrics with increase in monthly enroute traffic volume for period: 01/1998 to 05/2005.

Figure 6.13 shows time series trend of variation in monthly delay metrics for period: 01/1998 to 05/2005.

Figure 6.14 shows time series trend of variation in monthly enroute traffic volume.

Figure 6.15 shows variation in the seven monthly delay metrics with increase in monthly enroute traffic volume.

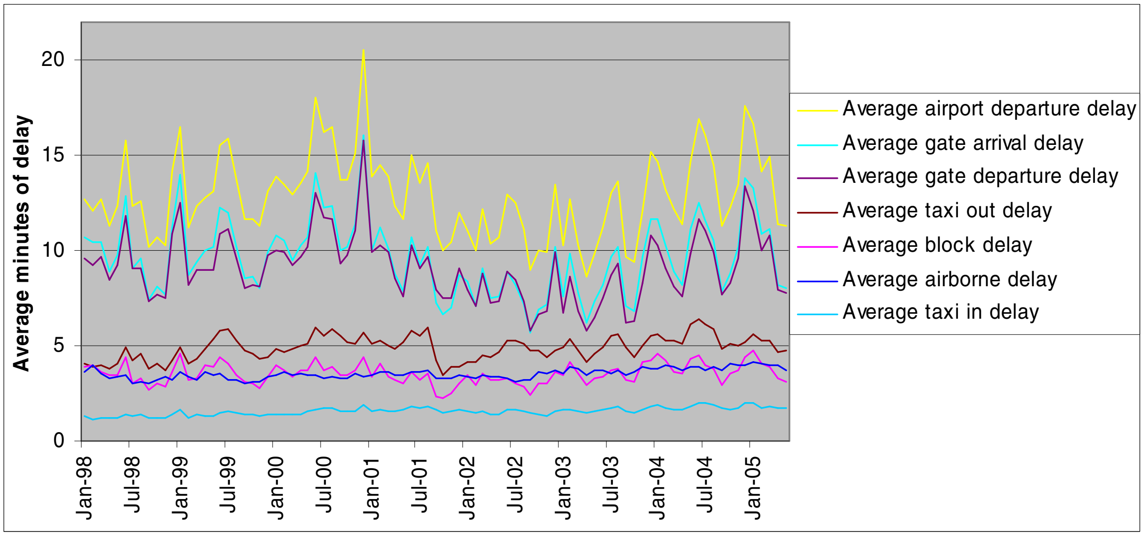

Figure 6.13 Time series trend of variation in seven monthly delay metrics

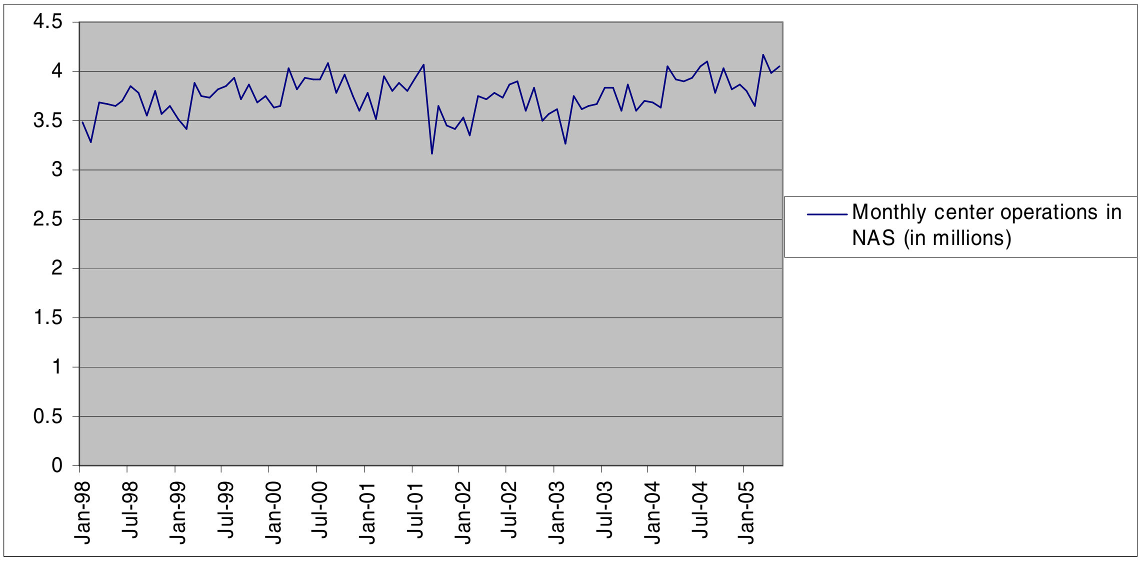

Figure 6.14 Time series trend of variation in monthly center operations in NAS

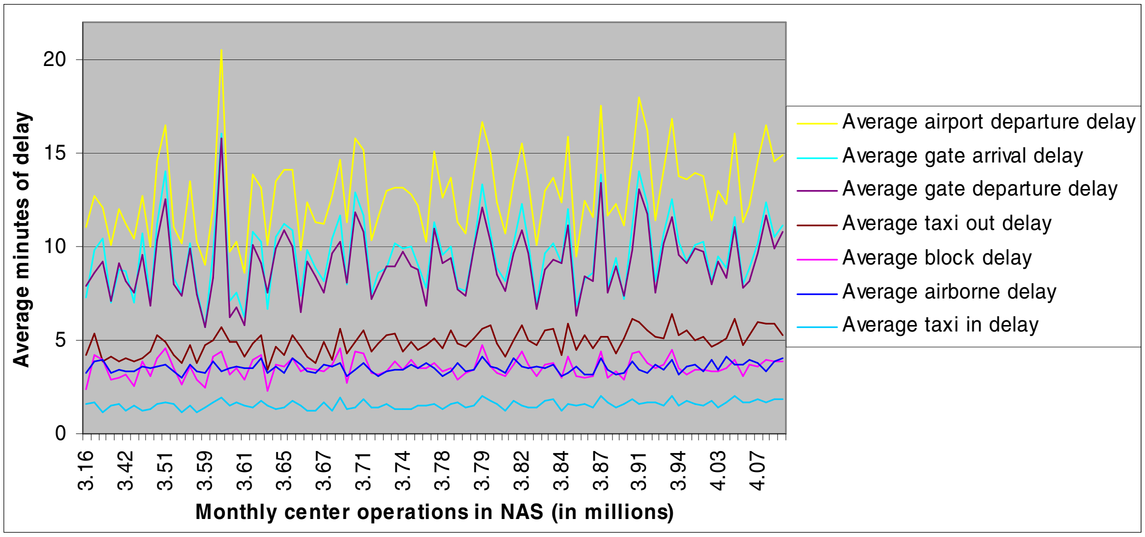

Figure 6.15 Seven monthly delay metrics vs. monthly center operations in NAS

The variation in time series trend of monthly enroute traffic volume is fairly constant from January 1998 to June 2004. The trend of enroute traffic volume shows a slight increase from June 2004 to May 2005. The time series trends of different types of delays roughly follow the time series trend of enroute traffic volume.

