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Potential Impacts of Very Light Jets on the National Airspace System

Philippe A. Bonnefoy* and R. John Hansman†
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

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Very light jets 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 capabilities 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, 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 light jet 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 increase the traffic load at the terminal airspace: terminal radar approach control. These impacts need to be taken into account to allow a successful integration of these aircraft in the National Airspace System.

I. Introduction

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.

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 months 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 entry of a new class of three to eight passenger turbofan-powered aircraft, very light jets (VLJs), is expected to further accelerate this growth.

Because of the potential entry of several thousands of VLJs over the next 10 years, there is some concern that VLJ traffic loads may create capacity problems in some areas of the National Airspace System (NAS). To assess this concern there is a need to predict their future operating patterns and evaluate the potential impacts of VLJs on the National Airspace System.

This paper presents an analysis of the potential impacts of VLJs in the U.S. National Airspace System through horizontal and vertical traffic pattern analyzes and modeling of network evolutionary dynamics. The first section of the paper presents an in-depth description and comparative analysis of the characteristics and performance of VLJs and LJs. Overlaps between the performance and capabilities of existing LJs and future VLJs motivated the analysis of the patterns of operation of the closest type of existing aircraft (i.e., light jets) in order to predict the future VLJ operating patterns. This analysis of spatial (horizontal and vertical) and temporal operating patterns is presented in Sec. III. Finally, the potential impacts of future very light jets are assessed and discussed.

II. Business Jet Spectrum Analysis and Aircraft Performance Comparison

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 turbofan-powered aircraft that have a maximum takeoff weight below 10,000 lb (Table 1). Existing LJs are defined to be between 10,000 and 20,000 lb. Higher in the business jet spectrum, medium jets are characterized by maximum takeoff weights between 20,000 to 35,000 lb. Heavy business jets have a maximum takeoff weight greater than 35,000 lb.

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 lb), certified in 1992, being the lightest twin turbofan-powered aircraft in the current business jet spectrum. The entry of VLJs expected in 2006 will extend downward the current business jet spectrum under 10,000 lb. However, from a vehicle and performance standpoint the thresholds between the two classes of aircraft is not as clear. An alternative 12,500 lb 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

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*Graduate Research Assistant, International Center for Air Transportation and Engineering Systems Division, 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.

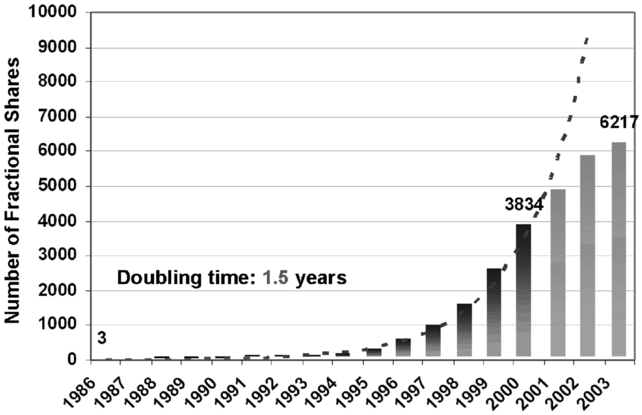

Fig. 1 Exponential growth of fractional shares from 1986 to 2000 [1].

commuter category airplanes from those air transport category aircraft certified under the FAR Part 25.

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, takeoff field length, maximum ceiling) published in the Jane's "All the World Aircraft" handbook 2004–2005, 2005–2006, and 2006–2007 editions [3–5].

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 three to eight passengers. To some extent, there is an overlap with existing LJs such as the Cessna CJ1 which can accommodate five passengers. In terms of acquisition price (adjusted to 2006 dollars) VLJs are expected to range from \$1.3 million to \$3.6 million compared to \$4 million to \$8 million for existing LJs. 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 lb) follow. The average cost per pound of aircraft, based on maximum takeoff weight, is roughly 550/lb. In terms of operational characteristics and performance, VLJs are predicted to exhibit slightly lower cruise speeds (from 340 to 390 kn) than existing LJs that have cruising speeds greater than 381 kn.

Very light jets are also expected to have maximum ceilings ranging from 25,000 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 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 takeoff field length performance (from 2100 to 3100 ft) than existing LJs that require runways from 3300 to 3993 ft.

