Projected Demand and Potential Impacts to the National Airspace System of Autonomous, Electric, On-Demand Small Aircraft

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Electric propulsion and autonomy are technology frontiers that offer tremendous potential to achieve low operating costs for small-aircraft. Such technologies enable simple and safe to operate vehicles that could dramatically improve regional transportation accessibility and speed through point-to-point operations. This analysis develops an understanding of the potential traffic volume and National Airspace System (NAS) capacity for small on-demand aircraft operations.

Future demand projections use the Transportation Systems Analysis Model (TSAM), a tool suite developed by NASA and the Transportation Laboratory of Virginia Polytechnic Institute. Demand projections from TSAM contain the mode of travel, number of trips and geographic distribution of trips. For this study, the mode of travel can be commercial aircraft, automobile and on-demand aircraft. NASA's Airspace Concept Evaluation System (ACES) is used to assess NAS impact. This simulation takes a schedule that includes all flights: commercial passenger and cargo; conventional General Aviation and on-demand small aircraft, and operates them in the simulated NAS.

The results of this analysis projects very large trip numbers for an on-demand air transportation system competitive with automobiles in cost per passenger mile. The significance is this type of air transportation can enhance mobility for communities that currently lack access to commercial air transportation. Another significant finding is that the large numbers of operations can have an impact on the current NAS infrastructure used by commercial airlines and cargo operators, even if on-demand traffic does not use the 28 airports in the Continental U.S. designated as large hubs by the FAA. Some smaller airports will experience greater demand than their current capacity allows and will require upgrading. In addition, in future years as demand grows and vehicle performance improves other non-conventional facilities such as short runways incorporated into shopping mall or transportation hub parking areas could provide additional capacity and convenience.

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I. Introduction

This paper presents results from a study that investigates the potential passenger demand and the effects on the National Airspace System (NAS) for an on-demand air transportation service that utilizes small aircraft with electric propulsion.

The concept as described in a paper by Moore[1], is the aircraft have autonomous navigation, terrain and vehicle avoidance technology, obviating the need for a trained pilot. A passenger-operator with minimal training enters the destination and allows the aircraft to fly to the destination. Alternatively, if a more active role is desired, the operator directs the aircraft in flight using simple controls that have inbuilt safety constraints. The aircraft has redundant systems, including propulsion, and includes functionality to land autonomously at the nearest landing site in the event of a vehicle or operator malfunction.

The use of electric propulsion reduces operating and maintenance costs and automation avoids piloting costs. The vehicles therefore have very low operating costs compared to conventional small aircraft. In addition, the aircraft fly at low altitudes and resolve conflicts with other air-traffic autonomously, so will need minimal interaction with the existing air-traffic management system.

The envisaged vehicles range in size from one or two seat, to four seats, can take off from short runways, have ranges of a few hundred miles and operate at speeds of one hundred and fifty to two hundred and fifty miles per hour. They may operate from existing small airports or perhaps into some larger airports with underutilized or purpose built short runways and from purpose built facilities near population centers or from facilities with fast ground-transportation connections to population centers.

The proposed business model is that the aircraft can be rented on-demand, a short time in advance of the planned trip and then take off from a facility near the passenger's origin and land near to the passenger's destination. The business model may be similar to the way conventional car rentals operate today or perhaps use the car-sharing business model: join; reserve; unlock; fly.

The trip lengths will be limited by the electric storage technology, initially to 150 - 200 miles in the near to mid-term, 5 to 15 years from now, increasing in the future as technology improves to 500 miles or so. In the nearer term, this type of vehicle competes mainly with automobiles, rather than as a competitor to current airline or air taxi-services.

II. Motivation/ Significance

Demand for air transportation has slowed in recent years and the number of communities served has reduced, due to the high cost of fuel and slow economic growth. According to FAA data[2], the number of primary airports with commercial service decreased from 419 to 376, a net reduction of 43, from the year 2000 to 2010. Despite this slowdown, the FAA's Terminal Area Forecast[3] predicts a 50% increase in demand from 2010 to 2035.

Even with increased demand, the problem of lost mobility is likely one that will remain or get worse as airlines consolidate and fuel costs continue to increase. To restore and enhance mobility to communities that lack easy access to air transportation requires game-changing technologies. Electric propulsion is one such technology that has the potential to reduce small aircraft passenger-mile cost to compare with those of cars.

The motivation for this study is to determine if achievable designs for small autonomous aircraft with electric propulsion have sufficient performance and low enough operating costs to make such vehicles a viable means of on-demand air transportation.

The key question that this study seeks to answer is:

> ***What is the unconstrained projected trip demand and geographic distribution of trips for autonomous electric vehicle operations?***

A secondary question that this study seeks to answer is:

> ***What is the impact of this increased number of operations on the future NAS and do existing small airports have sufficient potential capacity to meet the demand?***

The significance of the results presented in this paper is that with realistic designs, the performance of the vehicles studied is sufficient and the operating costs low enough to make them competitive with automobile transportation for trips lengths of a few hundred miles. This creates a large demand that can have a significant impact on the NAS unless the on-demand aircraft avoid using airports with commercial traffic. Such a vehicle, operated from small facilities can improve mobility to communities that lack commercial air service.

III. Technical Approach

The approach taken in this study is to use the Transportation Systems Analysis Model[4] (TSAM) to predict trip demand and NASA's Airspace Concept Evaluation System[5] (ACES) to investigate the impact on the future NAS.

TSAM is a demand prediction model under development by NASA Langley Research Center and Virginia Polytechnic Institute's Air Transportation Systems Laboratory. TSAM uses socio-economic and demographic modeling to make projections of future travel demand for trips longer than 100 miles. Projections for on-demand air transportation depend primarily on cost and convenience, assuming that any such system is proven safe and reliable. This type of air transportation service is also likely to be useful for shorter distance commuting, but these trips are not included in this study.

ACES is a fast time, distributed, agent-based simulation of the NAS. ACES has models of airports, airspace, aircraft performance, basic traffic flow management and other elements of the NAS. The primary input is a flight schedule simulating a day of NAS operations. Outputs can include measures of airspace loading, airport loading, and numbers of conflicts requiring avoidance maneuvers, delays, throughput, fuel-burn and distance flown amongst other metrics.

A large increase in aircraft operations has the potential to overwhelm NAS capacity. The on-demand traffic will mainly operate from small airports, fly at lower altitudes for shorter distances than most commercial traffic and impose minimal demands on the ATM system through autonomy. However, there may still be an impact on airspace congestion for operations near major metropolitan areas and some small airports could potentially have insufficient capacity for the projected on-demand trips. In addition, some on-demand traffic will likely fly into airports with commercial service, to connect with the airline network. This could potentially cause congestion at smaller commercial airports that are currently underutilized. For this study, the on-demand traffic can use small and medium sized airports with commercial service, but the demand model did not consider these flights as connecting to the commercial airline network.

This study uses ACES to assess any additional impact on the NAS caused by the on-demand traffic projected by TSAM. Analyzing sector loads identifies congested regions of airspace. Delays are analyzed for each hour of the simulation as recommended for NASA's Airspace System Program [6] (ASP) system-wide studies. Analysis of this data leads to an understanding of required NAS capacity to allow small-vehicle operations without disruptions to existing traffic.

IV. Vehicle Design Characteristics

The vehicle conceptual design, cost and performance justifications are the subject of a paper by Moore[7]. His paper considers three stages of technology level, advancing from a near-term to far-term design. The electric vehicle cost per seat mile is based on:

1. Extremely low effective fuel (energy) cost due to the use of electric propulsion, electricity is less costly than Aviation Gasoline (factor of ~1.3), electric motors are much more efficient than gasoline engines

(factor of ~3.5) and an electric vehicle can be more aerodynamically efficient (factor of ~1.1) resulting in an estimated five-fold reduction in energy cost.
2. Elimination of pilot costs due to autonomous operations.
3. Higher aircraft utilization and reduced fleet size required to meet a level of availability due to autonomous vehicle redeployment.
4. Advanced batteries that improve number of cycles, cost, energy density, and power density.
5. Improved efficiency, both aerodynamically and structurally.
6. High utilization derived through the high reliability of electric propulsion systems and very low maintenance required.
7. Low maintenance costs due to elimination of a gasoline engine.
8. Low vehicle manufacturing costs.

Table 1 lists the primary performance and operating characteristics. This study assumes those values as given by Moore, so they are not justified here. For comparison, performance of an existing conventional piston-engine propeller aircraft is included.

The total operating costs of the 2012 baseline technology aircraft are for a Cirrus SR22 and assume 50% load factor average (maximum load factor is 75%, three passengers plus pilot). The costs for the electric vehicles assume 100% load factor, since they are sized for the number of passengers and do not require a pilot. This study uses a range of operating costs for the electric vehicles since the actual costs are subject to uncertainty.

