High-Speed Mobility through On-Demand Aviation

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Nomenclature

ATLIT	=	*Advanced Transport Light Twin*
CFR	=	*Code of Federal Regulations*
CL	=	*Lift Coefficient*
CG	=	*Center of Gravity*
FAR	=	*Federal Aviation Regulations*
FLOPS	=	*Flight Optimization System*
HP	=	*Horsepower*
GA	=	*General Aviation*
IFR	=	*Instrument Flight Rules*
kWhr	=	*Kilowatt Hour*
LB	=	*Pound*
L/D	=	*Lift to Drag Ration*
MPH	=	*Miles Per Hour*
ODA	=	*On-Demand Aviation*
ODM	=	*On-Demand Mobility*
PAV	=	*Personal Air Vehicle*
SATS	=	*Small Aircraft Transportation System*
TBO	=	*Time Between Overall*
TRL	=	*Technology Readiness Level*
TSAM	=	*Transportation Systems Analysis Model*
UAS	=	*Unmanned Aerial Systems*
VFR	=	*Visual Flight Rules*
Whr/kg	=	*Watt Hours per Kilogram*

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I. Introduction

Game changing advances come about by the introduction of new technologies at a time when societal needs create the opportunity for new market solutions. A unique opportunity exists for NASA to bring about such a mobility revolution in General Aviation, extendable to other aviation markets, to maintain leadership in aviation by the United States. This report outlines the research carried out so far under NASA's leadership towards developing a new mobility choice, called Zip Aviation[1,2,3]. The feasibility, technology and system gaps that need to be addressed, and pathways for successful implementation have been investigated to guide future investment.

Figure 1: Zip Car Analogous Value Proposition: On-demand Access to Transportation that is Highly Distributed, while Offering New Business and Operating Models to Meet Traveler Needs

The past decade indicates exciting trends in transportation technologies, which are quickly evolving. Automobiles are embracing automation to ease driver tasks as well as to completely control the vehicle with added safety (**Figure 1**). Electric propulsion is providing zero tail-pipe emission vehicles with dramatically lower energy and maintenance costs. These technologies have not yet been applied to aviation, yet offer compelling potential benefits across all aviation markets, and in particular to General Aviation (GA) as an early adopter market. The benefits of such an adoption are applicable in the following areas:

- *Safety:* The GA market experiences accident rates that are substantially higher than automobiles or commercial airlines, with 7.5 fatal accidents per 100 million vehicle miles compared to 1.3 for automobiles and .068 for airlines. Approximately 80% of these accidents are caused by some form of pilot error, with another 13% caused by single point propulsion system failure.
- *Emissions:* Environmental constraints are pushing for the elimination of 100Low Lead (LL) fuel used in most GA aircraft, with aviation fuel the #1 source of lead emissions into the environment. Aircraft also have no emission control systems (i.e. no catalytic converters etc.), so they are gross hydrocarbon polluters compared to automobiles.
- *Community Noise:* Hub and smaller GA airports are facing increasing noise restrictions, and while commercial airliners have dramatically decreased their community noise footprint over the past 30 years, GA aircraft noise has essentially remained same, and moreover, is located in closer proximity to neighborhoods and businesses.
- *Operating Costs:* GA operating costs have risen dramatically due to average fuel costs of over $6 per gallon, which has constrained the market over the past decade and resulted in more than 50% lower sales and 35% less yearly operations.

Infusion of autonomy and electric propulsion technologies can accomplish not only a transformation of the GA market, but also provide a technology enablement bridge for both larger aircraft and the emerging civil Unmanned Aerial Systems (UAS) markets. The NASA Advanced General Aviation Transport Experiments (AGATE) project successfully used a similar approach to enable the introduction of primary composite structures and flat panel displays in the 1990s, establishing both the technology and certification standardization to permit quick adoption through partnerships with industry, academia, and the Federal Aviation Administration (FAA). Regional and airliner markets are experiencing constant pressure to achieve decreasing levels of community emissions and noise, while lowering operating costs and improving safety. But to what degree can these new technology frontiers impact aircraft safety, the environment, operations, cost, and performance? Are the benefits transformational enough to fundamentally alter aircraft competiveness and productivity to permit much greater aviation use for

high speed and On-Demand Mobility (ODM)? These questions were asked in a Zip aviation system study named after the Zip Car, an emerging car-sharing business model. Zip Aviation investigates the potential to enable new emergent markets for aviation that offer "more flexibility than the existing transportation solutions." These studies indicate that autonomy and electric propulsion technology infusions offer a unique opportunity to provide breakthrough capabilities for new high speed, on-demand travel alternatives that can leapfrog the need for future expensive ground-based infrastructure investment. At the same time, such investments offer a method of laying the foundation for these technologies to be incubated for commercial aviation at lower cost, and with lower initial certification thresholds due to the relatively poor capabilities of GA aircraft to permit early adoption and private market capitalization by rapid technology accelerations, as depicted in **Figure 2**.
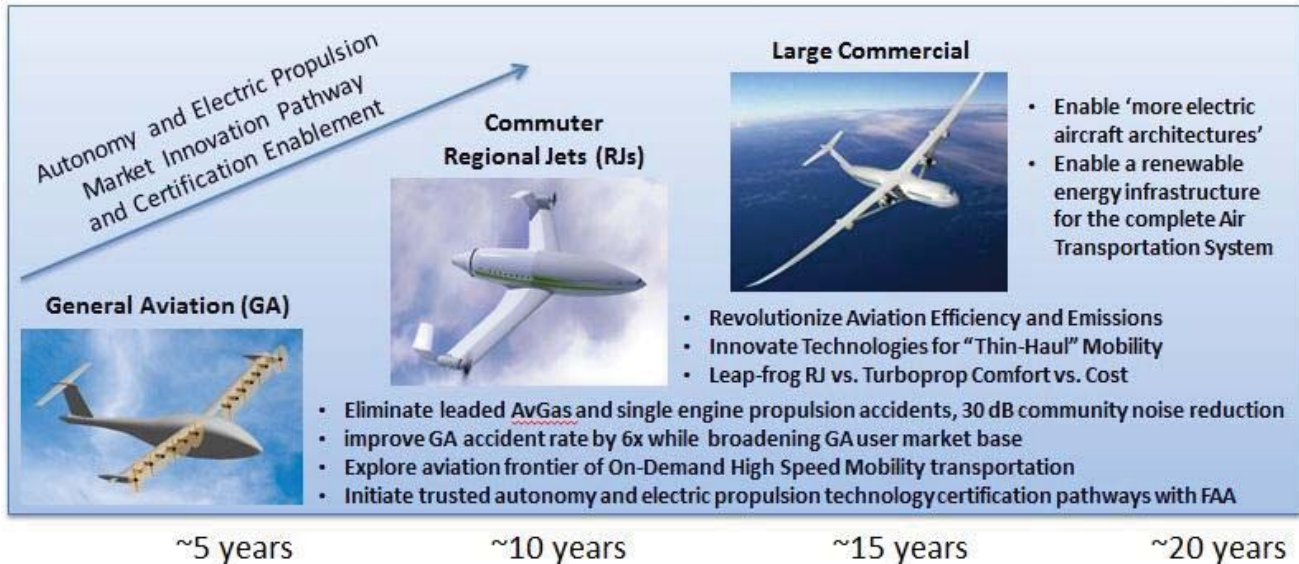

Figure 2: Autonomy and Electric Technology/Certification Pathways Benefit Existing and Emerging Aviation Markets

Autonomy and electric propulsion technologies have large developmental risks requiring long-term investment; especially, given the fact that civilian certification pathways aren't currently defined for autonomous and/or electric propulsion aircraft. Both these technologies require high degrees of integration to achieve maximum benefit, with integration yielding intense coupling between the aerodynamics, propulsion, and control systems. These systems combine to approach the ideal of solid state aircraft, with the aircraft being digitally controlled, potentially eliminating mechanical control surfaces through distributed thrust solutions. Automation technologies have the potential to reduce commercial aircraft to a single pilot crew, while integrating digital control systems with complementary human-machine interfaces to increase safety and reliability. Automation also has the potential to fundamentally enable small aircraft to provide on-demand aviation services with no pilot and minimal training standards that are equivalent to learning to drive a car; while at the same time being significantly safer than the existing GA operations. Imagine simplified user piloting that eliminates the need to use 25 to 40% of the available seats for the pilot(s), which is the case with current Air-taxi operations. Imagine small aircraft that can autonomously redeploy themselves to achieve incredibly high utilization rates with reduced fleet sizes, far greater regional coverage, and with high flexibility and efficient scheduling. Electric propulsion can be used on the ground and in the air by commercial aircraft to reduce emissions and be more energy efficient through non-primary power integration strategies. Electric propulsion can also provide disruptive technology change to smaller aircraft through primary power to enable more than a 10x reduction in energy costs that can be based on renewable energy strategies. Design and integration degrees of freedom are incredibly enhanced due to the nearly scale-free nature of electric propulsion to permit distribution and coupling between the aerodynamic, propulsion, and control systems, which in turn create the possibility for achieving fundamentally new mission capabilities that have not been possible with reciprocating and turbine based propulsion solutions. Imagine high-lift systems that are twice as effective but without significant structural complexity, or highly redundant propulsion systems that completely eliminate propulsion failure based accidents. Imagine fuel/energy costs which currently equate to 48% of the total operating costs of an Air-taxi operation, becoming less than 5%, while also dramatically reducing

maintenance costs and increasing fleet reliability. Imagine that at the same time, zero vehicle emissions are achieved, while community noise is decreased by such a large factor that noise is constrained to only within the boundaries of the small airports where these aircraft operate. Taken together, autonomy and electric propulsion provide an opportunity to fundamentally alter the constraints and objective functions that bound the current aircraft design and operation space. This specific Zip study investigates the intersection of these technology frontiers and the conditions for establishing on-demand aviation market feasibility, as NASA explores the possibility of enabling anyone, or anything, to fly anywhere, at any time. Investment in these technologies not only creates the foundation for a new aviation vision that embraces emergent stakeholders, but also establishes the potential for existing aviation stakeholders to benefit from targeted high risk research that can address pressing needs that include cost, efficiency, safety, emissions, and community noise.

II. Zip Aviation Goals

The Zip Aviation system study goal is to achieve an order of magnitude increase in "Mobility Reach," that is, a 10x increase in the land area that can be accessed with a standard daily travel time allowance of 1.25 hours. The automobile is the existing solution for the vast majority of on-demand transportation, with the U.S. Department of Transportation statistical data indicating an average ground speed of ~35 mph in small cities and ~27 mph in large cities[4]. At this speed, the Mobility Reach is 1335 sq. miles (or a daily accessibility radius of 21 miles). Achieving a ten-fold increase to 13,350 sq. miles would yield an accessibility radius of 66 miles, or a factor of 3.2 improvement in average speed to 105 mph. The impact of such an increase in Mobility Reach is shown in **Figure 3** for the San Francesco Bay area, showcasing the land area that would be accessible based on an average daily time spent traveling, and depending on the transportation technology available.
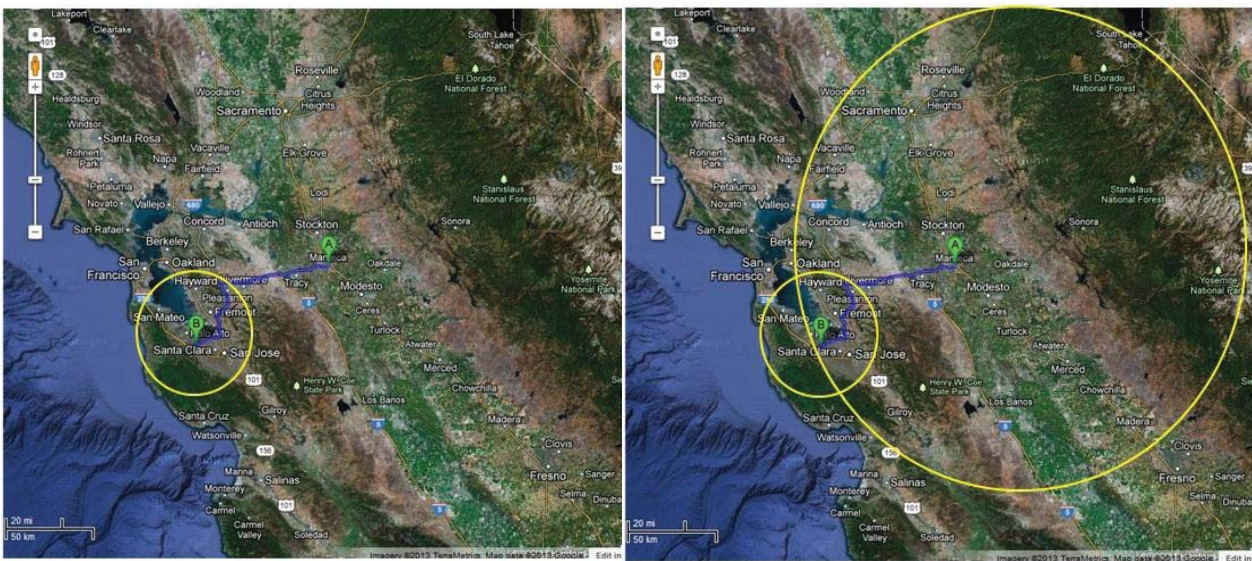

Figure 3: Mobility Reach of the San Francesco Bay Area, for Existing Ground Auto Based Travel as well as through a Zip Aviation Transportation System. An Example of Super Commuter Trip is shown from Manteca to the Silicon Valley (2 hours each way by car)

Given the constraints of automobile ground travel (safe road speed limits, stop lights, traffic congestion, etc.), it is difficult to imagine that automobiles could ever achieve this goal, even with the application of any future technologies. In addition, ground travel requires a large amount of route infrastructure investment that is inflexible to changing needs, with added geographic constraints (mountains, water ways, etc.) causing congestion bottlenecks. Moreover, ground travel essentially forces one-dimensional transportation solutions. Establishing three-dimensional transportation solutions through aviation can yield higher average speeds, overcome route infrastructure costs, eliminate ground terrain limitations, avoid indirect routing, and enable incredible new degrees of route flexibility. **Figure 3** also shows an example of "Super Commuter"[5], a 2 hour each way daily commute from Manteca to the Silicon Valley. A recent New York University's Rudin Transportation Center study indicates that over 600,000 individuals in the U.S. meet this definition of commuting more than 90 miles each way. The Silicon Valley in particular demonstrates severe constraints that prevent high speed, on-demand ground mobility,

and therefore, provides a nearly ideal early adopter market for Zip Aviation. This includes many geographical constraints, ideal year round weather, high differential property values within the expanded Mobility Reach area, insufficient population density to achieve cost effective mass transit, and severe limits to the future transportation options that can be pursued. Centralized ground transportation solutions (i.e. high speed rail) has the potential to achieve similar average speeds, however are only practical in geographic locations of high population densities, and involve severe up front infrastructure and land rights costs. Unless the U.S. engages in major societal change to embrace European urban planning through population concentration, high speed mobility requires solutions that inherently offer distributed and on-demand capabilities. Denying high-speed transportation accessibility inhibits U.S. regional growth and productivity opportunities, and exacerbates existing urban congestion delays.

