Concept of Operations for Highly Autonomous Electric Zip Aviation

Mark D. Moore[1]
NASA Langley Research Center, Hampton, VA 23681

A new class of on-demand aircraft is envisioned, with emergent capabilities that are well beyond the existing fleet of aircraft. These aircraft are labeled as Zip aircraft, similar in nature to Zip rental cars that permit a new transportation choice that can achieve increased operational flexibility, high utilization, low environmental impact, an easy user experience, and all at low amortized cost at equivalent safety to auto and airline. Such aviation services could dramatically improve regional transportation accessibility, by providing fast distributed transportation between rural and urban areas of the expansive U.S. to dramatically improve productivity. Electric propulsion and autonomy are technology frontiers that offer tremendous potential to achieve these characteristics, with fundamentally lower operating costs. Operating costs could be achieved through extremely low fuel/energy, maintenance, and piloting costs, accompanied by very high utilization, reliability and load factors. These two technology disciplines are at an inflection point in terms of being able to meet vehicle performance for short range missions, while providing additional characteristics such as ultra-low emissions, community noise and greater safety. Over the past decade, many on-demand operators have attempted to establish an early adopter market, but have experienced limited success due to current vehicle and airspace technology limitations and a lack of governmental support for this emergent capability. The current state of the art characteristics are compared across travel modes, with a description of the proposed changes, and then an evolutionary proposed solution from early adopter to high volume production market with the resulting impacts. The potential for a vibrant future in on-demand aviation markets is examined to dramatically improve regional productivity. However, there are many complex gaps that currently exist across vehicle technologies, autonomous systems, airspace control, system-of-system network solutions, and advanced regulations which must be filled through collaboration across public and private partnerships.

Nomenclature

DoD	=	Department of Defense
FAR	=	Federal Aviation Regulation
GA	=	General Aviation
GDP	=	Gross Domestic Product
NASA	=	National Aeronautics and Space Administration
ODM	=	On-Demand Mobility
TRL	=	Technology Readiness Level
UAS	=	Unmanned Aerial System
VLJ	=	Very Light Jet

[1] Aerospace Engineer, Aeronautics Systems Analysis Branch, MS 442 1 North Dryden St, AIAA Member.

I. Introduction

WHAT if the U.S. could experience an improvement in mobility of the same magnitude as the horse and buggy era to the automobile? If this can be accomplished, it has the potential to provide similar productivity increases that were the foundation of the expansive growth the U.S. experienced in the twentieth century. In an era where current transportation solutions are facing capacity limits, and non-linear growth of congestion delays, how can this possible? This paper discusses the potential for new technology frontiers to enable a new transportation solution, and lays out the basis of how this may evolve from the current solutions, to an incredible new societal capability for the 21st century. A concept of operations is developed, based upon a comparison of the characteristics that exist between transportation modes. The intent is not to propose a specific vehicle or concept, but a system comprised by of a set of characteristics that would establish a feasible approach to achieve the desired goal. Additional papers by the author discuss specific vehicles that could populate this transportation system. Because the automobile has been so successful as an on-demand transportation solution for multiple generations, it is easy to consider our current mobility to be an end-state. This is almost certainly not the case, with the predominant societal opinion at the turn of the last century that the horse and buggy would be the transportation solution for the foreseeable future. Figure 1 shows a plaque on display in front of one of the early automobiles at the Smithsonian American History Museum that discusses the challenges this new transportation solution faced as 'automobility' and 'devil wagons' were first introduced. Completely new infrastructure, government regulations, vehicle technologies, and societal perceptions were established over a 30 year period to go from a few early adopters to over 23 million vehicles. These vehicles improved the average travel speed from 8 mph to our average today of 33 mph, a 4 times improvement. What would another 4 times improvement yield, and how can this possibly be achieved to provide the mobility reach from our urban areas to throughout our rural regions?

Fundamentally a transportation solution providing a similar level of expansive mobility reach would require on-demand and distributed attributes. While scheduled and centralized transportation is highly effective in densely populated urban areas, they don't provide the flexibility or accessibility that is the basis of the success the automobile has enjoyed. The key

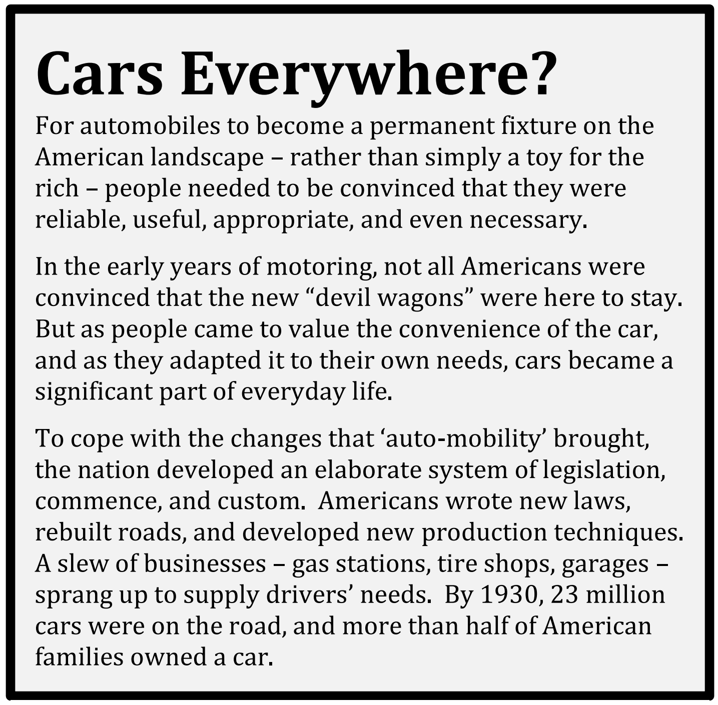

Figure 1. Smithsonian American History Museum Plaque on display in front of one of the early American automobiles.

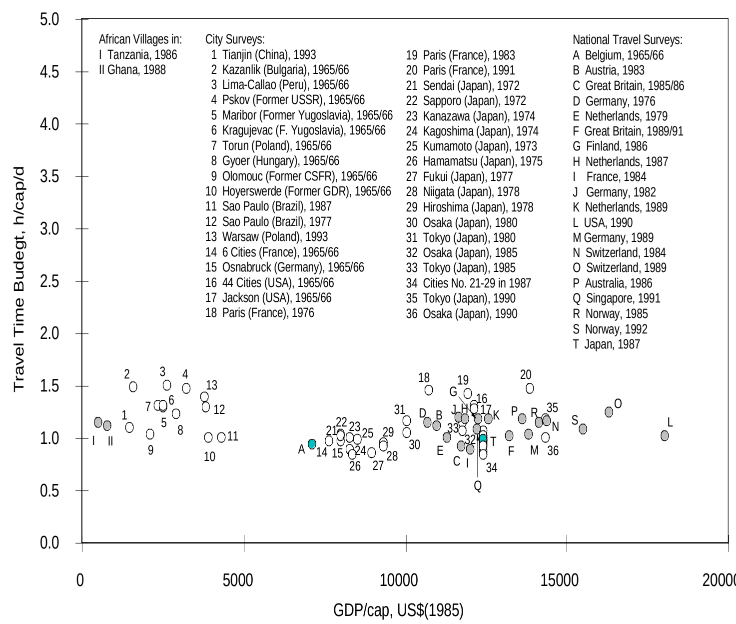

Figure 2. Travel Time per Day (hours) Compared to Country GDP (1985 $)

metric for evaluating the effectiveness of a transportation device is the 'Mobility Reach' that it enables. This parameter is defined as the area of land that is accessible with a daily travel allowance. Figure 2 shows an analysis by Schaefer that compares the average daily travel time across countries, as a function of their Gross Domestic Product (GDP). The startling result of this analysis is that people across highly different infrastructures, income, or even transportation technology level tend to have a similar allowance for how much time they are willing or able to travel each day. This average travel allowance equates to approximately 1.25 hours per day. Figure 3 depicts the