Included in table 1 are speculative values for the number of facilities available to on-demand aircraft in future years. There are currently 4,477 public use airports in the Continental U.S. The number of existing airports increases to 10,600 if private airports are included. For 2035 and 2050, the numbers assume facilities built wherever there is significant demand and space for a short runway.

Table 1. Vehicle Performance and Operating Characteristics

Year	**Technology**	**Cruise Speed (m.p.h.)**	**Range (miles)**	**Utilization (hrs./year)**	**Fleet Mix (seats)**	**Number of Potential Airports**	**Cost ($/seat mile)**
2012 Baseline	Piston/ Propeller, Gasoline (e.g. Cirrus SR22)	200	500	500	4	4,477 (existing public use)	1.71
2015	Electric/ Autonomous ELV1	150	200	1500	1,2,4	10,600 (existing private and public use)	0.20 to 1.00
2035	Electric/ Autonomous ELV2	200	300	3000	1,2,4	50,000	0.20 to 1.00
2050	Electric/ Autonomous ELV3	250	500	3000	1,2,4	250,000	0.20 to 1.00

V. TSAM Parameters and Assumptions

This study uses TSAM to forecast future demand for transportation. TSAM predicts the number of trips of more than 100 miles between each of the more than 3000 counties in the continental United States. TSAM uses county-level socio economic data, dividing travelers into five household income groups and two travel purposes, business and non-business, to forecast the number of trips. TSAM then allocates each of these trips to a mode of transportation. For this study, the available modes are commercial airline, automobile and the electric on-demand small aircraft.

The factors that determine mode selection are travel time, travel cost, route convenience and traveler demographics. TSAM determines the origin and destination airport choices and determines the distribution of passengers amongst the possible network routes in an origin-transfer-destination model, thereby providing route-level and airport-level demand projections. The daily flight projections also take into account seasonal variation, since non-business travel shows substantial demand variation throughout the year, whereas business travel demand is nearly constant.

The demand model uses the Woods and Poole Complete Economic and Demographic Data Source[8], which is a socio-economic forecast of U.S. household demographics out to the year 2040. Other data sources used to validate and calibrate the TSAM model include the 1995 American Travel Survey[9] (ATS), the Official Airline Guide[10] (OAG), and the Airline Origin and Destination Survey (DB1B)[11]. Automobile travel times and routes are determined using Microsoft MapPoint[12].

The model depicted in figure 1, uses a four-step transportation-planning framework:

1. Prediction of the total number of trips (Trip Generation)
2. Distribution of the trips generated amongst the origins and destinations (Trip Distribution)
3. Prediction of the mode of travel individuals will choose for these trips (Mode Choice)
4. Prediction of the route the travelers will choose for their trip (Network Analysis)

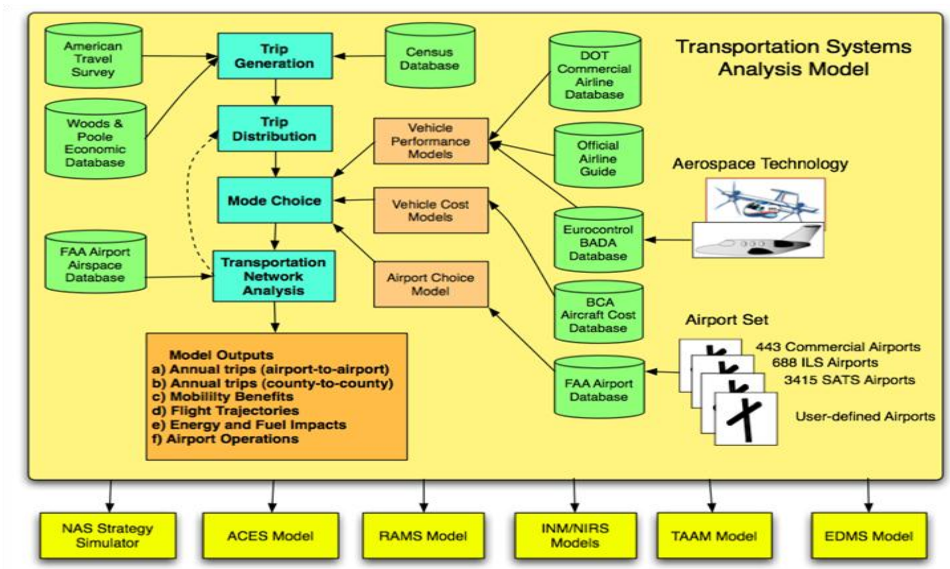

Figure 1. TSAM Model Structure

For this study, TSAM uses the electric vehicle characteristics listed in Table 1 to compute the demand for on-demand electric aircraft versus automobiles and commercial airlines as competing modes. A current generation General Aviation aircraft, the Cirrus SR22, is included for comparison. The demand forecasts are for a baseline year 2015 case using an SR22 for the on-demand traffic, and years 2015, 2035 and 2050 using the electric vehicles with the performance specified for the specific year.

The SR22 accommodates up to three passengers and a pilot, this study assumes an average load factor of 0.5 as a cost basis that is two passengers. For the electric vehicles, it is envisioned that a one, two or four passenger vehicle will be available based upon the party size of the traveling group to match the party size. Since the assumption is that, the different size electric vehicles have the same performance and the same cost per seat-mile, TSAM assumes there will be a vehicle available to match the party size.

For the year 2015, the current system of 4,477 public airports is used. For the year 2035 case, the concept envisages that the infrastructure would be enhanced to include 50,000 available landing strips and for year 2050, perhaps as many as 250,000.

Originally, the plan for this study was to model the numbers of airports as envisaged by the concept listed in table 1. However, the NASA Langley computing facility used by TSAM does not have sufficient memory to model the large numbers of airports for 2035 and 2050. Therefore, the analysis of sensitivity to demand with additional airports used the 4,477 public use airports in the Baseline and the 2015 cases, and the 10,600 public and private airports set in the 2035 and 2050 cases.

Instead of modeling additional airports, TSAM reduces access and egress times to represent the increased utility. The model uses census tract population data and geometries to determine the reduced access and egress times. Microsoft MapPoint computes the driving distance and time from each census tract to the closest airport. Census population data is used to compute the weighted average drive time and distance for each county and each airport set. Distribution of the on-demand county-to-county aircraft trips to the airport set takes two steps:

1. Distribute trips to and from a county to the census tracts in proportion to the county population.
2. Distribute the census tract demand to the four closest airports, inversely proportional to the reciprocal of the square of the distance to the airport.

TSAM baselines all costs in year 2000 dollars. The on-demand electric aircraft minimum cost of $0.20 per seat mile converts to $0.15 per mile in year 2000 dollars. These costs compete against airline and automobile costs. Assumed costs for automobile trips are $0.42 per mile for business and $0.14 per miles for personal travel in year 2000 dollars, from the American Automobile Association cost database. Airline costs are from the FAA DB1B ticket sample data and future cost projections assume the FAA projections of fare yields.

The final step is to develop a daily flight schedule from the annual airport-to-airport trip demand for the electric aircraft. Passengers making the same trip at similar departure times use an electric aircraft appropriate to their party size, selecting from one, two or four seat vehicles. TSAM assumes an average party size of 1.21 for business trips and 1.85 for non-business trips, based on ATS data. The cost calculation assumes 100% load factor, although in practice the party size may not exactly match the available vehicles.

The schedule times are set using a randomization approach that preserves time-of-day travel patterns determined from ETMS data. For trips beyond the range of the vehicle, the schedule includes multiple flight legs by assigning a stopover and increasing the travel time accordingly. The connecting leg could be in a different fully charged vehicle or in the same vehicle with a battery swap or possibly with a battery recharge, if feasible in a reasonable duration. TSAM assumes a 20-minute stopover for this study and limits the on-demand trips to two stops. The stopover time is only for the time that the vehicle is parked, additional time is added for landing, taxi and takeoff by the vehicle dynamics model.

Flight trajectories are generated using the performance of the electric vehicle specified in Table 1 appropriate for the given analysis year. The aircraft fly a great circle route using a nominal performance profile created for this study consistent with the Eurocontrol Base of Aircraft Data modeling approach[13]. The complete flight schedule for use in ACES simulations is a combination of the TSAM generated future schedules of commercial airline, cargo and General Aviation flights with the additional on-demand traffic for each corresponding year.

VI. ACES Simulation Setup

This study uses NASA's ACES NAS-wide simulation. ACES models the airspace and airport capacity constraints of the NAS and Traffic Flow Management (TFM) agent models delay traffic, if necessary, to ensure that capacities are not exceeded. Delays can be on the ground or in the air as directed by TFM. ACES determines delay at various stages of flight by comparing the trajectory flown in simulation with a computed unimpeded trajectory.

