This paper describes a methodology to predict on-demand air taxi services using emerging Very Light Jets (VLJ) technology in the future National Air Transportation System (NAS). The paper describes airspace and airport impacts of VLJ traffic considering an improved Next Generation Air Transportation System (NGATS). The analysis presented fits within the framework of the Transportation Systems Analysis Model (TSAM) developed by the Air Transportation Systems Laboratory at Virginia Tech for NASA Langley Research Center. TSAM uses traditional air transportation systems engineering techniques to: 1) predict the number of intercity trips generated in the country based on socio-economic factors, 2) distribute these trips across the country, 3) predict the most likely modes of transportation used to execute these trips, 4) predict flights and trajectories associated with air transportation trips, and 5) predict impacts of the intercity trips generated in the National Airspace System (NAS).

I. Introduction

Very Light Jets (VLJ) are small, turbofan-powered aircraft weighting up to 5,545 kg. (10,000 lb). VLJ aircraft have been in development since 1999. There has been considerable skepticism in the aviation community about the technical and economic feasibility of VLJ vehicles. However development has continued with start-up as well as established companies now developing VLJ aircraft. Eclipse Aviation announced its entry into the market in 1999, with Adam following in 2001. More recently established aircraft manufacturers announced their entry in to the market: Cessna, in 2002; and recently Embrear, an established air transport manufacturer, announced its entry in the market with the Phenom 100. Eclipse Aviation and Cessna have received aircraft certification for their products recently. Others are expected to follow suit shortly.

The motivation for this study is to examine possible airport and airspace impacts of emerging Very Light Jet aircraft operated into the National Airspace System (NAS). The study employs a large-scale transportation model developed at Virginia Tech for NASA to assess the demand for on-demand air taxi services using VLJ aircraft. The Virginia Tech Air Transportation Systems Lab developed the Transportation System Analysis Model (TSAM) to
assess impacts of small aircraft in the National Airspace System (1,2). TSAM uses county-level socio-economic data to forecast the number of intercity trips in the United States. The model uses proven transportation engineering methods to predict the number of travelers selecting among various modes of transportation (i.e., auto, airline, and other technologies like Very Light Jets and piston-powered aircraft operating as air-taxis). The demand for on-demand air transportation using VLJ aircraft has been evaluated at 2,300 public airports with an effective runway greater than 915 meters (3,000 ft.) meeting FAA criteria for visibility minima of 1,390 meters runway visual range (¾ mile) or less. The effective runway length has been adjusted by field elevation at a rate of 12% for every 328 meter (1,000 ft.) to derive credible runway lengths at medium and high elevations. The demand function at each airport is characterized in terms of daily person-trips and daily flight arrivals and departures.

The VLJ modeled in the analysis models a generic pressurized aircraft with six people (including two pilots), cruises at 676 km/hr (365 knots) and has a range of 2,037 km (1,100 nautical miles) with four occupants using National Business Aviation Association (NBAA) IFR reserves. The VLJ is equipped with two medium by-pass ratio turbofans producing 1100-lbf takeoff thrust at sea level static conditions. Detailed life cycle economic analysis of the aircraft has been modeled to understand the tradeoffs between demand and supply costs. The VLJ cost model methodology is described by Trani et al., (2).

II. Demand Modeling Framework

The modeling framework employs the Transportation Systems Analysis Model (TSAM), a model developed jointly by Virginia Tech and NASA Langley Research Center to study the potential demand of new aerospace technologies (1, 2). In past studies, TSAM has been applied to estimate the demand for the Small Aircraft Transportation System (SATS) (2). More recently, we have used TSAM to estimate the demand function for on-demand air taxi services using VLJ aircraft. Variations of this analysis are presented in this paper.

The Transportation Systems Analysis Model is a multi-mode intercity trip demand model that predicts long distance travel (one-way route distance greater that 100 miles) in the continental U.S. The model follows a traditional multi-step, multi-modal transportation planning framework where trips are: 1) produced, 2) distributed, 3) split into modes, and 4) assigned to routes. One key element of the TSAM model is its ability to predict intercity travel in the presence of multi-mode alternatives. The model in essence predicts the mode choice of travelers based on trip characteristics and traveler demographics. The framework of the model is shown in Figure 1.

