

Investigation of the Potential Impacts of the Entry of Very Light Jets in the National Airspace System

Philippe A. Bonnefoy* and R. John Hansman†

*International Center for Air Transportation, Department of Aeronautics & Astronautics
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139 USA*

Very Light Jets (VLJs) constitute a class of three to eight passenger turbofan-powered aircraft that will enter service in 2006 and will need to be integrated into the National Airspace System. An aircraft performance analysis showed similarities between the predicted performance and capability of Very Light Jets and the performance of existing Light Jets. Based on this an analysis of operating patterns of existing Light Jets was used to predict how Very Light Jets will be operated. Using 396 days of traffic data from the FAA Enhanced Traffic Management System (ETMS), the operating patterns of existing Light Jets were analyzed. It was found that 64% of all the flights flown by Light Jets had their origin, destination or both within the top 23 regional airport systems in the continental United States. This concentration of LJ traffic was found in areas of the air transportation system that are currently exhibiting dense traffic and capacity constraints. The structure of the network of routes flown by existing Light Jets was also studied and a model of network growth was developed. It is anticipated that this concentration will persist with emerging Very Light Jet traffic. This concentration of traffic at key areas in the system will have implications for air traffic control management and airport activity. For regional airport systems, core airports are expected to saturate and, reliever airports will become critical for accommodating traffic demand. The entry of Very Light Jets will significantly increase the traffic load at the terminal airspace; Terminal Radar Approach Control (TRACON). These impacts need to be taken into account to allow a successful integration of these aircraft in the National Airspace System.

I. Introduction

A. Business aviation growth trends

Business aviation has grown significantly over the last 15 years. The fleet of business jet (BJs) aircraft has increased by 67% from 1994 to 2004 [1]. The reason for this increase can be traced, in part, to the emergence of fractional ownership programs in the 1980s provided by operators such as NetJets (1986), Flexjet (1995) and Flight Options (1998). This concept of fractional ownership allowed corporations or individuals to share an aircraft for a fraction of the total cost and therefore expanded the market base for on-demand transportation.

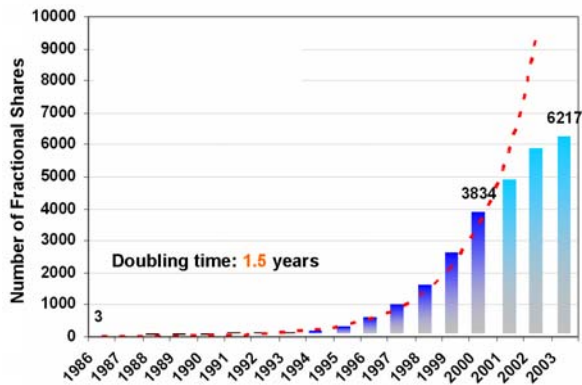


Figure 1. Exponential growth of fractional shares from 1986 to 2000 [1]

* Graduate Research Assistant, Engineering Systems Division, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Office 17-110.

† Professor and Head of the International Center for Air Transportation, Department of Aeronautics and Astronautics and Engineering Systems Division, 77 Massachusetts Avenue, Office 33-303. Fellow AIAA.

The advantage of fractional ownership over charter includes the ability to operate under Federal Aviation Regulations (FARs) Part 91 (as opposed to FAR Part 135) which allows more operational flexibility. Figure 1 depicts the growth of fractional ownership shares [1]. The rapid growth was moderated somewhat in 2001 due to the slowing of the U.S. economy. However, 2005 market figures showed a rebound and strong signs of growth. For the first nine month of 2005, the shipment of business aircraft from U.S. manufacturers has increased by 30.4% compared to 2004 with 510 units shipped [2]. The availability of Very Light Jets (VLJs) is expected to further accelerate this growth.

B. Motivation

The entering class of three to eight passenger turbofan-powered aircraft, Very Light Jets (VLJs), is expected to increase the growth of business aviation activity. There is some concern that VLJ traffic loads may create capacity problems in some areas of the National Airspace System (NAS). In order to assess this concern there is a need to predict their future operating patterns in order to evaluate potential impacts on the National Airspace System.

In order to predict the future VLJ operating patterns the patterns of operation of the closest type of existing aircraft (i.e. Light Jets) were analyzed. This was motivated by the significant overlap between the performance and capabilities of existing LJs and future VLJs. While the lower acquisition and operating costs of VLJs may be different than existing LJs, it is expected that price elasticity will increase the fleet size but the operating patterns should be similar at the aggregate level. Traffic will be driven by

underlying socioeconomic factors such as population/business distribution, income and discretionary budgets and competition from other modes of transportation. Because these factors evolve slowly, the underlying demand drivers for VLJs will be somewhat similar to the ones of existing LJs over the next 10 to 15 years.

II. Business Jet Spectrum Analysis and Aircraft Performance Comparison

In order to understand the differences and similarities between VLJs and the existing business jets, a comparative analysis of aircraft performance and characteristics was performed.

A. Very Light Jets: Downward extension of the current business jet spectrum

For the purpose of this study, Very Light Jets are three to eight passenger turboprop-powered aircraft that have a maximum takeoff weight below 10,000 lbs (Table 1). Existing LJs are defined to be between 10,000 lb and 20,000 lbs. Higher in the business jet spectrum, medium jets are characterized by a maximum take-off weights between 20,000 lbs to 35,000 lbs. Heavy business jets have a maximum takeoff weight greater than 35,000 lbs.

The 10,000 lb threshold between very light and light jets has emerged from an historical perspective, distinguishing two generations of aircraft, with the Cessna CJ1 (10,600 lbs), certified in 1992, being the lightest twin turboprop-powered aircraft in the current business jet spectrum. The entry of VLJs expected in 2006 will lower the current business jet spectrum under 10,000 lbs. However, from a vehicle and performance stand point the thresholds between the two classes of aircraft is not as clear. An alternative 12,500 lbs threshold has also been considered. This threshold separates the aircraft that are certified under the FAR Part 23 airworthiness standards for normal, utility, aerobatic and commuter category airplanes from those air transport category aircraft certified under the FAR Part 25.

Aircraft name	Maximum Take-off Weight (lbs)	Aircraft Category ^a	FAR ^b
LearJet 35	17,000	Light Jet	Part 25
Cessna Excel	16,630	Light Jet	Part 25
Hawker 400	16,300	Light Jet	Part 25
Cessna Bravo	14,800	Light Jet	Part 25
Cessna CJ3 ^c	13,870	Light Jet	Part 23
SJ30 ^c	13500	Light Jet	Part 23
Beech Premier I	12,500	Light Jet	Part 23
Cessna CJ2	12,375	Light Jet	Part 23
Cessna CJ1	10,600	Light Jet	Part 23
EV-20	9,250	Very Light Jet	Part 23
HondaJet	9,200	Very Light Jet	Part 23
Adam 700	7,600	Very Light Jet	Part 23
Mustang	7,330	Very Light Jet	Part 23
Spectrum 33	7,300	Very Light Jet	Part 23
Avocet	7,160	Very Light Jet	Part 23
Eclipse	5,640	Very Light Jet	Part 23
Diamond	4,750	Very Light Jet	Part 23

^a Aircraft categories are based on the National Business Association (NBAA) classification for light, medium and heavy jets. The very light category was defined based on a 10,000 lbs threshold.