The variation in the trends of the seven monthly delay metrics with increase in monthly enroute traffic volume is shown in figure 6.15. The plot shows that an increase in enroute traffic volume is causing an increase in some types of delays, whereas other types of delays are unaffected by an increase in enroute traffic volume.

The following forms of delays are most affected by enroute traffic volume

1. Average airport departure delay

2. Average gate departure delay

3. Average taxi out delay.

4. Average block delay

Variation in trend of the following delays is fairly constant indicating that these delays remain unaffected by enroute traffic volume.

1. Average airborne delay
2. Average taxi in delay

6.8. Interpretation of results

6.8.1 Interpretation of results from section 6.7

The daily models performed very poor compared to monthly models and month-specific models. All the thirteen delay metrics in sections 6.7.1 and 6.7.2 showed poor results for the daily models. It was found that twenty four hour period is not sufficient to capture the effect of temporal propagation of delays. The effects of temporal propagation of delay have been discussed in section 3.3.1 of literature review.

A total of thirteen delay metrics were analyzed using monthly models and month-specific models. Monthly models for four delay metrics showed high goodness of fit. Month-specific models for eleven delay metrics showed significantly high goodness of fit compared to monthly models for the same metrics. The reasons for high explanatory power of month-specific models have been explained in next section.

All the models were estimated by using two functional forms, the hyperbolic functional form and power functional form. In all the models the two functional forms were compared for their goodness of fit .Both the functional forms performed equally well.

Results of models estimated using hyperbolic functional form have been discussed below:

Interpretation of results from section 6.7.1:

Monthly model for metric, “Fraction of center operations in NAS which are delayed due to enroute congestion” showed an R squared value of 0.45.Monthly model for metric “Fraction of delayed operations delayed due to enroute congestion” showed an R squared value of 0.34.

The R squared values of monthly models were low indicating that much of the variation in the data was still unexplained. The month-specific models for both the delay metrics showed very high goodness of fit for all twelve calendar months of the year. The month-specific model for the metric “Fraction of center operations in NAS which are delayed due to enroute congestion” showed the highest R squared value of 0.85 for month of May. Month-specific model for metric “Fraction of delayed operations delayed due to enroute congestion” showed highest R squared value of 0.77 for the month of July.

Interpretation of results from section 6.7.2:

Relations were estimated between eleven different forms of delays and enroute traffic volume to identify the forms of delays used to reduce air delays caused by enroute congestion. The eleven different forms of delays used in this analysis are listed below:

1. Average minutes of ground delay
2. Fraction of center operations which are departure delayed.

3. Fraction of center operations which are delayed enroute.
4. Fraction of center operations which are arrival delayed.
5. Average gate departure delay
6. Average taxi out delay
7. Average airport departure delay
8. Average airborne delay
9. Average taxi in delay
10. Average block delay
11. Average gate arrival delay

Results of monthly models:

Monthly models were estimated for eleven delay metrics. Monthly models for only two delay metrics - “average ground delay” and “fraction of center operations departure delayed” showed good explanatory power (R squared values greater than 0.4).

Monthly models for 9 other delay metrics showed very poor explanatory power.

Monthly models for delay metrics, “average ground delay” and “fraction of center operations which are departure delayed” showed R squared values of 0.50 and 0.39 respectively.

Results of month-specific models:

The results of month-specific models for delay metrics along with the calendar months are listed in table 6.20.

Table 6.20

1.	**Average ground delay**	**12 months**	
2.	Fraction of center operations which are departure delayed	12 months	
3.	Average taxi out delay	8 months	January, March, April, May, June, August, October and November
4.	Average airport departure delay	4 months	June, August ,October and November
5.	Average block delay	3 months	September, October and December
6.	Average gate departure delay	1 month	December

It was found that the following forms of delays are used to reduce air delays caused by enroute congestion.

1. Ground delays
2. Taxi out delay
3. Airport departure delay
4. Gate departure delay

Monthly models and month-specific models for the following delay metrics showed very low R squared values. It could be proposed that the following forms of delays are not used to reduce air delays caused by enroute congestion:

1. Airborne delay
2. Taxi in delay
3. Gate arrival delay

Statistical analyses showed that there is a relation between block delay and enroute traffic volume. ASPM computes “average block delay” as the difference between actual gate-to-gate time and scheduled gate-to-gate time. Hence, block delay includes airport departure delay, taxi out delay, airborne delay, taxi in delay, and gate arrival delay. Statistical relation was not seen between delay metrics-airborne delay, taxi in delay, and gate arrival delay and enroute traffic volume. Statistical relations were seen between enroute traffic volume and delay metrics -airport departure delay and taxi out delay.

It is possible that the explanatory power of the delay metric “block delay” is because of strong statistical relations between enroute traffic volume and delay metrics -taxi out delay and airport departure delay.

6.8.2 Interpretation of results from section 6.7.3

In sections 6.7.1 and 6.7.2, types of delays are identified which are used to reduce air delays caused by enroute congestion. Airport departure delay, gate departure delay and taxi out delay were identified as the types of delays used to reduce air delays caused by enroute congestion.

In section 6.7.3, trend analyses of different types of delays over time and with increase in enroute traffic volume is studied. This analysis confirms the results of the statistical analyses which showed that airport departure delay, gate departure delay and taxi out delay are used to reduce air delays caused by enroute congestion.

6.8.3 Relation between delays and enroute traffic volume in the NAS

It is found that a hyperbolic function is applicable for estimating relations between delays and enroute traffic volume in the NAS. As the enroute traffic demand approaches NAS capacity, a small increase in traffic demand causes an asymptotic increase in delays. The hyperbolic function used in the analyses fits the delay-volume data very well.

Wieland 2004 shows confidence in his models by explaining that the relations between delays and traffic volume are estimated from recorded data and not from simulation models. Similar to Wieland, confidence can be placed in the results of the estimated statistical models, since these models are estimated from delay and traffic data recorded by FAA databases.

The monthly models developed by us gave poor results for all delay metrics. The R squared values of these monthly models ranged from 0.34 to 0.58.

Month-specific analyses were performed for the same data which were used to estimate monthly models. Month-specific models gave very good results compared to monthly models. A significant proportion of variation in the data can be explained with the month-specific models. It is proposed that the monthly operational capacity of enroute airspace could differ considerably for different calendar months of the year. Monthly capacity of enroute airspace could differ for each calendar month of the year because of the following reasons:

i. Month-specific weather influences the monthly operational capacity of the enroute airspace. Operational capacity of enroute airspace is different for each calendar month of the year. Weather is responsible for the significant variation in the data in the models developed by us. Month-specific models can explain a significant proportion of variation in data, which is caused by weather.

ii. Air traffic demand in the NAS is different for each calendar month of the year. ATC system implements different programs in NAS during specific calendar months of the year .These programs are implemented to increase efficiency of the NAS and to reduce delays in the system.

6.8.4. Reasons for low explanatory power of the monthly and month-specific models

The following reasons are responsible for the low explanatory power of the monthly models and month-specific models estimated in sections 6.7.1 and 6.7.2.

i. Factors affecting the hyperbolic relation between delays and demand in the NAS

Wieland 2004 explains that the simple queuing relation used in his models is valid if the monthly enroute operational capacity of NAS is held constant.