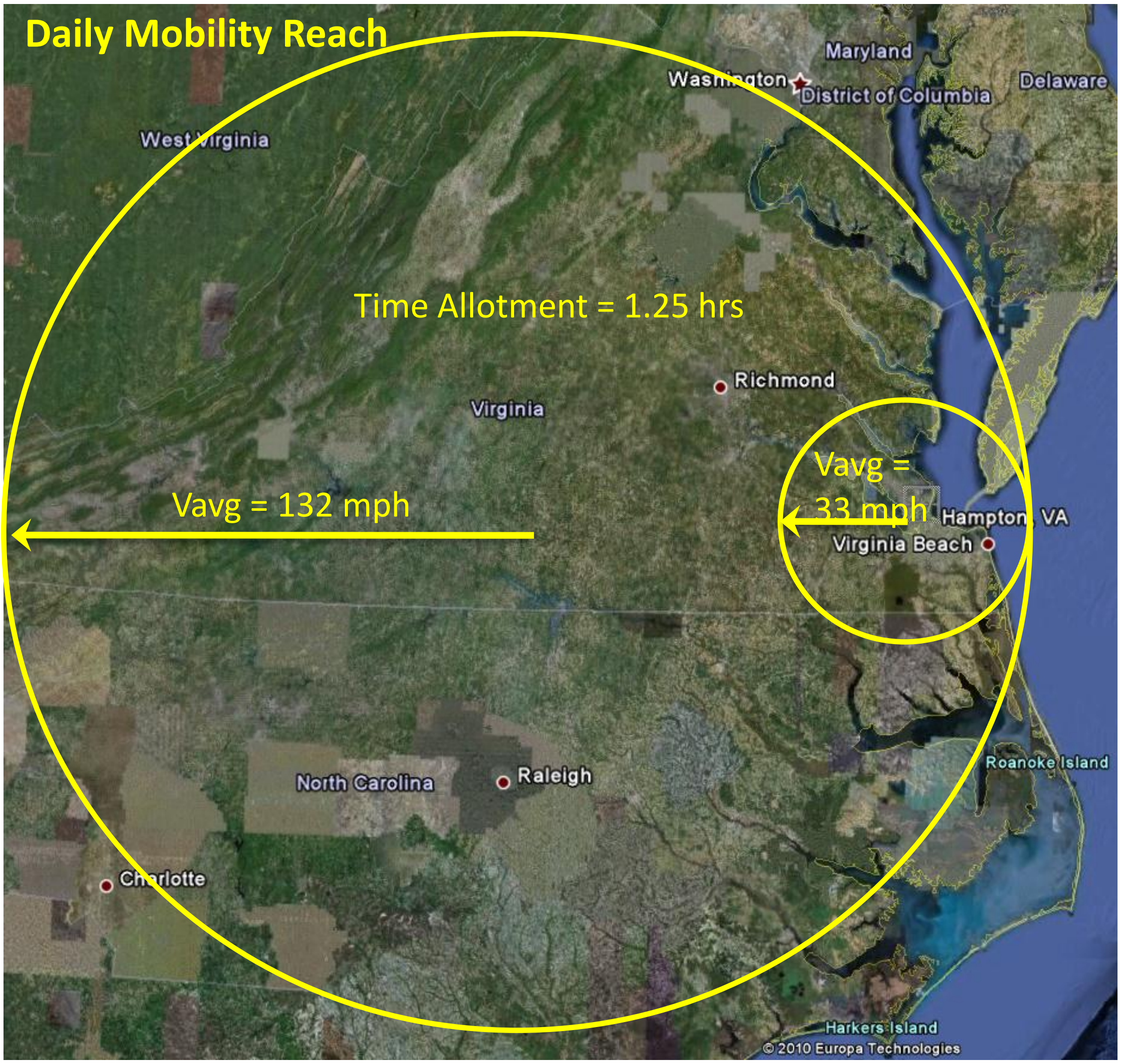

Figure 3. Daily Mobility Reach in the Hampton Roads area of Virginia based upon a daily travel time allotment and the average velocity available for current and potential future on-demand mobility.

Mobility Reach in the Hampton Roads area around NASA Langley Research Center, Virginia region for this average daily time allotment, using the average Department of Transportation auto speed, along with the resulting Mobility Reach if another 4x improvement can be achieved. The resulting impact on the metric is a squared function of this average speed, so that the daily resource area that is reachable is increased by a factor of 16. While infrastructure advances may be pursued to improve the automobile Mobility Reach, there is no question that an order of magnitude improvement is outside of the grasp of this existing transportation solution; and that if such game changing improvements are to be achieved then new technology solutions need to be investigated. If such a capability could be developed, the result is stunning, with a daily Mobility Reach extending from merely the Hampton Roads area, to almost the entire state of Virginia and much of North Carolina; enabling a daily reach from Charlotte to Washington D.C. and all the rural areas in between which are now considered inaccessibility with our current transportation technologies. The key point of the Figure 3 map is that high speed mobility will permit the center of each user to change, instead of being confined to live where they work. How can such high speed mobility be achieved without incredible infrastructure investment to build the equivalent of autobahns going to every small town in America?

II. Proposed Solution

The system operational concept is called 'Zip Aviation', and is derived from a current trend towards achieving lower cost of ownership for automobiles through car-sharing. Several additional AIAA papers address other aspects of this transportation, including a demand and airspace impact study, a comparative assessment of automation benefits and penalties, along with papers describing aircraft performance modeling with lower risk as well as more aggressive advanced concepts that take advantage of the unique characteristics of electric propulsion. A comparative discussion of the currently available mobility choices are presented to better understand the proposed solution,. In particular, the prior attempts at achieving 'Air-Taxi' operations are presented, and the feasibility gaps that existed to diminish their practicality towards widespread adoption.