^b Federal Aviation Regulations (FAR)

^c The Cessna CJ3 obtained an exemption from the FAA for a Part 23 certification instead of a Part 25 despite its maximum take-off weight greater than 12,500 ft. Similarly, the Sino Swearingen SJ30 was also certified under Part 23.

Table 1. Current business jet spectrum with the extension to the future very light jet category [3]

B. Aircraft performance comparative analysis

A comparative analysis of the characteristics of VLJs and existing LJs was performed to support the use of LJ operational patterns as a predictor of VLJ operations. This analysis was based on aircraft physical characteristics (i.e. number of passenger seats), cost (i.e. list price) and performance metrics (i.e. range, cruising speed, take-off field length, maximum ceiling) published in Jane’s “All the World Aircraft” handbook 2004-2005 and 2005-2006 editions [3][4]. Because several emerging aircraft (e.g. Embraer Phenom 100 and the Spectrum 33) had not yet been included in Jane’s, aircraft manufacturers’ data was used [5][6].

Table 2 presents a summary of the predicted performance of VLJs considered and the reported performance of the existing LJs. Very light jets are expected to carry from 3 to 8 passengers. To some extent, there is an overlap with existing LJs such as the Cessna CJ1 which can accommodate 5 passengers. In terms of acquisition price (adjusted to 2006 dollars) VLJs are expected to range from \$1.3m to \$3.6m compared to \$4m to \$8m for existing LJs, \$8m to \$16m for medium jets and \$16m and higher for heavy jets. The predicted acquisition price of VLJs extends the linear relationship between price and aircraft weight that light, medium and heavy jets (up to 40,000 lbs) follow. The average cost per pound of aircraft, based on maximum take off weight, is roughly \$550/lbs. In terms of operational characteristics and performance, VLJs are predicted to exhibit slightly lower cruise speeds (from 340 to 390 kts) than existing LJs that have cruising speeds greater than 381 kts.

Predicted aircraft characteristics and performance criteria	Very Light Jets		Light Jets	
	Min	Max	Min	Max
Number of passenger seats ^a	3	8	5	10
Maximum Take-off Weight (lbs)	5640	9250	10,600	17,000
Acquisition cost (in 2006 \$m adjusted for inflation)	1.38 ^b 1.29 ^c	3.65	4.42	8.33
NBAA Range (nm)	1,100	1,750	1,178	2,500
Cruising Speed (kts)	340	389	381	462
Maximum ceiling (ft)	41,000	45,000	41,000	51,000
Take-off field length (ft)	2035 ^b 2,155 ^c	3,100	3,280	3,993

^a not including pilot and copilot front seats. In single pilot operations, the right front seat could be utilized as a passenger seat.

^b single engine very light jet

^c twin-engine very light jet

Table 2. Summary of characteristics and performance between very light and light business jets [3][5][6]

Very light jets are also expected to have maximum ceilings ranging from 25,000 ft to 45,000 ft with single engine aircraft limited to 25,000 ft. Twin engine VLJs are expected to have maximum operating ceilings from 41,000 ft to 45,000 ft. In the light, medium and heavy business jet category, some aircraft are capable of flying up to 51,000 ft). VLJs are predicted to exhibit operating ranges from 1100 to 1750 nautical miles which are similar to existing LJs. Finally, VLJs are expected to have shorter take-off field

length performance (from 2100 ft to 3100 ft) than existing LJs that require runways longer than 3300 ft.

C. Airport availability and possible utilization based on predicted performance of very light jets

Figure 2 shows the take-off field length at maximum take-off weight, (assuming standard atmospheric conditions at sea level) for the business jet spectrum. Expected take-off field length requirements of VLJs vary from 2000 to 3100 ft[‡].

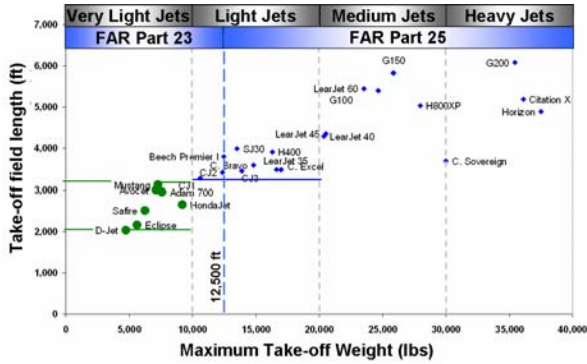


Figure 2. Published take-off field length of very light, light, medium and heavy business jets [3][4][5][6]

This performance will allow VLJs to be operated at airports with shorter runway lengths. The additional runway availability can be seen in Figure 3 that presents the number of runways that are currently available in the continental United States by runway length based on Federal Aviation Administration (FAA) Form 5010 Master Airport Records database [7]. There are over 6400 runways in the continental United States over 3000 ft available to VLJs while this number drops to 3075 for those larger business jets which require runways of at least 5000 ft. It should be noted that most VLJ operations will not be at maximum takeoff performance; however the shorter takeoff field length will clearly increase the set of airports utilized by VLJs.

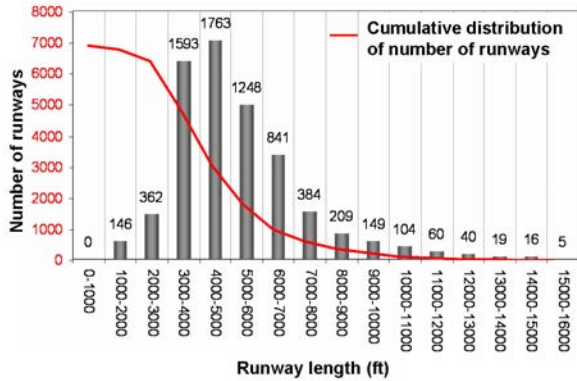


Figure 3. Runways available at public airports in the continental United States by runway length [7]

[‡] Compared to other categories of aircraft, the very light jet take-off field length requirements fit between the single engine piston aircraft and large turboprops requirements.

The number of runways accessible to a category of aircraft is only one metric for assessing infrastructure capabilities. The geographic location of these airports must also be considered. Figure 4 shows the geographical distribution of public airports with runways longer than 3000ft accessible by VLJs. It can be seen that airports are more concentrated in the eastern half of the United States and on the West coast, with clusters of airports close to the major metropolitan areas such as New York, Chicago, Dallas, Los Angeles, and San Francisco.