In the past, Zip aviation would have been described as the short haul market that wasn't well serviced by airlines, especially as routes continued to contract to only those that were the most profitable. But in the context of future markets, it's more appropriate to call this the 'long tail' market, based on Chris Anderson's "The Long-Tail: Why the Future of Business is Selling Less of More"[6]. The long-tail market strategy is to provide new alternatives to specific portions of the specialized needs market that are currently poorly served by the products designed to meet the main market. For aviation, the current main market where the vast majority of revenue passenger miles are conducted is the airline hub and spoke system, with about 75% of all travel conducted from operations relating to the approximately 30 largest U.S. airports. While each individual thin tail travel market is relatively small, there are a huge number of them, so that the aggregation of all the thin tail rips is as large (or larger) than the current mainstream market, as shown in **Figure 4**. The goal of Zip Aviation is to meet the needs of this Thin Tail market.
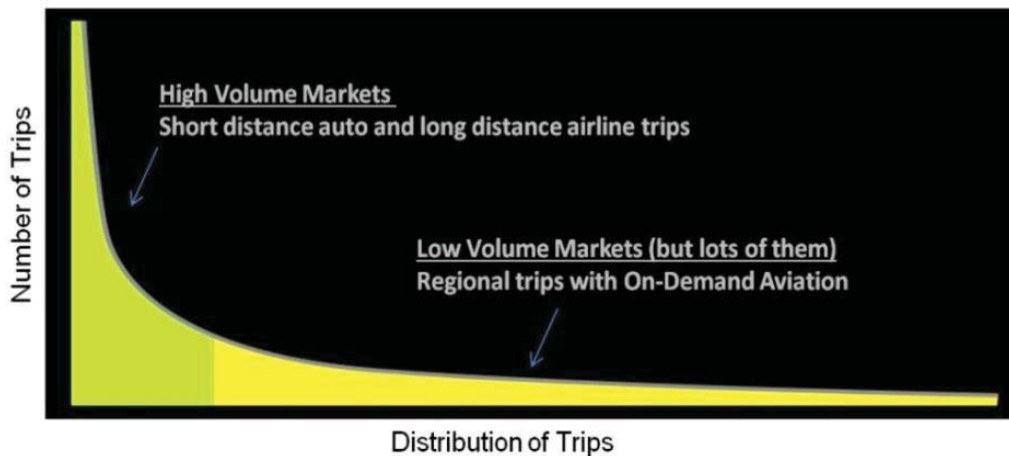

Figure 4: Centralized Mainstream Markets versus Distributed Long-tail Markets Defined by a Power Function, with the Integrated Area of each Providing Equal Market Size

III. Concept of Operations

As part of this study, an analysis was performed using the NASA's Transportation System Analysis Model (TSAM) to establish the potential demand across the U.S. for these shorter range regional trips. TSAM is a strategic modeling tool that can predict intercity transportation demand, which was developed in partnership between NASA Langley and Virginia Tech for more than a decade. It employs socio-economics and demographics across all 3091 U.S. counties and across five different income levels by combining data from the DOT American Travel Survey[7], Woods and Poole[8] demographics, and census[9] total intercity trips. This tool evaluates competing mode choices for personal and business travel between commercial air, automobile, train, and new transportation modes, based on the user value of time, cost, availability, speed, and accessibility of each travel mode. The resulting analysis provides fully burdened door to door trip assessments (including both ground and air legs and even account for local ground speeds using map based trip planning), and is therefore a predictor of the best transportation choice across the U.S. population for any given trip.

In the TSAM model study, assumptions were developed across the study team for the delays incurred between the individual trip legs (i.e. how long it takes to check out a Zip aircraft, etc.), and a sensitivity analysis was performed to understand the dependence on the Zip aircraft cruise speed (150, 200, 250, and 300 mph), cruise range

(200, 300, and 500 miles), total cost per mile ($0.20 to $4.00 per passenger mile), and Zip airport availability over time. Trip demand was assumed as an extrapolation of the current census trip data increasing over time. The assumptions and an example mission are shown in **Figure 5**, along with a typical daily distribution for the trips that result in a Zip aircraft mode choice. The airport availability for Zip travel was assumed based on three dates of service. Travel in 2015 used the existing 4,477 public small airports (which exclude commercial hub airports); while in 2035 the use of the existing 10,680 public and private small airports was assumed. If an on-demand aviation system using Zip aircraft were to evolve into a successful market, there would be an increase in airport distribution that is even greater (i.e. to locations such as malls, which are distributed well with population density, with approximately 50,000 malls existing in the U.S. currently). However, the sensitivity to the number and distribution of Zip airports was found to be not significant, and therefore the increased number of airports would be required (as this market develops) more for increased capacity. As can be seen in **Figure 5**, the average predicted trip distance is less than 200 mile range. The short range nature of these regional trips is what permits electric propulsion to be a disruptive technology enabler, even within the next 10 years with relatively poor levels of battery energy density, and to potentially and fundamentally alter GA vehicle characteristics.
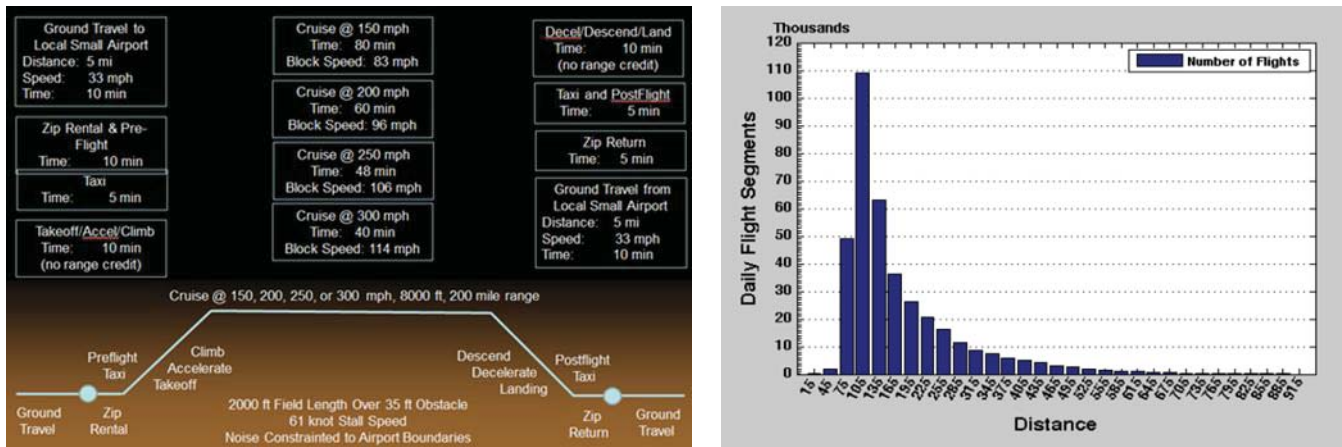

Figure 5: Concept of Operations Assumptions, and the Distribution of Daily Trip Distance (in miles)

The initial start-up of Air-Taxi operators over the past decade provides valuable lessons learned that have been incorporated into this study. Only a few of these Air-Taxi operators continue to operate today as a result of a combination of the economic disturbances to venture capital starting in 2008, as well as the existing available aircraft characteristics and airspace restrictions resulting in highly non-optimal operations. The predicted short average stage lengths are consistent with those experienced by such Air-taxi operators as DayJet and SATSair. These two operators chose very different aircraft. DayJet flew the new Eclipse 500 (**Figure 6**), a "low cost" twin turbofan configuration that could carry 5 people at speeds up to 380 mph at 41,000 feet altitude for a distance of 1000 nm. SATSair flew the Cirrus SR-22 (**Figure 6**), a relatively new single engine piston aircraft that uses a carbon fiber composite structure to carry 4 people at speeds of 200 mph at 10,000 feet altitude for distances up to 500 nm.

Both operators achieved utilization rates of about 500 hours per year, which is about 5 to 6 times lower than that of commercial airlines. These low number of hours were a function of the reliability of the aircraft, and resulted in a significant cost per mile due to the relatively high acquisition costs (~$2.15 million for the Eclipse 500 and ~$700,000 for the Cirrus SR-22) being amortized over a small number of hours. The resulting total operating costs were quite high, with the economic analysis models used for this study estimating $5.20 per mile for the Eclipse, and $3.09 per mile for the Cirrus. The resulting cost per passenger-mile is also determined by taking into account the average load factor, and pilot seating needs. DayJet flew with 2 pilots for insurance and customer acceptance reasons, requiring 40% of the capacity of the aircraft to be non-revenue producing. SATSair used a single pilot that required 25% of the available seats. The typical load factors, these "on-demand" operators such as DayJet and SATSAir experienced, was somewhere between 1.3 to 1.8 passengers per trip (which is highly similar to that experienced by automobiles that averages 1.7). The resulting average cost per passenger mile was $2.80 to $4.00 for the Eclipse and $1.72 to $2.38 for the Cirrus. These high operating costs are also driven by high fuel/energy costs (aviation gas averages over $6.00 per gallon currently) and poor vehicle efficiencies (achieving

between 20 and 50 passenger mpg, while commercial aircraft achieve 50 to 100 passenger mpg). The vehicle lessons learned from this prior Air-Taxi market include the following guidance for Zip aircraft:

- Be highly reliable to achieve at least 1500 hours/year of utilization, with 3000 hours/year highly desirable
- Be appropriately sized for the on-demand mission to achieve average load factors of 75 to 90%, similar to airlines

Figure 6: Eclipse 500 (left) and Cirrus SR-22 (right) Aircraft used in Air-Taxi Operations

- Eliminate the pilot burden in terms of seat space, payload weight, cost, and availability across the fleet
- Achieve greatly improved efficiencies with dramatically lower fuel/energy costs
- Fly at altitudes relevant to an average range of less than 200 miles, while being able to extend this range when needed

IV. Airspace Modeling

In addition to the above, there are many other important attributes required to achieve feasible operations that will be acceptable to communities and users. As part of the demand modeling, an initial analysis was conducted using NASA's Airspace Concept Evaluation System (ACES) simulation of the National Airspace System to determine the level of congestion and delay that would occur with the predicted number of Zip flights. An example of such an analysis indicated that the traffic in the near-term would increase from a baseline number of 76,271 daily flights to 321,062 flights in 2015 (a 4.3x increase in traffic, and in 2035 further increasing to a factor of 6.9x). In many regions of the U.S., the airspace sectors were saturated, with the peak number of aircraft in a sector increasing to 200-500. However, the concept of operations envisaged for Zip aircraft is for high levels of autonomy, so the current sector loading limits that are due to controller workload would likely not apply. Surprisingly, most parts of the U.S. could accommodate the increased number of trips through inherent distribution and avoidance of hub airports. Therefore, there is clearly a need for the Air Traffic Management (ATM) system to be able to accommodate a much greater volume of traffic, both centralized and distributed, by incorporating advanced airspace technologies. Likely Zip aircraft, and other distributed operations such as UAS, would be independent of the ATM system with some minimal interaction.