The objective of this paper is to establish a basis for understanding a high speed, on-demand mobility transportation system that can provide a valuable *addition*, not a replacement, to existing transportation solutions. Automobiles are great short distance vehicle solutions, commercial airlines are great long distance vehicle solutions, and trains are valuable for high density population corridors. But there is currently no good travel solution for mid-range regional travel, especially when geographic obstacles such as mountains and water ways fundamentally restrict ground travel access into choke points that force congestion. Limited transportation mobility reach, or accessibility, results is resource scarcity within user daily travel areas, resulting in higher land and housing cost than in the outlying areas. Depending on the level of resource scarcity that results, i.e. Washington D.C. versus the Hampton Roads, the increase in land/housing cost can reach a factor of 2 to 10 times higher costs. The two largest fractions of U.S. household income go towards housing (~34%) and transportation (~17%), with each household utilizing their own value functions to determine the value of proximity distance and the ratio of these expenses. Therefore the possibility is raised that even if a new transportation system were more expensive to an individual, if it provided increased Mobility Reach, the result could be a savings in total household expenditures, while providing additional degrees of freedom for households to evaluate their value functions across work, leisure, schools, family, etc. as resource constraints are aggressively pushed back. This trade-off between housing and transportation costs in particular offers the opportunity for early adopter of a new transportation system within the top 5 and 20% of U.S. income distribution, which have experienced significant increases over the past 30 years. The number of trips that

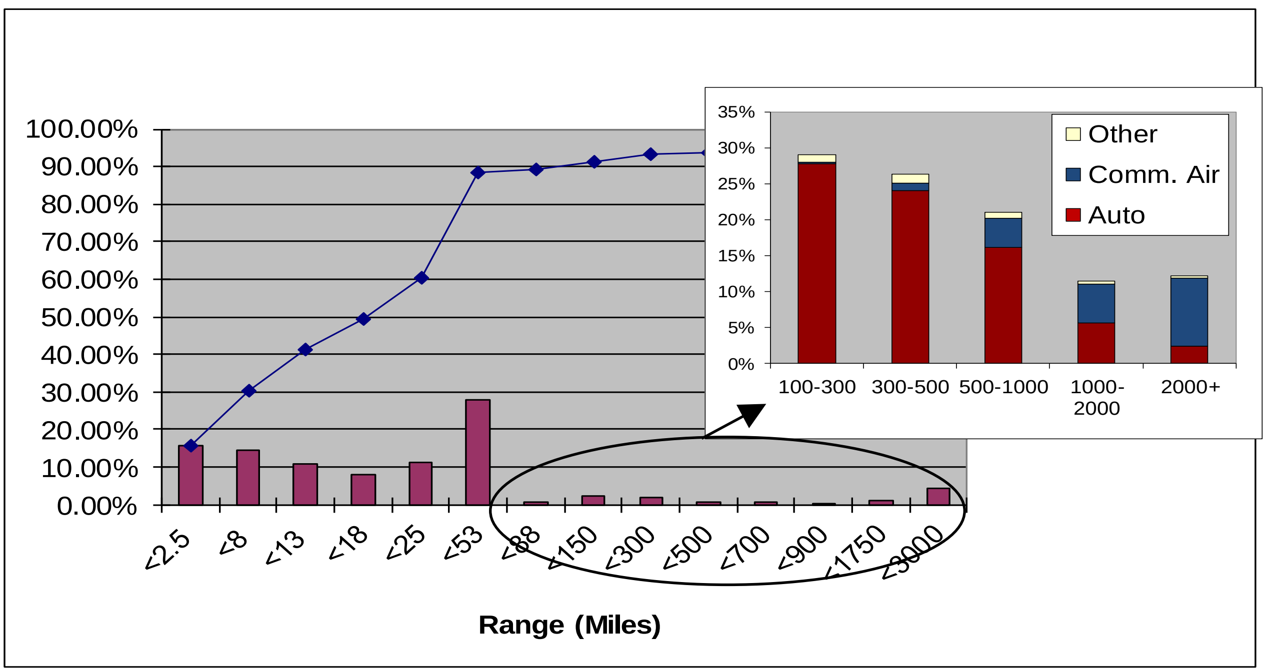

Figure 4. Distribution of trips based upon travel distance cumulative miles, for all auto trips taken (left) and comparatively between autos and commercial airlines with trip distances greater than 100 miles (right).

are taken at the mid-range distances are significant, and shown in Figure 4, both for distances less than and greater than 100 miles. Autos account for 76% of all trip miles, with airlines accounting for only 19%; autos even account for the majority of trips at trip distance out to 1000 miles indicating a preference for some characteristic of autos preferable to airlines. The key point of this figure is that there is a substantial trip demand that exists for regional travel between 50 and 300 miles that are almost entirely captured by automobiles, even though they achieve relatively low average speeds, with indirect routes due to ground constraints and limited roadway choices. The fact that there are no current expedient methods to perform these regional trips suggests that if a faster transportation solution existed, that an even larger latent trip demand would exist, if the transportation solution achieved competitive characteristics such as cost, ease of use, reliability, convenience, comfort, accessibility, and availability. Obviously achieving such characteristics is a tremendous challenge that a vehicle by itself can't achieve, but requires a complex new transportation system to be developed, just as the automobile system was developed 100 years ago.

The goal of the proposed On-Demand Mobility (ODM) system is to achieve higher door-to-door trip average trip speeds. But the research of Schaefer suggests that such a system would not yield a reduction in the daily travel time of users, but instead expand the number of miles users would travel in a single day. Such a suggestion means that with many more miles traveled, such a system would need to be far more efficient than current vehicles to achieve a sustainable, environmentally acceptable, transportation solution. Another requirement is that the vehicles must be capable of achieving high utilization rates to amortize the vehicle cost over a large number of yearly operation hours. Therefore achieving high reliability, at a reasonable cost of operation is essential to support the assumption of high utilization. While turbine engines achieve such reliability, piston engines have substantially lower reliability. Since the stage lengths required for regional travel are expected to be relatively short range, electric propulsion offers a new potential method of achieving remarkable reductions in emissions and energy costs, as well as reliability. Since these operations would be taking place at highly distributed small airports with a significant number of operations to achieve capacity with smaller vehicle passenger sizes, achieving low community noise is also a requirement. Electric propulsion also offers significant noise advantages, both through low motor noise and improved propeller noise characteristics due to variable rpm capability. A method of achieving a large user base and economies of scale cost improvements, without requiring pilots to be restricted by Federal Aviation Regulations (FAR) Part 135 to 8 hours per day, is to implement high degrees of vehicle automation to achieve an ease of use with minimal training requirements that enables user operators. Maximizing the availability of the vehicles, at a load factor that is similar in size to the trip party size, with the smallest possible fleet will be a major factor in the feasibility of such an operational concept. With automation replacing the pilot, the payload available for a vehicle is increased with the potential to achieve higher load factors. Availability is also increased by not having to schedule pilots along with vehicles. A unique characteristic of such a system utilizing high degrees of automation, is the potential to perform automatic redeployment as a Unmanned Aerial System (UAS) to the next trip request, and thus decrease the cost and burden of the 'dead head' route. These vehicle characteristics are well beyond what any General Aviation aircraft currently possess, so that there is a strong dependence on autonomy and electric propulsion technologies to achieve a feasible system concept.