Figure 4. U.S. public airports with at least one runway longer than 3000 ft [7]

D. Potential flight demand for very light jets

Another aspect of importance in the assessment of the impact of the entry of VLJs is the total number of flights that they will add to the NAS. This will be a function of both the number of aircraft entering the system and the frequency of use (i.e. average number of flights per day).

In the assessment of the fleet size, VLJs are expected to both serve as partial replacement of existing General Aviation (GA) aircraft such as turboprop and high-end piston aircraft and are also expected to stimulate the development of large scale on-demand air taxi networks which may constitute the largest share of the VLJ market.

Because VLJs have lower costs than existing LJs and will offer better performance (i.e. cruise speed) than comparably priced turbo props [3] (e.g. Pilatus PC-12, TBM-700, etc.), VLJs have the potential to enter the system in significant numbers. In its 2005-2016 forecasts [9] the FAA predicted that there will be 4,600 VLJs in the National Airspace System by 2016. In 2004, Honeywell Aerospace [10] predicted 4,500 to 5,500 VLJ deliveries over the next 10 years excluding the on-demand per-seat and charter segment of the market. Rolls Royce forecast 8,000 VLJs will be delivered by 2023 [11]. Other forecasting groups such as the Teal Group are less optimistic and forecast 2,310 VLJ aircraft deliveries between 2006 and 2016 [8]. As of July 2006, the cumulative backlog of orders for the three major VLJ manufacturers (Eclipse Aviation, Adam Aircraft, Cessna and Embraer) was approximately 3025 aircraft. For comparison the existing size of the jet powered business aviation fleet for all weight categories was 8425 in 2004 [9].

In order to estimate the frequency of use of these aircraft, one must assess the modes of operations of VLJs. Very light jets are expected to be utilized under the following modes of operations; the *owner flown* mode where

the aircraft is owned and operated by individuals or companies, *fractional ownership programs* similar to the existing business models (e.g. NetJets, Flexjet, Flight Options), *clubs*, and finally *large scale on-demand air networks*. Even within the category of large scale on-demand segment there are various business models; the *charter model* which is similar to existing charter operations where the passenger rents the entire aircraft for the duration of the flight, the *per-seat model* where passenger can book flights on a single seat basis, and business models that mix both concepts. Finally, VLJs are also expected to be utilized for carrying high value freight. In terms of the frequency of use, the highest frequencies are expected in the large scale on-demand air networks. Schedules could include 3 to 7 flights per day (including repositioning flights) [12]. In contrast owner flown aircraft are typically flown less than one flight per day on average.

As a consequence, of the different possible modes of operation and the varied predicted rate of entry there is a wide range of potential flight demand for VLJs ranging from 4,000 to 20,000 flights per day in 2016. This uncertainty in the demand must be taken into account in the assessment of the potential impacts of VLJs.

III. Potential Very Light Jet Operating Patterns

A. Methodology and data

In order to analyze the operating patterns of existing LJs as a surrogate for VLJ operations, data of actual flights from the FAA Enhanced Traffic Management System (ETMS) was used. For each IFR or ATC managed flight in the U.S., this database provided the aircraft type, airports of departure and arrival, aircraft position (latitude, longitude and altitude) and speed information.

For the analysis of the actual traffic patterns, a dataset of 396 days of traffic was analyzed. The data was composed of a full and continuous year of traffic. This data set included 365 days of data from October 1st 2004 to September 30th 2005. To complement this dataset, another set of 31 days of data from days from the mouths of January, April, July and October spanning from 1998 to 2004 was utilized.

In addition to the ETMS flight database, a database of civil airplanes was used. This database is composed of 869 types of airplanes including 99 business jets of which 29 were light business jets. For the purpose of evaluating light jet operating patterns the light jet types were sorted out of the database. The light jet types used were; Citation 1 & 1-SP, Citation Jet 1, Citation Jet 2, Citation Jet 2-SP (Bravo), Citation Jet Ultra, Citation Jet Excel, Learjet 23-24-25-28-29-31-35, Diamond 1 MU30, Beech jet 400 and Hawker 400. Complementing the aircraft database, a database of 24,912 landing facilities worldwide was also used for the identification of the origin and destination airports reported in the ETMS flight data. This database also provided latitudes and longitudes for each landing facility. The ETMS airport database was supplemented with the FAA Form 5010 airport database that provided additional airport information such as runway characteristics (i.e. length, pavement type) and available instrument approaches at the airports. In the following analysis 12,007 public and private airports –of any

runway size- where used for the extraction of flights from the ETMS flight database.

An extensive data quality assurance process was used to filter data with missing information fields such as; aircraft type and clearly flawed trajectory data. In addition international flights and military and helicopter operations were filtered out. The filtered data accounted for 70% of the total number of flights in the raw data.

B. Temporal Analysis

A total of 20.5 million domestic flights performed by all types of aircraft in the NAS over the 365 days -from October 1st 2004 to September 30th 2005- of traffic were analyzed. From those 20.5 million flights, 1.73 million (8.5%) were identified as having been flown by business aircraft (including very light, light, medium and heavy business jets). Figure 5 places the volume of traffic by business jets in the perspective of traffic by other categories of aircraft that were flown in the National Airspace System during the same time period. The volume of flights varies widely from day to day especially between week days and week-end days. Overall a low seasonal variation of traffic was observed. For the 30 day moving average, the difference between the trough and the peak of flights was 15%.

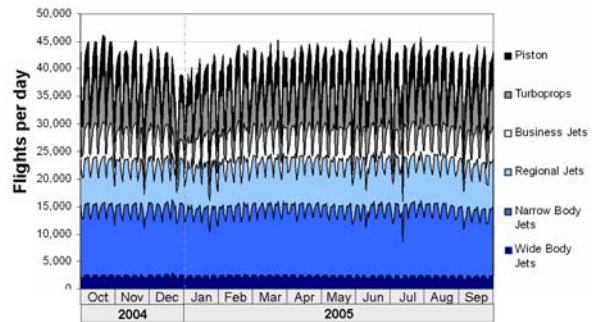


Figure 5. Daily traffic volumes over one year (from October 2004 to September 2005) for all aircraft type

From the set of flights flown by business jets, 811,300 were flown by LJs over the 365 days of data. Figure 8 shows the volume of traffic from LJs between Oct. 01 2004 and Sept. 30 2005 with its 7 day moving average.