The small air vehicles that are the subject of this study operate autonomously with minimal interaction with ATM. These vehicles will use flight deck based technology to detect and resolve conflicts and will not require permission to cross-sector boundaries. For these reasons, the simulation was set up with unconstrained sector capacity values.
This study assumes that the small air vehicles are free to use any region of airspace, although they do not use major airports. However, they will operate at much lower altitudes than commercial traffic due to the short trips and

vehicle operating characteristics. The majority of the on-demand traffic cruises at 4000 ft. to 10000 ft. For this study, sector loads are determined using current sector boundaries, even though these would certainly change or may even be eliminated in the future NAS.

The on-demand traffic did not use the FAA designated large hub airports for this study, although they use the medium and small hubs. For 2015, the on-demand traffic used 4,477 airports; all public airports in continental U.S., minus large hubs and for 2035 used 10680 airports; all public and private airports in minus large hubs

Since the large commercial airports are not the focus of this study, the capacity values used were current values and assumed future values increased by a scaling factor to ensure sufficient capacity to meet projected demand for the year 2035. Table 2 lists the airport capacities used in this study for the top 28 major U.S. airports, for the current capacity and future years. The future capacity values are not necessarily realistic; they ensure that the commercial airline traffic delays are not excessive.

Table 2. ACES Assumed Capacities for FAA Large Hub Airports

Airport	Current (used for 7/22/2010 and 2015)	2035 Simulation	
	Total Ops	Total Ops	Factor Increase
1. ATL - Hartsfield-Jacks. Atlanta Intl.	200	360	1.8
2. BOS - Boston Logan Intl.	131	144	1.1
3. BWI - Baltimore/Washington Intl.	108	108	1.0
4. CLT - Charlotte Douglas Intl.	130	195	1.5
5. DCA - Ronald Reagan Wash. Nat.	88	114	1.3
6. DEN - Denver Intl.	266	266	1.0
7. DFW - Dallas/Fort Worth Intl.	279	279	1.0
8. DTW - Detroit Metro Wayne	195	195	1.0
9. EWR - Newark Liberty Intl.	91	164	1.8
10. FLL - Fort Lauderdale Intl.	86	112	1.3
11. IAD - Washington Dulles Intl.	134	147	1.1
12. IAH - George Bush Houston	198	257	1.3
13. JFK - NY John F. Kennedy Intl.	86	189	2.2
14. LAS - Las Vegas McCarran Intl.	105	137	1.3
15. LAX - Los Angeles Intl.	164	197	1.2
16. LGA - New York LaGuardia	77	139	1.8
17. MCO - Orlando Intl.	225	225	1.0
18. MDW - Chicago Midway	69	76	1.1
19. MIA - Miami Intl.	146	204	1.4
20. MSP - Minneapolis/St. Paul Intl.	160	192	1.2
21. ORD - Chicago O`Hare Intl.	185	315	1.7
22. PHL - Philadelphia Intl.	97	165	1.7
23. PHX - Phoenix Sky Harbor Intl.	152	182	1.2
24. SAN - San Diego Intl.	58	75	1.3
25. SEA - Seattle/Tacoma Intl.	84	134	1.6
26. SFO - San Francisco Intl.	105	137	1.3
27. SLC - Salt Lake City Intl.	133	160	1.2
28. TPA - Tampa Intl.	104	104	1.0

The potential capacity is unknown for the small airports and future on-demand facilities. In the simulation, capacity was set to 60 operations per hour, assuming a single runway. This is achievable by the design of the small electric vehicles, if the only consideration is to maintain single occupancy of the runway.

ACES can also meter arrivals and departures over the respective airspace fixes. Future year simulations did not use fix metering, to ensure that the only constraint is runway capacity.

The operating model for the on-demand vehicles assumes that in the near-term (2015) they will operate from current public smaller airports with a minimum 2000 ft. paved runway available, which is around 4,477 airports. By 2035 the vision is that around 50,000 facilities will be available and in the far-term (2050) as many as 250,000. This requires advances in take-off and landing performance, so that many more locations are available for building short runways, shopping malls and parking lots near transportation hubs for example.

This study used the existing network of 4,477 small public airports for the year 2015 and the 10,680 public and private airports for 2035, because it was impractical to upgrade ACES to the 50,000 or 250,000 facilities that the concept envisages for the farther term. Using the existing airports enables identification of those regions of the U.S. that require additional capacity.

VII. Flight Data Sets

ACES requires a Flight Data Set (FDS) input file that defines the flight schedule, i.e. departure airport and time, arrival airport and time; route of flight, cruise altitude and speed for each flight. Table 3 lists the flight data sets used for this study. The FDS file includes commercial, cargo, domestic, international, and general aviation IFR flights and for the future years, the projected on-demand flights, from TSAM. The number of flights excluding on-demand reduces slightly when on-demand is an option; due to competition between modes. The “TSAM Projected On-demand Trips” section contains an analysis of the demand numbers.

The basis for all FDS used in this study is a day of traffic recorded on 7/22/2010 by the FAAs Enhanced Traffic Management System (ETMS). This baseline day has a high volume of traffic. It is one of a set of 12 days of traffic used by the FAA for their analysis.

Each flight data set contains 42 hours of traffic, for ACES simulation. The analysis uses the middle 27 hours of data. The pre-traffic allows the en route load to build and ACES TFM agents to stabilize. The post-traffic period allows flights that took-off within the time of interest to land. The time of interest spans 27 hours to cover a full day plus the 3 hour time zone difference across the U.S. starting at 5.00 a.m. Eastern.

Table 3. ACES 42-hour Flight Data Sets

Flight Data Set (42 hours of traffic)	No. of Flights Excluding On-demand	Factor Increase from baseline	No. of On-demand Flights	On-demand % of Total	Total No. of Flights	Factor Increase from baseline
7/22/2010 baseline	74,150	---------------	0	--------------	74,150	---------------
2015	77,711	1.05	0	--------------	77,711	1.05
2015 + Electric Vehicle	76,271	1.03	244,791	76.24	321,062	4.33
2035	126,050	1.70	0	N/A	126,050	1.70
2035 + Electric Vehicle	123,243	1.66	388,441	75.91	511,684	6.90

VIII. Results and Discussion

The results presented in this section use TSAM demand projections. NAS impacts analysis are from NAS-wide simulations of 27 hours of flight operations. All the results assume ideal conditions, with VMC airport capacities.

A. TSAM Projected On-demand Trips

The TSAM generated demand projections use the vehicle characteristics listed in Table 1 as described in the "TSAM Parameters and Assumptions" section. TSAM predicts annual person trip demands between counties and between airports resulting in the totals listed in Table 4 for an assumed cost of $0.20 per passenger mile. A Cirrus SR22 based service is included for comparison in the year 2015. This Cirrus SR22 based service has all the same assumptions as the electric vehicle assumptions except with additional projected cost and the actual Cirrus SR22 performance and range. The estimated lowest cost of the electric vehicle is only $0.20 per passenger mile, compared to $1.71 for the SR22. This increases the demand by a factor of 15.5, indicating the substantial demand for this type of low cost air service. In future years the numbers of on-demand trips increases very rapidly, driven not only by projected population increases but also by the improved electric vehicle performance listed in Table 1.

TSAM does not generate additional new demand specifically for the electric vehicle trips. Instead, passengers divert from airline flights or automobiles to the on-demand flights. In the 2035 case, the electric vehicles take 665.6 million person trips annually at the lowest cost envisaged of $0.20 per passenger mile from the 1.76 billion annual long distance trips. That is 38% of all trips longer than 100 miles. Passengers that divert from automobile take most of these trips; 82% of the on-demand trips come from automobile trips longer than 100 miles. The other 18% are gained from airline flights, mostly from shorter flights that do not exceed the 300-mile single leg range of the 2035 electric vehicle. This reflects the performance of the electric vehicles that compares well with automobiles but is not competitive with airlines for longer trips.

As discussed in the "Technical Approach" section, this study is for trips greater than 100 miles, and does not include use of electric vehicles for commuting. There could be substantial additional demand diverted from automobile trips to on-demand flights for commuting.

Table 4. Total Annual On-demand Trip Estimates at $0.20 per Passenger Mile.

Year	Aircraft	Total Annual Person Trips	Trips Diverted From Automobile (% of on-demand total)	Trips Diverted From Airlines (% of on-demand total)
2015	Cirrus SR22	25,665,00	23,277,000 (91%)	2,388,000(9%)
2015	ELV1	389,490,000	357,925,000 (90%)	40,565,000 (10%)
2035	ELV2	665,646,000	543,712,000 (82%)	121,934,000 (18%)
2050	ELV3	896,970,000	660,001,000 (74%)	236,969,000 (26%)

Table 5 shows the number of flights generated to satisfy the corresponding trip demand listed in table 4.

Table 5. Daily On-demand Flights at $0.20 per Passenger Mile.