Another critical attribute to achieve is improved safety. Currently small aircraft suffer from accident rates substantially higher than those of automobiles or airlines. While airlines have experienced dramatic safety improvements over the past decades, smaller aircraft have been left behind with over 90% of accidents a result of either pilot error or propulsion system failure. Adverse weather also impacts the safety (as well as trip completion rate and ride quality) for small aircraft. Improvements in these areas have lagged for small aircraft primarily related to the low wing loading of these smaller aircraft. Airlines use advanced high-lift systems to achieve wing loadings of ~120 lbs/ft^2, while small aircraft have wing loadings of only 15 to 30 lbs/ft^2. Commercial aircraft also fly above the weather at substantially higher cruise altitudes. Zip fleet feasibility also requires these on-demand aircraft to achieve dramatic reductions in emissions and noise. The vast majority of GA aircraft today use 100 LL gasoline, which is responsible for more lead pollution into the environment than any other source. Aircraft also have no emission control systems, while automobiles have incorporated sophisticated solutions to achieve dramatic pollution reductions over the past 40 years. GA aircraft community noise levels have remained essentially unchanged over this same time period; while commercial aircraft have experienced vast improvements. Clearly, it is not feasible to add hundreds of thousands of daily Zip aircraft flights based on the technologies available to small aircraft today, or the airspace they need to access. Zip aircraft, and the system which they operate within, must incorporate additional operational capabilities to:

- Provide non-scheduled operations under Federal Aviation Regulation (FAR) Part 135 Subpart K that avoid conflicting with existing airline traffic
- Provide non-sector based airspace control that is scalable and robust, with advanced separation assurance
- Achieve dramatically lower emissions that eliminate the use of 100 LL fuel
- Provide a 6x improvement in safety to be equivalent to automobiles, or 110x to be equivalent to airlines

- Achieve ~30 dB lower community noise than the existing small aircraft to enable frequent community operations without annoyance
- Provide improved ride quality and cabin noise than the existing small aircraft

V. Demand Modeling

The Zip mission range selected for demand modeling was 200 miles (along with 45 minutes of Instrument Flight Rule IFR reserves), with a minimum cruise speed of 150 mph (with higher speeds desirable), as well as a 2 or 4 persons payload of 200 lbs per person. These aircraft would fly from small local airports using a 2000 feet field length, with the resulting noise signature limited to 55 to 60 dBA at the airport boundaries, to minimize impact on the community experiencing frequent operations. Zip aircraft would have a level of autonomy that permits operation with minimal training similar to that for automobiles, with a degree of automation designed to achieve the highest level of complementary safety between human and vehicle for a given cost. This autonomy must avoid the significant training required for pilots, while dramatically reducing the degree of human error to achieve at least automotive safety statistics. Zip aircraft would be based on redundant electric propulsion systems that exhibit high reliability, high efficiency, very low noise, compactness, the ability to be distributed across the airframe, high specific power to weight ratios, and zero emissions. Their utilization would be at least 1500 hours/year to amortize the vehicle cost and achieve small fleet sizes per regional coverage area. The total operating cost goal to be achieved is less than $1.00 per passenger mile. A unique characteristic of Zip aircraft is the ability to autonomously redeploy from one airport to another as an UAS, although not necessarily at the same safety level. Redeployment is important to achieve fleet operation's economic feasibility through the smallest possible fleet size that can also provide the highest possible user accessibility. Prior Air-Taxi operations demonstrated a large number of "dead-head" non-revenue flights, where the aircraft must be repositioned to get to the next user. Therefore, autonomy that can enable automatic redeployment is highly synergistic to the concept of operations for Zip aircraft.

The TSAM demand modeling results, as shown in **Figure 7**, indicate the number of potential person trips that could be competitively captured, as a function of assumed total operating costs. The market demand for currently available Air-Taxi aircraft is relatively small (at costs of at least $1.40 per passenger mile at high load factors). If Zip aircraft costs of less than $1.00 per seat mile can be achieved, nonlinear increases in market size occur. As a reference to compare, the cost of automobile travel used in the TSAM modeling is $0.19 per mile for personal use, and $0.55 per mile for business use. The demand modeling demonstrates that a large potential market exists for autonomous, electric Zip aviation, as a more ambitious follow-on to the Air-Taxi market; if the assumed aircraft characteristics can be achieved. This demand estimate is predicated based upon achieving dramatically improved vehicle and airspace capabilities that requires new technology infusion. However, in several ways this demand modeling is pessimistic, because, it did not include any new latent demand that can be generated by the improved utility of this new mode of transportation that currently does not exist. The analysis also did not take into account shorter commuting trips, which would increase trip demand at ranges of 50 to 100 miles.

After completing the TSAM analysis, the remainder of this study focused on determining the feasibility of the demand model assumptions, to establish criteria required for an on-demand and distributed aviation system. These efforts included investigations into the key enabling autonomy and electric propulsion technologies that are most relevant towards meeting the
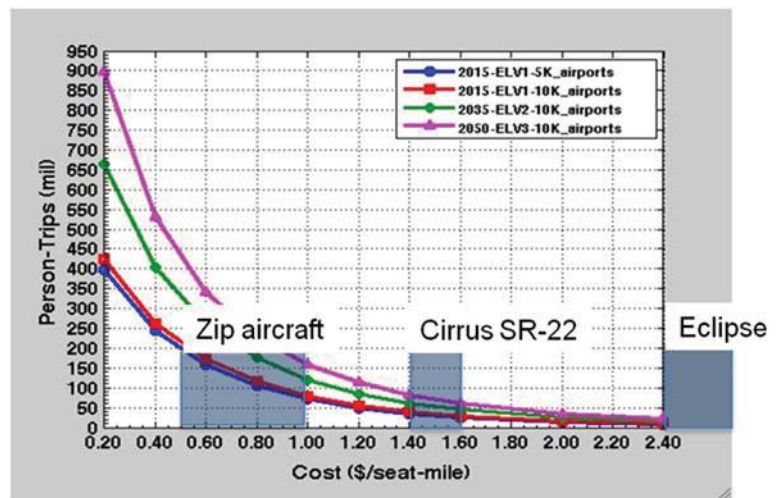

Figure 7: Zip Aviation Trip Demand in 2015 with ~5,000 and ~10,000 Airport Availability for Aircraft that have 200 miles Range at 150 mph Cruise Speed, as well as in 2035 with Assumed Aircraft of 300 miles Range at 200 mph, and in 2050 with Assumed Aircraft of 500 miles Range at 250 mph

desired aircraft characteristics. Baseline models of the existing aircraft were developed to calibrate the analysis tools, with a focus on the Cirrus SR-22. The Cirrus was analytically converted into an electric aircraft to understand the differences, if an incremental approach were taken in applying Zip technology with high certainty of the resulting performance. Sensitivity analyses were then performed to understand the impact of electric propulsion, as applied to this specific Zip mission. Advanced concepts were then developed that could take full advantage of the new technologies, as well as other synergistic integrated technologies to determine the extent of potential benefits. A detailed life cycle emissions analysis was then performed to understand the benefit of achieving ultra-low carbon solutions in comparison to hydrocarbon-based aircraft. Finally, economic sensitivities were performed to determine the feasibility of achieving total operating costs of less than $1.00 per seat mile. A detailed economic analysis was not attempted, because of the high degree of uncertainty that exists in the vehicle cost with the advanced technologies used in this conceptual design study. Instead, a series of assumptions were made, indicating the resulting impact on total operating costs incrementally. The total operating cost is by far the most critical parameter determining Zip's market feasibility.

VI. Baseline Modeling of State-of-the-Art and Design Space Exploration

The Cirrus SR-22 was selected as the most relevant baseline aircraft because it has successfully been applied to the Air-Taxi mission with the greatest cost effectiveness, while also being comparatively well suited to the Zip design mission. In terms of the Single Engine Piston GA market; the Cirrus has achieved one of the highest production volumes, with about 500 units fabricated per year. The Cirrus has applied advanced features such as a Ballistic Recovery System Parachute, carbon fiber structure, flat panel displays, anti-icing, and autopilot navigation aids. The aircraft was modeled with system analysis tools including Vehicle Sketch Pad, vortex lattice and parasite drag buildup, a custom cooling drag model, Hamilton Standard empirical propeller analysis, and Flights Optimization System (FLOPS) mission evaluation. Significant performance data was available from the Cirrus Pilot Operating Handbook to calibrate the analysis and reduce the analysis error to less than 10%.

The current approach towards the development of electric aircraft is simply to "re-engine" the vehicle with direct replacement of the reciprocating engine with an electric motor and battery storage. Such an approach is far from optimal, because electric propulsion has extremely different characteristics than reciprocating engines. However, it does provide an incremental approach towards understanding technology impact, and the key parameters that define the new technology. Differences such as cooling drag, power lapse with altitude, and other altered characteristics between the propulsion systems were captured in the modeling. For instance, the cooling drag decreased from ~5% to ~1% of the total cruise drag with the electric variant at the design cruise condition (with the cooling drag being as high as 12% at the off design conditions). A significant effort went into understanding the impact of the reserve requirement, and how this correlated with the last 20% of battery energy (which was considered only usable in reserve flight to avoid damaging the batteries at complete discharge). A compromise between the 30 minute loiter Visual Flight Rule (VFR) and the 45 minute loiter plus cruise to an alternate Instrument Flight Rule (IFR) reserve requirements was used for the Zip mission; that is, a 45 minute loiter but with no alternate airport range required. Zip aircraft will be required to operate with IFR-like capabilities, with many weather related issues yet to be addressed.   However, many areas of the U.S. are relatively free of weather issues as pertains to the operation of small aircraft, as they rarely experience icing or severe weather.

Electric propulsion is mostly characterized by the power to weight and efficiency of the motors, and the specific energy and discharge rate of the electricity stored. Only batteries were considered due to their rapid improvement and infiltration into the automotive market. Current performance levels of electric motor and batteries were selected based on the state-of-the-art (3 hp/lb motor weight, 89% overall electric propulsion drivetrain efficiency, and 200 Watt (W) hr/kg battery energy storage), along with advanced levels for the years 2035 (4.5 hp/lb, 95%, and 600 Whr/kg), and 2050 (7.5 hp/lb, 95%, and 1200 Whr/kg). Vehicle sensitivities were conducted across these assumed technology states.

Compared to the baseline Cirrus SR-22 (a 3400 lbs gross weight vehicle), a 2015 electric SR-22 was able to reduce the total propulsion system weight by 498 lbs through electrification (due to electric motors offering significantly improved power to weight ratio compared to reciprocating engines). This difference in motor weight was then applied towards batteries to determine the resulting range. At the 2015 technology levels, the resulting range and payload is dramatically reduced with the application of an electric powertrain, with a single person payload only capable of either 61 or 40 nautical miles, depending on the speed and L/D (compared to the baseline

values of 4 passengers able to travel 500 nm for the reciprocating engine). But with improved battery technologies in 2035, **Figure 8** shows an increase in both the payload and range. These results indicate that retrofit approaches

2015 Tech Level (200 Whr/Kg Batteries)
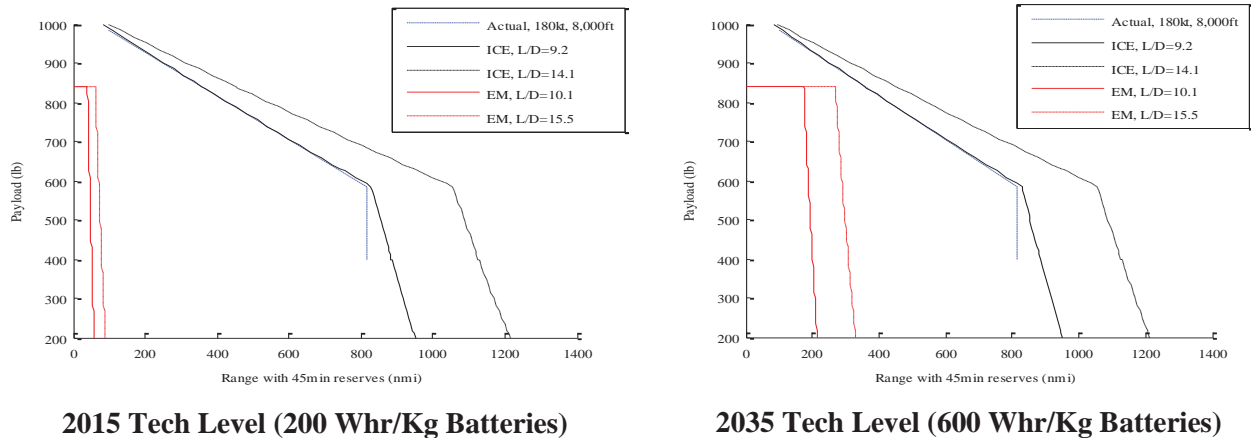
2035 Tech Level (600 Whr/Kg Batteries)

Figure 8: Range Payload curves of the Existing Internal Combustion Engine (ICE) Cirrus SR-22 (blue and black lines) Compared to Electric Motor (EM) SR-22 (red lines); the Higher L/D Cases are Flown at ~150 mph, while the Lower L/D Cases are at 200 mph Cruise Speeds

to existing aircraft would not provide attractive near-term solutions, if equivalent ranges to an existing hydrocarbon aircraft were required. However, if the mission range is reduced to 200 miles, reasonable solutions exist at battery technology levels that are estimated to be achieved within the next decade; especially, if the aircraft are redesigned for higher aerodynamic efficiencies, due to their high sensitivity to the energy required.

Across the different sensitivity analyses performed, by far the greatest sensitivity factor is the battery specific energy, and a variation of only this parameter is shown in **Figure 9**, comparing the 2015, 2035, and 2050 assumed technology states. This sensitivity analysis shows that at the near-term range of 200 miles (plus reserves), achieving a battery specific energy of ~400 Whr/kg is a critical feasibility condition, with highly non-linear penalties until that technology level is reached, and only incremental benefits at higher specific energies. This curve would be of a similar shape if a different range were to be selected, but with a completely different critical specific energy feasibility condition. Therefore, to design a Zip aircraft with a 200 mile design range, a critical mission feasibility condition is two times the current specific energy value of batteries that enables relatively near-term electric/battery use for aircraft.
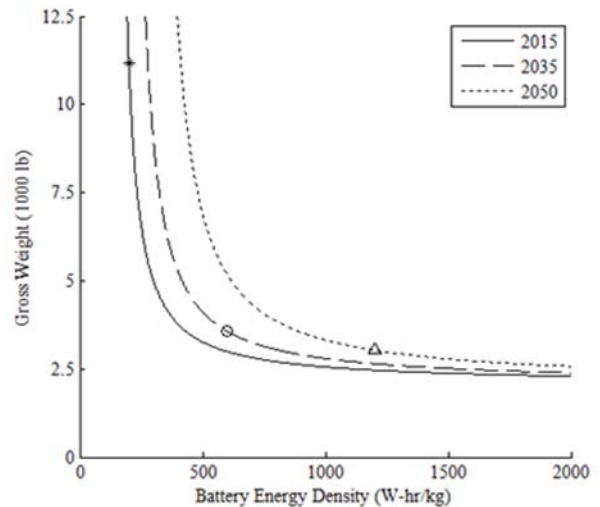

Figure 9: Sensitivity of Vehicle Gross Weight (lbs) to Battery Energy Density (Whr/kg) Across the Assumed Technology States in 2015 (200 Whr/kg), 2035 (600 Whr/kg), and 2050 (1200 Whr/kg)

VII. Electric Propulsion Technologies

In September of 2011, NASA completed the Green Flight Centennial (GFC) Challenge that demonstrated the ability of an aircraft, purposefully designed for electric flight, to achieve a 200 mile range with extremely high efficiency. The winning aircraft used a combination of advanced propeller, electric motors, and batteries for very high propulsive efficiency, along with synergistic benefits to achieve a high structural efficiency with a useful load fraction of 60% through mass span loading (and taking advantage of electric aircraft being a constant weight vehicle), as well as high aerodynamic efficiency through extensive laminar flow and a high aspect ratio wing. This vehicle achieved 403 passenger mpg, 4x better than the Boeing 787. This GFC prize fundamentally changed the perception of the potential that an electric flight has to offer, with the NASA Chief Technologist stating, *"Today we've shown that electric aircraft have moved beyond science fiction and are now in the realm of*

practice.'' A key lesson learned from this activity is that developing isolated electric technologies is insufficient to achieve transformative vehicle change, but that significant research needs to be accomplished to integrate the electric propulsion technologies that offer inherently different characteristics (highly compact motors, high power to weight, highly efficient at full and part power, full power at variable rpm capability, zero emissions, low cooling drag, high reliability, scale-free sizing, high emergency supplemental power ratings, low noise, low vibration, digital control, non-air breathing, no motor power lapse with altitude, lower energy cost, etc.). This competition has opened the door to aviation experiencing a propulsion technology revolution, not experienced since the 1940's when turbine engines were introduced.