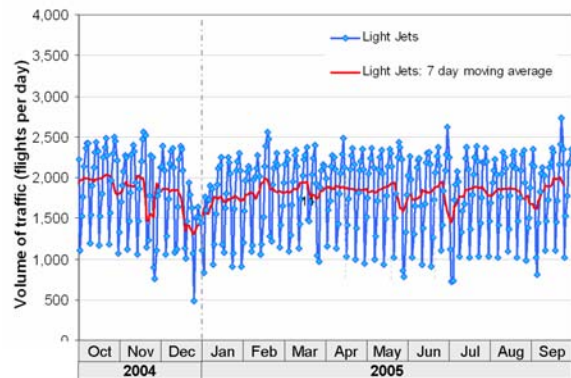


Figure 6. Daily traffic over one year (from October 2004 to September 2005) of existing light jets

Figure 7 shows the average number of flights per day from Monday to Sunday that is normally distributed around

the mean. It was found that traffic was higher and less volatile on Tuesdays and Wednesdays but was lower and more volatile on Saturdays and Sundays.

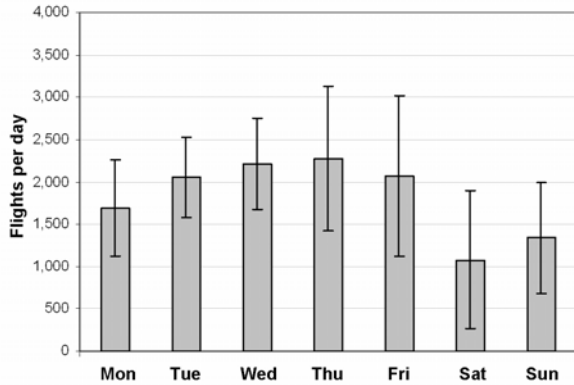


Figure 7. Weekly traffic pattern of existing light jets (average number of flights per day with $\pm 3\sigma$)

This weekly pattern of traffic by LJs was found to be similar to the weekly patterns of all the traffic (Wide Body Jets, Narrow Body Jets, Business Jets, Turboprops, Piston) except for Saturdays and Sundays (Sundays being busier days for LJs while Saturdays were the busiest weekend say for the overall traffic). This is consistent with the business nature of these light jet flights; since Saturdays are not business days in the United States. In addition, business jets are often repositioned on Sundays for early departures on Mondays.

C. Traffic loads by aircraft type within the light jet aircraft category.

Light jets accounted for over 46% of the total business jet traffic in the dataset, the most frequently operated aircraft being the Cessna Citation C560, the Learjet 35 (L35), Beechcraft/Hawker 400 (BE40). It was also found that only 20 business aircraft types accounted for 90% of the overall business jet traffic.

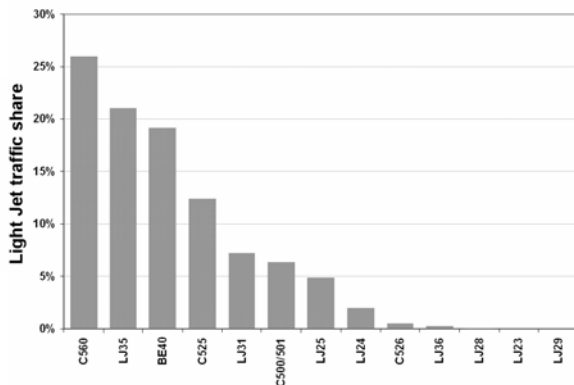


Figure 8. Traffic share of existing light jets.

D. Spatial analysis: Horizontal operating patterns

In order to understand the distribution of operating patterns across the Continental United States and assess the concentration of traffic, an analysis of the horizontal patterns

of existing LJs was performed using the position reports and the origin and destination airports for each flight extracted from the ETMS dataset. Figure 9 shows a density plot of flights performed by existing LJs during one 24 hour period in January of 2004 over the Continental United States.



Figure 9. Density of 24 hour of traffic by existing light jets in the Continental United States (Jan 2004)

As can be seen in Figure 9, traffic is not uniformly distributed over the United States. A large fraction of the traffic occurs on the eastern half of the country with some high density traffic over California. Dense traffic concentrations are observed around key metropolitan areas such as New York, Chicago, Atlanta, Dallas, Miami, etc.

Flight stage lengths from the overall data set are presented in Figure 11. It was found that the stage length distributions for all business jet classes generally followed a log normal distribution with means of 590 for LJs and 780 miles for all business jets with standard deviations of 700 and 1150 miles respectively. The modes were found to be 175 for LJs and 150 for all business jets.

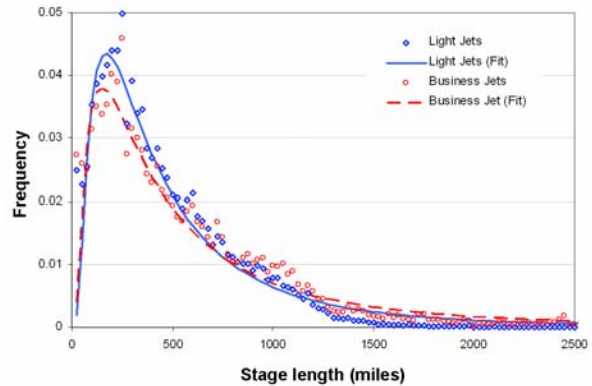


Figure 10. Stage length distributions for light jets and business jets

The stage length distribution for all business jets is slightly skewed to large stage lengths as compared to the LJs due to the longer range capability of medium and heavy business jets.

Two slight deviations from the log normal curve fit were observed. First for very low stage lengths, more flights were observed than what the log normal distribution would predict. In fact, it was found that 3% of all flights had stage lengths lower than 25 miles. The reason for this spike in short haul flight is thought to be due to repositioning flights that frequently occur for charter or fractional ownership program operations where the operator of the aircraft

relocates the aircraft at the point of departure of the next revenue flight. The second deviation is a truncation which occurs above 1100 miles for LJs and is a consequence of the range limitations.

From all business jets, it was observed that 60% of the flights were below 500 miles and 86% were below 1000 miles. For the light business jet class 66% of the flights have stage length shorter than 500 miles and 92% are shorter than 1000 miles. It is expected that the stage length distribution performed by VLJs will not differ significantly and that most of the flights will be shorter than 500 miles. The flight stage lengths have implications in terms of the altitude at which aircraft are flying. From an optimal flight path stand point, shorter flights require a cruising altitude lower than for flight with long stage length.

• **Analysis of the concentration of traffic of light jets**

The analysis of horizontal patterns of LJs over the 2004/2005 period was extended with the computation of traffic loads at each airport in the NAS. Table 3 shows the distribution of traffic loads by airport taken from the overall dataset. It was found that the distribution of traffic at airports was not uniform with airports such as Teterboro (TEB) and White Plains (HPN) in New York regional airport system, Washington Dulles (IAD) close to Washington DC, Midway (MDW) close to Chicago, Las Vegas (LAS) etc. capturing very high traffic loads.