Four key computational modules comprise TSAM. Each module represents one of four transportation planning steps (1). These modules are shown in blue in Figure 1. All four modules are described in more detail in a companion document to this paper. The model employs several databases shown in the green cylindrical shape containers in Figure 1. Databases include socio-economic data (Census, American Travel Survey and Woods and Poole), airline schedules and travel times (Official Airline Guide), airline fares (Department of Transportation), auto travel times and routes (MapPoint), airports and their characteristics (FAA database), and aircraft technology and their corresponding travel time information. For the on-demand air taxi mode, vehicle costs and performance functions are obtained using external models described in this paper. These are critical inputs to TSAM because passenger make mode choices based on perceived door-to-door travel times, door-to-door trip costs, convenience factors, etc. TSAM employs a nested logit model to assess the likelihood that a passenger will select either commercial air, auto or air taxi as the mode of transportation to make trips from countries across the U.S. The family of logit models employed in TSAM are described by Trani et al., (1).
Figure 1. Transportation Systems Analysis Model (TSAM).

TSAM predicts annual passenger trip demands between counties and between airports. These demand values are manipulated outside the model to produce daily demands and eventually daily flights scheduled between origin and destination airport pairs. Figure 2 illustrates the procedure to convert annual demand into daily flights. The flowchart starts on the left hand side with annual person trips produced by the model. Airport-to-airport matrices by aviation mode of travel are standard outputs of the model. A study of seasonal effects using ATS data is used to adjust the number of travelers for each quarterly period in the typical year. This seasonal variation is important because non-business travel patterns show substantial variations through the four quarters of the year. Business travel patterns are nearly equally distributed across the four quarters of the year.

Quarterly demands are then converted into daily demands using a simple proportional allocation scheme. For example, the quarterly demand values are adjusted by a factor of 1/90 to reflect daily demands. Daily on-demand services are distributed across time (24 hour period) using a Monte Carlo distribution scheme. This approach uses an empirically-derived hourly demand distribution of travel behavior obtained from the FAA Enhanced Air Traffic Management System (ETMS) data. This approach produces demands for VLJ services by the hour at 2,300 airports (or at any airport set studied). Passengers are grouped in travel parties at each airport to consolidate passengers willing to travel from similar origins to similar destinations with closely spaced departure times. Party size information obtained from ATS records is used to produce passenger loads and predict flights needed to satisfy the demand function. The average business party size is 2.13 and the average non-business party size is 3.40.

An acceptance factor of 76% for VLJ has been used in the final estimation of VLJ demand based on a survey conducted by Virginia Tech to understand the percent of the flying population who would be willing to fly in VLJ.
aircraft. The survey presented the characteristics and a pictorial representation of a typical VLJ aircraft to airline passengers.

![Diagram of TSAM Model](image)

**Figure 2.** Methodology to Predict On-demand Daily VLJ Traffic in the NAS Using the Transportation Systems Analysis Model (TSAM).

### III. Aircraft Performance and Cost Models

To understand the potential effect of VLJ aircraft operating in the NAS we model a generic pressurized turbofan-powered aircraft with a maximum carrying capacity of six people (four passengers plus two pilots). The aircraft has a maximum cruise speed of 676 km/hr (365 knots) and a practical range of 2,100 km (1,130 nautical miles). The VLJ is equipped with two medium by-pass ratio turbofans producing 454 kg. (1000-lbf) uninstalled takeoff thrust at sea level static conditions. The maximum operating altitude is 12,500 meters (41,000 ft.) at low to intermediate aircraft weights.

A representation of the high-speed drag polar for the aircraft is shown in Figure 3. The drag polar is parabolic with adjustments made to the zero lift drag coefficient term at high speeds to model appropriate drag divergence effects of a low swept wing employed in the VLJ aircraft. For simplicity in this preliminary analysis, available thrust is modeled as a table function of both mach number and altitude as shown in Figure 4. The thrust lapse rate used is typical of modern turbofan engines with moderate by-pass ratios. Figure 5 illustrates the payload-range diagram characteristics of the VLJ modeled for three cruise altitudes at a constant cruise Mach number. As can be observed from the figure, the VLJ modeled can fly 2,100 km with 3 passengers (plus baggage) and two pilots. The aircraft performance modeling in TSAM requires synthesizing Figures 3 and 4 into a BADA-style performance file (PTF file). This text file includes the nominal performance of the vehicle for three flight regimes (climb, cruise and descent) and various altitudes.
Figure 3. Very Light Jet Cruise Speed Drag Polar.