Similarly, the hyperbolic function used in the estimated models is valid only if the monthly enroute operational capacity of NAS is held constant.

The monthly enroute operational capacity of NAS could be affected by many factors. Wieland 2004 has explained factors affecting monthly enroute operational capacity of NAS, which have been discussed in section 3.3.3 of literature review. The factors proposed by Wieland 2004 are summarized below:

1. Airspace, airport and procedural restrictions
2. Scheduling patterns i.e. Mix of freight traffic and point – to – point and hub and spoke passenger traffic. Scheduling greater number of flights during midnight and 5:00 AM local time.
3. Change in control procedures, pilot skills, controller workload, and winds
4. Adjustments in the behavior of the users of the system which could include excessive cancellations of flights, schedule adjustments, more frequent use of off peak times, serving different airports, and changes in size of aircraft and service frequency.
5. Regulatory changes like the current slot auctioning at LGA airport
6. Programs implemented by FAA to increase the capacity of NAS like Operational Evolution Plan (OEP).
7. Planned future improvements and changes resulting from a change of business practices adopted by the aviation service providers.

ii. Incorrect measurement of air traffic demand imposed on the NAS.

In section 3.2.2.1 of the literature review it has been explained that characteristics of aircraft and operations cause varying levels of ATC complexity.

ATC complexity affects the workload on the controllers and ATC system. Depending upon the characteristics of aircraft and operations, the same number of operations can cause different workload on the system. The current measure of system workload (NAS demand) is operations per unit time which does not capture the ATC complexity involved in controlling those operations.

Kies 2004 explains that an increase in traffic volume of regional jets can cause increased congestion in enroute airspace and at some airports. Regional jets can also cause an increase in congestion and traffic complexity in transition airspace where climbs and descents of aircraft take place.

The current model uses monthly operations as a measure of enroute air traffic demand. Monthly operations do not represent the ATC complexity imposed by those operations and the true demand imposed on the system. This could be one of the reasons for low variance in the monthly and month-specific models.

iii. Effect of localized airspace congestion in the NAS

The aggregate analysis for entire NAS using monthly and daily measures of enroute traffic volume and delays could average the effect of localized congestion and delays which occur at a specific place and time in NAS.

In section 5.7.1, it was found that congestion in a considered sector or center does not increase excess distances traveled by flights or time delays imposed on flights passing through that sector or center. The problem of aggregating this analysis in time and space is that, the effect of traffic congestion in a sector will be averaged out.

Simulation software's need to be developed which can model time delays (circular holding, MIT restrictions and ground delays) imposed on flights and excess distances traveled by flights (rerouting of flights around a sector and "vectoring") because of congestion in parts (sectors, fixes and jetways) of enroute airspace.

6.9. Drawbacks of analyses

The drawbacks of analyses performed in section 6.7 have been discussed below:

6.9.1. Drawbacks of data used in the analyses

In the analysis, enroute traffic volume is measured in terms of center volume in all centers of NAS. OPSNET center volume data has been used for estimating enroute traffic volume. In section 3.3.5.2 of literature review, we have discussed the accuracy and advantages of OPSNET center volume data in representing the total enroute traffic in NAS.

The delay data from OPSNET and ASPM databases were used in the analysis. The delays provided by OPSNET and ASPM databases do not represent the total delays in the NAS. The drawbacks of delay and traffic volume data provided by each database have been discussed below:

Delays from ASPM database:

By agreement with the FAA, ASPM flight data are filed by certain major air carriers for all flights to and from most large and medium hubs (31 airports). The ASPM database also includes data from the Airline Service Quality Performance (ASPM) database, Enhanced Traffic Management System (ETMS) database and Aeronautical Radio, Inc. (AIRINC). ASPM database provides delay and traffic data for 55 airports in NAS.

Delays from OPSNET database:

OPSNET provides data for delays and traffic volume for IFR traffic, non IFR traffic, flights which file plan and flights which do not file flight plan with the ATC system. OPSNET data are recorded by all air traffic control (ATC) facilities, except the flight service stations. OPSNET provides delay and traffic data for a total of 539 airports in NAS.

Drawbacks of data:

ASPM does not provide delay data for all flights in NAS; however unlike OPSNET database it provides delay data for less than 15 minute delays. Average delay from ASPM database was used in the analyses. It is assumed that the average delay from ASPM database represents the average delay for all traffic operations in NAS.

OPSNET provides delay data for all flights in NAS. However OPSNET provides delay data for only greater than 15 minute delays. In section 6.7, relations have been estimated between OPSNET delays and enroute traffic volume. These delay volume curves underestimate the total delays caused by enroute traffic volume.

6.9.2. Drawbacks of month-specific models

The main drawback of the month-specific analysis is that few data points were available for regression analysis. Data points in the month-specific datasets varied from maximum of sixteen data points to a minimum of six data points.

CHAPTER VII: CONCLUSIONS

In this study, relations are estimated among enroute traffic, controller staffing and ATC system performance. The following three main relations are estimated:

1. Relation between controller staffing and enroute NAS air traffic
2. Relation between controller performance and air traffic in NAS sectors and centers
3. Relation between ATC system performance and enroute NAS air traffic

Conclusions for each of the three estimated relations are discussed separately in sections 7.1, 7.2 and 7.3.

7.1. Relations between controller staffing and enroute air traffic in the NAS

During discussions with controllers it was found that air traffic operations and ATC complexity are used as a basis for staffing controllers in sectors. In the literature it is seen that difficulties arise in the measurement of ATC complexity. In section 7.1.1 the impact of enroute traffic on ATC complexity and controller staffing is studied.

In section 7.1.2 findings from the literature, the FAA controller forecasting model, and FAA`s controller staffing standards and analyses are used to develop a relation between controller staffing and enroute traffic. The results of estimated relations between controller staffing and operations are discussed. The factors which bias the estimated relations between controller staffing and operations are explained in section 7.1.2.2.

7.1.1. Relation between enroute traffic, ATC complexity and controller staffing

For developing a macroscopic relation between controller complexity, controller workload and traffic volume for the entire NAS, it is proposed that regardless of airspace complexity, an increase in traffic volume will cause increase in controller complexity and workload. The use of the HCI metric developed by FAA to staff controller positions supports the hypothesis that traffic characteristics can be used to measure complexity and workload on controller. (The HCI metric is discussed in section 3.1.5.2)

In section 4.1.1 relations are estimated between ATC complexity (HCI-Hourly Classification Index) and air traffic operations which show that center complexity increases linearly with center operations. *ATC controller grade levels and salaries in centers increase linearly with NAS center operations.*

Based on the literature review and analyses it is shown ATC complexity increases with enroute traffic. Hence the variable “operations per unit time” captures the ATC complexity involved in controlling those operations. In this study, operations per unit time is considered as a measure of controller staffing for sectors and centers and for entire NAS.

7.1.2. Relation between controller staffing and enroute traffic

A proposed relation between controller staffing and enroute traffic is based on findings from the literature and FAA controller staffing standards. The FAA controller forecasting model (FAA 1991) uses linear regression to relate controller staffing with forecasted annual center operations. Hence, it is found that controller staffing grows at least linearly with air traffic operations. Findings from sections 3.1.6, 3.1.7 and 4.1.2 support the hypothesis that the numbers of air traffic controllers required are at least equal to those predicted by the linear regression staffing models used by FAA. Since the controller staffing model equations are linear, it is found that the controller staffing grows at least linearly with air traffic operations. The findings from sections 3.1.6, 3.1.7 and 4.1.2 which support the proposed relation are explained in section 7.1.2.1.