Airport code	Airport name	Annual operations
TEB	Teterboro	32,629
DAL	Dallas Love Field	19,709
LAS	Mc Carran Las Vegas Int.	19,443
MDW	Chicago Midway International	19,138
CMH	Port Columbus International	18,958
PKD	Dekalb-Peachtree	18,143
APA	Centennial - Denver	17,597
IAD	Washington Dulles International	17,454
HPN	White Plains - New York	14,750
CLT	Charlotte/Douglas International	13,571
BHM	Birmingham International	13,048
HOU	Houston Hobby	12,992
PBI	Palm Beach International	12,052
PTK	Oakland County	11,714
PHL	Philadelphia International	11,391
VNY	Van Nuys	10,977
MEM	Memphis International	10,829
SDL	Scottsdale	10,676
BNA	Nashville International	10,531
SNA	John Wayne-Orange County	10,497

Table 3. Top 20 airports in terms of light jet operation volumes

In order to measure the concentration of traffic in regional airport systems around major airports, a classification of airports was performed. Major airports were defined as those which handled more than 1% of the entire passenger traffic in the U.S. There were 29 major airports in the continental US. A regional airport system was defined as all airports within 50 miles of one of the 29 major airports. Shown in Figure 11 are the 23 regional airport systems. Note that this is 6 less than the number of major airports as some regional airport systems include multiple major airports (e.g. LGA, JFK, EWR in the New York regional airport system, or DCA, IAD, BWI in the Washington regional airport system).

It was found that 64% of all the flights flown by LJs that either departed or landed at one of the airports within these 23 regional airport systems. Of all light jet movements (departures or arrivals) 12% of the movements were at major

airports and 27% at surrounding airports (airports within 50 miles of the major airport). These figures indicate that light jet traffic and VLJ traffic will be concentrated within key areas of the National Airspace System.

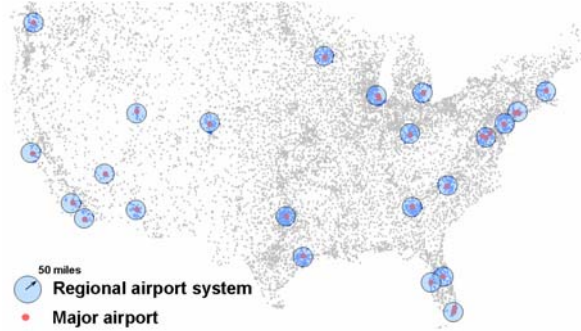


Figure 11. Regional airport system in the Continental United States used as reference for existing light jet traffic concentration analysis

• **Analysis of interaction of light jet traffic with commercial traffic within the national airport system**

In order to understand the interactions between light jet traffic and other traffic, a comparative analysis of light jet traffic and commercial traffic (flights flown by wide body jets, narrow body jets and regional jets) was performed. Figure 12 shows the volumes of light jet traffic plotted against volumes of commercial scheduled traffic at 12,007 airports in the continental U.S. for the Oct04-Sept05 period.

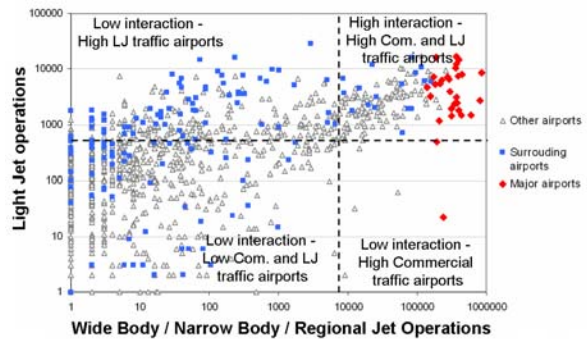


Figure 12. Categorization of landing facilities in the Continental United States commercial and light jet traffic

The set of airports was divided into four categories based on the amount of traffic (i.e. commercial and light jet traffic) and the level of interactions between LJs and commercial traffic. The mean value of the number of flights per year was used to divide the airport set into 4 categories (represented by the dotted lines on Figure 12). It was found that 159 airports exhibited high interaction and high traffic (for both commercial and light jet traffic). Most of major airports (27 out of 29) are in this high interaction high traffic category. The 284 airports in the low interaction/high LJ traffic category are airports where significant VLJ activity is expected. The low interaction/high commercial traffic category and the low interaction/low traffic category included 8 and 2032 airports respectively.

• **Airport and runway utilization**

In order to assess the utilization of infrastructure by existing LJs, two airport aspects were considered; the navigational aid available at the airport and the length of its runways. It was found that for commercial traffic, only 37 airports handled 70% of the total volumes of scheduled commercial flights in the U.S. and 90 % of the traffic is handled by 85 airports. The 700 ILS equipped airports handled 99.5% of the total traffic. This observation shows the significant concentration of scheduled commercial operations. The level of concentration of traffic was found to be lower for LJs, however ILS equipped airports were still found to handle a significant fraction (83.1%) of the overall volume of operations by LJs. The transition from ILS to space based precision approach capability is expected to increase IFR accessibility at less equipped airports and allow exploitation of underutilized airports both within the 23 major regional airport systems and across the US.

The observed light jet utilization of runways is shown in Figure 13 which presents traffic share performed at airports that have at least one runway longer than a specified length. For example, 95% of the existing light jet traffic is performed at airports that have at least one runway longer than 5,000 ft and 60% is performed at airports with runways longer than 7,000 ft.

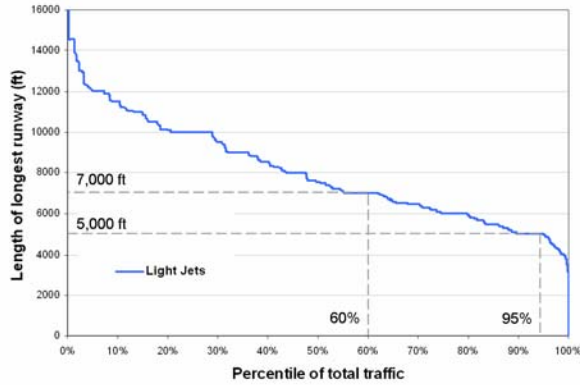


Figure 13. Light jet utilization of airport by runway length and aircraft type

Light jets are capable of using airports that have runway length as low as 3280 ft (for the Cessna CJ1), however a significant fraction of their traffic is performed at airports that have long runways (e.g. 62% of the traffic is performed at airports with runways longer than 7000 ft). Other factors such as airport location (vs. demand location), ground services, ground connectivity at the airport, etc. influence the distribution of traffic at those airports. Similarly, it is expected that even though VLJs that will have short take-off field length requirements, only a small fraction of the operations will occur at airports that have such short runways (3000 ft to 4000 ft range).

E. Spatial analysis: Vertical operating patterns

In order to analyze the vertical operating patterns of light jets the position reports along flight path for each flight from the Enhanced Traffic Management Data were used. From the position reports, the highest altitude of each flight (highest cruising altitude) was recorded and plotted (Figure 14) against the flight stage length for five categories of

aircraft; wide body jets (e.g. Boeing 767, Airbus 300), narrow body jets (e.g. Boeing 737, Airbus 318/319/320/321), regional jets (e.g. Bombardier CRJ200, Embraer E145) and business jets. Business jets were segregated in two categories; medium/heavy and light jet.