Year	Aircraft	Daily Flights
2015	Cirrus SR22	85,657
2015	ELV1	1,319,525
2035	ELV2	2,113,633
2050	ELV3	2,824,792

Figure 2 shows the sensitivity of the annual person-trip demand to customer cost of the trip for years 2015, 2035, and 2050. The demand drops sharply as the trip price increases. When the cost of the vehicle increases to $0.60 per seat-mile from the $0.20 envisaged lowest cost, the demand is approximately 40% of the lowest cost value for all analysis years. When the cost increases to $0.80, the demand is only about 27% of the low cost levels.

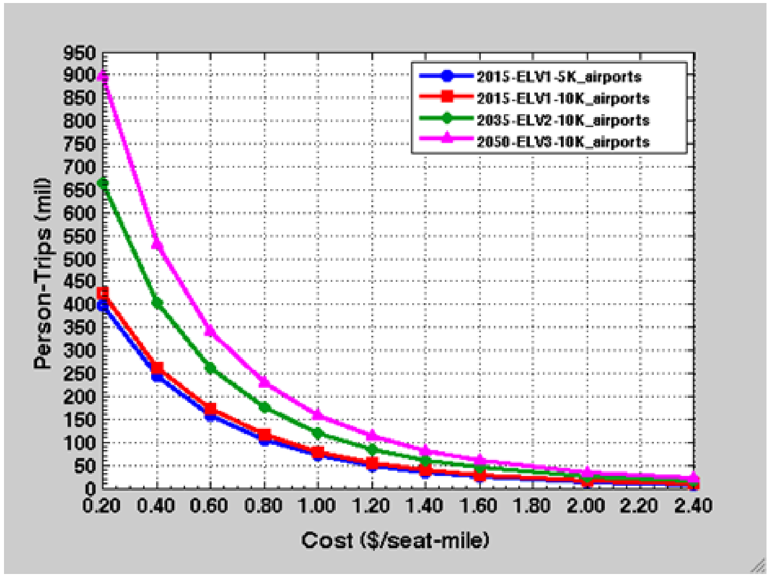

Figure 2. Sensitivity of Annual Person-Trip Demand to Cost

Figure 3 illustrates the sensitivity of on-demand annual person trips to cost by mode. At higher cost levels, business travelers that have a high value of time are the main users of the on-demand service. At a cost of about $0.40 per seat-mile, the on-demand service starts to compete with automobile and commercial airlines in price and generates a non-business demand about equal to the business traveler demand. At the lowest cost envisaged by the concept of $0.20 per seat-mile the on-demand mode is very competitive and diverts significant market share from the automobile and short-range commercial airline travelers for both business and non-business travelers.

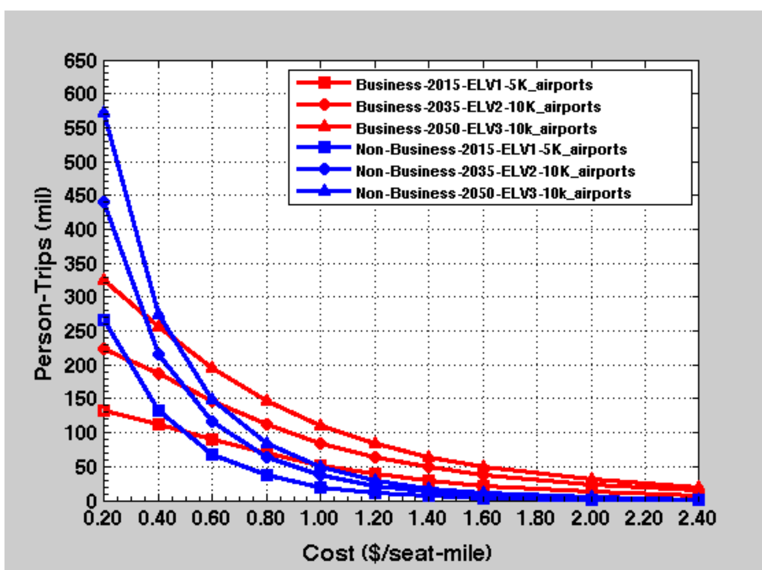

Figure 3. Sensitivity of Person-Trip Demand to Passenger Cost by Mode

Figure 4 illustrates the share of person-trips by mode with change in passenger cost. At all, cost points the on-demand service generates most of its demand by diverting trips from automobiles. The on-demand mode begins to generate significant demand at costs of around $1.00 per seat-mile. As costs reduce further for the 2035 and 2050-year scenarios, the on-demand services divert significant demand from short-range commercial airlines flights. Note the for all cost points there are few on-demand person-trips captured from commercial airline trips for the 2015 year scenario. This is due to the short projected range of the vehicle of 200 miles. In the 2050 case, when the vehicle range is 500 miles and the speed is 250 mph significant commercial airline demand is diverted to the on-demand service when the costs are less than $0.40 per seat-mile.

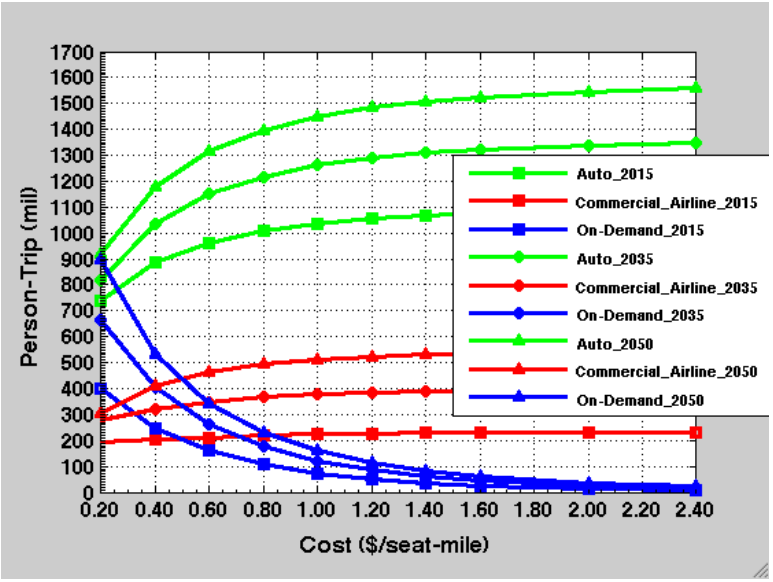

Figure 4. Sensitivity of Person-Trip Demand to Cost by Mode

Figures 5 and 6 depict the number of operations at airports for commercial plus General Aviation (GA) traffic and for the on-demand traffic respectively. In both cases, the traffic load closely follows the distribution of population that is concentrated in the Eastern half of the U.S. and on the West Coast. However, there is significant on-demand traffic in the less populated parts of the U.S. indicating that a low-cost on-demand air service could improve mobility to those communities.

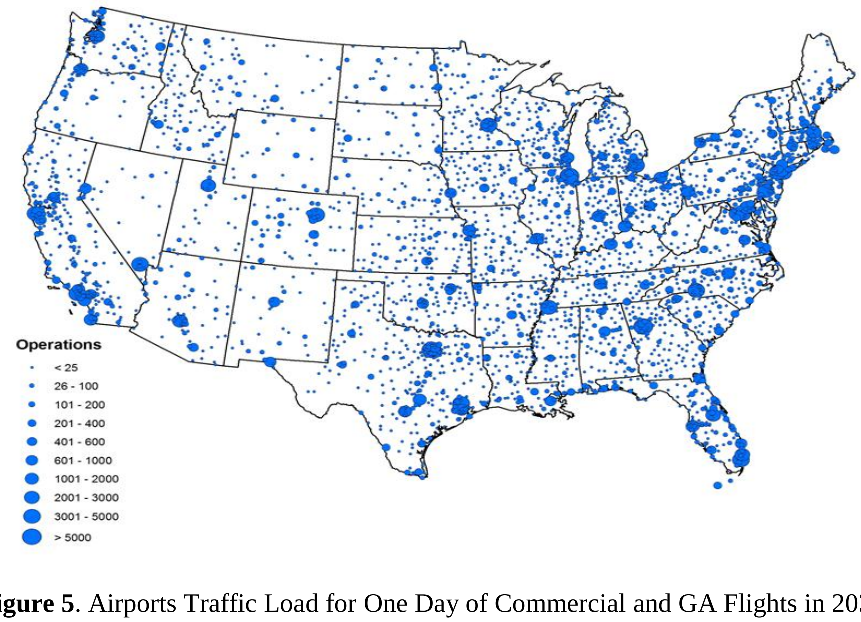

Figure 5. Airports Traffic Load for One Day of Commercial and GA Flights in 2035.