7.1.2.1. Findings from sections 3.1.6, 3.1.7 and 4.1.2 which support the proposed relation between controller staffing and enroute traffic.

Findings in the literature review, FAA controller staffing models and standards, and analyses are the basis for the hypothesis that the controller staffing grows at least linearly with air traffic operations.

1. An increase in center operations will cause an increase in controller task times and controller staffing for handling same number of operations in center. This finding has been discussed in detail in section 3.1.6.
2. There are diseconomies of staffing additional controllers to sectors. This finding has been discussed in detail in section 3.1.7.
3. The creation of additional NAS sectors through resectorisation causes an increase in controller staffing. This finding has been discussed in detail in section 3.1.7.
4. With growth in air traffic operations during off-peak periods, additional staffing of controllers will be required during off-peak periods. This finding has been discussed in detail in section 3.1.7.

In section 4.1.2 relations are estimated between the growth of air traffic operations during the peak 1830 hours and second busiest 1830 hours of a 365 day period in center. Results show that the relation between peaking factor and air traffic is linear for three out of five centers. Growth rate for operations is similar for peak and off-peak periods in some centers. As center operations increase during off-peak periods, additional staffing of controllers and flight data positions will be required during those periods.

The entire NAS should be considered in estimating relations between controller staffing, and enroute traffic. It is discussed in the literature that coordination exists among different ATC units and the ATC system performs tactical and strategic planning for the entire NAS. Different programs implemented by ATC system are also implemented for entire NAS.

In section 4.1.3 it is found that relations estimated between “monthly onboard controller staffing” and “monthly center operations” did not show the hypothesized expected relation in which controller staffing grows at least linearly with operations.

Relations estimated for entire NAS and individual centers did not exhibit the proposed relation between controller staffing and enroute traffic. It is suggested that this unexpected result is biased by factors which affect the estimated relations. These factors are identified based on literature. The factors which bias the estimated relations between controller staffing and enroute traffic have been discussed in literature and are summarized in section 7.1.2.2 below.

7.1.2.2. Factors which bias the estimated relations between monthly onboard controller staffing and monthly enroute operations in NAS centers

1. The effect of improvement in ATC equipage and individual differences among controllers like work experience, age, training and performance of controllers could affect the estimated relations.

2. The strategic and tactical planning and air traffic management performed by ATC personnel other than the controllers could bias the relations between controller staffing and operations in sectors and centers of NAS.

3. Controllers are assigned different ATC grade levels. In the estimated relations it is assumed that controllers belonging to different grade levels are equal in terms of handling air traffic activity. Other ATC positions which control air traffic are not included in the measure of controller staffing.

4. The variable “monthly onboard controller staffing” in a center may not represent total number of controllers who worked at a center facility in a month. An explanation is provided in section 4.2.3. The variable “monthly onboard controller staffing” in a center does not capture the total controller work time spent by controllers in a month

Such analyses may be tried in the future with SISO data using the variable “Monthly controller work hours in a center”.

These results do not show the proposed relation between controller staffing and enroute traffic. This analysis should be repeated using variable “Monthly controller work hours in a center”.

In section 4.1.4 the adequacy of controller forecasting model is evaluated by comparing model predicted controller staffing with the actual on board controller staffing. The result of the analysis and its effect on the relation proposed between controller staffing and enroute operations is discussed below:

7.1.2.3 Assessing the adequacy of current controller forecasting model.

It is found that the FAA model predicted controller staffing is greater than the actual onboard controller staffing for the considered data. It can be concluded that the controller forecasting model (which uses linear regression to relate controllers and operations) provides more than adequate air traffic controllers in NAS centers. Based on these results it is difficult to draw any conclusions regarding the proposed relation between controller staffing and enroute traffic.

Analyses in section 4.1.3 do not support the hypothesized relation in which controller staffing increases at least linearly with air traffic operations. This is due to bias caused by factors which affect the estimated relations. These factors are discussed in section 7.1.2.2. However findings in section 7.1.1 and 7.1.2 support the proposed relation between controller staffing and enroute traffic. Feasible analyses for estimating relations among controller staffing, enroute traffic and factors affecting controller staffing are limited by the data which the FAA records.

7.2 Relations between controller performance and air traffic in NAS sectors and centers

Controller workload and performance measures are developed for sectors and centers in NAS. Models are developed to estimate relations between controller workload and performance in sectors and centers. In the literature it is found that the controller performance metrics for a sector/center can be biased by congestion in successive enroute sectors/centers along flight paths. Hence models are developed to relate controller performance in a center/sector and congestion in successive centers/sectors. Flights between a city pair are analyzed, wherein controller performance in a center is related to congestion in all the successive centers on flight paths. Three models which are discussed in sections 5.4.1 to 5.4.3 are developed. In the literature it is found that controller performance metrics may be biased due to terminal congestion, weather, runway capacity constraints and equipment failures. Hence care is taken in choosing data for sectors/centers and time periods so that the flights are not delayed due to those causes.

In another analysis the performance of R and R & D controller staffing configurations in a sector is compared in managing the air traffic activity assigned to each configuration

The conclusions based on the analyses and results of estimated models are discussed below:

7.2.1. Conclusions based on results of the models used to estimate relations between controller performance and air traffic in sectors and centers

Relation between controller performance and air traffic in sectors and centers

Delays and excess distances traveled by flights are considered as measures of controller performance. Based on the literature, a relation in which delays grow nonlinearly and steeply as enroute traffic increases was expected for NAS sectors and centers. Similarly a linear relation with a positive slope was expected between excess distance traveled by flights and enroute traffic in sectors and centers of NAS.

Results from models show that there is no relation between controller performance and controller workload metrics. Results from scatter plots developed between controller performance and controller workload show almost flat relations in all cases. t test results also show that the values of controller performance metrics are equal under different levels of controller workload. Delay incurred by a flight in a center is the sum of delays in individual sectors. It is possible that varying congestion levels in individual sectors could affect the total delays in a center. Hence analyses are performed considering sector airspaces. However results obtained are similar to results for centers.

This shows that the current air traffic activity in sectors and centers of NAS does not significantly affect the performance of the controllers in controlling the air traffic in the same sectors and centers. The demand has not reached the capacity in sectors and centers of NAS. The current air traffic activity in sectors does not force controllers to impose time delays or excess distances on flights. In the considered data it is found that the ATC system, controllers and programs implemented by ATC system are functioning efficiently in controlling flights in sectors and centers so as not to delay flights because of congestion in same airspace.

It is found that the current staffing methods provide adequate controller staffing for different levels of traffic activity in sectors. The performance of controllers in sectors is not degraded due to understaffing of controllers.

It is found that the performance of a controller in a sector/center is not affected by congestion in any of the successive sectors/centers along flight paths passing through that sector/center.