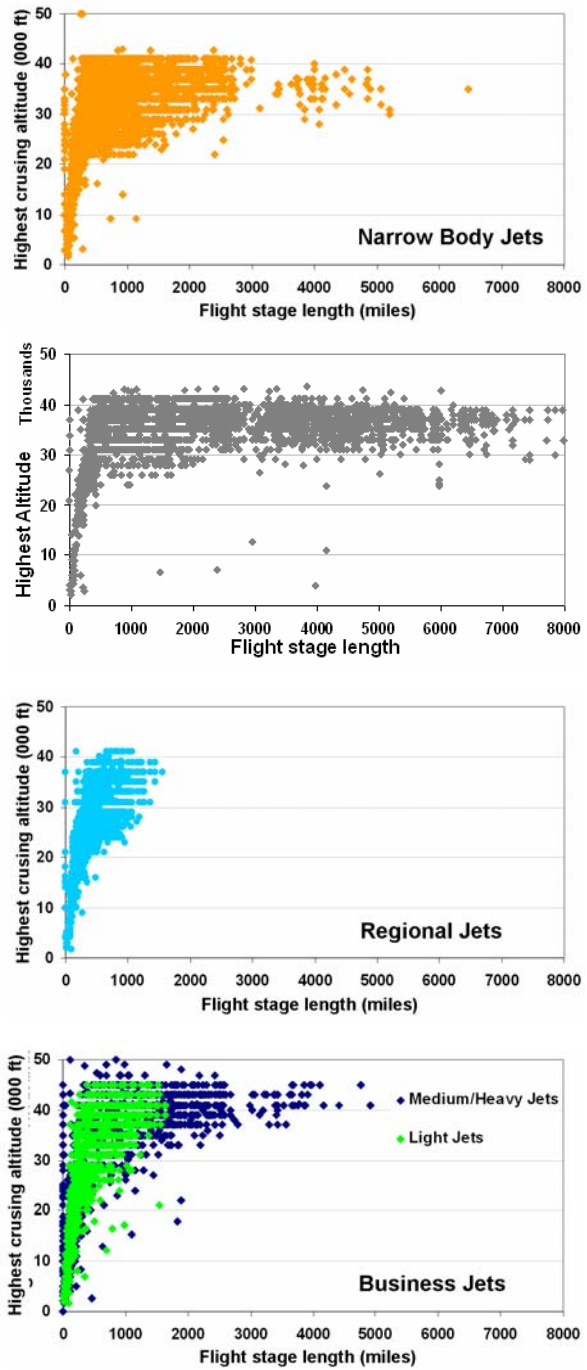


Figure 14. Distribution of maximum altitudes as a function of stage length for four categories of aircraft

It was found that medium/heavy jets and light jets were flown up to 51,000 ft and 45,000 ft respectively, which is their maximum certified ceiling respectively (Table 2). With narrow body, wide body and regional jets are flown up to 41,000ft, some business jets were found to fly above

commercial traffic (i.e. 16% of the medium/heavy business jet traffic and 10% of the existing light jet traffic was performed above 41,000 ft). Overall, the vertical patterns (altitude vs. flight stage length) of existing LJs are similar to those of regional jets (Figure 14).

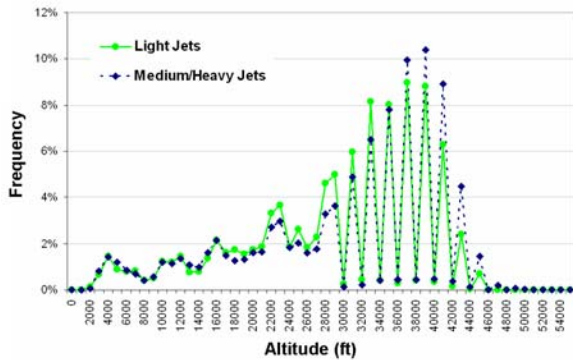


Figure 15. Distribution of the highest cruising altitude of flight for light and medium/heavy business jets

Figure 15 shows that business jets (medium/heavy and light jets) mostly have their highest cruise altitude between 29,000 ft (FL290) and 41,000ft (FL410). It was observed that 53% of all business jet flights were cruising between those flight levels, compared to 76% for narrow body jets.

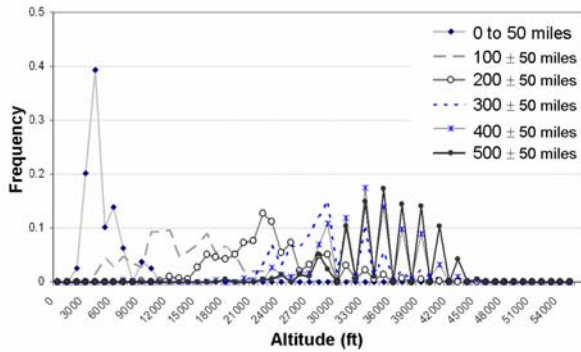


Figure 16. Altitude distribution for light jets by stage length

The stage length analysis that was performed and was presented in the previous section showed that a significant fraction of the flights performed by LJs had shorter stage lengths than 500 miles. The analysis of altitude patterns of existing LJs was extended to include the stage length influence on cruise altitude selection and assignment by air traffic control. Figure 16 shows the distribution of the highest altitude of the flights categorized by stage length from 0 to 500 ± 50 miles by increments of 100 miles. As range increases, the mode of the altitude distribution increases. For example flights with stage length distributions between 50 and 150 miles are more likely to be flown between 10,000 ft and 18,000 ft. For flights from 150 to 250 miles the mode of the distribution is located around 23,000 ft. Above 400 miles, the light jet traffic overlaps the airspace (from 29,000 ft to 41,000 ft) that is used by commercial aircraft (i.e. narrow body jets, wide body jets, etc.).

Due to the short flight stage lengths and potential restrictions to climb higher due to slower speeds than other

types of larger aircraft, it is expected that a significant fraction of the VLJ traffic will occur below 29,000 ft.

F. Network Analysis of Routes Flown by Existing Light Jets and Implications for Future Very Light Jet Traffic

In order to understand how the horizontal operating patterns of VLJs may evolve, a network analysis of the origin-destination routes (OD routes) flown by existing LJs was performed. In this network the nodes are defined as the airports (origin and destination) and the arcs represent non-stop flights between those airports.

• **Methodology**

From the set of flights flown from October 1st 2004 to September 30th 2005 in the ETMS data set, the network of OD routes was constructed and recorded in an adjacency matrix. The rows of the adjacency matrix represent the origin airports and the columns represent the destination airports. Each cell in the matrix represents the frequency of flights per year between airports in the network. Using the adjacency matrix, a statistical analysis of the network structure was performed.