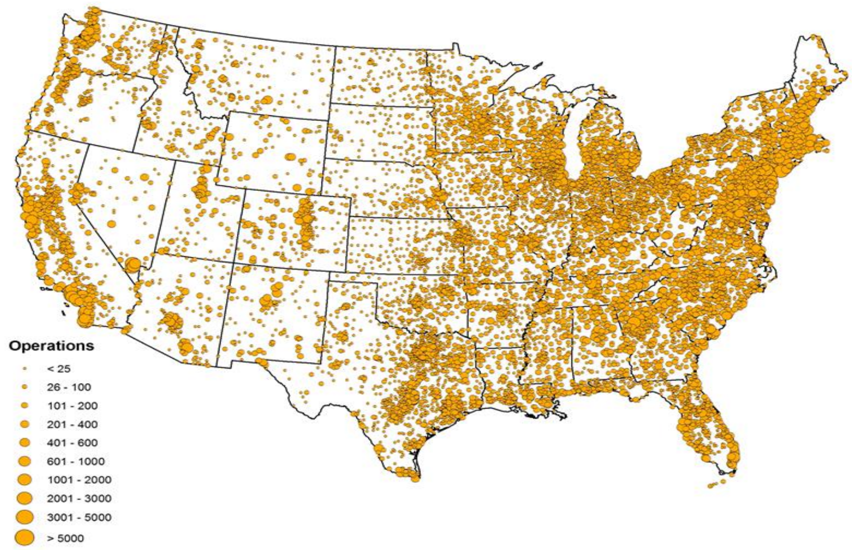

Figure 6. Airports Traffic Load for One Day of On-demand Flights in 2035.

Figure 7 shows the numbers of on-demand operations at the top 30 airports with significant number of operations. The attractiveness of airports like Teterboro NJ (TEB), Linden NJ (LDJ), College Park MD (CGS), Farmingdale NY (FRG), Essex County NJ (CDW), and North Las Vegas NV (VGT) is because of their close proximity to large population centers and the existing significant business aircraft activity at these airports.

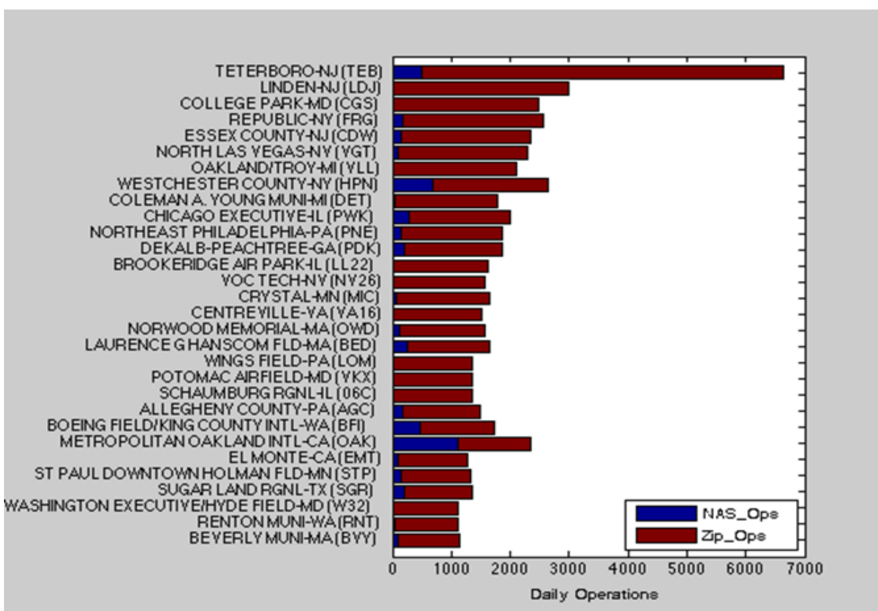

Figure 7. Daily Traffic Load at Top Airports with On-Demand Traffic in 2035.

Figure 8 shows the great-circle routes from origin-to-destination of trips using the on-demand air service. The plot only shows routes with three or more flights per day. This is about 32,000 origin destination pairs, about one fourth of the total number of pairs. The figure shows a high number of flights near populated areas of the United States, although there are a significant number of flights to and from less populated regions.

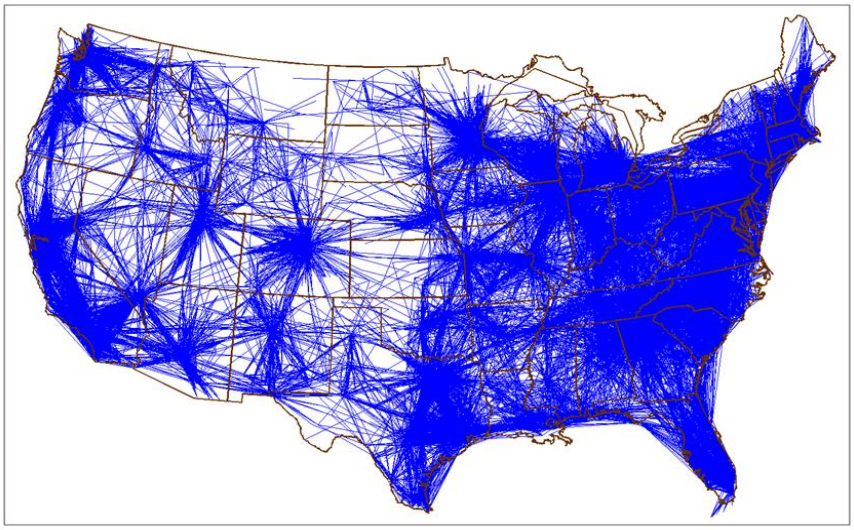

Figure 8. Distribution of One Day of On-demand Flights in 2035.

Figure 9 shows the distribution of distances of the on-demand trips. The average distance flown per on-demand flights is 153 statute miles (great circle distance between airports). Some trips exceed the range of the electric aircraft (300 miles in the Year 2035) because two flight legs are used. This study assumed a stopover time of 20 minutes between flight legs. There would be few, if any, multiple leg trips if the stopover time was large.

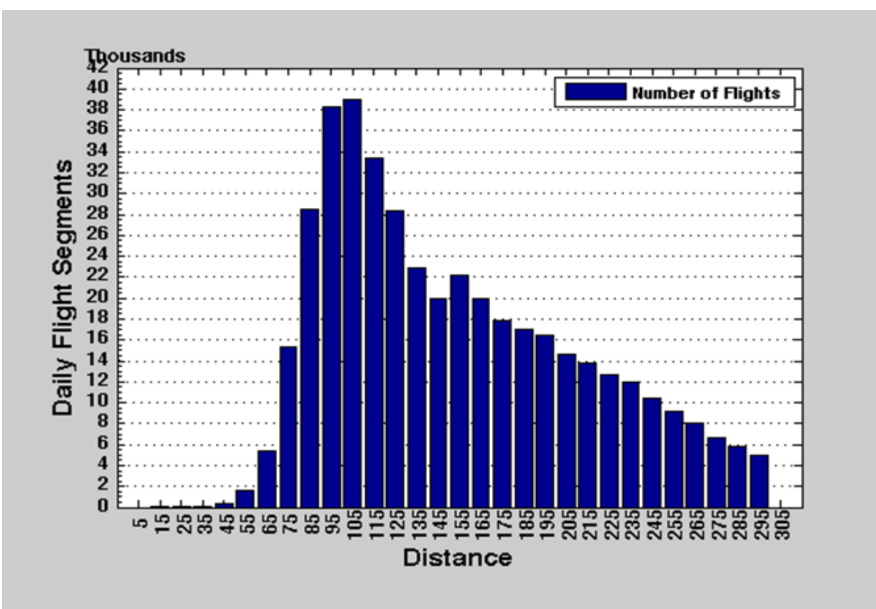

Figure 8. Distance Distribution of One Day of On-Demand Trips in 2035

B. Baseline Delays

The purpose of simulating the 7/22/2010 baseline-day traffic is to check that ACES results are similar to actual delays on a good-weather day in the NAS. The FAA collects delay data for 77 airports in the Aviation Systems Performance Metrics (ASPM) database. The ASPM reported mean gate-arrival delay is 13.6 minutes for this high volume day.

The baseline simulation uses current airport capacities, see Table 2. Sector capacities are set to current day values. The ACES mean delay for commercial passenger aircraft using the 77 ASPM airports is 32.0 minutes for the baseline. This is higher than the ASPM recorded value and for this case was primarily due to sector overloads. Repeating the simulation with unconstrained sector capacities reduces the delay to 4.5 minutes. For the purposes of this study, the match between APSM reported delay and ACES simulated delay is acceptable.

A very close match between ASPM data and simulation is not expected. The ACES results do not include any weather effects; there were some weather-related delays on the West Coast on 7/22/2010. This study does not include any off-nominal events, or any cascading delays for consecutive flight legs flown by the same aircraft. In addition, ACES measures delay compared to an unimpeded flight, whereas ASPM reports delay compared to the airline schedule that is likely to contain additional time to allow for delays.