C. Airport Availability and Possible Utilization Based on Predicted Performance of Very Light Jets

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

This performance will allow VLJs to be operated at airports with shorter runway lengths. The additional runway availability can be seen in Fig. 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 [6]. There are over 6400 runways in the continental United States over 3000 ft available to VLJs although 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 used by VLJs.

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

Table 1 Current business jet spectrum with the extension to the future very light jet category [3–5]

Aircraft name	Maximum takeoff weight, lb	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]	13,500	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 jet category was defined based on a 10,000 lb 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 takeoff weight greater than 12,500 ft. Similarly, the Sino Swearingen SJ30 was also certified under Part 23.

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

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 takeoff weight, lb	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	1100	1750	1178	2500
Cruising speed, kn	340	389	381	462
Maximum ceiling, ft	41,000	45,000	41,000	51,000
Takeoff field length, ft	2035[b] 2155[c]	3100	3280	3993

[a]Not including pilot and copilot front seats. In single pilot operations, the right front seat could be used as a passenger seat.
[b]Single engine very light jet.
[c]Twin-engine very light jet.

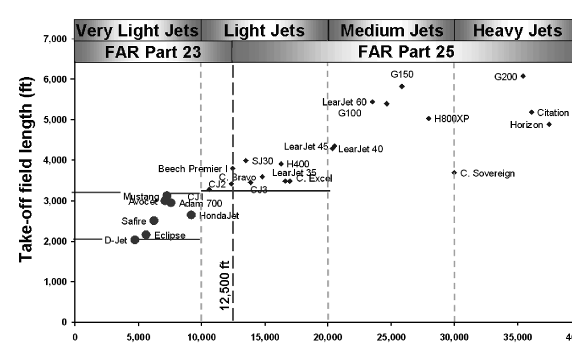

Fig. 2 Published takeoff field length of very light, light, medium, and heavy business jets [3–5].

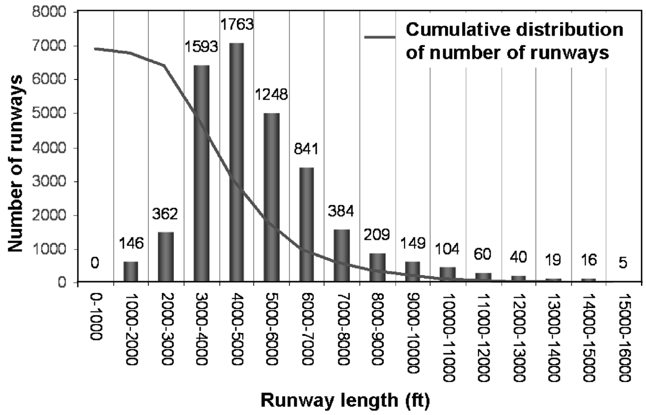

Fig. 3 Runways available at public airports in the continental United States by runway length [6].

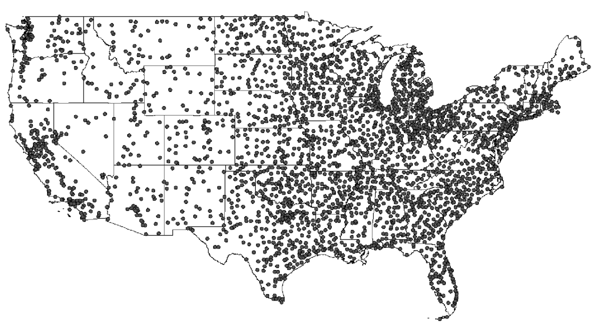

Fig. 4 United States public airports with at least one runway longer than 3000 ft [6].

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 3000 ft 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.

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 turboprops [3–5] (e.g., Pilatus PC-12, TBM-700, etc.), VLJs have the potential to enter the system in significant numbers. In its 2005–2016 forecasts [7] the FAA predicted that there will be 4500 VLJs in the National Airspace System by 2016. In 2005, Honeywell Aerospace [8] predicted 4500–5500 VLJ deliveries over the next 10 years excluding the on-demand per-seat and fractional ownership segment of the market. Rolls Royce forecast 7649 VLJs will be delivered between 2006 and 2025 [9]. Other forecasting groups such as the Teal Group are less optimistic and forecast 2310 VLJ aircraft deliveries between 2006 and 2016 [10]. As of July 2006, the cumulative backlog of orders for the four 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 [1].