Electric propulsion technologies have been rapidly progressing, with battery energy densities increasing at an average of about ~8% per year over the past 30 years. If battery energy density were to continue to compound at this same rate, a value of 400 Whr/kg would be achieved by 2020 to enable the required technology level to achieve competitive aircraft weights for a 200 mile range (as shown in **Figure 9**), while at the same time offering dramatic improvements compared to existing aircraft in noise, reliability, emissions, and operating costs. Significant increases in battery investment over the past decade offer the likelihood of higher rates of improvement than the historical norm, as basic research from the last decade begins to come out of the laboratory in this decade. Battery innovations are likely to experience discontinuous improvements, as fundamentally different chemistries and material approaches are pursued. A recent example is Envia, a small company funded by the ARPA-E BEEST program, which has pioneered the use of silicon-carbon nanotube anodes and demonstrated a leap to an energy density of 400 Whr/kg with its initial laboratory cell tests verified by Argonne National Laboratory. Similar advances across a wide spectrum of approaches are being pursued that offer not only improved specific energy, but also decreased internal resistance to achieve higher specific power (the rate at which the batteries can be drained) and rapid recharging times. These additional metrics are equally important to achieve feasible operations and avoid battery exchange after each flight. The cost per kWhr is also a critical feasibility enabler; however, to a lesser degree for high utilization Zip aircraft that can amortize the high costs over many hours of yearly use (something that has inhibited pure electric solutions for automobiles, which experience relatively low utilization rates). Instead, for Zip aircraft, it is more important to achieve robust lithium chemistries (such as lithium phosphate) that offer both increased cycle life and safety. As a comparison to existing reciprocating and turbine energy sources, 100LL and JetA hydrocarbon fuels have not seen any improvement in their energy densities or safety over the past 30 years, with cost per kWhr of gasoline experiencing its historical minimum in 1999 (accounting for inflation), and now exceeding 2.3 times that value in a little more than a decade. Therefore, long-term trends would indicate that alternative energy strategies will achieve much greater cost effectiveness in the future, and there are significant reasons to justify exploration of battery technologies for electric aviation solutions. Fuel cells and alternative electric storage systems (flywheels, ultra capacitors, etc.) were not investigated as part of this study. These other methods have not experienced consistent advances and investment, and continue to suffer from failing to meet expectations. A significant factor inhibiting development of fuel cells is their low conversion efficiencies (less than 50%) compared to batteries. This results in poor true vehicle life cycle energy use, especially important when long-term renewable energy sources are considered.

No work was done as part of this study on electric technologies, instead research results from others were assembled to develop the study assumptions and achieve a clear understanding of the state of the art and future forecasts. Argonne lab predictions were used as the basis for battery energy and power densities, life cycles, and costs. Some of these predictions are shown in **Figure 10**, along with the specific battery chemistries and material breakthroughs that are considered to be the likely major players in cells that are expected to reach the market place within the next decade. Again, the reason for interest in applying electric technologies to aviation at this time is because of the incredible technology and cost accelerations that are predicted by such reputable organizations, based on the billions of dollars of investment that has focused on this topic, motivated by the pervasive applications that exist from laptops to power tools, and from automobiles to aircraft.

Electric motors and controllers have likewise been experiencing significant improvement over the past decade. Again, no research was conducted in this study on these technologies; however, a parallel research effort conducted by the author has provided significant insight for the study assumptions. This parallel research study is on developing a series hybrid propulsion system with advanced Halbach Array alternators and generators. In this study, electric motor's specific power (including the gear box) was assumed to achieve a value of 3.0 hp/lb in 2015, 4.5 hp/lb. in 2035, and 7.5 hp/lb. in 2050. If gearboxes can be avoided (i.e. through distribution), the

motor's specific power assumptions were 4, 6, and 12 hp/lb. The controller's specific power was assumed at 0.05 lb/hp across all the years, with the controller efficiencies of 98% in 2015 and 99% in 2035 and 2050. The batteries were considered to have a constant 98% discharge efficiency (charging efficiencies weren't considered). The motor efficiency assumptions were 92.5% in 2015, 95% in 2035, and 97% in 2050. The values achieved in motor/alternator bench testing of the prototypes already exceed the assumed values in 2015. Through novel proprietary methods of sizing, integrating, and coupling the alternators and motors in distributed/direct-drive system architectures, the 97% alternator/motor efficiency is likely to be demonstrated this year, with 0% losses from the motor/alternator controller, while still exceeding the power to weight assumption in 2015. So, there is a strong justification to consider the study assumptions in this area to be conservative in the near-term. A key goal, as these technologies are integrated into advanced concepts, is to discover new ways of integrating electric motors that can avoid gearboxes, while still being able to operate the motors at an rpm, where high power can be extracted efficiently.

Figure 10: DOE Argonne Lab Battery Goals in Terms of Energy, Power Densities, and Costs

Figure 11 shows an efficiency map from one version of the Halbach Array motors being developed by LaunchPoint that highlights the change in efficiency with rpm. While over 90% efficiency is achieved over broad operating regions of rpm, it is highly desirable to operate these motors at peak efficiency at the cruise rpm and power condition. This figure also highlights the new degree of freedom that electric motors offer compared to combustion engines, wherein significantly different amounts of power can be extracted at completely different rpms; reciprocating and turbine engines have extremely limited capability to vary power with rpm, which is highly desirable at many flight conditions, especially when open propeller/rotor propulsors are used and community noise is an active constraint. **Figure 11** is also indicative of the size of the motors of interest for Zip aircraft when distributed propulsion solutions are pursued. Instead of integrating a single 310 hp reciprocating engine, such as for the Cirrus SR-22, many electric motors can be integrated at one tenth to one twentieth of the size. The overall power required of the motor is also decreased, simply because of the fact that power sizing typically occurs at high altitudes and in hot day conditions (like Denver in summer), when air breathing reciprocating and turbine engines experience a significant power decrease. Electric motors are insensitive to these high/hot conditions, except in a minor way due to the required motor cooling. This difference alone permits the electric motor to be downsized to 240 hp, from 310 hp. There are other important reasons why it is preferable to be working with smaller power sized electric motors. Distribution of the
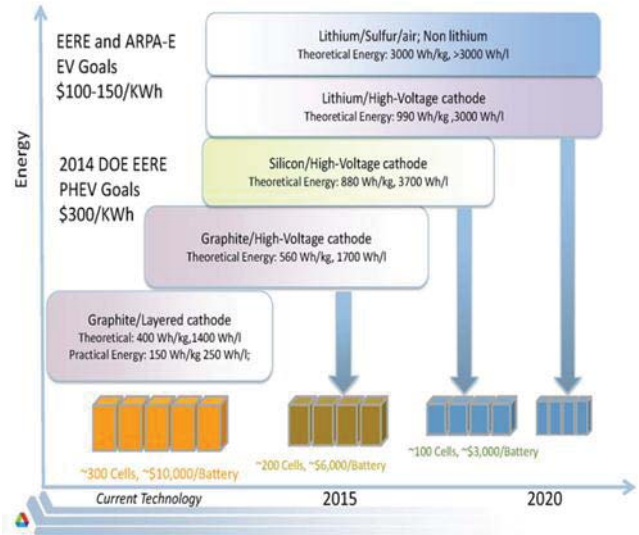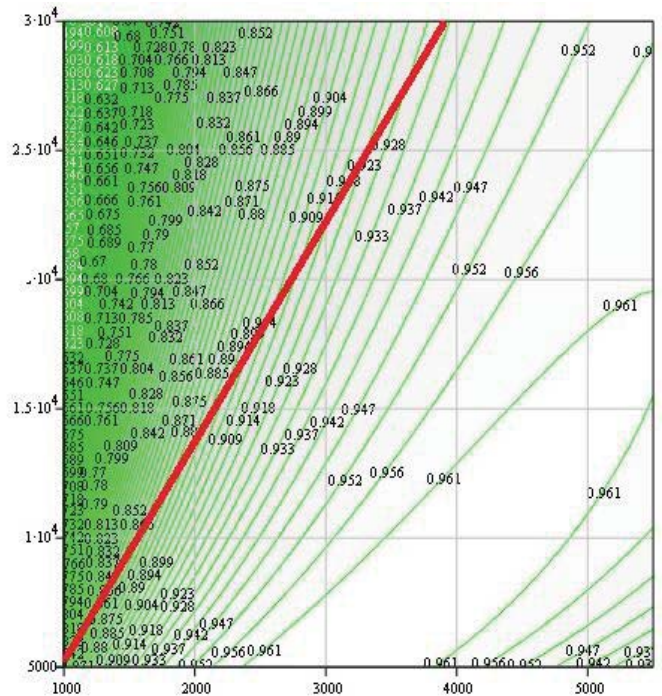

Figure 11: Halbach Array Motor/Alternator Efficiency Map, as a Function of Horsepower (vertical axis) and Rotational Speed in rpm (horizontal axis), with the Thermal Limit Shown as the Red Line

motors permits improved cooling, and thereby avoiding liquid cooling systems for large cores. Also, the power electronics industry provides incredibly inexpensive, efficient, lightweight, reliable, and versatile electronic controls for smaller motors. However, if motors of sizes greater than a few hundred horsepower are pursued, lightweight power electronics simply haven't been developed by the industry, because there aren't compelling markets that would justify the large investment expense. By working with smaller electric motors, aviation has the potential to leverage extensive investments by automotive and other industries. Developing the power electronics at large scale would also be costly, and is likely to be unwarranted, as distributed electric propulsion integration is shown to achieve more optimal system solutions.

The desired Zip feasibility battery metrics include an energy density of 400 Whr/kg, a life span of 2000 cycles, a specific power of 1000 W/kg, and recharge times to >80% of capacity in less than an hour, at a cost of $200 kWhr. With these characteristics, battery electric small aircraft can achieve competitive vehicle weights for the typical Zip range of 200 miles. However, even though the median range is less than 200 miles, it isn't reasonable to only be able to conduct 50-60% of the desired mission ranges. For this reason, until batteries energy densities can approach 1000 Whr/kg (to cover over 90% of the mission ranges), the use of range extending small engines is an additional essential feasibility criterion. The size and weight of the range extender engine can be kept small by having the engine operate at the start of the mission to feed the batteries in a series hybrid mode of operation. At typical Zip aerodynamic and propulsive efficiencies, a 4 place Zip aircraft can achieve 500 mile range, while also using up the batteries with only an approximately 30 kW engine, and carrying less than 50 lbs of fuel at specific fuel consumptions that are available in the near-term for this engine size. Such an engine can be optimized for a single operating point to achieve peak efficiency. A lightweight diesel, or micro-turbine plus recuperator, direct driving an alternator can provide solutions capable of achieving an installed engine plus fuel weight of less than 100 lbs. Several companies are currently developing such engines (GSE, Metis, Azmark, Locust, etc.) for a series hybrid application that would be capable of using bio-fuels to maintain a net zero carbon emission solution. However, it is important to realize that when using the range extender engine, the fuel/energy costs will be dramatically higher than for the shorter ranges, where only the battery electric energy is used. This energy cost differential is explained in detail in the Economics section of this report.

VIII. Autonomy Technologies

Another part of the study assessed the potential roles and associated capabilities and requirements the automation technology could play in enabling Zip aviation. Currently, the need to either become or hire a professional pilot is a significant barrier to the Zip aviation concept. Self-flown operations are limited by the high cost of training (e.g. ~$35,000 for initial IFR certification) and time required (~1,500 hours of experience) to become an effective all-weather pilot. While hiring a professional pilot accounts for a relatively small portion of the current cost of chartering a small aircraft (~16%), this percentage becomes larger and limiting, if the cost reductions associated with electric propulsion and high-vehicle utilization are achieved. In addition to the direct challenge of obtaining piloting services, the accident rate of single-pilot operations, in which human-error plays a large role, is also a significant deterrent to small aircraft use by much of the population. The current fatal accident rate of GA is estimated to be 7.5 per 100 million vehicle miles. This risk is comparable to riding a motorcycle. In comparison, the fatal accident rate for automobiles is estimated to be 1.3 per 100 million vehicle miles, and the rate for transport aircraft is approximately 0.068 per 100 million vehicle miles. For the purposes of this study, the automobile accident rate was assumed to provide an "adequate" near-term level of safety for the Zip concept that would be acceptable to many potential users, while the airline rate was considered a long-term, desired level of safety.