• **Statistical network analysis**

From the adjacency matrix several network characterization metrics were derived. The light jet airport network based on traffic from Oct. 2004 to Nov. 2005 was found to be composed of 2537 airport nodes and 167,774 OD route arcs connecting these airports. The density of the network was found to be 0.05 indicating that the number of arcs in this network represents only 5% of the total possible connections. The total number of possible connections for an undirected network is $(n*(n-1)/2)$, where n is the number of nodes in the network. In the case of the light jet network, the total number of arcs in the network is 3.22 million connections.

The structure of the network was also characterized with the detailed analysis of how airport nodes were connected among each other. Certain airports nodes were found to be highly connected (e.g. Dekalb-Peachtree airport, Teterboro airport, Mc Carran International/Las Vegas airport, Chicago Midway airport were found to have respectively 701, 693, 688 and 681 connections to other nodes –also referred to as the degree of a node-). In contrast a very large number of airports were found to have very low number of connections (i.e. 886 airports have 10 or less connections).

Networks with very few highly connected nodes (hubs) and a large number of nodes with few connections for which the degree distribution follows a power law are referred to as scale free networks. These networks that exhibit power law degree distributions have special properties among which they are said to be scalable. This implies that the network can grow and change scale without constraints. Such networks are represented by a linear relationship on a log-log scale (as shown on Figure 18). However, it was found that the network of routes flown by LJs did not follow a power law distribution (Figure 17).

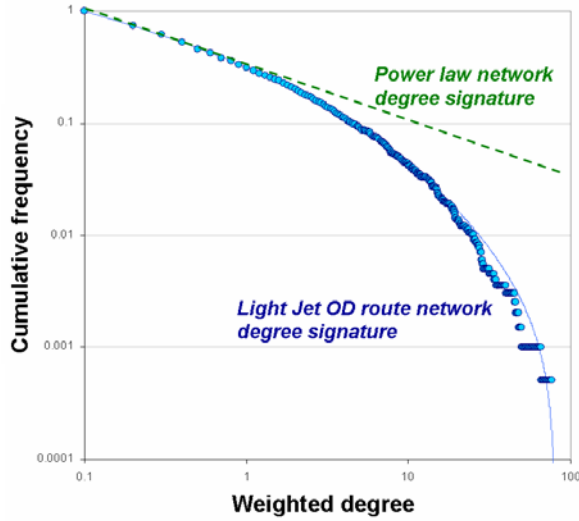


Figure 17. Degree distribution of the existing light jet network

Network with power law degree distribution have been found to result from preferential attachment dynamics [13][14]. This implies that as the network grows, new arcs are more likely to become connected to existing nodes that have large degrees. In other words, the attractiveness of a node is function of its actual connections to other nodes in the network, its weight in the network.

For the LJ network in Figure 17, as the network grows new arcs are added without limitation at the low degree airports in the network. However, for the high degree airports it is observed that the cumulative frequency falls below the power law growth curve indicating that the airports are limited in their ability to add new arcs due either to demand or capacity limitations. These networks are referred to as sub linear growth networks.

Because the network clearly exhibits sub linear growth at its key nodes, the network was represented through sub linear network growth models based on preferential attachment mechanisms that lead to non power law networks such as those described by Krapisky and Redner [16].

The rate of growth of the number of nodes of degree k can be expressed as:

$$\frac{dN_k}{dt} = A^{-1} [A_{k-1} \cdot N_{k-1} - A_k \cdot N_k] \quad (1)$$

with k the degree of a node, N_k the number of nodes with degree k . A_k is the attractiveness of a node which for a non-weighted[§] network, A_k is proportional to the degree of a node. Because data of the frequency of flights on each arc of the network was available, a weighted network representation was used. In this case, A_k is the degree of the node weighed by the frequency on the incoming and outgoing arcs. Normalizing A_k we find A_k/A representing the probability that an arc connects to a node with degree k , where

[§] A non-weighted network is a network for which all arcs (OD routes) have the same weight regardless of traffic or frequency on those arcs.

$$A(t) = \sum_{j \geq 1} A_j \cdot N_j(t) \quad (2)$$

With $N_k(t) = t \cdot n_k$ and $A(t) = \mu t$ the rate equation can be expressed as follow with n_k being the frequency of nodes with degree k .

$$n_k = \frac{\mu}{A_k} \prod_{j=1}^k \left(1 + \frac{\mu}{A_j} \right)^{-1} \quad (3)$$

For sub-linear kernels $A_k \propto k^\gamma$, the solution is:

$$n_k \propto k^{-\gamma} \exp \left[-\mu \left(\frac{k^{1-\gamma} - 2^{1-\gamma}}{1-\gamma} \right) \right] \quad (4)$$

for $\frac{1}{2} < \gamma < 1$

This solution was found to be the best fit for the degree distribution of the light jet network with $\gamma = 0.72$. This finding indicates that the rate of growth of traffic at airports will be proportional to $(A_k/A)^{0.72}$ (i.e. their attractiveness modified by this sub linear growth factor).

Implications of sub linear growth of the light jet network

The sub-linear preferential attachment mechanisms found in the light jet network has implications in terms of the growth of the network with the entry of VLJs. It implies that airports that already constitute important nodes with dense traffic are going to attract more traffic (i.e. creation of new connections to other accessible airports, and reinforcement of the frequency on existing arcs). For instance airports, such as Teterboro, Dallas Love Field, Las Vegas Mc Carran International, Midway, etc. will capture even more traffic. Table 4 displays the percentage of traffic growth (generated by the entry VLJs) for the top 20 airports in the continental United States. Overall, these 20 airports will total 11% of the overall growth of VLJ traffic. Similarly, the top 100 airports (from the set of 12,007 airports) will capture 35% of additional traffic by VLJs. At some point, saturation due to capacity constraints will limit the growth of traffic at these airports.

Airport code	Airport name	Percentage of Traffic growth
TEB	Teterboro	0.96
DAL	Dallas Love Field	0.67
LAS	Mc Carran International – Las Vegas	0.66
MDW	Chicago Midway International	0.66
CMH	Port Columbus International	0.65
PDK	Dekalb-Peachtree	0.63
APA	Centennial - Denver	0.62
IAD	Washington Dulles International	0.61
HPN	White Plains - New York	0.54
CLT	Charlotte/Douglas International	0.51
BHM	Birmingham International	0.50
HOU	Houston Hobby	0.50
PBI	Palm Beach International	0.47
PTK	Oakland County	0.46
PHL	Philadelphia International	0.45
VNY	Van Nuys	0.44
MEM	Memphis International	0.44
SDL	Scottsdale	0.43
BNA	Nashville International	0.43
SNA	John Wayne-Orange County	0.43

Table 4. Top 20 airports with the highest preferential attachment factors (attractiveness)

G. Implications of the Integration of Very Light Jets into the National Airspace System

The introduction of VLJs into the National Airspace System will have implications for airport and Air Traffic Control at both the Enroute and Terminal level.