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 used 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 the 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 a passenger can book flights on a single seat basis, and business models that mix both concepts. Finally, VLJs are also expected to be used 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 three to seven flights per day (including repositioning flights) [11]. 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 4000 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

Although the acquisition and operating costs of VLJs may be different than existing LJs, it is expected that through price elasticity the fleet size will increase but the operating patterns should be similar at the aggregate level. Very light jet 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.

Related work on this problem was also conducted by Trani et al. [12] through a bottom up approach, starting from population distribution and socioeconomic factors that were used to forecast future volumes of traffic by very light jets. This paper presents a different approach that treats the overall volume of VLJ traffic parametrically and uses LJs as a surrogate for future VLJ operating patterns to assess the potential impacts of VLJs.

A. Methodology and Data

To analyze the operating patterns of existing LJs, data of actual flights from the FAA Enhanced Traffic Management System (ETMS) was used. For each instrument flight rule (IFR) and air traffic control (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 were composed of a full and continuous year of traffic. This dataset included 365 days of data from 1 October 2004 to 30 September 2005. To complement this dataset, another set of 31 days of data from days from the months of January, April, July, and October spanning from 1998 to 2004 was used.

In addition to the ETMS flight database, a database of civil airplanes was used. This database was 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 and 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

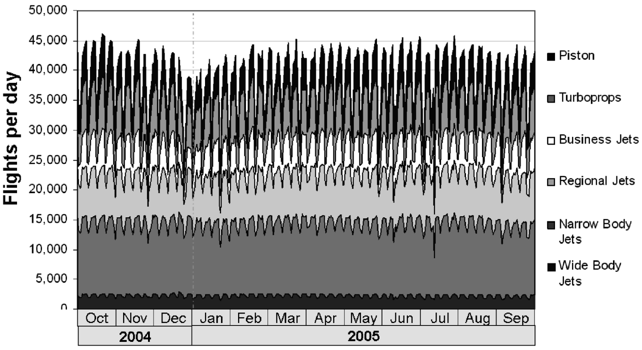

Fig. 5 Daily traffic volumes over 1 yr (from October 2004 to September 2005) for all aircraft types.

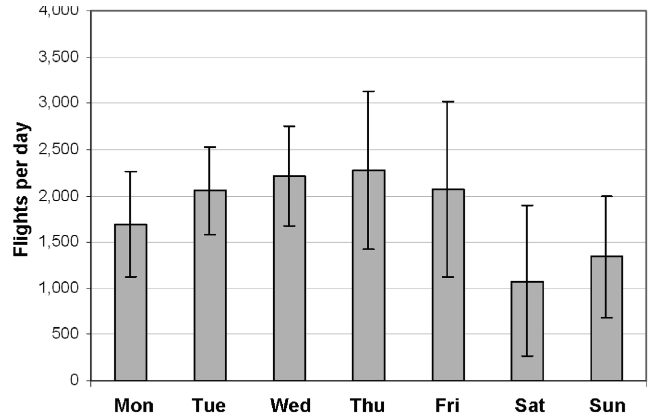

Fig. 7 Weekly traffic pattern of existing light jets (average number of flights per day with $\pm 3\sigma$).

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—were 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 1 October 2004 to 30 September 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 weekdays and weekends. 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%.

From the set of flights flown by business jets, 811,300 were flown by LJs over the 365 days of data. Figure 6 shows the volume of traffic from LJs between 1 October 2004 and 30 September 2005 with its 7 day moving average.

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.

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 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), and Beechcraft/Hawker 400 (BE40). It was also found that only four types of light jets accounted for 79% of the overall light jet traffic (Fig. 8).

D. Spatial Analysis: Horizontal Operating Patterns

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 h period in January of 2004 over the continental United States.

As can be seen in Fig. 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.

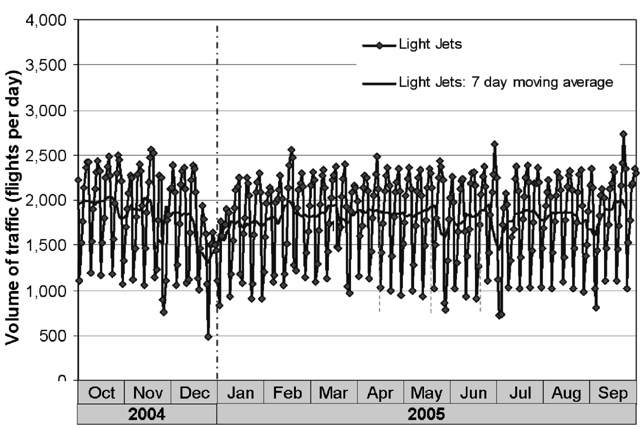

Fig. 6 Daily traffic over 1 yr (from October 2004 to September 2005) of existing light jets.