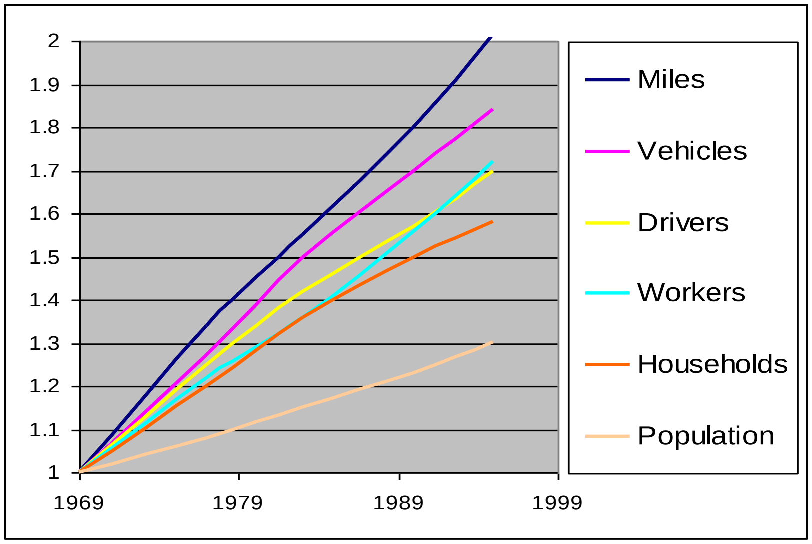

Figure 5. Number of miles traveled, autos, drivers, laborers, households, and population in the U.S., normalized to 1969.

III. Current Solution

Current transportation solutions are comprised of automobiles for short distance on-demand trips, metro and rail provide both short and mid-range for high density urban areas, and airlines for long distance trips. As shown in Figure 4, over 30% of all auto miles traveled, and almost 30% of all trips over 100 mile range pertains to trip distances of 25 to 300 miles. Intuitively the number of trips at very short ranges should be significantly more than at distances at 50 miles, and this is accurate. While there are far more trips at the shorter distances, the total number of miles traveled are not as high (i.e. one 50 mile trip equates to 50 one mile trips). Therefore, significant demand already exists for mid-range trips, even though there is not a vehicle well suited to achieve these trips with a high average door-to-door speed. On-demand vehicles maximize flexibility, while scheduled vehicles maximize the vehicle productivity and cruise speed, which does not equate to maximizing the user productivity or door-to-door speeds because of the significant overhead burdens that exist within a scheduled transportation system. Understanding the competitive capture of each transportation mode is the subject of another AIAA paper "Projected Demand and Potential Impacts to the National Airspace System of Autonomous, Electric, On-Demand Small Aircraft" by Jeremy Smith and Jeff Viken. This research shows significant cost sensitivity, with a large market capture from current auto and airline trips for cost per seat mile of less than $1.00 (2000 year dollars), even competing against auto costs of $.42/mile business travel and $.19/mile personal travel. The current distribution of 10,000 small airports provides sufficient distribution for an infrastructure that enables short enough ground travel times to still provide a trip time advantage, even for Zip aircraft with cruise speeds of only 150 mph. So the question exists, what vehicle characteristics must exist to support such a market, and why don't these characteristics exist in currently available vehicles?

Current General Aviation (GA) aircraft are essentially designed for two markets, the personal/recreational single engine piston and corporate/business jet markets. Neither of these markets achieves the high utilization of commercial airliners, and thus were not designed for the required high reliability. A number of new Very Light Jets (VLJs) have been developed over the past decade, with the intent of supporting the emerging Air-taxi market which has some similarity to the Zip aviation mission intent. The most successful of those designs have been the Eclipse 500 and Cessna Mustang. While initially priced at an unrealistically low price of $832,000 per unit, the resulting price of the Eclipse 500 once it reached production was $2.15 million. The Eclipse 500 is a four to five person, twin jet with relatively low bypass ratio P&W 610F engines designed for a cruise range of over 1000 nm at 380 mph at 41,000 feet. The Cessna Mustang is priced at $2.65 million, with highly similar specifications and a larger passenger cabin. An aircraft also adopted for the Air-taxi mission, but from the single engine piston side of the GA market, is the Cirrus SR-22. This aircraft holds four passengers but with half the performance, designed for a cruise speed of approximately 200 mph at an 8000 foot altitude, at one fourth the cost with a fully equipped model costing $619,000. These existing aircraft are likely the best candidates for Zip operation, and a comparison of these aircraft

Figure 6. Cirrus SR-22 (left) and Eclipse 500 (right)

along with several others was performed by Muharrem Mane and William Crossley in their paper "Preliminary Cost Feasibility Study of Air Taxi Operations". Their analysis concluded that the SR-22 provided the best value proposition even above a 400 mile range, and that the increased performance did not justify the increased cost for these short ranges; with relatively small total door-to-door time differences. This analysis is highly useful for understanding the tradeoff between the user value of time compared to the vehicle operating cost and performance, but doesn't answer many of the other questions concerning operations feasibility. Looking at several of the Air-taxi company experiences can help to provide insight into the most desirable characteristics.

Quite a few Air-taxi companies sprung up in the previous decade, although only few continue to operate today as Air-taxi services. While this market failure can be somewhat attributed to decline of economic conditions that started in 2008, there are also indications that the aircraft were not well optimized for the Air-taxi mission use, and that airspace restrictions resulted in additional inefficiencies. A few examples of these AiTaxi operators include DayJet (Florida), SATSair (Virginia), ImagineAir (Georgia), LinearAir (New York), SkyWay (Eastern U.S.), OpenTaxi Systems (nationwide) as well as related fractional ownership companies such as NetJets, Marquis Jet, OurPlane, FlexJet, Flight Options, AvantAir, PlaneSense, and Citation Shares. Many Charter air service providers continue to thrive, with only nuanced differences between Air-taxi and air charter. This may be an indication that more than anything else, the start-up Air-taxi operators were a victim of poor timing due to the complete collapse of venture capital availability after 2008. Fractional ownership are differentiated by the requirement to purchase at least a 1/16 share of an aircraft. The differentiator between Air-taxi and Charter would likely be the assumed fleet availability to provide true on-demand service. A collaborative association, Air Taxi/Air Charter Association (ATXA) was also formed to "bring on-demand air travel to mainstream travelers worldwide" and has attempting to establish standards such as Global Distribution Systems (GDS), which would permit on-demand carriers to have the same on-line fare visibility to potential passengers as airlines to potential customers. A consortium for Air-Taxi companies, Personal Air Transportation Alliance (PATA), was also established to help facilitate partnerships across aircraft companies, operators, related businesses, and regional airports. The operators perform their flights under FAR Part 135 Subpart K which was set up to accommodate flexible operations, or Part 135 which covers commercial aviation. For the most part, the Air-taxi operators have chosen either the Eclipse 500 or Cirrus SR-22 for their operations, with DayJet and SATSair providing valuable case studies for future attempts at ODM.

No published lessons learned documents exist from the Air-taxi operators, and information is extremely sparse on this topic. However, any future aviation ODM system needs to evolve from the basis formed by these pioneering companies. Since the data is proprietary, it is likely that this information will never be publically available. However, a best attempt was made by internal cost analysis and data mining to present a portion of the problems that these early on-demand aviation pioneers faced. This information should not be perceived as 100% accurate, but the best available to the author. If a detailed understanding of these operators is desired, readers will need to find and discuss these details with the experts who experienced the many nuances of establishing a new transportation system. Given these limitations on information, DayJet and SATSair are discussed as the on-demand aviation early adopters.