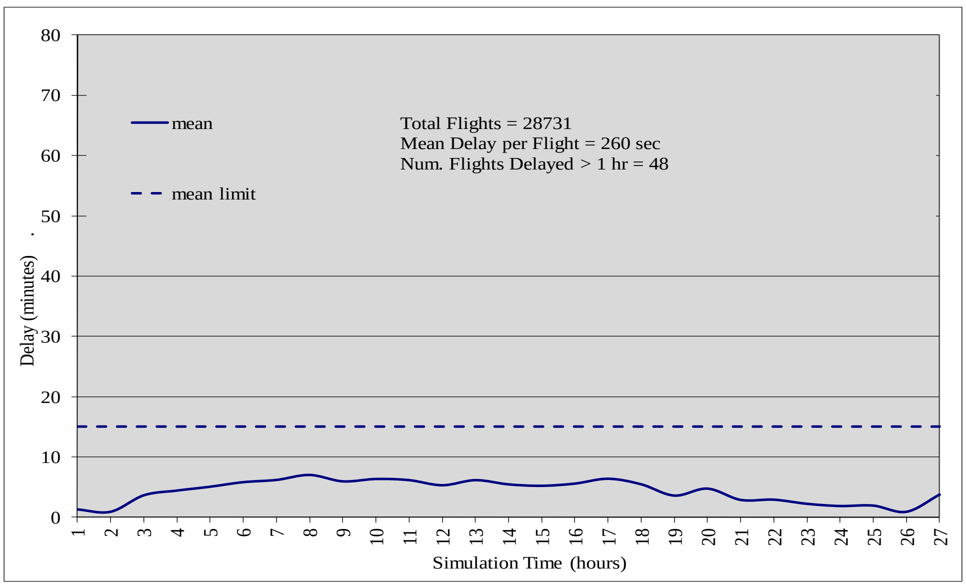

Figure 9. Commercial Passenger Flight Delays for 7/22/2010 Baseline Scenario

Figure 9 shows simulation results from ACES, for the 7/22/2010 baseline day scenario with unconstrained sector capacities. Delay is gate arrival delay compared to an ACES unimpeded flight. The chart shows the mean delay for each hour of simulation time for commercial passenger flights, compared to acceptable limits. Mean delay is below 15 minutes in all hours of the simulation indicating that NAS performance is acceptable for the purposes of this study. The mean delay for all commercial airports from ACES simulation for the time of interest is 4.3 minutes. This is slightly less than the 4.5 minutes recorded by ACES for the ASPM airports only. The complete airport set also includes the less busy airports, so mean delay is lower as expected.

C. Establishing the Required NAS Airports Capacity for the Projected Commercial Airline Demand in Future Years

For this study, the focus is on-demand traffic operating from smaller airports, but first it is necessary to establish the required capacity of the larger airports for future years. Delays will be untenable for the future commercial airline demand with current airport capacities and mask any additional delays caused by the on-demand traffic.

Table 6 shows the delays for the time of interest obtained from ACES simulation for the 2010 baseline and with TSAM projected demand in 2015 and 2035 using the current airport capacities in Table 2. All data is for unconstrained sector capacities.

Table 6. Commercial Passenger Flight Delays for Future Years Scenarios with Current Airport Capacities

Scenario	Number of Commercial Passenger Flights	Mean Delay Per Flight (s)	Number of Flights Delayed > 1 Hour	Factor Increase in Commercial Passenger Flights Demand Over 7/22/2010
7/22/2010 Baseline	28731	260	48	-
2015	30873	336	475	1.1
2035	54074	5902	16668	1.9

The delays for 2015 are somewhat greater than 7/22/2010 values but it was unnecessary to scale the airport capacity values. For 2035, the delays are untenable. Analyzing the hourly airport demands from ACES data enables identification of overloaded airports and determination of the amount that capacity needs to increase. Table 3 in the "Simulation Setup" section lists the factor increase for 2035 and the corresponding assumed capacities for the busiest 35 U.S. airports.

As a check that the scaling factors are sufficient, the simulation for year 2035 was repeated using the increased capacities. In addition to scaling the major airports capacities, the small single runway airports capacities were set to 60 per hour as explained in the "Simulation Setup" section. The delays listed in table 7 are acceptable for the purposes of this study.

Table 7. Commercial Passenger Flight Delays for 2035 Scenario with Scaled Airport Capacities

Scenario	Number of Commercial Passenger Flights	Mean Delay Per Flight (s)	Number of Flights Delayed > 1 Hour	Factor Increase in Commercial Passenger Flights Demand Over 7/22/2010
2035	54025	297	1019	1.9

D. Impacts to the NAS from Projected On-demand Operations in Future Years

The results presented in this section use the TSAM demand projections assuming $1 per seat mile total operating cost for the electric aircraft. This is a cautious assumption since analysis by Moore[7] indicates that costs could be as low as $0.20 per seat mile, as described in the "Vehicle Design Characteristics" section. Using a cautious assumption on costs makes it less likely that demand will be over-estimated. In addition, the NASA Langley ACES computing set-up is limited to around 400,000 flights per day in the simulation and run-times take many hours. Running an ACES flight data set with the demand projected at $0.20 per seat mile is not currently practical.

D.1 Airspace Congestion

As explained in the "Simulation Setup" section, sector-loading constraints do not apply to any vehicle (commercial included). For analysis purposes, a sector loading count gives an indication of throughput and identifies busy airspace regions. Sector loads are determined using current sector boundaries, even though these would certainly change or may even be eliminated in the future NAS.

Figures 10 and 11 show the peak load for the top 10 busiest sectors from ACES simulation for each study year.

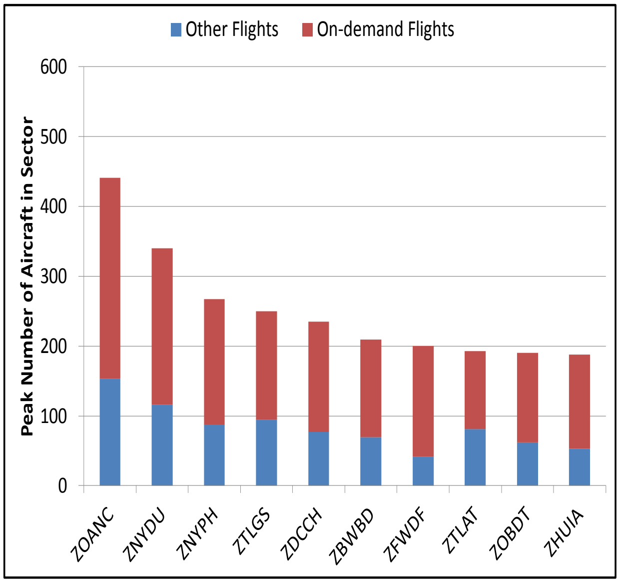

Figure 10. Sector Peak Loads for 2015 Demand

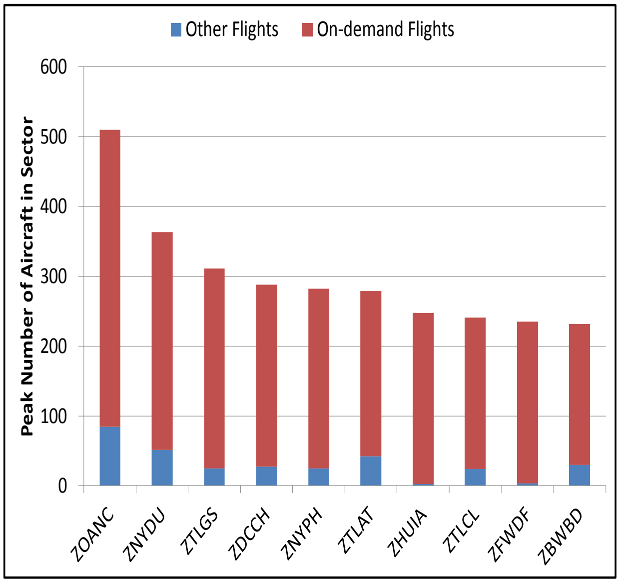

Figure 11. Sector Peak Loads for 2035 Demand

A controller in today's ATM system can typically handle a maximum of around 20 aircraft. The peak sector counts are much larger than this due to the additional on-demand traffic. However, the concept for the on-demand vehicles is for autonomous operations, and it is not within the scope of this study to determine the feasibility of handling this level of traffic. The expected loads set a design requirement for the automation capability. Peak loads could be much higher than shown should lower vehicle operating costs be realized, since this analysis used a conservative assumption for costs. The busiest sectors for on-demand traffic are all low-level sectors, below 18,000ft. The busiest sector is ZOANC in the Oakland Center.

The geographic locations of the busiest sectors for the 2035 scenario are shown in figure 12.