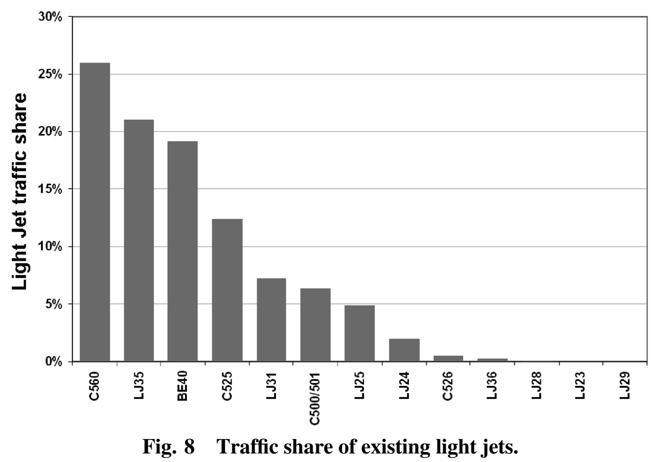

Fig. 8 Traffic share of existing light jets.

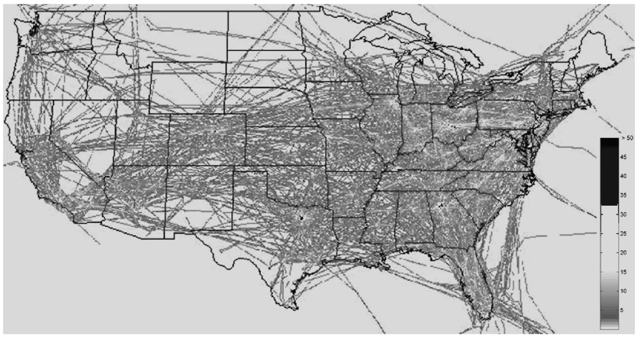

Fig. 9 Density of 24 h of traffic by existing light jets in the continental United States (January 2004).

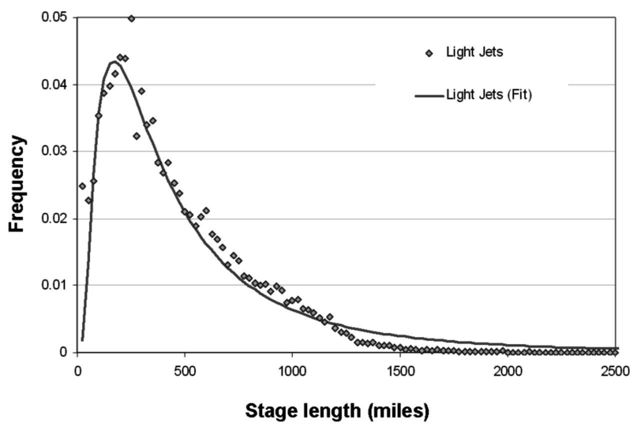

Fig. 10 Stage length distributions for light jets and business jets.

Flight stage lengths from the overall dataset are presented in Fig. 10. It was found that the stage length distribution for LJs followed a log normal distribution with a mean of 590 miles and standard deviation of 700 miles. The mode of the distribution was found to be 175 miles.

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.

It was found that 66% of the flights have stage lengths 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 standpoint, shorter flights require a cruising altitude lower than for flights with long stage length.

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

Airport code	Airport name	Annual operations
TEB	Teterboro	32,629
DAL	Dallas Love Field	19,709
LAS	McCarran Las Vegas International	19,443
MDW	Chicago Midway International	18,958
CMH	Port Columbus International	18,143
PDK	Dekalb–Peachtree	17,597
APA	Centennial—Denver	17,454
IAD	Washington Dulles International	14,750
HPN	White Plains—New York	13,571
CLT	Charlotte/Douglas International	13,048
BHM	Birmingham International	12,992
HOU	Houston Hobby	12,052
PBI	Palm Beach International	11,714
PTK	Oakland County	11,391
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

1. 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 the New York regional airport system, Washington Dulles (IAD) close to Washington, D.C., Midway (MDW) close to Chicago, Las Vegas (LAS), etc. capturing very high traffic loads.