Figure 4. Very Light Jet Maximum Climb Thrust Function (2 engines).
Detailed life cycle economic analysis of the aircraft has been modeled to understand the tradeoffs between demand and supply costs of potential on-demand air taxi operations. The VLJ cost model methodology is described in detail by Trani et al., (2) and is summarized here for the sake of completeness. The aircraft cost model is a life cycle cost model developed using a Systems Dynamics modeling environment. The model considers the following aircraft cost contributions explicitly: a) facilities cost (hangar and office space); b) periodic costs (engine, paint, refurbishing, avionics, mid-life inspection, etc.); c) variable costs (fuel, oil, parts, miscellaneous, maintenance, etc.); d) fixed costs (hull insurance, liability, maintenance software, property tax); e) personnel costs (pilot salaries, benefits); f) training costs (initial, maintenance, recurrent training, etc.) and g) capital and amortization costs (percent resale value, interest rate, purchase cost).

The cost model is a required input to TSAM since passenger decisions are made based on the economics of travel cost and time for each mode of transportation. Figure 6 illustrates the Systems Dynamics model developed in STELLA 9.0 – a Systems Dynamics software tool. The model presented in Figure 6 produces cost per seat-mile travel for on-demand services under various assumptions. Typically, stage length, annual utilization, load factor, network efficiency, number of pilots, crew salaries and many other input variables can be changed to study various realizations of cost per seat-mile of the new air taxi mode. In general, the model presented in Figure 5 produces non-linear costs per seat-mile for various stage lengths and annual utilization factors. A sample representation of the Systems Dynamics model is shown in Figure 6. The figure illustrates the sensitive nature of cost for service for two VLJ annual utilization rates (1000 and 1200 hours per year) and for variations in the stage length flown.

It should be clearly stated that because of any of the many uncertainties surrounding the operations of a new family of jet aircraft, it is plausible that large standard deviations in the cost estimates are possible for the VLJ vehicle. However, considering cost estimates studied over a three-year period under the SATS Program, our best estimate is that VLJ air taxi operator costs would oscillate between $1.85 to $2.25 per seat-mile for an airport network structure with 10-20% short repositioning flights. These numbers reflect recent high fuel costs ($4.50 per gallon of Jet A fuel in the U.S.).
Figure 6. Life Cycle Cost Systems Dynamics Aircraft Cost Model (STELLA 9.0 Model).

Figure 7. Calculated On-demand Service Cost for VLJ Aircraft.
IV. Scenario Modeling

The Next Generation Air Transportation System (NGATS) planned by the Joint Program and Development Office (JPDO) promises significant gains in mobility for air travelers through improvements in air traffic management, airspace and airport capacity and added system safety (10). A stated goal of JPDO is a 30% reduction in gate-to-gate travel time for air travelers. Considering current trends in airport processing times, the reductions in gate-to-gate travel times are expected to come primarily from savings in passenger processing and slack times at airports as shown in Table 1. Analysis of current trends in flight tracks and airline schedule times across the NAS suggests that if NGATS is implemented, a modest reduction of 5% in the airline schedule times might be feasible in the long term due to more direct routings and better air traffic management. Both of these effects contribute to time-savings for passengers using airline services. In the case of on-demand air taxi operations, no credit is given to VLJ operations because these operations have relatively short processing times (20 minutes) at the origin and destination airports.

TSAM considers travel time components including processing times at airports and in-vehicle times to quantify the probability that a passenger selects a mode while traveling between two counties. Using the values presented in Table 1, we run a series of NGATS scenarios to understand the effects of a more efficient commercial airline system in the demand for on-demand air taxi services. We ran scenarios with NGATS using socio-economic and demographic forecasts for years 2015 and 2025. The results are presented in the following sections of the paper.