Both DayJet and SATSAir initialized service in a localized region, with DayJet focusing operations in Florida with Eclipse 500 aircraft. DayJet developed a sophisticated ticket pricing system based on user travel needs matching with prices ranging from $1 to $4 per seat mile. The load factors of these operators are unknown, but relatively low load factors of approximately 1.3 passengers per flight (a 26% load factor) are assumed. The average stage length flown was less than 200 miles, resulting in an aircraft that was operating well off its design mission that provided more than five times that capability. The high cruise design speed is less of an advantage at these distances, in terms of the total door-to-door travel time that includes ground travel, check-in, taxi, climb, descent, etc.; so it is questionable whether a 380 mph aircraft that incurs higher costs to achieve that speed is justified. The fuel burn associated with operating this higher performance aircraft is another non-optimality. Typical operating altitudes were more likely to be around 18,000 feet, resulting in relatively high fuel costs per mile traveled. When operating at altitudes less than 10,000 feet, which relates to a significant portion of a 200 mile range, the FAA requires speeds of less than 250 knots so that high speeds can't be utilized. On top of these penalties, DayJet operated all their flights with a 2 pilot crew. Only a single pilot is required under Part 135 regulations. The primary reasons for this may have been passenger acceptance to instill confidence in a higher safety rate, as well as potentially achieving a lower insurance cost. Since Air-taxi pilots tend to be paid at a far lower pay scale than commercial airlines (i.e. $30,000 per year), the direct cost is not a huge cost burden. However, indirect piloting costs increases the true pilot costs, specifically due to non-revenue flights (deadheads) and the loss of revenue potential for two of the five seats while carrying an extra 200 pound pilot. Operating slower aircraft such as the SR-22 with two pilots would result in an even greater burden due to the lower productivity of the slower vehicle. The projected total cost of operation for the Eclipse 500 aircraft is approximately $5.20 per mile at current aviation fuel prices with a 2 crew assumption. However, the number of trips that can be captured from auto or airline at a price of $4 per seat-mile rate is quite small (as indicated in the previously referenced demand study by Viken and Smith), resulting in a likely infeasible fleet solution due to the small number of aircraft required to meet that demand, which would in turn limit the availability of aircraft to meet on-demand service needs.

SATSair operated in the southeastern states of Virginia, North Carolina, Maryland, Delaware, and Georgia with Cirrus SR-22 aircraft. There rate structure was far more simplistic, with essentially rental of the vehicle with a single pilot at a price of $2.60 per mile (2009 dollars, not seat mile cost), which inflated to current year dollars and fuel prices equates to $3.09 per mile. The estimated cost of operation for the SR-22 with a pilot is $3.09 (2012 dollars) without fleet costs, and results in a breakeven yield. SATSair was likely being operated at or near breakeven to initiate their service; they also had special lease/purchase deal from Cirrus who was encouraging this new business model which would also be beneficial to their future sales if successful that would have decreased their vehicle amortization and financing costs. The SR-22 appeared to be fairly well matched to the mission, except that similarly it was designed for a 1000 nm range and therefore incurred more structural weight than optimal for a shorter range. From a speed to cost perspective, the Eclipse is a slightly better value than the SR-22

Both aircraft have a similar concern in that each was designed for annual utilizations of approximately 500 hours, and may have a difficult time achieving 1500 hours. The Eclipse 500 has the additional issue that it is designed with a 69 knot stall speed versus 60 knots for the SR-22, permitting the SR-22 to operate from shorter field lengths on the order of 2000 foot, while the Eclipse 500 would require 2500 to 3000 foot field lengths. The higher stall speed is a result of the higher wing loading of the Eclipse, resulting in improved ride quality for the passengers. Passenger acceptance is also increased for the Eclipse due to improved cabin noise characteristics, through the avoidance of tractor propeller configuration that results in vortices slapping the front windshield. Passenger acceptance for propeller aircraft may be lower based on the perceived and real safety that a dual turbine engine configuration provides. In terms of community noise, both aircraft meet FAA standards; however, there are different standards for propeller and turbofan propulsion. Frequent operations of either of these aircraft would likely impose a community noise issue. From an emissions perspective the Eclipse utilizes JP fuel, and the Cirrus uses 100 Low Lead fuel, both having no emissions control so that if significant numbers were flown in fleets there would be a community emissions burden. Just as with any aircraft currently, operation of these aircraft requires highly proficient pilots, and provides high-end avionic flat panel suites and near-all weather Visual Flight Rule (VFR) and Instrument Flight Rule (IFR) flight. Both aircraft suffer from high operating costs resulting from high amortized vehicle costs, non-optimum designed aircraft to the Air-taxi mission, approximately $5 per gallon fuel costs, poor load factors, piloting costs, low utilization associated with relatively low vehicle reliability, and high maintenance costs. All these factors combined to limit the profitability of the Air-taxi operators. Clearly a feasible set of conditions were not provided for Air-taxis to be successful, and they weren't, with almost all Air-taxi operators no longer in operation But lessons learned provide a valuable understanding from which to apply technologies to new aircraft concepts that are designed specifically for an ODM mission and concept of operations that maximize the probability of success. Comparing to the study by Viken and Smith, the question becomes how can a cost of below $1 per seat mile be achieved with an average passenger payload of 1.3 to 1.8, or a total vehicle cost (if it could ideally be matched to a fractional person) of $1.30 to $1.80 per mile? Additionally, if that cost can be achieved, the follow-on question becomes how can the incredibly high traffic volume be accommodated in the airspace, with community acceptance for flights occurring an average of every 60 seconds, while achieving high safety and other the other characteristics previously discussed?

Vehicle Cost:	Yearly Utilization, Reliability, Fleet Size
Design Mission:	Range, Speed, Payload Size, Load Factor
User Access:	Aircraft Ease of Use versus Pilots, Stall Speed/Field Length, Availability
Operating Cost:	Everything Above + Efficiency/Cost of Fuel, Type of Fuel, Maintenance
User Experience:	Ride Quality, Comfort, Cabin Noise, Perceived Safety, Real Safety
Community Acceptance:	Noise, Emissions

Table 1. Mapping of ODM Aircraft Feasibility Characteristics that Determine a Probability of Success

Aircraft are just one part of the total ODM system, with equally important contributions from airports, ground travel providers, airspace access and capacity, fleet and business model, etc. But many of these additional factors are based on infrastructure that is well established, or infrastructure that will be extremely difficult to change until operators induce a large enough market to require change. Increasing airport availability would be one such factor, however 4,477 public airports with 2000 foot field lengths already exist, with Viken and Smith identifying a total of 10,680 if private 2000 foot airfields are included. This number of airports excludes hubs for commercial airlines, as segregation is assumed between these small aircraft and commercial airline traffic. Some aspects would naturally occur and easily be accommodated as the market demand develops, such as rental or Zip car availability at every airport. The airspace capacity discussion is left for Smith's discussion, which identifies sample airport capacity issues as well as sector saturation. Clearly airspace regulations and management would need to change; however, the FAA NextGen is already implementing several elements of the needed changes. Automatic Dependent Surveillance-Broadcast (ADS-B) Out has been mandated by the FAA by 2020 in many types of airspace, which enables aircraft to know the position and trajectory of other aircraft in the vicinity to improve situational awareness and avoid air-to-air collisions. In the following section, a proposed follow-on to Air-taxi's is proposed from an advanced aircraft perspective that can utilize new technologies to address the feasibility gaps that currently exist.