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 U.S. A regional airport system was defined as all airports within 50 miles of one of the 29 major airports. Shown in Fig. 12 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 either departed or landed at one of the airports within these 23 regional airport

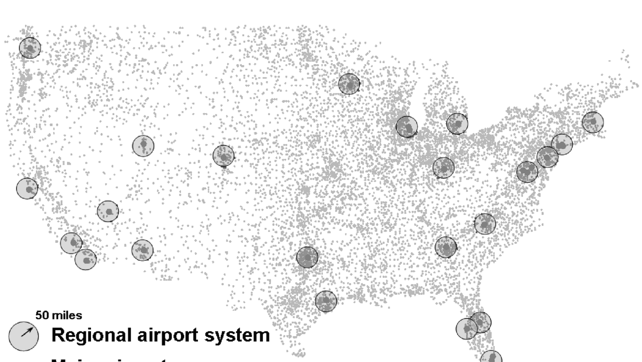

Fig. 11 Regional airport system in the continental United States used as a reference for existing light jet traffic concentration analysis.

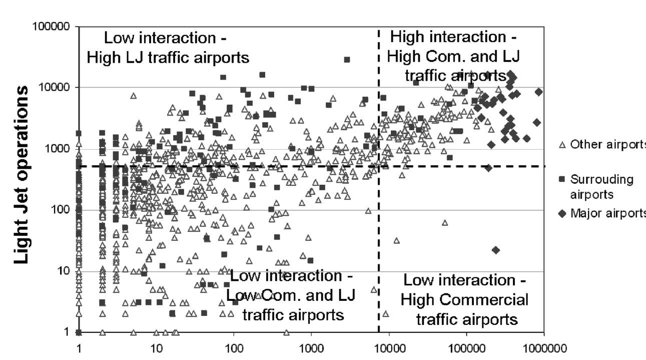

Fig. 12 Categorization of landing facilities in the continental United States commercial and light jet traffic.

systems (Fig. 11). 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.

2. Analysis of Interaction of Light Jet Traffic with Commercial Traffic Within the National Airport System

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 October 2004–September 2005 period.

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 four categories (represented by the dotted lines in Fig. 12). It was found that 159 airports exhibited high interaction and high traffic (for both commercial and light jet traffic). Most 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.

3. Airport and Runway Use

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 instrument landing system (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 a space based precision approach capability is expected to increase IFR accessibility at less equipped airports and allow exploitation of underused airports both within the 23 major regional airport systems and across the U.S.

The observed light jet use of runways is shown in Fig. 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 5000 ft and 60% is performed at airports with runways longer than 7000 ft.

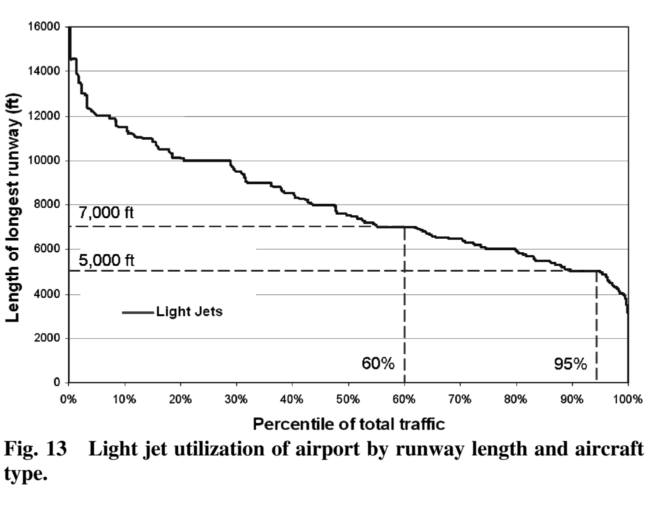

Fig. 13 Light jet utilization of airport by runway length and aircraft type.

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 takeoff field length requirements, only a small fraction of the operations will occur at airports that have such short runways (3000– 4000 ft range).

E. Spatial Analysis: Vertical Operating Patterns

To analyze the vertical operating patterns of light jets, the position reports along the 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 (Fig. 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 jets.