A significant aspect of the automation study was a comparative assessment of three human-automation function allocation concepts or "archetypes." From the perspective of the role of the human operator, these archetypes are; 1) a concept where the human functions as an "expert" (i.e. a pilot), 2) an "operator" similar to today's automobile driver, and 3) a "user" who for practical purposes is a passenger and is not required for successful operation of the vehicle. These human-automation archetypes can also be described from the perspective of the aircraft and its systems as, 1) evolutionary, 2) semi-autonomous, and 3) fully autonomous respectively. These roles are differentiated by the degree of responsibility and authority of the agents (human and machine), as well as the underlying functional capabilities and reliability required to perform the associated tasks. Greater capability and responsibility on the part of the human of course requires increased training (initial, and possibly recurrent depending on the required highly specialized skills). Greater operational reliance on the human also increases the probability of

"pilot" error, although whether such an error results in loss of safety depends on the overall human-automation system, and the automation's ability to help mitigate errors.

Figure 12 : NTSB Compiled Data for Personal Aviation Indicating the Cause of Accidents (left) and the Relationship of Human Error Potential Induced by the Pilot or Automation Designer

It should also be recognized that as **Figure 12** depicts, shifting operational responsibilities from the human on-board to automation does not necessarily eliminate the possibility of "human" error. Rather, it shifts it to humans involved in the design process. Designers typically have sufficient knowledge of routine situations, and are "expected" in non-normal situations such as engine failures, to develop automation that can respond to these situations, using largely pre-scripted responses. However, achieving critical levels of safety without the possibility of human assistance requires automation that can effectively respond to unforeseen situations and/or combinations of situations. So far, the automation technology is very "brittle" in such situations, as it has essentially no general intelligence, common-sense world knowledge, or even the ability to perceive unexpected situation elements. All three human-automation archetypes must perform the same set of functions involved in the safe conduct of a flight. The basis for these functions in this study was the current pilot licensing and operational requirements (e.g. Code of Federal Regulations (CFR) 14 Parts 61, 91, and 135) and supporting material (e.g. the Aeronautical Information Manual). It should be noted that in addition to core in-flight tasks (e.g. aviate, navigate, communicate and perform associated sub-tasks….), the functions that are safety critical include tasks such as physically inspecting the airframe prior to flight (i.e. preflight walk around), loading and securing cargo and passengers within the weight, and c.g. tolerances, and taking due care with any potentially hazardous items (aerosols, flammables, batteries, etc.). Such tasks require a high degree of physical mobility and dexterity, as well as general knowledge, making them challenging (and expensive) to fully automate. **Figure 13** summarizes the key aspects of the three allocation archetypes with their principle strengths and weaknesses. The evolutionary and fully-autonomous concepts can be easily understood, with the qualifier that the fully-autonomous concept is likely to require some level of off-board human support, such as ground handlers (e.g. to perform the preflight and loading tasks mentioned earlier) and remote emergency pilots. In many regards, the semi-autonomous concept has a range of in-flight capabilities similar to the fully-autonomous concept, as shown in **Figure 14**. For example, should the operator become disabled, the aircraft can autonomously execute an emergency landing (with potential oversight from an off-board monitor).

Figure 13 : Autonomy Allocation Archetypes (left) and their Principle Strengths and Weaknesses (right)

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However, this sort of fully-autonomous operation is reserved as an emergency capability, and the normal mode of operation is for the semi-autonomous aircraft to collaborate and interact with the operator, such that key decisions and actions are shared and cross-checked (similar to a 2-pilot crew), thus improving the reliability and performance of either type of agent individually. In this concept, all, essentially deterministic, inner-loop control tasks are delegated to the vehicle automation through a flight-critical control system that provides direct-flight path control as the lowest control level the operator is trained to interact with. Outer-loop perception, judgment, and decision making tasks are shared by both the agents to leverage human operator's inherent flexible perception and general intelligence, and the automation's vigilance and multi-tasking abilities. By retaining meaningful human involvement in the less deterministic outer-loop aspects of flight operations, the certification requirements and unknowns on the automation are significantly eased. Of course, this easing comes at the expense of some-level of formal operator training, although this training is targeted to be comparable in extent to automobile driver education. Also, active collaboration imposes additional requirements on human-machine interface to facilitate the required operator engagement and provide reversionary protections, should this engagement be absent (e.g. the automation acts more autonomously, but with a bias towards ending the flight safely, rather than completing the nominal mission plan).
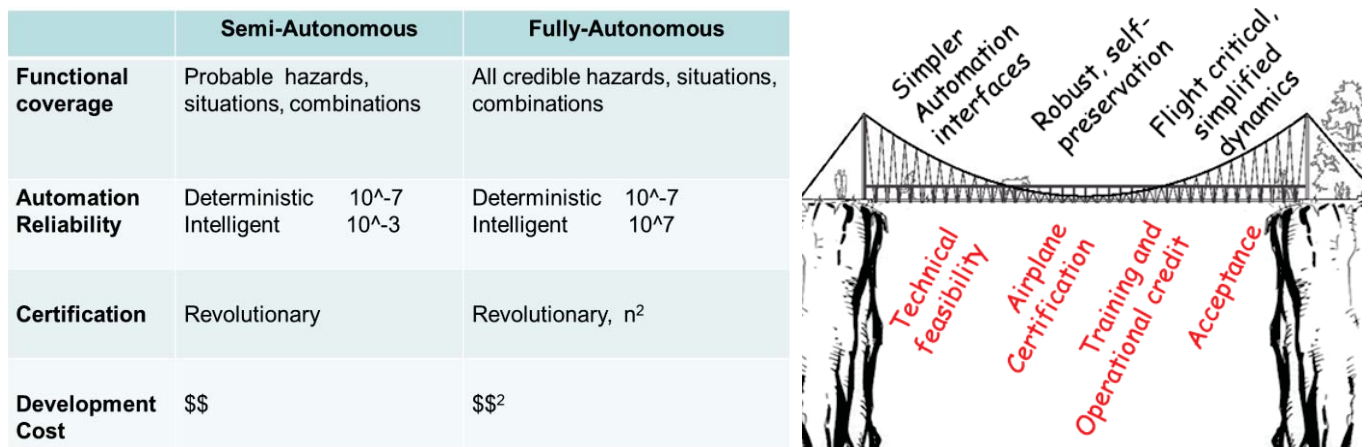
	Semi-Autonomous	Fully-Autonomous
Functional coverage	Probable hazards, situations, combinations	All credible hazards, situations, combinations
Automation Reliability	Deterministic 10^{-7} Intelligent 10^{-3}	Deterministic 10^{-7} Intelligent 10^{7}
Certification	Revolutionary	Revolutionary, n^2
Development Cost	$$	$^{2}

Figure 14 : Comparison of Semi and Fully Autonomous Capabilities (left), and the Autonomy "Bridge" (right) Required to Transcend Current Capabilities to Future Autonomous Solutions

Any of three archetypes offer the potential to dramatically decrease the accident rate of small aircraft, which as mentioned earlier is dominated by pilot error by the categories with red arrows, as shown in **Figure 12** (left). Even the evolutionary concept can, through limited authority envelope protection, synthetic vision displays, and improved decision aids, reduce these accident categories sufficient to achieve the initial goal of automotive-like safety. However, going beyond the automotive-level safety requires greater reliance on automation technologies embodied in the advanced Zip concepts. While long-term approaches to autonomy are certain to yield fully auto-nomous solutions, the Zip operational requirements and regulatory considerations indicate that an "incremental evolutionary" approach is the likely autonomy technology infusion pathway. The three archetypes can be thought of as forming a bridge between the present and fully-automated vehicles in the distant future (**Figure 14**, right). By following a process of planned evolution, rapid progress to full or near-full autonomy can be made, as statistical evidence from actual flight operations is absorbed into the system design in a controlled and fail-safe fashion, to achieve the maximum safety per cost. The FAA will insist on such automation strategies to ensure safe implementation, and it is reasonable for them to do so; as discontinuous jumps in technology that haven't been validated by statistical operational evidence would pose unacceptable risks.

VIIII. Advanced Concepts and Synergistic Technologies

Compared to the results that have already been shown relating to simplified retrofitting of the existing aircraft to electric propulsion, additional performance benefits are possible through taking advantage of the greater degrees of freedom that electric propulsion integration offers. Advanced concepts were developed to explore these new degrees of freedom that show three different integration strategies. The three strategies looked at limited distribu-tion to position the propulsion to achieve synergistic drag reduction, as well as, more extreme distribution to

achieve much greater interdisciplinary coupling. Distributed propulsion is highly synergistic to electric propulsion because of its relatively scale-free nature. The power to weight and efficiency of electric motors are essentially constant across a very broad scaling range, which enables high degrees of distribution to be pursued without penalty. This is fundamentally different than turbine or reciprocating engines that suffer significant penalties as size is decreased.   However, such integration advances require substantial propulsion-aerodynamic-control interaction analysis and optimization. Such designs are more complex, and for this reason, haven't yet been flight validated. But, design complexity doesn't necessarily mean fabrication complexity, as design repetition and economies of scale can be applied to achieve unique redundancy and safety benefits without an increase in vehicle cost.

The first concept (eV-Twin) approaches electric integration from a modest evolutionary airframe design perspective. This concept was inspired by a hydrogen fuel cell electric concept developed by the Naval Research Laboratory (NRL), called the Ion Dasch, as shown in **Figure 15**, along with the derivative Zip concept. This concept eliminates fuselage scrubbing drag by moving the propulsors to a V-tail (typically 2 to 3% of the total drag), while at the same time improving visibility and reducing the noise/vibration caused by the motors in the passenger cabin, and the propeller vortices slapping the windshield. This is only possible due to the extreme light weight and compactness of electric motors compared to reciprocating engines. By mounting the motors on the V-tail, larger propellers can be driven to increase propulsive efficiency without requiring long landing gear. Such a strategy was also employed with great success by the Green Flight Challenge contestant from the University of Stuttgart, but with a single tail and propulsor. This motor placement also allows for the thrust to be closer to the aircraft center line to reduce a pitching moment contribution or engine-out yawing moment. Modifications to the original NRL concept were made to account for four passengers (instead of two), by removing the large hydrogen tank and fuel cells, and replacing them with batteries in the wing with a span loading distribution for alleviation of root wing bending moment (since the vehicle weight is fixed with a battery electric vehicle).
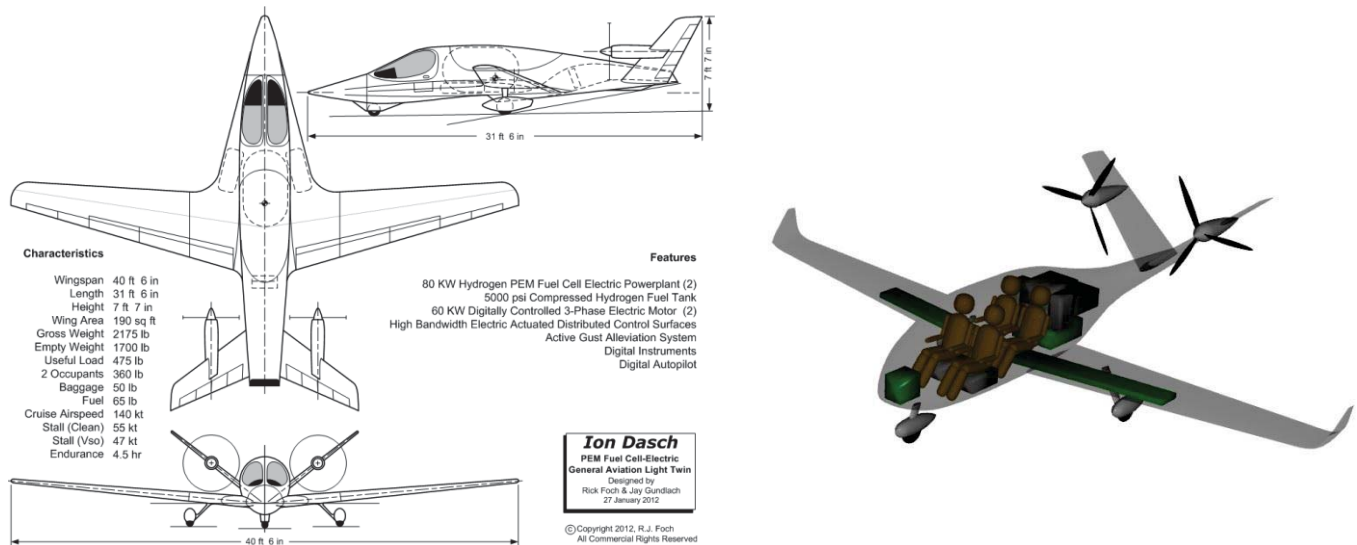
Figure 15: NRL Ion Dasch Fuel Cell Concept (left) and Derivative Zip eV-Twin Battery Electric Concept (right)

The key benefit of this concept is an improvement of installed propeller efficiency of at least 8% at the cruise condition, and improvement as high as 30% at off design conditions due to the ability to vary motor rpm to operate at near optimal advance ratios. Another significant improvement with this concept is a reduction in power to only 228 hp (down from 310 hp for the baseline Cirrus SR-22 operating at a similar gross weight, when assuming the desired battery specific energy of 400 Whr/kg to accomplish the 200 mile design range plus 45 minute reserves). This reduction in power is a result of the increased propeller disc area, higher propeller efficiency, and elimination of power lapse at the high/hot engine sizing condition at takeoff and climb. The cruise engine sizing is also fundamentally different, since reciprocating engines need to be operated at ~65% of the peak

power to achieve reasonable Time Between Overhaul (TBO) of 2000+ hours. Electric motors are able to operate at their peak steady temperature design power rating, with temporary higher power rating for 30 to 60 seconds to heat saturate the motor in an emergency condition. Unfortunately, this configuration layout doesn't permit a decrease in tail surface area due to higher velocities from the propeller, since the tail sizing condition takes place at landing with very low power (and therefore low induced propeller velocities). An additional negative aspect of this concept is that a gearbox is required for each propulsor that decreases both the electric motor's effective power to weight and powertrain efficiency. The overall eV-Twin concept has only achieved an improvement in Lift to Drag (L/D) ratio of ~19% compared to the SR-22 baseline (with a similar wing span), which is quite modest compared to the more aggressive electric propulsion integration strategies.