While aspects of the airspace and ground infrastructure will be discussed, the majority of those aspects will continue to be developed as experts integrate their various perspectives from each of the disciplinary knowledge areas.

IV. Vehicle and System Changes

Zip Aviation is a proposed on-demand aviation transportation system that utilizes advanced technology small aircraft to provide high speed regional mobility. In the past, this has been described as the short haul market which is being increasingly poorly serviced by the major airliners as they contract routes to those that are most profitable. But in the context of future new markets, it may be more accurately called the 'long tail' market that relates to selling a large number of unique items in small quantities. This market strategy is described in detail in Chris Anderson's "The Long-Tail: Why the Future of Business is Selling Less of More". This strategy can be visualized by looking at a power law graph that shows the head or central part of a probability distribution where the peak condition exists, but has a long tail distribution where a larger portion of the probability distribution exists, but is spread out. The goal is that this new long tail mobility architecture can increase the mobility reach by at least an order of magnitude and provide access to dramatically more resources in an expansive country such as the U.S. But providing a fundamentally new mobility solution is a massive undertaking that can't possibly be achieved without government leadership and participation. This is especially true today in comparison to the emergence of the automobile transportation system 100 years ago. Automobiles were able to become established in the absence of, or with very minimal, federal regulation. While they were supplanting the horse and buggy, there was very little regulation that limited the new vehicles to organically grow. Many limitations were present, such as the lack of infrastructure (i.e. paved streets and highways) that required local, state and federal government actions. But the regulatory environment today is complex and comprehensive, as air traffic already exists with entrenched needs that are in conflict with emergent market needs. The civil UAS market is demonstrating the difficulty of establishing a new aviation market, even when industry has products ready and customer are anxious to put those products into the airspace. The UAS market, in particular the small UAS market, will likely share many technologies, from electronics, information, and autonomy systems, to design tools and manufacturing practices for high volume aerospace products. Leadership from NASA and the FAA are essential, in partnership with U.S. industry and academia to create these new aviation markets.

The proposed Zip aircraft feasibility characteristics are pulled from Table 1, with an approach selected for achieving dramatic improvements across all these areas through the implementation of autonomy and electric propulsion technologies. Both of these research frontiers are currently experiencing dramatic technology accelerations that are likely to continue through the next 30 years. Vehicle autonomy technologies are already being applied to automobiles, such as the Goggle Driverless Car, with similar efforts by almost every auto company. Car autonomy is likely a far more difficult problem than small aircraft autonomy, due to extremely close proximity distances in a highly unpredictable environment filled with ground clutter. The fact that a driverless vehicle is first being performed with an automobile, instead of aircraft demonstrates the increased regulatory hurdles and liability concerns that currently exist in aviation, both because of the consequence of a failure and the inherently small product volumes and profit potential. The adoption of vehicle autonomy is likely be an evolution as users become increasingly comfortable and statistical improvements in safety can be proven. While achieving a fully autonomous solution that is highly affordable for small aircraft will likely require several decades, the leveraging of automobile derivative technologies and high production volume could make this happen much more rapidly than expected. But full autonomy is far beyond the current technical state of the art. Even Google's Driverless car is limited to ~1000 miles between human interventions which is impressive, but a long way from being driverless for practical uses. In aviation certification requirements must also be satisfied, which makes the problem far more challenging (the auto realm seems largely content using liability and insurance to encourage safe design). Realistically the way to move forward is incrementally with increasingly capable automation combined with interface and interaction design that keeps the "pilot" engaged without being overwhelmed. Pilot is in quotes to indicate that they have different skills they today's pilot with more emphasis on higher-level decision making and judgment, with less on the lowest-level stick and rudder skills. Inner-loop control automation is needed to enable simpler, care-free handling and envelope/hazard protection (loss of control is currently the highest cause of fatalities for pilots). This can be relatively simple at first through such avionics as the Garmin's ESP and evolve into flight-critical augmentation as experience is gained and the FAA is willing to consider reduced training requirements. With inner-loop control autonomy implementation the physics are relatively straightforward and deterministic. Achieving flight-criticality is much easier with inner-loop than in the outer-loops which involve perceiving and responding to the much more variable external environment. An outer-loop control strategy is to create a cooperative partnership between plane and "pilot" comparable to a rider and a well-trained horse. This means that the airplane has instinctive or reactive intelligence (which is much simpler than general, human intelligence) relative to expected environmental factors and is generally biased toward self-preservation in the absence of decisive pilot direction. Notionally, if in the outer-loop, the pilot, and automation are each reliable to 10^{-3} or better, have dissimilar failure modes and can independently detect and cooperatively resolve hazards, then critical reliability will be achieved. Over time, as experience and confidence is gained with the automation, it can assume greater authority and responsibility, perhaps achieving a capability where the human pilot becomes optional.

The second critical technology set to enable Zip Aviation is electric propulsion. Many are currently highly skeptical of the impact this technology set can have on aviation, and almost entirely this is due to their perspective that battery energy storage is a hard an active constraint that results in uncompetitive aircraft to reciprocating or turbine solutions. But comparing the propulsion characteristics by themselves, outside of the context of an integrated aircraft system, in insufficient. In addition, it is assumed that the missions for which aircraft were designed with reciprocating or turbine technology should be exactly the same as for aircraft using a completely different propulsion technology set. While aircraft design in the past has clearly been based on metrics of speed, range and payload – this will likely not be so definitely the case in the future. Higher fuel costs, carbon emission taxes, community noise curfews, and passenger satisfaction are becoming increasingly important. These new metrics bias designs tremendously to the characteristics that electric and hybrid-electric offer; i.e. 2-3x efficiency, noise reduction, zero emission, vibration reduction, complexity reduction, maintenance reduction, reliability improvement, lightweight, lower purchase cost, lower operation costs, variable rpm operation without a gearbox, zero lapse rate with altitude, etc. Electrics also offer incredible new degrees of design freedom because of their compact and scale-free characteristics (i.e. power to weight and efficiency is the same across wide scaling, which is certainly not true for turbines that suffer tolerance and Re# scaling issues. Reciprocating engine suffer from cubic volume scaling with square friction surface area, causing substantial increases in loses and thermal issues at smaller scales. Therefore, prior engine technology was biased against distribution and use at smaller sizes. Utilizing distribution to improve synergistic interactions with aero/controls/structural loading has the potential to achieve dramatic interdisciplinary improvements. Just because hydrocarbon-based turbines enjoy incredibly high fuel energy content to provide incredibly high range capabilities, this doesn't mean that future aircraft missions will require such long range capability. The companion paper "Performance Analysis and Design of On-Demand Electric Aircraft Concepts" by Patterson, German and Moore shows the potential of full electric aircraft to achieve a 200 mile range competitively with the SR-22 at battery energy levels of 400 Watt hour per kilogram. While currently available lithium batteries are available at 200 Whr/kg, companies such an Envia (which has received significant funding from ARPA-E as part of the BEEST program) are already demonstrating 400 Whr/kg with reproducible lab experiments through the use of silicon anodes and HCMR cathodes. Tremendous investments are currently being made in high energy and power density batteries, with substantial progress. Similarly high specific power electric motors are available with 2 to 4 times better performance than reciprocating engines, and demonstrated laboratory bench tests of electric motors as high as 5 to 10 horsepower per pound.