It was found that medium/heavy jets and light jets were flown up to 51,000 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 41,000 ft, 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 (Fig. 14).

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

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 ATC. Figure 16 shows the distribution of the highest altitude of the flights categorized by stage length from 0 to 500 $\pm$ 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 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 to 41,000 ft) that is used by commercial aircraft (i.e., narrow body jets, wide body jets, etc.).

Because of 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

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 nonstop flights between those airports.

1. Methodology

From the set of flights flown from 1 October 2004 to 30 September 2005 in the ETMS dataset, 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.

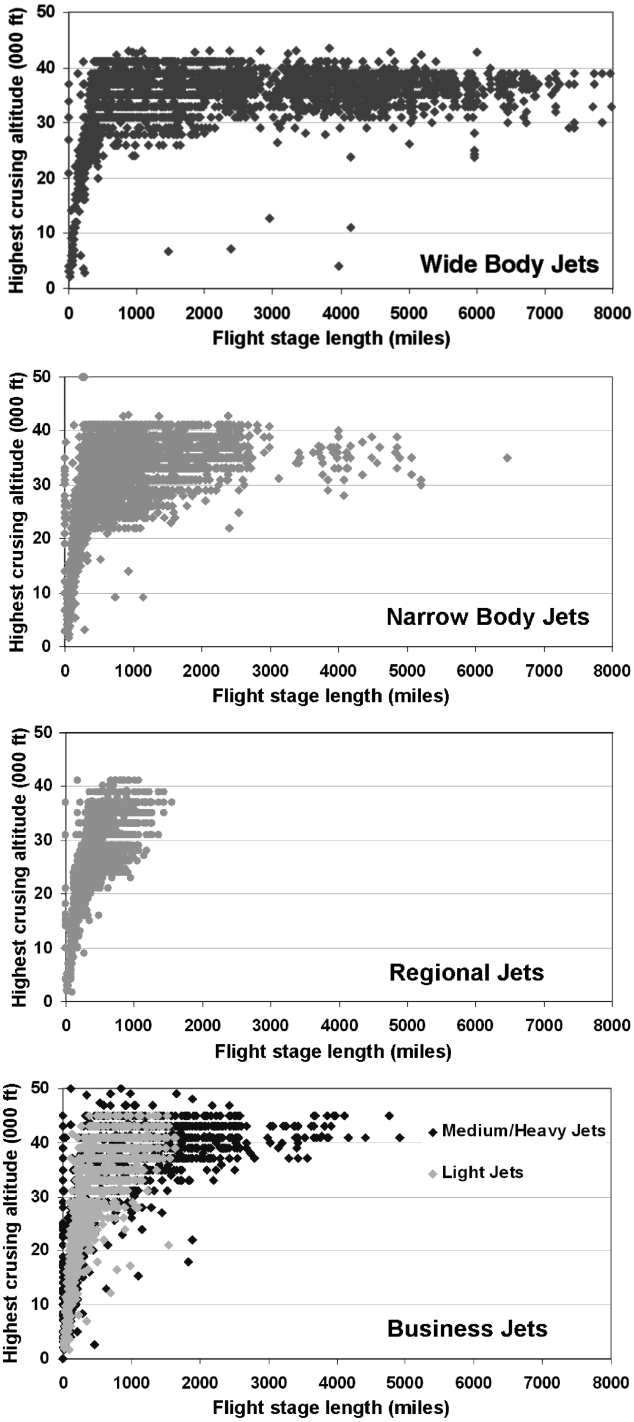

Fig. 14 Distribution of maximum altitudes as a function of stage length for four categories of aircraft.

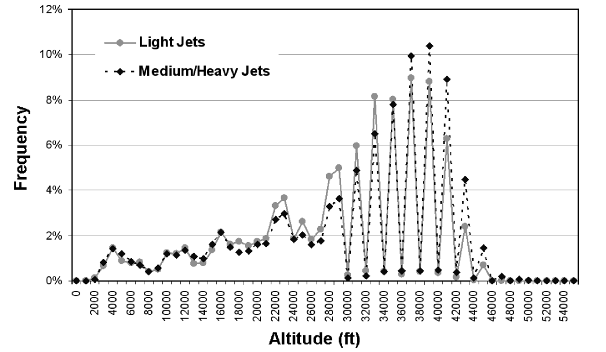

Fig. 15 Distribution of the highest cruising altitude of flight for light and medium/heavy business jets.