The second advanced concept implements a strategy of achieving drag reduction through locating the thrust where a significant synergistic improvement can result. This concept limits the degree of distribution and focuses on achieving a significant aerodynamic efficiency improvement, based on the prior design exploration results showing that aircraft L/D is the second highest parametric sensitivity (after battery energy density, which was fixed at 400 Whr/kg). The cruise speed selected was for the near-term goal of 150 mph to further minimize the energy required, compared to the 200 mph cruise speed of the Cirrus SR-22 baseline. This concept is based on the Swept Wing Inboard Flap Trimming (SWIFT) developed by Steve Morris and Ilan Kroo of Stanford University, which is well understood as a single person production sailplane, with a detailed dataset for increasing the design accuracy, as the concept was extrapolated to a 4 passenger aircraft. As a flying wing concept, the SWIFT configuration only achieves a CLmax (maximum lift coefficient) of approximately 1.3, compared to ~2.0 for the SR-22. However, to reduce this penalty and avoid significantly lower wing loading, a C-wing configuration was implemented that positions a horizontal tail on top of the vertical tail as a pitch trimming surface (which increases the CLmax to 1.6). The C-wing was also developed by Ilan Kroo as a mechanism to achieve non-planar aerodynamic efficiency improvements, due to the circulation of the wing being carried across the vertical and horizontal tails, to achieve a higher effective span. At the height to span ratio of ~10%, the effective span in increased by 12% (while achieving a lower wing bending moment and a lower skin friction coefficient due to larger chord length at a fixed wing size).

The electric version of SWIFT (e-SWIFT) takes the further step towards increasing the effective span by positioning a large diameter propeller at the tip of each horizontal tail (which is where the wing vortex is shed). With the propeller ahead of the wing tip vortex, and spinning in the opposite direction of the tip vortex, an additional induced drag reduction is achieved. This is an effect well documented by NASA Langley's wind tunnel and flight experiments in the 1980s, with a theoretical analysis method established by Miranda of Lockheed[10]. The maximum induced drag reduction would be achieved with the highest propeller induced axial velocities through a smaller diameter propeller, and while ideal for cruise, this causes engine sizing penalties due to the takeoff and climb requirements of the decreased thrust, resulting from smaller diameter propellers. While induced drag reductions of as high as 40% are possible at these conditions, the configuration only achieves a ~15% reduction in drag (compared to a comparable C-wing with no propellers present). Just like the prior EV-Twin concept, the larger diameter propellers permit a lower required power and low tip speed operation, with electric motors providing variable rpm across a broad power rating to optimize the advance ratio across operating conditions. Positioning the propellers in this fashion also promotes acoustic wing shielding of the propeller noise during takeoff to achieve community friendly operations (another critical Zip aviation goal, since a high volume of operations at small airports will require dramatic reductions in aircraft noise). Electric motors are a key enabler for this configuration due to their lightweight and compactness. Another key synergistic technology employed on the e-SWIFT is a fuselage boundary layer propulsor that improves the propulsive efficiency. This technology was previously investigated through a series of wind tunnel tests by Goldschmied in the 1960's through 1980's[11]. The benefit is derived from reaccelerating only the slow boundary layer air from the fuselage (and sizing the propulsor not to use any free stream air), to fill the fuselage wake (and thereby eliminate the fuselage drag through the applied power). This Boundary Layer Ingestion (BLI) achieves an efficiency of up to 130% for this portion of the applied thrust. The combined effect of the wingtip and BLI propulsor (with ~35% of the thrust coming from the BLI propulsor to match the amount of fuselage drag) yields a net aircraft installed efficiency of 106%. This efficiency is greater than 100% only due to the use of the Froude model as the comparative baseline, and is not indicative of violating any boundaries of physics. Additional drag improvements were achieved in this concept through a proverse fuselage pressure gradient design, and decreased landing gear drag through a retracting nose gear and well faired main gear. Further drag reduction was achieved by improved packing efficiency with the

back to back seating that was implemented, with an 18% reduction in the fuselage wetted area due to fuselage shortening. This seating configuration was also important for limiting the Center of Gravity (CG) excursion on a configuration that has such a short pitch trimming moment arm. Typically, this type of seating is less desirable than all front facing seats; however, this raises another important issue relating to Zip aircraft; and that is the goal of "right sizing" the vehicle for the Zip mission's typical load factor, with the assumption of eliminating the need for a pilot. With an average load factor of 1.7 passengers, carrying the full burden of a 4 passenger aircraft at all times results in significant penalties. This compromise in the seating layout permits 4 passengers for those trips where required, while minimizing the penalty associated with the 2 additional seats that are empty on the majority of flights. **Figure 16** shows the SWIFT sailplane and the as well as the derivative e-SWIFT concept.

Figure 16: SWIFT Single Person Sailplane (left) and Zip e-SWIFT Concept (right) for Moderate Speed/High Aerodynamic Efficiency

The e-SWIFT concept resulted in an aircraft for the 200 mile range plus 45 min reserve mission with a battery weight of 360 lbs (or a battery pack of 65 kWhr at 400 Whr/kg of specific energy). The total mission energy required is 5.9 times less than that required for an SR-20 aircraft (which is a slower version of the SR-22 with only a 200 hp reciprocating engine instead of the 310 hp engine). At this slower cruise speed of 150 mph, the SR-20 is a better comparative baseline. The SR-20 is also a 4 passenger aircraft with a 200 lbs lower gross weight than the SR-22. The gross weight of the e-SWIFT is 165 lbs less than the SR-20, with 42% higher aerodynamic efficiency. One design choice, where a drag penalty was incorporated due to the use of external battery pods, increased the wing parasite drag by 22%. This was done because of the need to achieve rapid battery exchange in the near-term, until rapid battery recharge capability is achieved. In addition, by span loading the battery weight, a lighter wing structural weight is achieved, while also accomplishing greater battery safety in the event of a fire, which could be contained external to the fuselage without smoke containment issues for the passengers. One negative aspect of this concept is that the lower wing loading results in poorer ride quality and increased sensitivity to gusts or inclement weather. Since the feasibility of Zip aviation will require operation under IFR conditions, implementing strategies that can achieve higher wing loading to improve all weather operation is highly desirable.

The third advanced concept takes an aggressive approach of laterally distributing the thrust across the wing to achieve a high lift system capable of a CLmax of 5.0, while avoiding the structural wing complexity of multi-element systems that are capable of a lesser CLmax value. This concept is the culmination of everything learned across the other concepts, with an additional goal of increasing the wing loading by a factor of 3 to 62 lbs/ft^2 (the same as regional jets) to achieve high aerodynamic efficiency, but at higher speeds and improved ride quality than the other concepts. The key to achieving such a design is to reduce the wing area through an incredibly effective high lift system that permit permits a wider speed bracket (the ratio of cruise speed to the takeoff speed that is still capable of meeting a 2000 ft. field length requirement). Distribution of the propellers across the wing permits the effective dynamic pressure of the wing to be increased and achieve greater lift, without increasing the wing circulation. Using many small propellers provides the highest propeller induced velocities over the entire wing surface. Fewer propellers using the same total power would result in lower induced velocities and a larger effective streamtube. This approach of using a total of 14 small diameter propellers permits a direct drive electric motor solution to achieve the lowest electric motor specific weight. Also important is the promotion of the best velocity

distribution across the wing surface, since radial velocity distributions are present across each propeller. This is accomplished by 'stacking' of the propellers so that alternating motor/propellers are at different distances from the wing to permit intermeshing propellers. Typically performing such intermeshing would dramatically increase the noise, while decreasing the efficiency of the propellers. However, as part of the associated electric propulsion research being performed by the authors, detailed OVERFLOW and WOPWOP analyses have indicated that favorable noise and efficiency benefits can be derived, if synchronization of the propellers can be achieved. Unique phase coupling experiments have also been conducted by the authors across multiple propellers to achieve a master-slave operation of the electric motor's Electronic Control Modules (ECM) that is capable of precise syncing of the propeller blades. This permits each propeller blade to remain out of phase with the adjacent propeller blade so as to maintain a 90 degree azimuth separation. Combining this phasing of the blades with precise axial offsets (in relation to the blade diameter and shed tip vortex spacing), offers a unique benefit that can only be achieved through distributed electric propulsion. This type of vehicle configuration would never be undertaken through a mechanical system of shafts and gearboxes because of the extremely complexity, weight, efficiency losses, and resulting poor reliability. But with distributed electric motors, none of those penalties are present. Even if ECM syncing is lost due to an individual blade failure, the propeller blades are still axially separated so that blade strikes would be avoided (with only increased noise and lower efficiency resulting). The motor sizing criteria for this concept is based on the required induced propeller velocities at the 61 knots stall speed. While technically the FARs permit multi-engine aircraft to exceed the 61 knots stall speed limitation, this constraint is still applicable to Zip aircraft in order to maximize takeoff/landing safety (which is based upon these speeds), while still being able to meet the 2000 feet field length (which equates well with acceptable human comfort levels for acceleration and braking). The motor sizing resulted in 240 hp required across the 14 different 3 feet diameter propellers, yielding a total static thrust of 1584 lbf. At the 61 knots stall speed, a propeller velocity multiplier ratio of 1.26 is achieved at this power and disc loading. The Advanced Technology Light Twin (ATLIT) high lift system[12] developed at NASA Langley in the 1970's was applied to the wing, since detailed analysis and wind tunnel test data were available that confirmed a CLmax of 3.1 could be achieved with the GAW-1 airfoil with only a single element fowler flap. The combination of increased dynamic pressure caused by the propellers and the ATLIT high lift system yield a CLmax of 5.0 for this configuration of Zip E- ATLIT, shown in **Figure 17** . While trailing edge propeller integrations were investigated and would yield a greater CLmax through improvement in the circulation as well, the aft integrations were complicated by poor structural attachment methods to the wing, which would have resulted in significant separation and loss in lift through negative interactions with the propeller structural attachments and the wing upper surface.

Additional synergistic drag reduction approaches can be used in this concept. With the propeller flow only over the wing, no wasted scrubbing drag exists, since the additional velocity of the propellers is accomplishing increased lift (instead of simply increased parasite drag). However, at the cruise condition, the induced velocities are only barely greater than the freestream velocities, so this effect is not substantial (this is not true at the lower velocities where large differentials exist between the propeller and freestream velocities). A newly developed version of a Boundary layer Ingesting (BLI) propulsor has been developed for the aft fuselage to achieve the maximum benefit at the lowest possible input power. This, much smaller diameter BLI propulsor, permits a smaller diameter fan that is better matched to the boundary layer thickness, and thereby avoids internal flow separation problems. The wing aspect ratio is pushed to as high as

Figure 17: Zip e-ATLIT High Speed, High Wing Loading, Highly Distributed Concept

reasonable, due to the small required wing area coupled with the desire to maintain as much span as possible for aerodynamic efficiency. An aspect ratio of 20 was selected based on aero elastic concerns, and it is an active constraint on this design. Battery tip tanks are applied to span load the batteries, however the combination of this distributed wing mass and high aspect ratio requires more detailed analysis to ensure that aero elastic problems can be avoided. This concept utilizes a tail that carries lift when flaps are retracted to prevent a large trim moment during their deployment. The result of this is reduced longitudinal stability, requiring a control system to provide

artificial longitudinal stability. Since the tail carries lift in cruise, a high aspect ratio tail is utilized; however, the aspect ratio of the tail is less than the wing, which keeps the C_{Lalpha} of the tail less than the wing to ensure the wing stalls before the tail.

A moving battery pack located on rails in the tail boom allows the vehicle to maintain its proper CG location at various passenger loading configurations. It will even enable the vehicle to fly with no one onboard to allow autonomous deadheading to the next airport to pick up passengers, while maintaining the same trim control characteristics. The e-ATLIT concept achieves a gross weight of 2875 lbs, with an empty weight of 1650 lbs, also requiring a 66 kWhr battery pack. The key difference is that the e-ATLIT can achieve a cruise speed of 200 mph at a 12,500 feet altitude, while only requiring 76 hp at the cruise condition. Another intriguing capability of electric aircraft is their ability to fly at higher altitudes without motor power lapse. This enables significantly higher cruise speeds at high altitudes, while accomplishing the same range with the same total energy use. This unique characteristic of electric aircraft permits this concept to achieve a cruise speed of 240 mph at 25,000 feet or 300 mph at 38,000 feet, requiring 112 hp (and even 350 mph at 50,000 ft on 127 horsepower, before the Mach and wing sizing prevent higher cruise altitudes). However, it is questionable whether such short mission ranges will permit such high altitude operation, and attempting to use altitudes above 12,500 feet will require pressurization (and with operation above 25,000 feet causing conflicts with commercial air traffic). An important difference associated with electric aircraft is that the rate of climb barely decreases with altitude, while reciprocating aircraft experience a significant lapse rate with altitude so that even turbocharged aircraft are limited to less than 25,000 ft altitudes. For example, in this study the climb rate was required to match that of the Cirrus SR-22 at 1400 ft/min, with this rate decreasing at higher altitudes so that the time to climb to a specific altitude increases. The e-ATLIT concept has significant excess power all the way up to 50,000 ft due to the decreasing density, and no loss in motor power with altitude. Even for short range missions, such high climb rates may make it desirable to operate electric aircraft with parabolic trajectories that seek the highest possible altitude at the mid-point. Boost-glide trajectories may also be optimal, even to the point of using reserve energy to achieve a more rapid highest altitude, and then recharge the reserve portion of the battery in descent (even with the inherent losses that would be present from the propeller/motor). As part of this study, a simplified pressurization system for mission durations of approximately one hour has been identified, based upon a carbon air tank and CO_2 scrubbers, to minimize the amount of energy required for pressurization. Subsequent versions of this concept have been developed that use complete wing tilt instead of the ATLIT fowler flap. Modest wing tilt (such as used in the F-8 Crusader) can be accomplished relatively easily with less structural complexity than the Fowler flap on the ATLIT highlift system, while providing greater lift effectiveness at takeoff due to thrust vectoring, and providing the added benefit of increased drag at greater tilt angles during approach (while still permitting full power to be applied without acceleration to achieve the necessary induced propeller velocities).