The potential impact of these two technologies is described below relating to each of the feasibility characteristics shown in Table 1 to indicate the level of change targeted for Zip Aviation, compared to prior Air-taxi operations.

Vehicle Cost

In the nearer-term, the implementation of both autonomy and electric propulsion technologies will result in more expensive vehicle costs. For 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 current GA. Development costs of the required certified software will also be incredibly expensive, with 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 current GA aircraft (i.e. ~500 units per year), that strategy alone will not enable reasonable cost levels in comparison to the prior Air-taxi SR-22 costs. Total operating costs need to be reduced by 50% to achieve a large demand; therefore a strategy of achieving high yearly utilization to amortize the vehicle costs has been selected. Such a strategy is a factor of three greater than prior Air-taxi operations and a factor of ten greater than typical GA use. Therefore achieving high vehicle reliability is the critical goal for effectively amortizing the vehicle cost. Such a strategy is highly synergistic to pilotless operations and electric propulsion, as a more 'solid state' aircraft is achieved. The reliability of electric motors, batteries and controllers are well proven and dramatically higher than a mechanical reciprocating engine, and certainly on par, but likely superior to turbine engines. Another major factor impact the feasibility of the vehicle cost, is the number of vehicles that are required in a fleet to provide a specified availability. Minimizing this fleet number of aircraft while achieving the highest availability is proposed to be achieved through use of autonomy and an "Optionally Piloted Vehicle" strategy to achieve automatic redeployment of the vehicle. This autonomous redeployment of the vehicle would decrease the burden of non-revenue flights and permit rapid response 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 is not being performed as part of the current Zip system study, but would be an iterative subsequent study across the demand, aircraft, and fleet sizing.

A utilization goal of 1500 hours per year was selected based on achieving just over 4 hours per day of daily use with highly reliable electrically powered aircraft, with the autonomy technologies providing user pilots and automatic redeployment for deadhead routes to minimize the number of aircraft required in the fleet to support an availability that is yet to be determined.

Design Mission

Based on the short stage lengths experienced in prior regional Air-taxi operations, a 200 mile range was selected for the nearer-term. As battery energy densities are increased over time, this range would extend further to permit several stage lengths to be flown before recharging, or accommodate the longer outlier legs that could not be accommodated. The long-term range required would likely be satisfied a 500 mile, with an intermediate level of 300 miles. Nearer-term speeds were selected to achieve maximum aerodynamic efficiency to accommodate battery energy densities without sophisticated high lift systems. However, the energy required for a specific range is independent of speed, and instead dependent on the weight, lift to drag ratio (L/D), propulsive efficiency, and engine efficiency; this can be confirmed by looking at the first principles Breguet range analysis as discussed in the Patterson, German and Moore paper. However, the L/D is highly coupled to cruise speed by wing area and the C_{Lmax} that can be generated by the wing. Electric propulsion provides many opportunities to dramatically improve the C_{Lmax} through distributed propulsion coupling to the wing aerodynamics. Couple this to the unique attribute that electric aircraft experience no thrust lapse with altitude and the fact that electric motors achieve far greater specific power than reciprocating engines. Therefore it is likely that long-term electric aircraft will provide significantly faster cruise speeds than existing single engine piston GA aircraft such as the Cirrus SR-22. For these reasons the near-term cruise speed was selected to be 150 mph which is well within simple high-lift system capabilities for providing high cruise L/D ratios for minimal energy flight, with cruise speeds of 200 and 250 mph in the longer-term. There may need to be an evolution from hybrid-electric to fully electric vehicles, depending on the near-term advancement of both battery energy and power density. The initial 200 mile range is marginal, and if extensive recharge time is required, instead of fast battery fleet swapping or rapid recharge, then the ability of small reciprocating engines to provide parallel or series hybrid range extenders would provide technology gap filling. However, hybrid electric solutions remove or reduce many of the electric benefits, such as for emissions and altitude lapse rate.

Passenger load factors are a key determiner of achieving true efficiency and minimal cost of travel; oversizing the vehicle yields to enormous losses by carrying much unnecessary weight and capacity. Automobiles contain a single occupant for over 70% of all trips, with an average load factor of 1.7 people per vehicle. As previously discussed Air-taxis achieved load factors of 1.3 to 1.8 passengers per flight. But autos have far lower growth factors than aircraft, that is, the amount of growth (added weight) a vehicle experiences as the payload weight is increased. Conventional takeoff aircraft typically experience a growth factor of 3, while vertical takeoff and landing aircraft experience growth factors of 4 to 6; automobiles experience growth factors of less than 1.5. So there is far less sensitivity in vehicles being oversized and carrying low load factors than for aircraft. If there were no penalties, obviously larger vehicles would always be selected (i.e. a Sport Utility Vehicle over a compact), and even with small penalties people often choose the increased flexibility of the large vehicle, even if the it's is going to be used as a daily commuter. Therefore 'right sizing' the vehicle to the trip need is one of the most significant aircraft design chooses that can be made, which in turn burdens the fleet management with insuring the right size vehicle can be available when necessary. This becomes even more important as the user replaces the pilot, and the pilot seat becomes available for us. With piloted operations, a two place aircraft would be the smallest solution, which also happens to guarantee a 100% load factor (even though the true load factor is only 50%). Clearly SATSair or DayJet could not possibly have chosen to use 2-place aircraft due to their 1.3 to 1.8 average load factors (and that was with passenger taxi trip pooling instead of true on-demand) as well as their small fleet sizes which required increased vehicle flexibility. Therefore the assumption that a fleet should merely be comprised of 4-place aircraft needs to be re-examined with a user pilot technology adaptation, with 2-place aircraft being right sized to the ODM mission, and essentially being nearly equivalent to piloted 4-place Air-taxi's. Achieving nearly 100% load factors are the key to current profitable airline operations, and this fleet and aircraft design decision alone can result in the total operating cost being reduced from $3.09 per seat mile for the SR-22 carrying 1 pilot and 1 passenger, to $.77 per seat mile; without any other vehicle improvements except for the implementation of autonomy technologies and right sizing. This single change fundamentally alters the feasibility of on-demand aviation, driving costs down into the regional where Viken and Smith shown enormous trip demand market potential. It is likely that to achieve optimal load factor a 1-place aircraft should even be considered as detailed fleet analysis is conducted to determine if the percentage of single occupant trips is similar to automobiles (which is highly likely). The structural efficiency of a 1-place aircraft will be somewhat lower (i.e. more structural weight per passenger at smaller sizes) and the cost of autonomy likely equivalent for a 1-place aircraft to a 4-place aircraft, so clearly the cost per seat mile will increase to some degree with the smaller vehicles. It's reasonable to question the feasibility of a 1-place aircraft, and ask why automobile companies don't manufacture 1-place cars. Motorcycles are a close equivalent to 1-person cars, however there isn't a significant cost differential between a small 4-place car and a motorcycle, and the 4-place car is far more useful. In addition, the environment of operation must be considered; for safety reasons a 1-place would likely never be acceptable to the majority of car buyers because they realize several ton trucks will be operating just a few feet away from them at high speeds. However, a 1-place aircraft would be as safe, or safer, than larger aircraft, due to ballistic recovery parachutes providing greater effectiveness at the lower gross weight vehicle sizes. So if 70% of the aviation ODM trips are single occupant, it is likely that a Zip fleet should consider 1-place aircraft to achieve optimal vehicle performance and cost.