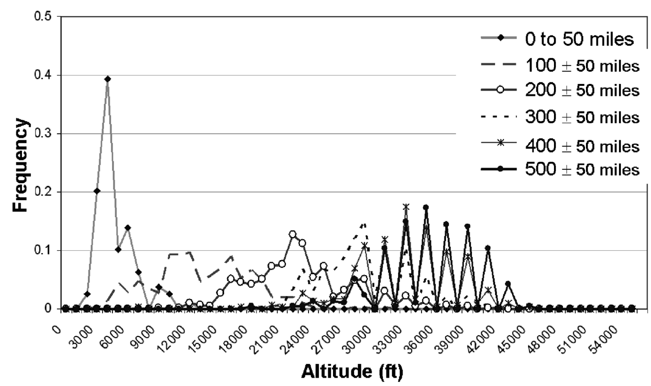

Fig. 16 Altitude distribution for light jets by stage length.

Using the adjacency matrix, a statistical analysis of the network structure was performed.

2. *Statistical Network Analysis*

From the adjacency matrix several network characterization metrics were derived. The light jet airport network based on traffic from October 2004 to November 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 3.22×10^6 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, McCarran International/Las Vegas airport, and 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 a 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 in Fig. 17). However, it was found that the network of routes flown by LJs did not follow a power law distribution (Fig. 17).

Networks 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 a function of its actual connections to other nodes in the network, its weight in the network.

For the LJ network in Fig. 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 indicting 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 sublinear growth networks.

Because the network clearly exhibits sublinear growth at its key nodes, the network was represented through sublinear network growth models based on preferential attachment mechanisms that

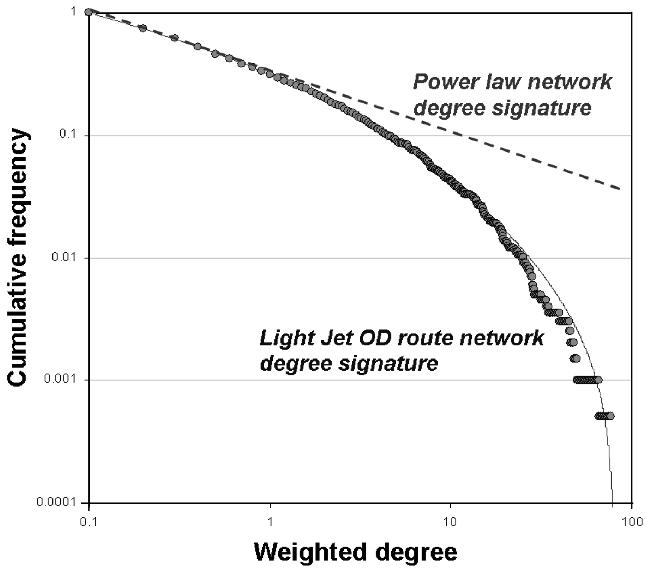

Fig. 17 Degree distribution of the existing light jet network.

lead to nonpower law networks such as those described by Krapivsky and Redner [15].

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

$$\frac{dN_k}{dt} = A^{-1}[A_{k-1}N_{k-1} - A_k N_k] \tag{1}$$

with k the degree of a node, and N_k the number of nodes with degree k. A_k is the attractiveness of a node which for a nonweighted[§] network, A_k is proportional to the degree of a node. Because data of the frequency of flights on each arc of the network were 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

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

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

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

For sublinear kernels $A_k \propto k^{\gamma}$, the solution is

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

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 sublinear growth factor).

3. *Implications of Sublinear Growth of the Light Jet Network*

The sublinear preferential attachment mechanisms found in the light jet network have 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 McCarran 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.

IV. Discussion and Conclusions

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

Analyses of the operating patterns and network structure of existing LJs were performed and informed the assessment of the potential impacts of the introduction of VLJs into the National Airspace System (i.e., airport and air traffic control at both the enroute and terminal level).

A. 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, McCarran/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 underused airports in the regions will gain importance. These dynamics of "secondary business/general aviation airports" are similar to the dynamics of the emergence of

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

Airport code	Airport name	Percentage of traffic growth
TEB	Teterboro	0.96
DAL	Dallas Love Field	0.67
LAS	McCarran 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

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

secondary airports—to major commercial airports—that have been observed over the last 30 years in the United States [16].