Comparison complexity exists due to the need to compare not only vehicle performance, but the entire system concept of operations and the resulting fleet utilization for the modular vehicle concept. Each of these advanced concepts is just a first step in investigating a completely new design space, enabled by technologies that are fundamentally changing the resulting capabilities. Many additional concepts were brainstormed as part of this study; however, insufficient time was available to perform the required analyses to establish them as credible concept alternatives. Enormous potential exists for the development of such advanced concepts, as the inherently short range and small passenger capacities of on-demand aviation mission is combined with disruptive electric propulsion and autonomy technologies capabilities.

X. Community Noise and Emissions Life Cycle Analysis

Noise and emissions need to be aggressively targeted for improvement if communities are to embrace the large number of predicted Zip operations at costs of less than $1 per seat mile. Currently, the SR-22 noise measurements indicate nearly 85 dBA at the FAA certification conditions, which is the maximum noise permitted for propeller aircraft in that weight class. Embracing the goal of no noise outside of the airport boundaries suggests a ~30 dB reduction is required, which calls for designing the aircraft with a strong bias towards the acoustic signature. Applying low tip speed propellers in combination with electric motors is a powerful combination that is likely to achieve this goal, with a combination of variable pitch and variable speed motor operation (which electric motors can achieve without a gearbox). Electric motors offer the possibility of operating at nearly ideal advance ratios across the entire mission. Existing piston engines can't apply low tip speed propellers in the same way, without incurring performance losses and integration penalties. Likewise, small

aircraft currently have no incentive to achieve lower noise due to the established propeller noise certification levels that haven't been challenged by advanced technology demonstrators to indicate what is achievable, and thereby lead to new phased standards similar to what commercial aircraft have experienced through staged implementation.

Emissions likewise can be drastically reduced, or even totally eliminated, depending on whether just the vehicle emissions, or total energy lifecycle emissions, are taken into account. If only the vehicle emissions were considered, then electric Zip aircraft would be considered to produce zero Green House Gas (GHG) emissions. However, until electricity is produced from renewable sources, such a limited view doesn't provide an accurate assessment of the true environmental impact. Hence, a detailed life cycle emissions analysis was performed that analyzed both the vehicle cycle (the emissions related to the vehicle and battery production) and the fuel cycle (the emissions related to the energy/electricity production) to provide a complete view of the true emissions. This emission comparison included the baseline SR-22 vehicle to show the difference between the hydrocarbon based small aircraft emissions to that of the electric. For comparing these two different energy sources, 100LL aviation fuel is taken to produce 18.4 lbs of CO_2 per gallon consumed (slightly different from that of automobile gas at 19.1). The amount of energy equating to each gallon of 100LL fuel is 35.2 kWhr, resulting in 240 grams of CO_2 per kWhr (of the total energy contained within the 100LL fuel). The CO_2 from electricity generation is highly variable depending on the region of the U.S. considered; California electricity is the cleanest at 329 grams of CO_2 production per kWhr. The U.S. average is 689 grams per kWhr, with the emissions from solar PhotoVoltaic (PV) farms producing 10.7 grams per kWhr (due to the emissions related to the production of the PV amortized over the expected life span). If reciprocating engines were efficient in converting the hydrocarbon fuel into power, then the existing reciprocating engines would compare very well to even the cleanest of U.S. electricity. However, the SR-22 engine is only 28% efficient at the ideal cruise condition; and this is one of the more efficient aviation engines available today. In comparison, electric motors analyzed in the Zip study are already capable of achieving a motor efficiency of 97%, controller efficiency of 99%, and battery/conditioning efficiency of 98% at the cruise condition to achieve a combined system efficiency of 94%. It is this 3.4x difference in power generation efficiency that results in hydrocarbon solutions yielding such high emissions. It is also far less penalty to apply emission reduction solutions to centralized electricity production generation equipment, than to attempt to apply Emission Control Systems (ECS) on the vehicle (such as currently in automobiles, while no small aircraft utilize any type of ECS). From an initial emissions comparison of a the SR-22 reciprocating engine to a Zip electric motor system, it is calculated that the SR-22 produces 857 grams of CO_2 per kW of shaft power, while the Zip electric motor system produces 350 (for CA power) and 733 (U.S. average) grams per kW of shaft power. When the added vehicle efficiency improvements are also considered, this 3.4x difference in engine efficiency becomes a 5.9x difference in the total vehicle system efficiency (as detailed in the Advanced Concept section). This causes the emissions differential to further expand from being 2.5x higher than CA and 1.2x higher than the U.S. average, to 4.3x and 2.0x higher respectively. Even without renewable based electricity production, substantial GHG emission reductions can be achieved through implementation of electric technologies, and therefore, Zip aviation has the potential to achieve substantially lower emissions levels. If renewable based electricity is utilized, the emissions for this new transportation choice effectively go to zero.

Current concept investigations include looking broadly at the capabilities that electric propulsion and automation can bring about, which are fundamentally different than that possible with prior propulsion and control solutions. The ability to achieve autonomous redeployment makes the feasibility of a single person vehicle that's optimized for the condition that represents the vast majority of trip demand (i.e. ~70% of auto trips having just a single person in the vehicle). The ability to achieve modular concepts that can take advantage of approaches that would permit the more expensive portion of the vehicle (the flight module) to be highly productive, while the less expensive portion of the vehicle (a ground module) is able to detach offers compelling economic benefits that also fit into this autonomous redeployment capability. A host of different ground modules could be used, from simple FedEx cargo pods, to passenger carrying pods, or even the development of pods that could permit roadable use to achieve a complete transportation capability. A modular concept would certainly be less aerodynamically efficient and involve extra weight penalties to achieve the modular capability, however, separation of vehicle function also provides significant benefits if the flight portion of the vehicle is able to maintain high utilization for ranges that are less than the typical ODM missions. If the flight portion of the vehicle were able to parasitically exchange energy with the ground modules, this could maximize the ability for the flight vehicle to remain in the air indefinitely to maximize the productivity. Electric propulsion is potentially a good fit with this sort of

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capability. The main point here is that there is a very fertile and open design space that hasn't been explored, which these new technology frontiers enable.

In order to have a more precise analysis of the emissions between the existing hydrocarbon and electric aircraft, the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, developed by Argonne National Laboratory, was used to perform emissions analysis in a direct comparison of the SR-22 aircraft to the Pipistrel G4 electric aircraft (which was the winning aircraft at the NASA Google GFC 2011" competition). The G4 was selected because highly accurate flight data and energy consumption results are available from the competition to ensure accurate comparisons, instead of merely comparing an advanced concept, which hasn't even been built. Both the SR-22 and G4 aircraft are sized for the same 4 passengers payload; however, the comparison is somewhat flawed as the G4 flew at an average speed of 108 mph, while the SR-22 was flown at a speed of 190 mph, and hence, the comparison should be considered optimistic (yet highly accurate) in terms of the emissions benefit. The GREET method permits the entire production and
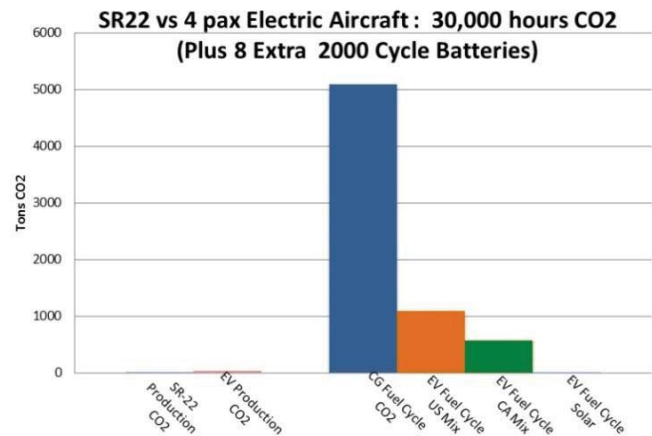

Figure 18: Vehicle Life Cycle and Fuel Life Cycle Emissions for a 30,000 hour Airframe Lifetime, Demonstrating a 10x Reduction in CO2 Life Cycle Emissions for Zip Electric Aircraft when Using a California Mix of Electricity Sources

energy life cycle to be considered, as there are many misconceptions about the emissions created during the production of lithium batteries (in addition to other misconceptions concerning lithium batteries such as the scarcity/cost of lithium, even when it currently accounts for only 3% of the battery production cost). **Figure 18** shows the GREET analysis results, with a further increase of the emissions benefit to 10x and 4.8x the U.S. average and CA electricity; or about a 2.5x further improvement than that indicated for the Zip aircraft flying at the same speed as the SR-22. These results are quite consistent, and lend credibility to prior Zip emission benefit calculations since the G4 achieved an L/D of ~33 (as a measure of aerodynamic efficiency), or about 1.7x that of the Zip concept. Achieving a higher L/D is substantially easier at lower flight speeds for aerodynamic, structural, and sizing reasons. **Figure 18** clearly shows that the emissions relating to vehicle and battery production cycle are relatively inconsequential compared to the energy cycle, over the 20 years life span of the vehicle. This analysis included accounting for replacement of the batteries in order to provide a total of 16,000 battery cycles over this lifetime.

XI. Economics

The total operating cost of Zip aircraft is the main market feasibility criteria. While safety, community noise, efficiency, emissions, and comfort are all additional necessary criteria that must be satisfied, the cost will essentially determine the extent to which the Zip market can effectively compete across alternative transportation solutions. In the near-term, the implementation of both autonomy and electric propulsion technologies will result in more expensive vehicle costs; however, these technologies offer compelling long-term potential for radical reduction in operating costs. Relating to autonomy, the vehicle will be burdened with more sophisticated electronics, sensors and avionics to achieve the desired state of a user not requiring extensive piloting training, but being able to interact with the vehicle to achieve an even higher level of safety than the current GA aircraft. Development costs for the required certified software will also be incredibly high, with the UAS development programs providing indicators of the scale of that cost. For electric propulsion, large battery packs with the latest specific energy advances will be expensive, even in comparison to the high cost of aviation reciprocating engines. While a large market that supports high production volume will provide economies of scale in comparison to the extremely low production rates of the current GA aircraft (i.e. ~500 units per year), that strategy alone will not enable reasonable cost levels in comparison to the previous Air-taxi costs. These technology development costs were not evaluated as part of the Zip economic analysis, as they involve high uncertainty that is directly linked to the level of Federal investment supports in these emerging technology areas, and also in developing their certification pathways.

Instead, economic sensitivity analyses were performed based on the well understood fleet operation cost of the SR-22, to capture a first order total operating cost differences from implementing electric and autonomy technologies.

Change in cost from charter SR-22 (piloted)
- Baseline = $440/hr
- 12x lower energy cost = $259/hr
- Increase utilization to 1500 hrs/year = $235/hr
- Increase utilization to 3000 hrs/year = $222/hr
- Off peak battery recharge = $215/hr
- Elimination of pilot costs = $162/hr
- Engine maintenance reduction of 50% = $148/hr

Result is a reduction in operating costs of 66%

If, instead of a 50% load factor, and the pilot is eliminated, and the vehicle is sized for a 2 pax, this suggests that **<$.50 per pax mile is possible.**
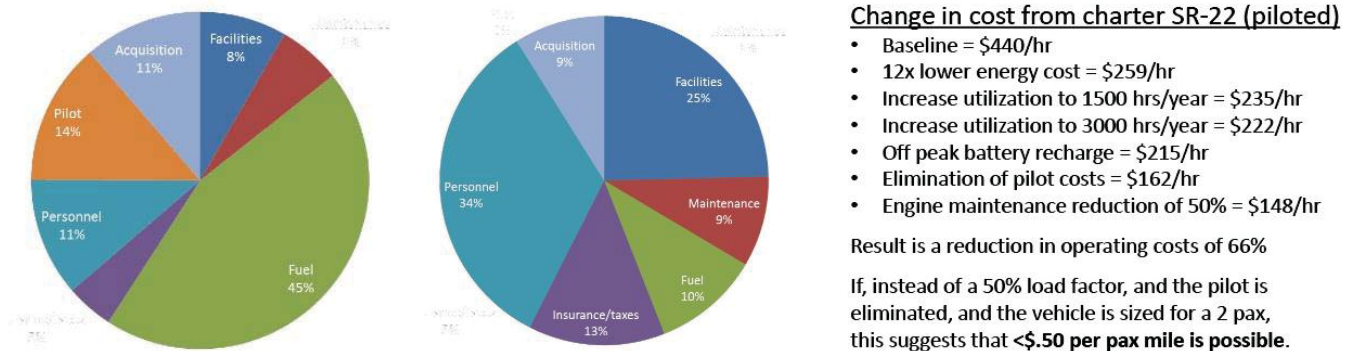
Figure 19: Baseline SR-22 Charter Costs (left), with Zip Technology Impact Assumptions (right) Applied as Sensitivities to Achieve the Resulting Total Operating Cost Distribution (center)