Comparison of results with the relation proposed by Howell et al 2003

Results are compared with the relation between traffic activityand average excess distance (traveled by flights), which has been proposed by Howell et al 2003. Based on this comparison it is seen that the current traffic levels in sectors and centers of NAS can be categorized into the "route structure regime" (figure 3.3). Howell et. al. (2003) explain that traffic levels in the airspaces are such that flights are restricted to stay on route structure, but extensive maneuvering is not required to control traffic flow. Excess distance traversed by flights in this regime is almost constant.

Howell et al. 2003 propose that the normalized traffic activity in the route structure regime is between 30% to 70% of the peak traffic activity. Hence it is suggested that the current traffic activity is between 30% to 70% of the maximum activity which could be handled in sectors and centers. Howell at al 2003 propose implementation of tools or initiatives to reduce the excess distance in this regime. They also report that the current congestion levels in sectors cause nominal delays because of sector capacity limitations. Howell et al 2003 report results obtained by the FAA Technical Center using NASPAC simulation. That FAA study is reported to show that enroute sector capacity limitations by the year 2010 will cause “inefficiency” (excess distance delays) comparable to the delays caused in “route structure regime”. That FAA study is also reported to show that by 2020 enroute sector capacity constraints will be the greatest cause of (inefficiency) delays.

The results of performance comparison of the R controller staffing configuration with R & D controller staffing configuration (in a sector) in managing the air traffic activity assigned to each staffing configuration are discussed below:

7.2.2. Performance comparison of R and R & D controller staffing configurations

For some sectors it is found that the performance of the two different controller staffing configurations is not equal and no specific staffing configuration performed better than the other.

The facility managers and supervisors use their judgment and consider complexity in assigning an additional D controller to a sector. The traffic activity and corresponding controller workload subjected to the two controller staffing configurations could be different. We conclude that the current method of staffing an additional “D” controller to a sector could be inadequate for some sectors in NAS. The above results are based on the assumption that the controller performance metrics are affected only by controller workload caused by air traffic in same sector, since required care is taken in choosing the sectors and time periods.

From data analyses, it is found that a single sector or center airspace is insufficient for estimating relations between controller performance and controller workload in the same sector or center. That is unsurprising, since congestion effects easily spill beyond a small airspace. It is concluded that the relations between controller performance and air traffic should be estimated considering entire NAS. The following difficulties are encountered while estimating relations between controller performance measures and air traffic congestion in a sector or center.

7.2.3. Difficulties in estimating relations between controller performance measures and air traffic congestion in a sector or center.

i. Factors which bias the controller performance metrics and estimated relations

Although care is taken in choosing data for sectors/centers and time periods the relations estimated between controller performance metrics and controller workload metrics could be biased. Based on statistical analyses for some models it is found that different types of operations could have restrictions imposed on them because of terminal and airport congestion at arrival airports or congestion in the upstream enroute centers on the route of the flights.

ii. Drawbacks in the data used to estimate relations

1. It is found that simulation models are not suitable for estimating delays imposed on flights due to sector and center congestion. Simulation models employ built-in rules to

delay flights. Hence it is decided to use flight track data to measure delays caused by sector and center congestion. The ETMS boundary crossing data used for analyses had errors and did not consist of all flights traversing the airspaces. ETMS data are identified as the best source of flight track data recorded by FAA, so despite the above drawbacks ETMS data are the only source of flight track data which can be used for the proposed analyses.

2. There are drawbacks in models analyzed in section 5.4.3. Few data points are available for analysis. Analyses can be performed only for those flights which fly through the same centers in the same sequence along their flight paths. This analysis could not be performed for sectors since detailed ETMS data are not recorded for sectors.

7.3 Relations between ATC system performance and enroute air traffic in the NAS

It is found that the relations between controller (ATC system) performance and enroute air traffic cannot be estimated for individual sectors and centers in NAS due to the factors which bias the controller performance metrics and the difficulties in estimating these relations. These factors are discussed in section 7.2.

Based on literature and the relations estimated for sectors and centers, it is found that the following considerations should be employed for estimating relations between controller (ATC system) performance and enroute air traffic.

7.3.1. Considerations in estimating relations between ATC system performance and enroute air traffic in the NAS

i. The relations are to be estimated for entire NAS

The enroute capacity of the NAS is not only limited by the performance of controllers staffed in its sectors. The performance of entire ATC system needs to be evaluated in reducing delays caused by enroute traffic volumes in the NAS. The factors which make it necessary to estimate relations for NAS are discussed in section 3.3.1.

ii. The relations are to be estimated by considering monthly and daily measures of delays and enroute traffic volumes

The factors which make it necessary to estimate relations by considering daily and monthly measures of delays and enroute traffic volume are discussed in section 3.3.1.

iii. The need to use recorded delay data to estimate relations

The suitability of simulation models is studied to estimate relations between NAS performance and enroute traffic. The limitations of simulation models for estimating the relations are discussed in section 3.3.2.1. This necessitates the use of recorded data on the movement of flights in the NAS, consisting of flight transit times and distances traveled. Based on these data, analyses are proposed to estimate relations between flight times, excess distances traveled by flights and enroute traffic volumes. It is found that the NAS performance measures -flight times and excess distances are biased. These difficulties in estimating relations are explained in sections 9.1 and 9.2.

Analyses are proposed considering sector MAP values and enroute delays caused by Traffic Management processes as measures of system performance. These proposed analyses are discussed in sections 9.3.1 and 9.3.2 and could not be performed due to unavailability of data.

A need is identified for using recorded delay data to estimate relations between recorded delays and enroute traffic volume in NAS. OPSNET data are identified as the best source of data on delays due to enroute traffic volumes. The advantages of OPSNET data are discussed in section 3.3.5.

Relations are estimated between delays (specifically caused by enroute congestion) and enroute traffic volume in the NAS. In the literature it is found that ground delays, taxi out delay and departure delays are imposed on flights at the origin airport to reduce air delays caused by enroute airspace congestion. Relations are estimated between eleven different forms of delays and enroute traffic volumes to identify the different forms of delays used to reduce air delays caused by enroute airspace congestion. Time series trends and trends in variation of delays with increase in enroute congestion are useful for identifying delay types used to reduce air delays.

Daily and monthly models are developed for estimating relations between delay metrics and center operations in the NAS. In daily models, daily measures of delays are related with daily NAS center operations. In monthly models, monthly measures of delays are related with monthly NAS center operations. Month-specific models are also developed considering same calendar month of successive years as data points. The following conclusions are reached based on results of analyses and estimated models.

7.3.2. Conclusions about relations between delays and enroute traffic volumes in the NAS

The daily models perform very poorly compared to monthly models and month-specific models. All the considered delay metrics in analysis show poor results for the daily models. It is concluded that considering days as time periods is not sufficient for capturing the effect of temporal propagation of delays. Month-specific models show the highest goodness of fit, followed by monthly models. A total of thirteen delay metrics are analyzed using monthly models and month-specific models. Monthly models for four delay metrics show high goodness of fit. Month-specific models for eleven delay metrics show significantly higher goodness of fit compared to monthly models. The need to develop monthly models and month-specific models is discussed in sections 6.4.3 and 6.4.4 respectively.