- **Implications for airports**

The results from the preferential growth model indicate that there will be significant growth at currently high activity airports which are often within metropolitan areas. Out of the 20 airports with largest growth, presented in Table 4, 15 are located in the regional airport systems around metropolitan areas (i.e. Teterboro, Dallas Love Field, Mc Carran/Las Vegas, Chicago Midway, Dekalb-Peachtree, Centennial Denver, Washington Dulles, White Plains/New York, Charlotte International, Houston Hobby, Oakland county, Philadelphia International, Van Nuys, Scottsdale, John Wayne Orange county airport). The entry of VLJs is expected to have a significant impact on these airports. In addition, these airports will also experience the continuous growth of business aviation from larger aircraft (i.e. light, medium and heavy jets). Some of these airports will ultimately reach their limit capacity. Teterboro airport in the New York region is already showing signs of saturation. In this case, business jet traffic will have to redistribute to other closely located airports. These under-utilized airports in the regions will gain importance. These dynamics of “secondary business/general aviation airports” are similar to the dynamics of the emergence of secondary airports -to major commercial airports- that have been observed over the last 30 years in the United States [17].

The network is also expected to grow at the low activity (low degree) airports outside metropolitan areas (e.g. Port Columbus International, Birmingham International, Palm Beach International, etc.) These airports will continue to grow and attract new traffic as VLJs will enter service. The impacts of the entry of VLJs is not as significant for this set of airports since they exhibit excess capacity and are located in low density terminal area airspace.

- **Implications for air traffic control**

- **En-route**

Because of the lower climb performance and cruise speeds for VLJs compared with commercial jets, VLJs will need to be segregated from faster traffic on high density corridors. Very light jets are predicted to exhibit lower cruise speed (from 340 to 390 kts) than existing LJs. From an air traffic control perspective in the en-route flight segments, this difference in cruise speed will have implications for the integration of VLJ traffic with traffic by other aircraft (i.e. larger business jets, regional jets, narrow body jets) that have cruising speeds greater than 400 kts. Integrating slower aircraft implies larger number of speed conflicts (faster aircraft having to pass slower aircraft). This performance limitation can be alleviated through altitude segregation - keeping slower aircraft at lower altitudes than other fast traffic-. From the vertical pattern analyses of LJs and the distribution of operational maximum cruising altitudes as a function of range that were presented in section III.F, it is believed that due to the short stage length of the flights and

potential restrictions to climb higher due to slower speeds than other types of larger aircraft, a significant fraction of the VLJ traffic will occur below 29,000 ft.

- **Terminal Areas**

The analysis of the airport utilization and the identification of significant concentration of traffic within airport systems around major metropolitan areas showed that the terminal areas (airspace within 50 miles of the core airports) are likely to be the part of the airspace where interactions between VLJs and other traffic interactions will be the strongest. Even though VLJs may use underutilized airports within the regional airport system around a major airport, traffic to and from these airports interacts at the terminal area level and at its boundaries with traffic from large airports.

IV. Conclusions

A comparative analysis of the characteristics and performance of Very Light Jets (VLJs) and existing Light Jets (LJs) was conducted and showed that the predicted performance of VLJs will overlap with the performance of existing LJs in terms cruise speed, range, maximum ceiling. As a consequence of this analysis, it was found that a 12,500 lbs threshold, based on certification standards, for the definition of VLJs is more appropriate than the current 10,000 lbs threshold.

Analyses of the operating patterns and network structure of existing LJs were performed. It was found that traffic was concentrated around major metropolitan areas. It is believed that VLJs will also exhibit the same concentration of traffic due to similar underlying socio economic factors that currently drive the traffic of LJs. This projected increase in VLJ traffic will add to growth of commercial traffic resulting in increased interactions at major airports and surrounding airports.

The projected growth of traffic coupled with the concentration of traffic and airport interactions that were observed from the data, suggest that regional airport systems around major airports are the places in the system where the impacts of VLJs will be the most significant. This suggests that existing and future general aviation reliever airports will become instrumental in accommodating the entry of VLJs (and the growth of business and general aviation). Even with segregation of traffic at the regional level with the use of reliever airports, the issue of air traffic management at the airspace interface (i.e. TRACON level) will remain. Therefore the impact of the entry of VLJs on airspace workload is likely to be more apparent at the TRACON level. These foreseen impacts of VLJs motivate the need to investigate solutions for ensuring sufficient capacity at the regional level in addition to mechanisms and incentives for adequately distributing traffic within those regional airport systems in order to accommodate demand and the growth of all segments of the air transportation industry.

Acknowledgements

This work was supported by NASA Langley under grant NAG-1-2038 and by the FAA under contract DTFA01-01-C-00030'D.0#16. The authors would like to thank Dave

Knorr from the FAA and Prof. Alexander Bayen from Berkeley University for their help in accessing ETMS data. In addition, the authors thank the NASA/FAA Joint University Program participants for their feedback in addition to Aleksandra Mozdzanowska from the MIT International Center for Air Transportation.

References

- [1] National Business Aviation Association (NBAA), "Business Aviation Fact Book", 2004.
- [2] General Aviation Manufacturers Association (GAMA), "General Aviation Airplane Shipment Report", February 2006.
- [3] Jane's, "All the World aircraft", 2004-2005 edition.
- [4] Jane's, "All the World aircraft", 2005-2006 edition.
- [5] Embraer website.
- [6] Spectrum website.
- [7] FAA, 2004, Airport Master Records, Form 5010.
- [8] Teal Group forecast, 2006.
- [9] Federal Aviation Administration, "Aerospace Forecasts 2005-2016".
- [10] Honeywell, "14th annual Business Aviation Outlook, 2005-2015".
- [11] Rolls Royce Outlook 2005.
- [12] Bonnefoy P., "Simulation of Air Taxi Networks", Proceedings to the Winter Simulation Conference, 2005.
- [13] Newman M. E. J., "The structure and function of complex networks", Society for Industrial and Applied Mathematics, p.167-256, 2003
- [14] Dorogovstev S.N., Mendes J.F.F., "Evolution of networks", Oxford University Press, 2003.
- [15] Alexandrov N., 2004, "Transportation Network Topologies", NASA/TM-2004-213259.
- [16] Krapivsky P.L., Redner S., "Organization of growing random networks", Physical Review E, Volume 63, 066123, 2001.
- [17] Bonnefoy P., Hansman R. J., "Emergence of Secondary Airports and Dynamics of Regional Airport Systems", Massachusetts Institute of Technology, Master of Science Thesis, June 2005.