Table 1. Next Generation Air Transportation System Efficiency Factors.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Airport Processing + Slack Time (hrs)</th>
<th>Airline Scheduled Time Multiplier</th>
<th>Airport egress time (hrs)</th>
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<tbody>
<tr>
<td>Current NAS System</td>
<td>2.0 (Large airport hub)</td>
<td>1.00</td>
<td>0.75 Large airport hub</td>
</tr>
<tr>
<td></td>
<td>1.5 (Medium airport hub)</td>
<td></td>
<td>0.75 Medium airport hub</td>
</tr>
<tr>
<td></td>
<td>1.0 (Small airport hub)</td>
<td></td>
<td>0.50 Small/Non airport hub</td>
</tr>
<tr>
<td>NGATS:</td>
<td>1.0 (Large airport hub)</td>
<td>0.95</td>
<td>0.50 Large hub</td>
</tr>
<tr>
<td>Approximation of 30% gate-to-gate time reduction goal</td>
<td>1.0 (Medium airport hub)</td>
<td></td>
<td>0.50 Medium hub</td>
</tr>
<tr>
<td></td>
<td>0.75 (Small/Non-hub)</td>
<td></td>
<td>0.33 Small/Non hub</td>
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V. Results

To study the next generation air transportation system, we study the system with an array of VLJ scenarios where the cost of service is the main explanatory variable. Figure 8 illustrates the expected temporal variations in on-demand air taxi demand for VLJ aircraft as a function of cost for service. The results have been obtained using TSAM for 5 discrete years in the future. In this analysis, an aircraft production constraint has considered to understand the effects of supply-demand imbalance for the new on-demand VLJ business model. The figure has been derived using a maximum production capacity of all VLJ manufacturers restricted to 750 aircraft per year. The low cost solution ($1.85 demonstrates that in the year 2025 a total of 5400 VLJ aircraft might be required to satisfy the on-demand air taxi market alone. At cost of $2.50 per sent-mile around 3,400 aircraft will be required to satisfy the demand function predicted by TSAM in the year 2025 with NGATS.
Each time solution generated in Figure 8 yields a different daily flight demand in the system. Flight trajectories are generated in TSAM using the performance of the VLJ vehicle described in Section III of the paper. The procedure to adjust the annual demand to daily flights has been described in Section II of the paper. Trips beyond the range of the vehicle are assigned a stop-over, and travel times are adjusted accordingly. The flight trajectory is flown using a nominal performance profile consistent with the Eurocontrol Base of Aircraft Data model guidelines (8). The VLJ performance is randomized for weight distributions based on party size derived from the ATS survey. At the same time, the aircraft performance is randomized for temperature effects to make more realistic flight assignments in the system.

Figure 9 illustrates VLJ flights in the NAS to demonstrate the spatial distribution of origins and destination airports using on-demand air transportation. The figure illustrates the high incidence of VLJ flights near populated areas of the United States. The average distance flown per VLJ flights is 225 statute miles (great circle distance between airports). The average cruising altitude for VLJ aircraft is expected to be FL240 (24,000 ft.) This trend is very close to that observed for two popular light business jets (i.e., Cessna Citation Jets and Raytheon B400) as demonstrated in Figure 11. Figure 10 shows the resulting airport daily demands flown by VLJ aircraft in the NAS under the most optimistic scenario. The figure demonstrates that although 2,300 airports were potentially available to VLJ traffic, only 1,500 might receive traffic on a typical day. The daily flights are the result of a Monte Carlo simulation thus not all airports are used every day.

Figure 12 illustrates the potential impact of VLJ traffic in the NAS showing all 20 FAA Air Route Traffic Control Centers (ARTCC) in the U.S. It is interesting to state that under the most optimistic VLJ deployment scenario, some air route control centers could receive over 2,000 daily VLJ flights in the year 2025. As a matter of comparison, the FAA forecasts up to 14,000 flights in some of the busiest air route centers in 2025. Thus the potential of VLJ traffic should not be considered lightly.
Figure 9. Predicted Daily On-demand VLJ Flights in the NAS. Top Figure Illustrates the Demand at $1.85 per seat-mile. The Bottom Figure is the Demand at $2.25 per seat-mile. Year 2025 Woods and Poole Demographics.
Figure 10. Daily Airport Demands of VLJ Traffic in the NAS in the Year 2025 with NGATS in Place. The Top Figure Represents Daily Airport Operations with Air Taxi services at $1.85 per seat-mile. The Bottom Figure Represents Daily Airport Operations with Air Taxi services at $2.25 per seat-mile.
Figure 11. Cruise Flight Level Distribution for Existing Light Jets (Cessna Citation 525 and Raytheon B400) and the Very Light Jet Modeled in this Study.
Figure 12. Predicted VLJ Center Loads in the NAS. Top Two Bar Graphs Illustrate the Daily VLJ Load at $1.85 per seat-mile for High and Low Altitude ARTCC Center sectors, Respectively. The Two Bottom Graphs show the VLJ Load at $2.25 per seat-mile for High and Low ARTCC Center Sectors, Respectively. All Graphs Reflect Year 2025 Demographics and Socio-Economic Characteristics of the Woods and Poole Model.
VI. Conclusions