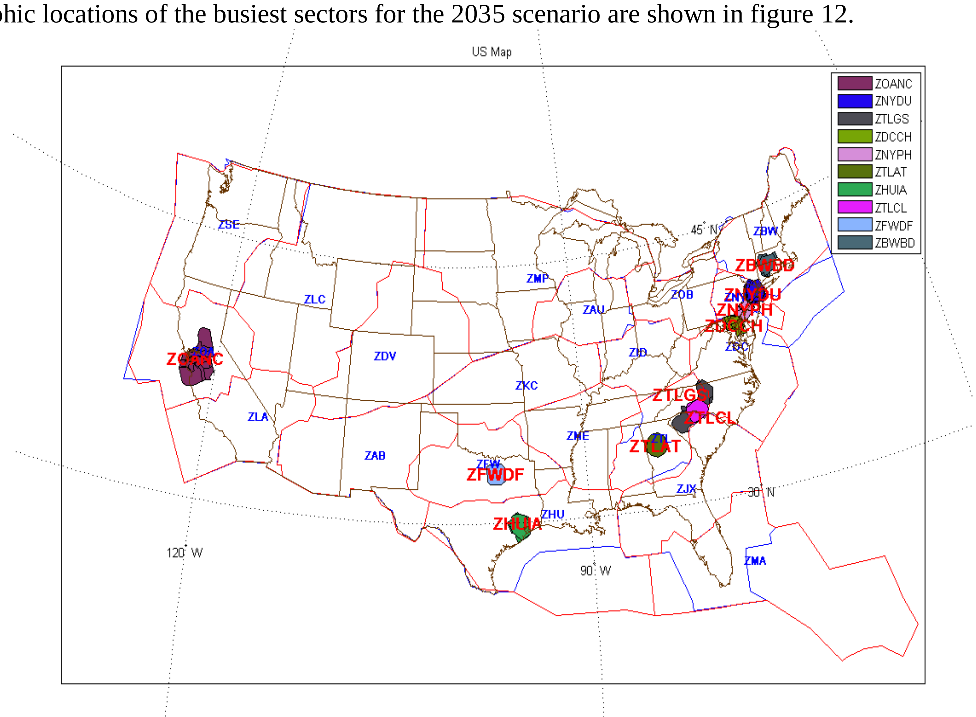

Figure 12. Locations of Busiest Sectors for 2035 Demand

D.2 Delays to Commercial Passenger Traffic due to Airports Overloading

Figures 13 and 14 show the delays to commercial passenger traffic only, with and without the on-demand traffic present in the simulation.

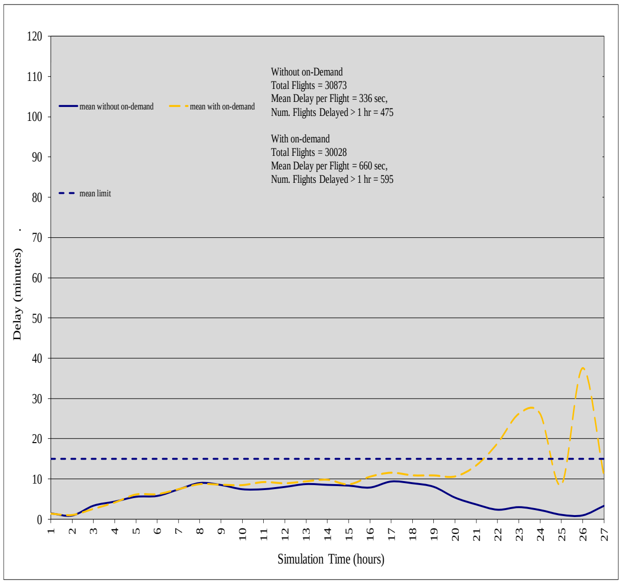

Figure 13. Commercial Passenger Flight Delays for 2015

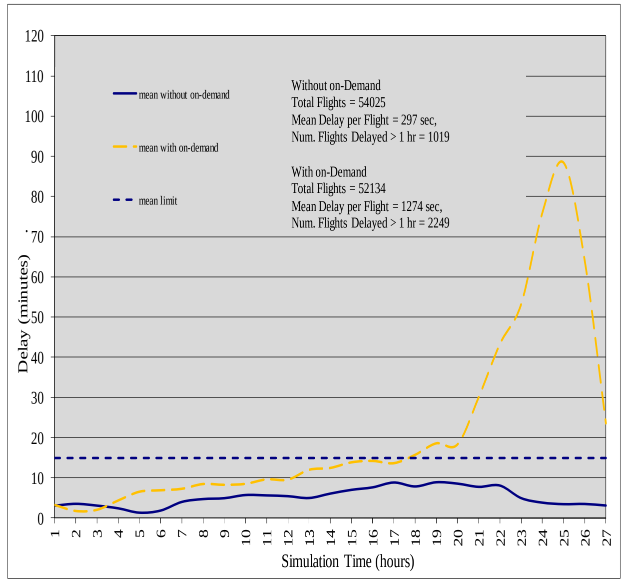

Figure 14. Commercial Passenger Flight Delays for 2035

Comparing delays with on-demand and without on-demand traffic for the 2015 scenario shows that there is a significant increase in commercial traffic delays. The mean delay to commercial flights nearly doubles to 660 seconds. For the 2035 scenario, mean delay per flight increases by 977 seconds to 1274 seconds. Overall, this adds considerable delay to the commercial flights towards the end of the day as the system does not have sufficient capacity; mean delay exceeds the desired 15-minute limit for this study for both scenarios.

Although on-demand flights do not use the large hub airports, there is considerable on-demand traffic to smaller airports that have commercial service. These smaller airports are currently mostly underutilized, but adding the on-demand traffic can exceed their capacity. Commercial flights from large airports that fly into these overloaded smaller airports then experience delays.

For example, McCarran International Airport, Las Vegas, NV (LAS) does not have on-demand traffic, but in the 2035 scenario has 22 commercial airline flights per day into Metropolitan Oakland International Airport, CA (OAK). These flights experience an increase in mean delay of 4.4 hours when on-demand traffic is present. OAK has 1234 on-demand operations per day and added to the existing traffic this exceeds the airport capacity. The ACES assumed capacity for OAK is 91 operations per hour in VMC and the peak demand for the 2035 scenario with on-demand traffic is 120 operations per hour. This compares to a peak demand without on-demand traffic of 46 operations per hour projected for 2035. In reality, this amount of on-demand traffic would never attempt to use OAK without infrastructure improvements.

This analysis of delays to commercial traffic indicates that in 2015 the volume of on-demand traffic that TSAM projects significantly impacts commercial traffic, assuming that airports capacity is the only constraint. This is simply a theoretical point of reference, since in practice the on-demand business could not provide the level of service that would satisfy the projected demand as soon as the year 2015. By the year 2035, delays to commercial traffic increase, since the on-demand traffic uses smaller airports that also have commercial service. This indicates that infrastructure improvements are required to existing small airports as well as (or alternatively) the provision of additional new facilities.

D.3 Delays to On-demand Traffic due to Airports Overloading

In the previous section, analysis showed that the presence of on-demand traffic significantly increases delays to commercial traffic. Figures 15 and 16 show the delays to the on-demand traffic present in the simulation. The mean delay for the on-demand flights exceeds the desired 15-minute limit as delays build throughout the day for both the 2015 and 2035 scenarios.

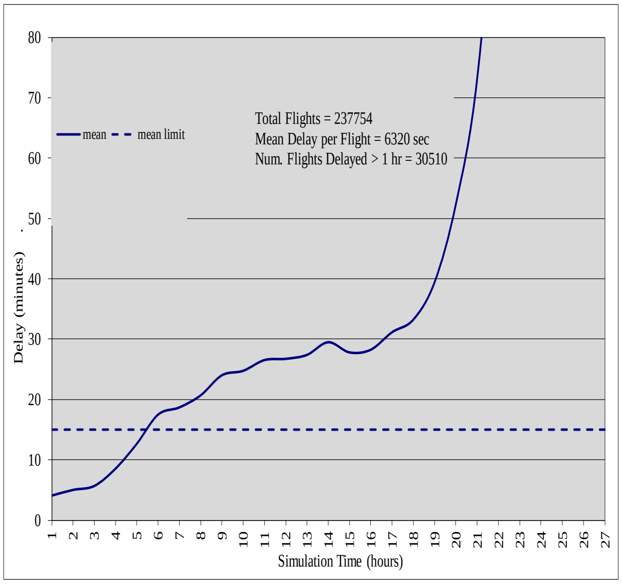

Figure 15. On-demand Flight Delays for 2015

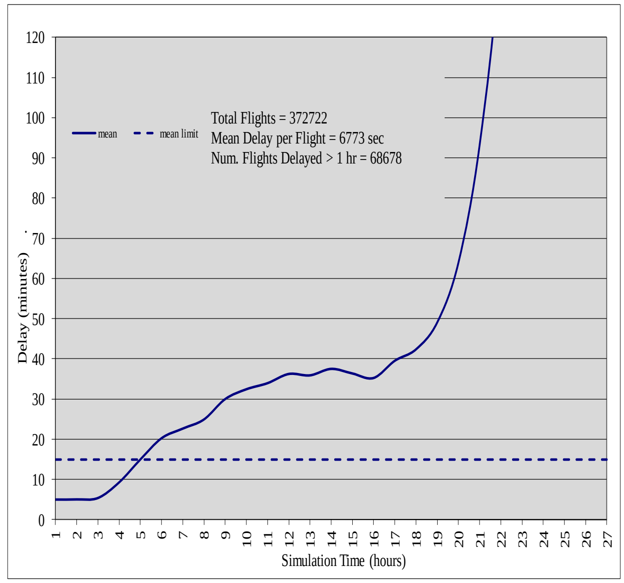

Figure 16. On-demand Flight Delays for 2035

In the 2035 scenario, figure 16, delays are very large, with over 68,000 flights delayed more than 1 hour. This is due to demand exceeding capacity at 222 of the small airports used by the on-demand traffic. The capacity assumed is 60 flights per hour for a single runway as explained in the "Simulation Setup" section. This is clearly insufficient for many airports during high-demand periods of the day. The ACES simulation uses the 10,680 publically available airports and does not model the 50,000 facilities that the concept envisages by the year 2035 indicated in Table 1.