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 because they exhibit excess capacity and are located in low density terminal area airspace.

B. Implications for Air Traffic Control

1. Enroute

The entry of VLJs in the National Airspace System will add some workload to air traffic control which confirms the conclusions of Yousefi et al. [17]. 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 kn) than existing LJs. From an air traffic control perspective in the enroute 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 kn. Integrating slower aircraft implies a 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 Sec. 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.

2. 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. An illustration of airport interactions can be seen within the New York regional airport system that is composed of New York La Guardia (LGA), Newark (EWR), J. F. Kennedy (JFK), Teterboro (TEB), and several other smaller airports. Operations between these four airports are highly dependent because of the intricate set of arrival and departure paths.

The projected growth of traffic coupled with the concentration of traffic and airport interactions that were observed from the data suggests 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., terminal radar control (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 to accommodate demand and the growth of all segments of the air transportation industry.

Acknowledgments

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References

[1] “NBAA Business Aviation Fact Book 2004,” National Business Aviation Association, Inc. (NBAA), Washington, D.C., 2004.

[2] “General Aviation Airplane Shipment Report—End of Year 2005,” General Aviation Manufacturers Association (GAMA), Washington, D.C., Feb. 2006.

[3] Jackson, P., Peacock, L. T., and Munson, K., “Jane’s, All the World Aircraft 2004–2005,” Jane’s Information Group, Alexandria, VA, 95th ed., 2004.

[4] Jackson, P., Peacock, L. T., and Munson, K., “Jane’s, All the World Aircraft 2005–2006,” Jane’s Information Group, Alexandria, VA, 96th ed., 2005.

[5] Jackson, P., Peacock, L. T., and Munson, K., “Jane’s, All the World Aircraft 2006–2007,” Jane’s Information Group, Alexandria, VA, 97th ed., 2006.

[6] “Airport Master Records, Form 5010,” Federal Aviation Administration (FAA), [online database], http://www.faa.gov/airports_airtraffic/airports/airport_safety/airportdata_5010 [retrieved 28 Sept. 2004].

[7] “FAA Aerospace Forecasts Fiscal Years 2005–2016,” Chap. V: General Aviation, U.S. Department of Transportation Federal Aviation Administration Office of Aviation Policy & Plans, 2005, pp. V14–V18.

[8] “14th Annual Business Aviation Outlook, 2005–2015,” Honeywell Aerospace, 2005.

[9] “Market Outlook 2006–2025,” Rolls Royce, 2006 ed., Sept. 2006.

[10] “Teal Predicts 10,087 Business Aircraft Worth $141.1 Billion Will Be Built in 2006-2015,” PR Newswire Association LLC, 16 May 2006.

[11] Bonnefoy, P. A., “Simulating Air Taxi Networks,” *Proceedings of the 37th Winter Simulation Conference WSC’05*, Winter Simulation Conference, Orlando, FL, 2005, pp. 1586–1595.

[12] Trani, A., Baik, H., Swingle, H., and Ashiabor, S., “An Integrated Model to Study the Small Aircraft Transportation System (SATS),” *Transportation Research Record 1850, TRB*, National Research Council, Washington D.C., 2003, pp. 1–11.

[13] Newman, M. E. J., “The Structure and Function of Complex Networks,” *SIAM Review*, Vol. 45, Pt. 2, 2003, pp. 167–256.

[14] Dorogovstev, S. N., and Mendes, J. F. F., “Evolution of Networks,” *Advances in Physics*, Vol. 51, No. 4, 2002, pp. 1079–1187.

[15] Krapivsky, P. L., and Redner, S., “Organization of Growing Random Networks,” *Physical Review E*, Vol. 63, No. 6, 2001, pp. 1–14.

[16] Bonnefoy, P., and Hansman, R. J., “Emergence of Secondary Airports and Dynamics of Regional Airport Systems in the United States,” M.S. Thesis, Massachusetts Institute of Technology, June 2005.

[17] Yousefi, A., Donohue, G. L., and Qureschi, K. M., “Investigation of En Route Metrics for Model Validation and Airspace Design Using the Total Airports and Airspace Modeler (TAAM),” *Proceedings of the 5th Eurocontrol/FAA ATM R&D Conference*, 5th USA/Europe ATM R&D Seminar, Budapest, Hungary, June 2003.