Potential On-demand VLJ flight schedule scenarios have been derived under NGATS using the TSAM model. The analysis for on-demand services using VLJ aircraft has uncertainty, as the market is untested. Nevertheless, there is an indication that VLJ aircraft could have a significant impact in the future NAS based on our demand estimates using a cost for service of $1.85 per passenger mile. The impact is less pronounced if the cost for service increases to $2.25 per seat-mile. As a result, national planners of the NGATS system should consider projected VLJ traffic into account.

If the 30% gate-to-gate travel time NGATS goal is achieved in 2025, NGATS could have a substantial effect in the demand for air transportation. Using the TSAM model, an 11% increase in commercial airline traffic is possible in the 2025 compared to the do-nothing alternative. Commercial airline demand is expected to benefit more from NGATS in the short term because airlines would be more efficient and competitive against VLJ air taxi services.

The current FAA forecast methodology partially reflects VLJ scenarios in the future NAS operations. Our analysis suggests that if on-demand air taxi companies offer point-to-point services at $1.85 per seat-mile, the utilization of the on-demand market vehicles is expected to climb to 800-1200 hours per year per aircraft for vehicles in the on-demand air taxi role.

Based on TSAM estimates supported by backlog orders of the three leading contenders for the current VLJ market (i.e., Eclipse, Cessna and Adam), it is possible to envision up to 4,100 VLJ aircraft flying in the NAS by 2017 (considering on-demand, fractional and personal services) in the most optimistic scenario. This assumes a maximum production capacity of 750 aircraft per year 3-4 years into the future.

VLJ services are expected to affect large metropolitan areas more than rural areas. The use of reliever and general aviation airports around metropolitan areas would help mitigate the impact of VLJ traffic on OEP airports. The key to the success of the concept is the balance between accessibility to airports near business centers and terminal procedures that do not disturb airspace patterns at busy hub airports. The use of Operational Evolution Plan (OEP) airports does not have a significant effect in VLJ demand nationwide. However, at the regional level some OEP airports could see a substantial number of VLJ operations due to their attractive location near large metropolitan centers. In most of our studies we have assumed that VLJ traffic will seldom go to large hub airports due to capacity constraints.

VII. Recommendations

Based on the analysis presented in this paper we make the following recommendations:

1) JPDO and FAA should consider a variety of VLJ deployment scenarios as part of future NAS architecture studies. These vehicles could have a significant effect in NAS terminal and enroute operations, ATC workload, airspace delays, etc.

2) OEP airports should be excluded from VLJ traffic to avoid congestion problems. Three OEP are attractive to VLJ users in our study (MDW, DCA and LAS). However, the analysis done here considers unconstrained capacity at these facilities and thus masks the negative effect that a congested airport offers to VLJ travelers.

3) Airport and airspace capacity constraints and delays should be integrated in the analysis of VLJ demand, as well as commercial airport demand, in a direct fashion. Current techniques to estimate air travel demand close the loop between demand and supply in an indirect fashion (usually demand is restricted after being compared with the supply function offered by airlines or airports).

4) As traffic congestion and delays are expected to increase in the NAS with the introduction of VLJ aircraft, planning for this activity should be undertaken as part of NGATS. Significant jet traffic volumes below flight level 300 will occur with the introduction of VLJ aircraft. This requires more analyses using high fidelity airspace simulators.
5) Further refinements to the interaction between VLJ and transport aircraft should be carried out using real-time flight simulators to estimate the workload impacts of mixing VLJ traffic and transport in the NAS. Precursor studies done by the FAA and the SATS program can shed some light on these effects.
References


8) DB1B, Bureau of Transportation Statistics (BTS),