A significant variation in the data in the monthly models could be explained with the month-specific models. The monthly operational capacity of enroute airspace could differ considerably for different months during a year for the following reasons:

a. Month-specific weather effects could significantly affect the monthly NAS capacity.

b. Air traffic demand in the NAS is different for each calendar month. ATC system implements different programs in NAS during specific months.

The following conclusions can be drawn based on the results of monthly models and month-specific models.

1. The hyperbolic function is applicable for relating the fraction of operations delayed due to enroute congestion and enroute NAS traffic volumes. The hyperbolic function is also applicable for relating the fraction of delayed operations which is delayed by enroute congestion and enroute traffic volumes in the NAS. The hyperbolic function fits the delay-volume data very well. These results show that as enroute traffic volumes, increase the fraction of operations delayed due to enroute congestion and the fraction of delayed operations delayed due to enroute congestion increase hyperbolically.

2. The hyperbolic function gives a good statistical fit when relations are estimated between different delay types and enroute traffic volumes in the NAS. The ATC system uses specific delay types to reduce air delays caused by enroute airspace congestion.

The following forms of delays are used to reduce air delays caused by enroute airspace congestion:

a. Ground delays
b. Taxi out delay
c. Airport departure delay
d. Gate departure delay

The ATC system appears to be quite efficient in keeping delays due to enroute congestion on the ground at the departure airports. This suggests that Ground Delay Programs have been effective in reducing air delays.

The following forms of delays are not used to reduce air delays caused by enroute airspace congestion.

a. Airborne delay

b. Taxi in delay

c. Gate arrival delay

Trend analysis of different types of delays performed in section 6.5.3 confirms the results of the monthly and month-specific models which show that taxi out delay, airport departure delay and gate departure delay are used to reduce air delays caused by enroute airspace congestion. Variation in trend of airborne delay and taxi in delay is fairly constant, indicating that these delays remain unaffected by enroute congestion.

The statistical models are estimated from delay and traffic data recorded by FAA databases. Hence confidence can be placed in the results of these models, as suggested by Wieland 2004. However a significant variation in data is still unexplained by the models. There also some drawbacks in the estimated models. These drawbacks and the reasons for variation in data are explained below:

7.3.3. Drawbacks of monthly and month-specific models

1. The delay-demand relations used in the models are valid only if the monthly enroute operational capacity of NAS is held constant, as suggested by Wieland 2004. There are factors which affect the enroute operational capacity of NAS, as suggested by Wieland 2004, which are discussed in section 3.3.3 of literature review.

2. Measurement of true demand imposed on ATC system

The characteristics of aircraft and operations lead to varying levels of ATC complexity and workload on controllers and on the ATC system. The monthly and month-specific models developed in sections 6.5.1 and 6.5.2 use monthly operations as a measure of enroute air traffic demand. The current measure of workload on controllers and ATC system is operations per unit time; it does not capture the ATC complexity involved in controlling those operations. Monthly operations do not represent the true demand imposed on the system and this could be one of the reasons for the low explanatory power of the models.

Reasons for low explanatory power of the models are discussed in section 6.8.4

3. Drawbacks of delay data used to estimate models.

The delay data from OPSNET and ASPM databases do not represent the total delays in the NAS. ASPM does not provide delay data for all NAS flights. Hence it is assumed that the average delay from ASPM database represents the average delay for all NAS traffic operations.

Although OPSNET provides delay data for all flights in NAS, OPSNET provides delay data only for delays exceeding 15 minutes. The delay volume curves estimated using OPSNET delays underestimate the total delays caused by enroute congestion.

7.4. Models and results which can be incorporated in the FAA NAS Strategy Simulator

In this study relations are estimated among enroute traffic, controller staffing and NAS performance. The following findings, results and models can be incorporated in the NAS Strategy Simulator currently being developed by FAA.

1. A relation in which controller staffing increases at least linearly with enroute air traffic operations is found in the NAS. The relation between controller staffing and enroute air traffic in the NAS has been estimated in chapter IV.

2. It is found that the relation between center complexity (HCI metric developed by FAA) and center operations is linear in the NAS. The relation between controller grade levels (wages) and center operations is found to be linear in the NAS. In section 4.1.1 regression analyses were performed by relating HCI metric to center operations in centers. The above finding is based on the regression analyses conducted for five chosen centers in the NAS.

3. The following models can be incorporated in the strategy simulator. These models were developed and estimated in sections 6.5, 6.6 and 6.7.

Model 1:

A monthly model is developed to estimate the relation between “Fraction of center operations delayed due to enroute congestion” and center operations in NAS

Model 2:

A monthly model is developed to estimate the relation between “Fraction of delayed operations delayed due to enroute congestion” and center operations in NAS

Model 3:

A monthly model is developed to estimate the relation between “average minutes of delay due to enroute congestion” and center operations in the NAS.This model is developed using models 1 and 2 discussed above.

Model 4:

i. A monthly model is developed to estimate the relation between “average ground delay” and enroute traffic in the NAS.

ii. Monthly models are developed to estimate relations between the following delay types and enroute traffic in the NAS

1. Average taxi out delay
2. Average airport departure delay
3. Average gate departure delay
4. Fraction of center operations which are departure delayed

CHAPTER VIII: RECOMMENDATIONS FOR FUTURE WORK

The recommendations for future research are discussed in sections 8.1 to 8.5.

8.1. Relation between delays due to controller understaffing and controller staffing/enroute traffic in the NAS

CFMU (Eurocontrol Central Flow Management Unit) computes minutes of delays due to understaffing of controllers. The procedure used by CFMU can be adopted to estimate delays due to understaffing of controllers in the US National Airspace System

Using these delay data, relations should be estimated between delays due to understaffing of controllers and controller staffing/enroute traffic in the NAS.

8.2. Analyses using the variable “controller work minutes in a center”

In section 4.2.3 relations were estimated between monthly air traffic operations and onboard number of controllers staffed in centers.

In the present study, after it was realized that the variable “Monthly onboard number of controllers staffed in a center” does not capture the monthly controller work hours in a center, the variable “Monthly controller work hours worked by all controllers in a center” was substituted in the revised analysis. SISO data were applicable, but only after considerable processing to extract them in the required format. Analysis 4.2.3 should be repeated using the SISO data.

The variable “controller work minutes in a center” should be used to estimate the following relations:

i. Controller staffing (controller work minutes) vs. enroute NAS traffic

ii. Controller staffing (controller work minutes) vs. NAS delays

8.3. Models estimated using minutes of delays due to enroute congestion (delays recorded by OPSNET by cause center volume)

For the enroute airspace relations among variables controller staffing, operations and NAS performance measures are to be estimated for entire NAS and not for individual sectors and centers in NAS. Minutes of delays due to enroute congestion should be used to estimate relations between delays specifically caused by enroute congestion and enroute congestion in NAS.

Monthly measures of delays and enroute congestion should be considered and monthly as well as month-specific models should be developed to estimate relations between delays and enroute congestion.

Data on minutes of delays caused by enroute congestion

The current FAA databases do not record minutes of delays caused by enroute congestion. The OPSNET database records operations delayed due to the cause "center volume". In section 6.5.1 models were developed(and estimated in section 6.7.1) to relate delays specifically caused by enroute congestion and enroute traffic volumes in the NAS. The following measures of delays were used for performing these analyses.