Table 8 shows mean delays for the on-demand traffic only, at the 10 small airports with most delay. Note that the number of operations shown includes only flights that were able to take off or land within the 27 hours of interest. Many more flights are scheduled than can be accommodated; this causes very large delays as ACES TFM agents hold flights on the ground.

Demand is concentrated in regions with the largest population and most economic activity as described in the "TSAM Projected On-demand Trips" section. This analysis clearly shows that to satisfy the projected demand, significant upgrading of existing facilities and building of new facilities is required.

New facilities in less populated parts of the U.S. will mainly increase convenience by reducing access and egress times, thereby improving mobility and increasing demand. This finding is subject to the caveat that this part of the analysis uses a cautions assumption of $1 per seat mile for the electric vehicle total cost, for reasons explained previously. Lower trip costs would result in many more over-loaded airports.

Table 8. Delays for On-demand Traffic at Top 10 Small Airports with Most Delay in 2035

	KTEB Teterboro Airport New Jersey	**KLDJ** Linden Airport Linden New Jersey	**KCGS** College Park Airport Maryland	**KCDW** Essex County Airport Caldwell New Jersey	**KVLL** Oakland/ Troy Airport Troy Michigan	**KFRG** Republic Airport Farmingdale New York	**KHPN** Westchester County Airport New York	**NV26** Voc Tech Airport Henderson Nevada	**KDET** Coleman A. Young Airport Detroit Michigan	**KPWK** Chicago Executive Airport Illinois
On-demand Operations	1908	1573	1540	1606	1713	2043	1381	1567	1724	1709
Total Operations	2103	1589	1540	1707	1723	2188	1915	1567	1772	1978
Mean Delay (s)	27350	19823	17700	15183	14318	13328	11959	7135	6583	6078

Figure 17 shows the scheduled hourly traffic demand for the year 2035 at the six small airports with most delay. The operations counts include existing GA traffic plus the additional on-demand traffic as listed in Table 2. The scheduled demand at each airport is much higher than the constrained demand shown in table 7. Teterboro Airport, New Jersey (KTEB) is the most overloaded, with over 500 operations per hour peak. The total scheduled demand in 27 hours is 6486 operations, whereas the number accommodated was only 2013. Teterboro is a busy GA airport today, used because of its convenience to New York. It has two runways and the assumed capacity in ACES simulation is 76 operations per hour.

The capacity for all of the single runway small airports was set to 60 operations per hour for this study. In fact, College Park Airport, Maryland (KCGS) and Essex County Airport, Caldwell, New Jersey (KCDW) have two runways, but for this study ACES sets the capacity to the single runway capacity. Both airports are still overloaded, even assuming 76 operations per hour. This analysis of delays to the on-demand traffic indicates that infrastructure improvements are required to existing small airports as well as (or alternatively) the provision of additional new facilities.

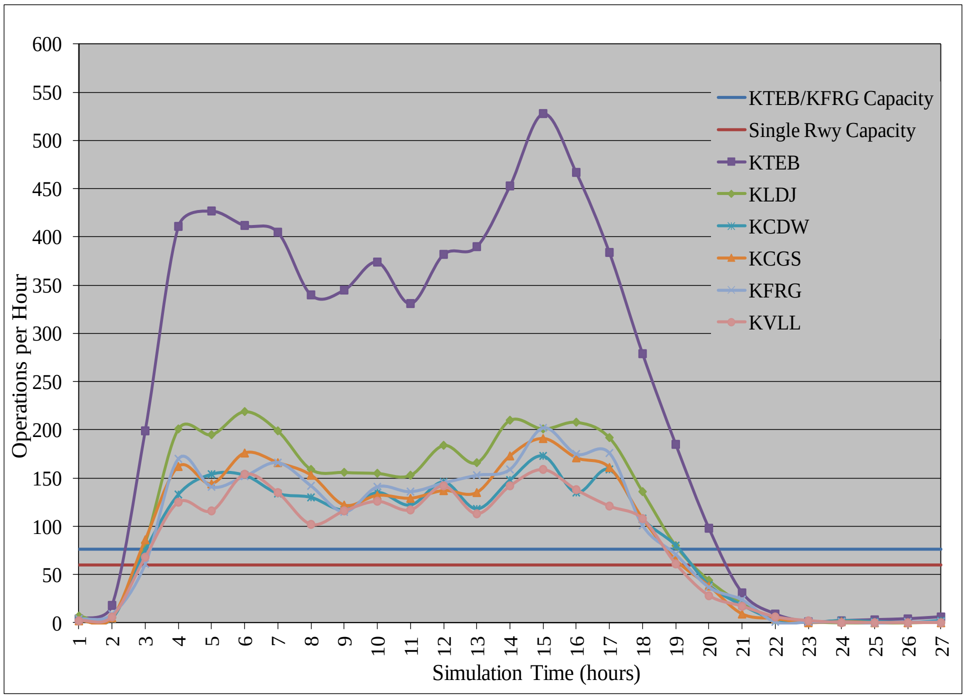

Figure 17. Small Airports Demand versus Capacity for 2035

IX. Conclusions

A significant finding of this study is that there is potentially a very large demand for trips using autonomous, electric, on-demand vehicles that have operating costs per passenger mile that are comparable to automobiles. As the performance of these vehicles improves in terms of range and speed capability, this brings much needed mobility to communities that currently do not have easy access to air-transportation.

This study projects that in the year 2035 the on-demand air vehicles take 665.6 million person trips annually at the lowest cost envisaged of $0.20 per passenger mile from the 1.76 billion annual total for all long distance trips. That is 38% of all trips longer than 100 miles. Most of these trips are diverted from automobile, 82% come from automobile trips longer than 100 miles. The other 18% are gained from airline flights, mostly from shorter flights that do not exceed the 300-mile single leg range of the 2035 electric vehicle.

The impacts on the NAS can be significant, due to the business model assumed for this study that allows on-demand traffic to use small and medium hub airports that have commercial traffic. The on-demand traffic will require upgrades to existing facilities or additional new facilities, to ensure that the demand does not overload existing airports.

Most of the on-demand traffic uses less congested airspace and flies at much lower altitudes than commercial airline traffic. Sector loads increase in low-level sectors with peak counts of over 500 aircraft simultaneously in a sector recorded for some low level sectors. However, since the on-demand traffic operational concept is for autonomous separation assurance and does not require permission to cross sector boundaries there is no direct additional load to the ATM system. It is the responsibility of the on-demand traffic to stay clear of other traffic. For 2035 and beyond, it is highly unlikely that the NAS will resemble the current system, so it is difficult to determine the farther term effects of the projected large volume of on-demand traffic.

The overall outlook for the type of on-demand service studied in this analysis is very positive, based on the cost and performance of the vehicles that Moore has determined from his analysis[7] to be achievable in the periods studied. This visionary concept has tremendous potential to increase passenger mobility, providing a fast and convenient travel alternative to automobiles, which bypasses congested highways, for trips of a few hundred miles.

This study did not include additional demand that could be generated by the improved utility of this new mode of transportation. Shorter distance commuter trips are also not included.

There are still many challenges to overcome. These include the technology challenges of energy storage and autonomy, although the researchers in these fields have determined that the vehicle designs studied here are realistic. The greater challenges are perhaps those of proving safety of operations, weather capability sufficient for reliable service and acceptance by passengers that are not pilots and are not familiar with any kind of general aviation transportation.

The results from this study answered the questions posed by showing that:

- There is potentially a very large demand for trips enabled by autonomous electric vehicle operations with the operating costs and performance characteristics assumed. This demand is concentrated in regions with the largest population and most economic activity, but there is significant demand in less populated regions of the U.S. This has the potential to improve mobility in regions without access to air services.

- The large number of on-demand operations projected can overload existing airports. On-demand traffic that uses airports with commercial service can cause additional delays to commercial traffic. Even if on-demand traffic does not use any airports with significant commercial traffic, demand projections indicate that many existing small airports do not have sufficient capacity. Infrastructure improvements and additional facilities are required to meet the projected future demand and minimize any impacts to the NAS.

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