The most significant economic benefit of electric propulsion relates to the fuel/energy costs. **Figure 19** shows the component breakdown of the total operating costs for a SR-22 charter operation (where the pilot costs are included with all other amortized costs). The fuel cost accounts for 45%, and by far is the largest single cost. This problem relates to a combination of high relative cost of aviation fuel (currently $6.25 per gallon, the U.S. average, or $.18 per kWhr), as well as poor aerodynamic and propulsive efficiency of the existing small aircraft solutions that result in high fuel burn. Average U.S. electricity rates are $.115 per kWhr, but average commercial rates are even lower at $.087, thereby providing a 2x multiplier just due to the change in energy source. Combining this advantage with the 5.9x difference in the energy used between the SR-22 and the Zip e-ATLIT advanced concept, the total difference in energy cost rises to a 12x. A case could be made that even lower electricity costs should be used for economic modeling, as many utility companies offer off-peak rates and electric vehicle subsidies. The use of off-peak rates alone drops the electricity rates further to $.06 per kWhr, while the electric vehicle off-peak rates are as low as $.045 per kWhr (however, since such rates are temporary, they were not used as part of the cost sensitivity analysis). So, assuming off peak charging can be accommodated by having removable battery packs (four packs per vehicle to achieve the desired utilization), then the fuel/energy costs are reduced by a factor of 17.3x. Such a reduction in cost provides a compelling potential benefit, and even with the high cost of batteries amortized over their cycle life, an order of magnitude reduction in energy cost can reasonably be expected to be achieved. Considering that 47% of the SR-22 charter costs are for fuel, such a reduction in fuel cost is highly desirable. Another key issue relating to the economic feasibility of electric vehicles is the need for them to achieve high utilization rates to amortize the high acquisition cost of batteries. The new Tesla Model S has the largest auto battery pack sized at 60 or 85 kWhr, with those batteries likely to cost around $400 per kWhr to yield a $24,000 to $34,000 cost. This size equates very closely to 66 kWhr battery size required for the Zip e-ATLIT concept. However, the value proposition offered currently for electric automobiles is quite poor, specifically because the utilization of those automobiles is quite low at ~350 hours per year. Quite simply, it doesn't make sense to make significant investments in a fixed cost asset and let it sit idle. Any electric vehicles, due to their high initial cost, need to be utilized at a high rate for their economics to make sense.

A strategy for achieving high yearly utilization rate to amortize the vehicle cost is required, not only to amortize expensive batteries, but also because, one of the next highest contributions to the total cost is the acquisition cost. A factor of 3 to 6x greater utilization than prior Air-taxi operations (500 hours per year), and a factor of 10x greater than typical GA use (150 hours per year) are assumed in this study. Therefore, achieving high vehicle reliability is a critical goal for effectively amortizing the vehicle cost, so that assumptions of 1500 hours per year are reasonable. Such utilization goal only requires 4 hours per day of operation, and commercial transports achieve substantially higher rates of about 8 hours/day. This utilization strategy is highly synergistic to pilotless operations and electric propulsion, as a more "solid state" Zip aircraft is envisioned. The reliability of electric motors, batteries and controllers are well proven and dramatically higher than any mechanical reciprocating

engine. While no specific comparative maintenance hours required per hour of flight were established for electric propulsion, a reasonable first approximation would be that the engine maintenance is reduced by 50%. Substantially higher reductions are likely based upon moving part count, engine/motor complexity comparisons, and component wear. Elimination of flight personnel and training cost accounts would result in a16.2% reduction from the baseline SR-22 charter recurring total operating costs per hour, if autonomy technologies can provide safe user operation. Another significant factor impacting the piloting cost is the number of vehicles that are required to provide a specified availability across a region. In order to minimize the number of fleet aircraft while achieving the highest availability, automatic redeployment of the vehicle is proposed as a Zip operational requirement. This autonomous redeployment of the vehicle would decrease the burden of non-revenue flights, and permit rapid responses without the concern of pilot availability or FAA pilot daily hour limitations. The aircraft fleet availability will need to be determined through a fleet model for a specific regional area based on the determined vehicle cost and related trip demand. Such a study was not performed as part of the Zip system study, but would be an iterative subsequent study to be performed across the demand, aircraft, and fleet sizing.

Application of each of these technology assumptions results in the economic results shown in **Figure 19**, where each of these potential benefits of electric propulsion and autonomy are incrementally applied to show their impact, starting from the highly accurately known costs of the SR-22. This sensitivity analysis indicates that a 66% reduction in total operating cost is possible, from $440 per hour of operation to $148 per hour. In addition, there is a potential for even greater cost reduction as the realization is made that the SR-22 (and future Zip aircraft) are operating with an average of only 1.7 passengers being carried in an aircraft that is capable of carrying 4 passengers. The cost per passenger seat mile of the baseline charter (at the maximum cruise speed of 200 mph) is $1.30 (while operation at the economy cruise speed of 180 mph would yield $1.44). With the Zip assumptions applied, the cost per passenger seat mile drops to $.44. However, this is optimistic because, the offsetting of increased acquisition costs of electric propulsion and autonomy haven't been applied.

While acquisition costs were not estimated, the key differentials resulting from the electric propulsion and autonomy were compared at a first principles level. Electric aircraft are not likely to experience nearly as much of a percentage cost increase as electric automobiles (compared to automobiles with reciprocating engines), specifically because of the incredibly low cost of high production reciprocating engines. While a crate complete 430 hp Corvette LS-3 engine can be purchased at a retail cost of $8300, the 310 hp Teledyne Continental IO-550-N engine's retail cost is $60,000. Some of this cost differential can be attributed to the engine being made for aviation, experiencing greater parts tracking, certification, and liability costs. However, the more accurate reason is these aircraft engines are made at very low production volumes (one hundredth of the auto engine rates). The actual technology level, quality, precision and reliability of automobiles engines is higher; due to production tooling and the elimination of touch labor that is used in lower production volume practices. It is likely that with production volumes of at least 2000 units per year, a Zip electric propulsion system could be produced at the same cost as the SR-22 engine, with approximately $25,000 relating to the battery, and $35,000 relating to the motors and controllers. The motor and controller costs will achieve higher economies of scale, since they are manufactured at a production volume that is an order of magnitude greater, as a distributed electric aircraft uses 12 motors per vehicle. The total engine size is also smaller due to the previously described sizing benefits, with the Zip E-ATLIT concept only requiring 240 hp. For this example, each 20 hp motor/controller would need to cost ~$3000. Joby Motors is currently selling electric motors for the Ultra-light aircraft market, with their JM-2 20 hp motor (28 hp peak) available at a retail cost of $3200, and the controller costing another $600. This motor is currently manufactured at very low production rates, and therefore, if reasonable production volumes are reached, a $3000 cost is likely to be achieved.

Automation costs are dominated by the required development and across the three levels of automation, they are estimated at $10, $240, and $1,110 million for Zip aviation (for conventional piloted system, semi-autonomous, or fully autonomous systems respectively). Clearly to achieve reasonable unit costs, these development costs need to be amortized over a substantial production volume. In addition, the aircraft avionics costs are estimated at $19,075 for a piloted aircraft, $42,775 for a semi-autonomous system, and $45,250 for a fully autonomous system. These vehicle costs include the costs of the flight controls/autopilot, operator interface, supporting avionics, and outer loop automation. While the cost of aircraft avionics and sensors are not substantially higher to achieve a fully autonomous aircraft, the development costs amortized over 20,000 aircraft (2000 units per year for

10 years) is $55,500, while a semi-autonomous system costs only $12,000. To achieve a reasonable total control system cost, semi-autonomous systems are of great interest for application to the Zip aviation mission.

If a mixed fleet of 2 and 4 passenger vehicles is utilized, a better degree of 'right sizing' of the aircraft to the passenger load can be achieved (with elimination of the pilot who requires one of the four seats and 200 lbs of the payload). This would enable much higher load factors with improved economics. The load factors are a significant issue relating to the economic feasibility, as commercial airliners live or die based on achieving a 90% load factor, and could never achieve profitability, if they operated at the 43% average value of prior Air-taxi operations. The right sizing of the aircraft has the potential to offset the increased acquisition costs of electric propulsion and autonomy, as the aircraft is reduced from a 4 passengers to 2 passengers vehicle to achieve significant acquisition cost savings. Looking at the distribution of Zip aircraft system's total operating costs after the application of vehicle technologies, over 50% relate to the ground infrastructure and personnel cost. These costs are outside of the scope of this study; however, there are possibilities that ground automation can also reduce these costs. Therefore, there are design and fleet strategies that can be pursued, where there is a reasonable expectation that $.50 per passenger seat mile can be achieved, and that of a $1.00 rate is a relatively easy goal.

XII. Conclusions

Many technical and regulatory gaps exist for establishing on-demand aviation that can achieve a large market share. However, small airport infrastructure already exists that can be leveraged to achieve a near-term capability. The goal of a Zip Aviation system is to achieve an order of magnitude improvement in mobility reach, thereby providing increased regional productivity and an alleviation of resource scarcity in established urban communities. **Figure 20** indicates a timeline for electric aircraft range and speed capabilities that was proposed at the beginning of this study, derived from extrapolations from the Technology Readiness Levels (TRLs) seen at the 2011 NASA GFC. However, this study indicates that such estimates are highly conservative, and that there is the potential, as aircraft are fundamentally redesigned to take advantage of unique electric propulsion characteristics, to jump to performance levels that were suspected not achievable until 2040 within the next 10 years. This is a unique NASA role to help advance the aircraft multi-disciplinary design; showcasing the incredible degrees of coupling that electric propulsion offers, and combining this with the incredible levels of investment the battery industry is experiencing. Just in the period it took to perform this study, the energy density of lithium batteries have gone from an accepted industry level of 200 Whr/kg to 240 Whr/kg with the introduction of the latest Panasonic 18650 cell. Not only is the energy density increased by 20%, but the chemistry is more robust to achieve a safer battery pack that can tolerate less battery management system oversight.

The advanced technologies from autonomy and electric propulsion are critical technology enablers for overcoming the many challenges experienced by the early adopter Air-taxi market over the past decade. Specifically, total operating costs can be decreased by two thirds, increased utilization through greatly improved reliability, improved user accessibility through self-piloting, while providing a sustainable energy solution that focuses on efficient and environmentally/community friendly solutions. At the same time these Zip aircraft will offer high speed mobility for people and goods at improved speed and comfort. Many additional and more detailed analyses are required to establish the feasibility of such a system. The current system study has looked at market demand, airspace impact, aircraft performance, advanced concepts, life cycle emissions, and economics, and laid a foundation from which future studies can add additional layers of detail.
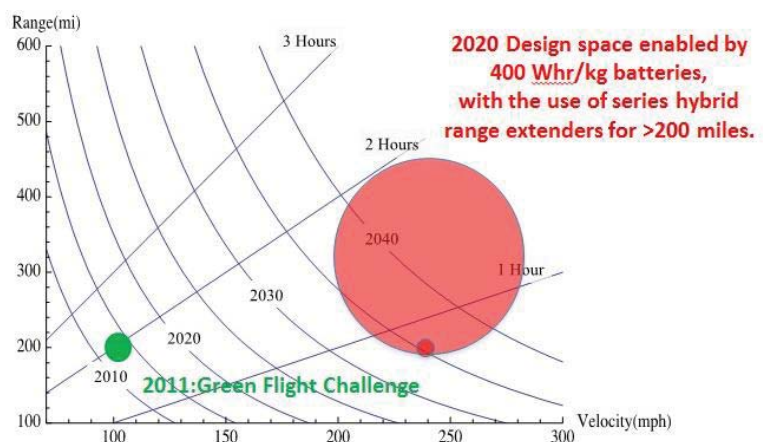

Figure 20: Electric Aircraft Performance Envelope, with 400 Whr/kg Battery and Range Extender Technologies Merging with Novel Electric Propulsion Integration for a Radical Acceleration of Electric Aircraft Feasibility

Next steps have been identified to work on advanced concepts in collaboration with established industry partners across the GA and automotive industries, as well as small and large aerospace companies. Additional modeling efforts are desired in looking at optimum climb/cruise/descent trajectories, along with detailed cost analyses for both acquisition and operating costs. Detailed aero-propulsive Computational Fluid Dynamics (CFD) needs to be performed of distributed electric propulsion systems, along with aero-elastic analyses that can verify the feasibility of higher aspect ratio wings with distributed masses. Further use of the new TSAM commuting model is required to better understand the shorter range potential of on-demand aviation, while comparing these results to Agent Based Modeling that can characterize and help to understand the emergent behaviors as new transportation systems compete with those that are well established. Future studies would ideally look at the markets from a regional basis to yield specific insights into regional transportation needs that can more precisely demonstrate the market impact (instead of averaging across dramatically different regional markets). Ideal regions for early adoption include areas with good weather, high property values, and geographical restrictions that limit ground transportation options. Specific technology investigations include simplified pressurization systems, range extender series hybrid turbine-alternators, anti-icing molecular nano coatings, advanced electric motors, hybrid battery packs that can achieve both high specific power and density, and expanding the understanding of human factors in applying autonomy to reduce human error. There are also highly valuable hardware experiments that can be conducted to quickly understand the unique characteristics of these new technology frontiers; both in autonomy and electric propulsion. Such experiments could be conducted at a small fraction of the cost of large aircraft experiments, with breakthrough capabilities demonstrated.

Two key questions to consider after reviewing these study results are whether an On-Demand Mobility aviation capability would provide value to the U.S., and whether it is reasonable to expect private industry to take on the high risks associated with developing such advanced technologies. Accomplishing trusted automation that can be certified is one of the great aeronautic challenges over the next 30 years; as this technology opens the door to millions of UAS and ODM aircraft operating safely. Accomplishing self-separating, distributed aviation operations that can be independent of the existing human controllers is the direct complementary need to autonomy. But these capabilities also require aircraft that are fundamentally different than small aircraft today; and electric propulsion has the capacity to interact with all other disciplines in positive synergistic ways to overcome the current deficits and create remarkable new flying machines.

Acknowledgements

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