1. "Fraction of NAScenter operations delayed byenroute congestion".
2. "Fraction of delayed operations delayed by enroute congestion"

Since the above variables do not measure delays, it becomes necessary to estimate delay-demand relations using minutes of delays caused by enroute congestion. Data from different databases (TMU (Traffic Management Unit) log, OPSNET) and data sources should be compiled to obtain data on minutes of delays caused by enroute congestion. The models proposed in section 6.5.1 should be estimated using variables –

1. “Average minutes/total minutes of delay due to enroute congestion”.
2. “Fraction of total time delays caused by enroute congestion”

The current online databases such as ASPM, FAA and OPSNET on the FAA APO website are very efficient in making the data accessible in form of a query model.

8.4. Revision of Position Classification Standard for ATC (FAA 1999), currently used by FAA to measure center complexities and assign controller grades & wages.

Considering the advancements made in simulation models to measure ATC workload, such models could be employed to measure different forms of ATC complexity which are currently not being measured by the FAA 1999 complexity guide. Currently FAA is revising controller staffing standards based on classification of sector complexity into 3 types, namely sectors with parallel flight routes, sectors with intersecting flight routes and sectors with feeder traffic (i.e. with fixes).

8.5. Revision and validation of FAA 1997 standards

Validation of the standards:

The validation of the 15 minute controller staffing model developed in FAA (1997) was performed by the ATO office (Mr. Elliott McLaughlin and his team) in a study entitled- “Trip Report Cleveland Air Traffic Control Facilities” in 2004. The validation of FAA

(1997) -15 minute controller staffing model has been performed for one facility. It would be desirable to extend that validation to additionalfacilities.

Revision of standards:

The need to update the standards is explained in section 3.1.8.

8.6. Analyses to be performed after obtaining the required data

8.6.1. Analysis 4.1.5 - Relation between number of dynamic sectors in a center and air traffic operations handled by that center

The dynamic resectorisation data are recorded at the individual facilities, but not sent to the ATO office. These data should be obtained from individual facilities for performing the analyses.

8.6.2. Analysis 9.3.1 - Sector MAP values are used to measure NAS performance, for estimating relations between NAS performance and enroute traffic volumes.

Analysis 9.3.1 should be performed after obtaining the required data.

8.6.3. Analysis 9.3.2. Enroute delays caused by Traffic Management processes are used as measures of NAS performance, for estimating relations between NAS performance and enroute traffic volumes.

Analysis 9.3.2 should be performed after obtaining required data.

8.7. Estimating three-dimensional relations among NAS enroute traffic demand, controller staffing and NAS performance. It is desirable to introduce a technology factor while estimating these relations, to study the effect of improvement in technology.

CHAPTER IX: UNREALIZED ANALYSES

Based on the literature review, four analyses were proposed to estimate relations between ATC system performance and enroute traffic volume in the NAS The four proposed analyses have been explained below in sections 9.1 to 9.3.

In sections 9.1 and 9.2, analyses have been proposed to estimate relations between enroute traffic volumes in the NAS and the flight times and excess distances traveled by flights from origin to destination airports. Drawbacks were identified in both the analyses. These drawbacks could bias the proposed relations.

Analyses 9.3.1 and 9.3.2 could not be performed due to unavailability of data required to perform those analyses.

Hence it is decided to use flight delay data recorded by FAA databases to estimate relations between delays and enroute traffic volumes in the NAS. In sections 6.5 to 6.8 models are developed and analyzed to estimate these relations. Flight delay data recorded by FAA databases are used to estimate these models.

9.1. Analysis proposed to estimate relations between flight times and enroute traffic volumes in the NAS

An analysis was proposed to study the effect of NAS enroute traffic volumes on the enroute flight times for flights between all city pairs in the NAS. Day or month was to be considered as the time interval for performing the analyses.

DFTI (Daily Flight Time Index) metric developed by Hansen (2004) was identified as a suitable measure of flight time traveled by an "average passenger commercial flight" in

NAS. Hansen 04 proposes DFTI as a measure of operational performance of NAS. DFTI is weighted average flight time for a set of city pairs. DFTI is calculated for 776 city-pairs which were connected by 7000 daily flights during period from1995 to 2002. Hansen and Leung (2003).Hansen and Leung (2003) explain that DFTI (Daily Flight time Index) is a daily performance metric, which measures daily variation in flight time and the components of flight time. DFTI is the sum of weighted Daily Average Flight Time components (DAFT) - origin delay, taxi-out time, airborne time and taxi-in time. DAFT are weighted average flight times wherein weights have been applied to city pairs based on their representation. Weights are applied for maintaining day-to-day comparability. DFTI considers changes in schedule padding and changes in city-pair distribution of flights. Monthly adjustment of city pairs and their weights is carried out. In Hansen 2004 DFTI is developed as a measure of total flight time which consists of components - daily average origin time, daily average airborne time and daily average destination time.

Hoffman and Voss (2000) explain that in high traffic conditions, speed controls over aircraft; traffic offloading and holding will increase the enroute time of a flight. It is proposed to estimate relations between total flight times and enroute traffic volumes for flights along a set of city pairs. It is proposed to estimate relation between daily and monthly DFTI values and daily and monthly center operations in NAS.

Drawbacks in the analysis

It was found that the proposed analysis could not be performed because of the following reasons:

1. DFTI metric is not developed by considering all city pairs in NAS. It is possible that enroute congestion for the set of city pairs used to compute DFTI could be different from the enroute congestion estimated for entire NAS.

2. Vast differences in the levels of enroute congestion between different city pairs could bias the variable "total enroute traffic volumes in the NAS" and its effect on "DFTI" metric.

3. It was also found that variation in flight times along the same city pair could be because of a variety of causes other than enroute traffic volume. It would be difficult be isolate the effect of enroute congestion on flight times for a city pair. Willemain et al. (2003) and Alj and Odoni (a) report that the following factors cause variation in flight times for the same city pair.

a. Wind

Wind causes variation in gate to gate times. Alj and Odoni (a)

Willemain et al. (2003) found that ASPM data on estimated enroute times for certain origin destination pairs showed large and consistent changes. He explains that most of the unexplained variation in estimated enroute times is because of wind forecast errors. He found that wind had an impact on estimated enroute times after comparing directional estimated enroute times.

b. Length of the filed routes and routes flown by flights

Willemain et al. (2003) explains that the routes filed by carriers can show great differences and the filed routes could be different from the routes actually flown.

However he also explains that the variation in estimated enroute time is not caused mainly by the differences in routes. He found that there was an 11% relative variation in estimated enroute time, however there was only a 3% relative variation in length of filed routes.

c. Weather

Alj and Odoni (a) found that weather causes variation in gate to gate time.

d. Airport congestion

Airport congestion affects gate-to-gate times. Alj and Odoni (a)

e. Aircraft equipment and ATM systems

Willemain et al. (2003) also attributed a portion of variation in estimated time enroute to aircraft equipment and ATM systems.

9.2. Analysis proposed to estimate relations between excess distances traveled by flights and enroute traffic volume in the NAS

9.2.1. Excess distances traveled by flights in enroute and terminal airspaces.

Howell et al. (2003) computed the excess distances traveled by flights from departure airports to arrival airports. Authors compared actual distance traveled by flights with the great circle route distance between the departure and arrival airports. Howell et al. (2003) studied the impact of terminal congestion on the total excess distances traveled by flights. Authors considered “enroute airspace” to exist beyond 50 nmi circles around origin and destination airports. Excess distances traveled by flights in enroute airspace were determined by comparing actual distances traveled by flights to GCR distances in the "enroute airspace". Analysis was performed using 24 hour flight track data from ETMS.

Authors concluded that terminal area restrictions cause excess distance traveled by flights to increase more as compared to enroute congestion. Authors report that 71 percent of the total excess distance traveled by a flight between departure and arrival airport is covered in the terminal airspace and remaining 29 percent of excess distance is traveled in the en route airspace.

Analysis performed by Howell et al. (2003) estimates the percentage of excess distance traveled by flight in enroute and terminal airspaces and percentage of excess distance traveled by flights because of terminal congestion. An analysis is proposed to study the effect of NAS enroute traffic volumes on the excess distances traveled by flights between all city pairs in the NAS. Day or month is to be considered as the time interval for performing the analysis.

9.2.2. Proposed analysis:

It is proposed to estimate the relation between NAS enroute traffic volumes and excess distances traveled by flights traveling between all city pairs in the NAS. Enroute traffic congestion is measured in terms of NAS center operations.

Drawbacks in the analysis:

It was found that the proposed analysis could not be performed due to the following reasons:

1. Bennett (2004) performed an analysis to study the excess distance traveled by flights which encounter busy sectors along their flight path. He found that a single congested sector along the path of a flight can significantly affect the excess distance traveled by the flight. In the proposed analysis the effect of localized congestion in sectors of NAS could bias the relation between NAS enroute traffic volumes and the excess distances traveled by flights from arrival to departure airports.

2. Drawbacks of measure "excess distance traveled by flights"

Excess distance metric cannot capture time delays imposed on aircraft due to airspace congestion. Ground delays imposed on flights due to airspace congestion cannot be captured by the excess distance metric .Drawbacks of excess distance metric have been discussed earlier in section 3.2.2.2. Howell et al. (2003) also admits that excess distance cannot capture ground delays imposed on flights and speed controls imposed on flights.

9.3. Analyses proposed to estimate relations between NAS performance measures and NAS enroute traffic volumes

9.3.1. Sector MAP value is used as a NAS performance measure for estimating relations between NAS performance and enroute traffic volume

MAP values for a sector:

MAP (Monitor Alert Parameter) values for a sector define the capacity of a sector. Monitor alert is a part of ETMS which evaluates traffic demand at all airports, sectors and fixes in US and produces an alert when demand is predicted to surpass capacity in a specific area. FAA (b).

Leiden and Green (2000) explain that monitor alert compares the predicted aircraft count in a sector (based on the ETMS data) with the sector capacity. When the sector aircraft count surpasses the MAP threshold, the traffic manager sends an alert along with the predicted traffic demand. TM specialists employ least restrictive actions to ensure that traffic demand does not surpass sector capacity. FAA (b) explains that the Traffic Management Specialists evaluate the situation and assist in traffic flow control by providing spacing and routes.

In section 3.3.1 of literature review it has been explained that ATC system uses Traffic Management processes to manage demand when the MAP values are exceeded in a sector. These TM processes cause delays to flights.

Studies in which MAP values have been used

Cooper, Jr et al. (2001) report the following analysis in which MAP values have been used.

1. CAASD has evaluated the operational impacts of the changes in National Route Program (NRP).Sector counts for each sector were compared to the MAP values specified for that sector, before and after the changes to NRP were made.

2. CAASD has also evaluated the operational impact of eliminating preferred routes by comparing sector counts for each sector to the MAP values.

Proposed analysis:

ATC system uses TM processes to prevent sector demand from exceeding sector MAP values. These TM processes cause delays to flights. The frequency and duration of events when MAP values are exceeded in sectors can be used as measures of system performance. The performance of ATC system is evaluated in managing enroute traffic volumes in the NAS.

An "event" is defined as a situation in which the sector demand has exceeded the sector map value for a single sector in NAS. The following monthly and daily measures of system performance are developed:

1. Frequency of events in NAS
2. Total duration of events in NAS

It is proposed to estimate relations between daily and monthly performance measures and enroute traffic volumes in the NAS. Enroute congestion in the NAS is measured in terms of NAS center operations.

Analysis 9.3.1 could not be performed due to unavailability of required data.

9.3.2. Enroute delays caused by Traffic Management processes are used as measures of NAS performance, for estimating relations between NAS performance and enroute traffic volume

When demand exceeds capacity in parts of the enroute airspace i.e. sectors, fixes and jet routes, ATC system employs traffic management processes to manage air traffic demand. Ground delay programs (EDCT and Ground Stops) are employed to delay flights on ground. Data on ground delays is recorded by OPSNET database.

ATC system uses the following TM processes to delay flights in air due to enroute congestion:

i. Miles in Trail restrictions
ii. Holding
iii. Rerouting

Klopfenstein et al. (1999) analyzed the above control procedures to "identify, quantify, and understand the nature of inefficiencies in NAS". The locations, times and causes for implementing these procedures were studied. The impact of these TM processes was studied in terms of delays imposed on flights. The number of flights delayed and the total time delays imposed on flights were studied. Analysis was performed for entire NAS by considering days and weeks as time periods. Klopfenstein et al. (1999) studied the following characteristics of MIT restrictions:

-Frequency of MIT restrictions and durations for which the MIT restrictions were imposed.

-Reasons for imposing MIT restrictions

-Number of flights affected by each restriction per unit time.

FAA Order 7210.3T states that FAA records a complete description of all TM actions/initiatives (e.g. ground delay programs, miles-in-trail (MIT), etc.) in TMU (Traffic Management Unit) log, with details including start and stop times, affected facilities and operations, and justification.

Proposed analysis:

It is proposed to evaluate the efficiency of ATC system in reducing enroute delays imposed on flights because of airspace congestion. ATC system uses the following TM processes to impose enroute delays because of airspace congestion:

i. Miles in Trail restrictions

ii. Holding

iii. Rerouting

The TMU log contains data on number of operations delayed and total minutes of delays caused by each TM process implemented in NAS. TMU log records the cause for implementing each TM process. The TMU log data can be used to estimate enroute delays caused by airspace congestion. Data on TM processes implemented due to enroute congestion needs to be used. The following daily and monthly measures of enroute delay are estimated:

1. Number of operations delayed by TM processes, when TM processes are implemented due to enroute congestion only.

2. Total minutes of delays caused by TM processes, when TM processes are implemented due to enroute congestion only.

It is proposed to estimate relations between daily and monthly measures of enroute delays and NAS enroute traffic volumes. NAS enroute traffic volume is measured as total center operations in all centers of NAS.

OPSNET database records delays greater than 15 minutes caused by center volume. These delays could be imposed on flights in ground and in air. Using the enroute delay estimation procedure explained above, total minutes of delays (including less than 15 minute delays) imposed on enroute flights because of airspace congestion can be estimated.

Analysis 9.3.2 could not be performed due to unavailability of required data.

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