The near-term range is selected to be 200 miles, with longer ranges (300 and 500) applied in later years as battery energy densities mature. The near-term speed is 150 mph, with higher speeds (200 and 250 mph) as electric motors mature to develop higher specific power. A fleet of mixed sized payloads to provide near optimal load factors would be utilized based upon at least 2 and 4 passenger sizes, with the possibility of a 1 passenger vehicle depending on subsequently determined vehicle cost and weight sensitivities.

User Access

Increasing the user access to Zip Aviation is mostly accomplished by dramatically increasing the user base, which is accomplished by removing the majority of training barriers for a self-driven vehicle as well as dramatically reducing the total cost of operation so that this new travel choice competes well against the alternatives. Autonomy has already been discussed in detail, with the specific degree of autonomy to be adopted depending on several factors. Nearer-term autonomy will likely involve autonomy in the inner-loop vehicle control with limited outer-loop control autonomy and in partnership with the user. Longer-term autonomy will likely involve full autonomy, but only after many years of development, and time to permit certification standards to establish the statistical basis to validate operational safety. User access is also determined by the airport proximity to desired travel locations and the vehicle availability resulting from fleet size and area of coverage. In the near-term, a 2000 foot field length permits the use of 4,477 public airports in the U.S., or 10,680 public and private airports. This number excludes hub airports that conduct commercial airline operations. The research of Viken and Smith suggests that there is not a significant sensitivity between these numbers of airports, that is, even 4,477 airports provide sufficient proximity to make the ground leg travel segment not very significant. However, their research also demonstrated that at costs of $1 per seat mile, many small airports became saturated in capacity and would require either additional runways, or less than 60 second spacing between takeoffs and landing operations. So the addition of private airports would likely help to meet node saturation limits, instead of improved ground time benefits (which would also exist). It is also likely that due to the relatively low takeoff and landing speeds, and quick runway turn-offs, that decreased time spacing could be accomplished. In the long-term, additional small airport nodes will be required to meet airfield traffic limitations. If electric aircraft are able to take advantage of aero-propulsive coupling to achieve Extremely Short Takeoff or Landing (ESTOL) performance (as discussed previously due to specific electric integration benefits). This may permit integration of shorter field lengths into locations where population densities and trip demand are already present. One possibility would be distribution of ESTOL fields at malls, which currently number about 50,000 in the U.S., with a small airfield encompassing a corner of a parking area (while accommodating flyover and setback requirements). In the very long term, if ODM were highly successful, increased distribution to a 250,000 number of airfields might be possible by locating ESTOL fields in office parks.

Runways of 2000 foot field length will be utilized, providing access to over 10,000 public and private small airports in the near-term. Operations are assumed to be conducted only at smaller airports, with segregation from *commercial airline hubs. Expansion to a higher number of airfields in the long-term, perhaps to 50,000 and 250,000 would take place if market demand and vehicle field length improvements can be achieved.*

Operating Cost

Reductions in total operating costs that include vehicle cost amortization, need to be dramatically reduced in order to achieve a large user base, economies of scale in vehicle production, and a large enough fleet to achieve high availability. Multiple strategies are implemented with the intent of achieving total operating costs between $.20 and $.80, a several time factor reduction to previous and existing flight operations. As previously discussed, the application of autonomy and aircraft right sizing alone has the potential to reduce total operating costs to less than $1.00 per seat mile. These additional factors would be applied on top on that improvement.

(1) Extremely low effective fuel (energy) cost due to the use of electric propulsion, based upon the following comparison that results in at least a 4 times reduction.

1 gal 100LL fuel = 35.3 kW hr
Current average 100LL cost is $5.50 per gallon, yielding a cost of $.155 /kWhr
Current average cost per kW/hr of electricity = $.115 /kWhr (however, off peak is substanitally lower)
Aviation gas cost to electricity ratio = 1.35x
Electric motor/controller/battery conditioner system efficiency = 90%
Aircraft engine that achieves a .45 brake specific fuel consumption = 28%
Electric motor to piston engine efficiency ratio = 3.21x
Overall decrease in energy cost due to propulsion system change = 4.33x

A 4.33 times reduction in fuel/energy costs results in a 16.5% reduction in total operating costs per hour. Additionally, integration of electric propulsion permits a cleaner aerodynamic design due to more compact motors. As discussed in the study by Patterson, German and Moore, gross weight parity can be achieved with battery specific energies of 400 Whr/kg for the shorter 200 mile ranges. Therefore no additional weight penalty is applied. There is also the potential for decreased maintenance cost of an electric aircraft which has been demonstrated by Prius taxi fleets.

(2) The application of autonomy to eliminate pilot costs, at the expense of increased vehicle purchase cost. The cost implications of this are to be determined, as details of an autonomous system are clearly identified to indicate the recurring costs that would exist, due to required electronic redundancy and reliability.

Elimination of personnel and training costs account would result in a16.2% reduction in total operating costs per hour. Combined these two cost reductions would result is a 29.7% reduction in total operating costs. Ignoring the difference in vehicle costs, if these two operating cost reductions are applied to a user piloted, electric SR-22-like aircraft that can achieve a 100% load factor, the resulting total operating would be $.54 per seat mile. Aircraft that are designed specifically to take advantage of electric technologies for synergistic improvements would likely achieve even lower per seat mile costs. If such a cost could be achieved, Viken and Smith predict that this mode of transportation would capture approximately 200 million person trips per year; which equates to over a 100 fold increase in market demand compared to SR-22 total operating costs at $1.71 per seat mile. Many unknowns exist in this predicted cost, so this should be considered as an ideal economic case, but even at $1.00 per seat mile, trip demand increases by a factor of about 50.

A reduction in total operating costs by a factor of at least 4 is targeted, through the application of high load factor aircraft that are right sized for the on-demand market, and electric propulsion that results in a factor of at least 4 time lower energy costs, as well as to be determined reduction in piloting costs.

User Experience

Electric aircraft are likely to be multi-engine, as there are almost no penalties to electric motors from scaling (specific power, efficiency, and cost), yet redundancy is added to provide the opportunity to avoid the perceived and real safety concerns of single piston engine experiencing engine out conditions. Batteries and motor controllers are also easily parallelized and distributable in electric aircraft to provide real safety advantages, and even with the increased complexity, still maintain dramatic improvements in reliability due to the high reliability of each subcomponent of the solid-state propulsion system. While approximately 20% of small aircraft accidents relate to propulsion system failure, almost 70% relate to pilot error. Therefore, to achieve commercial airline-like (or automobile-like) levels of safety, Currently multi-engine aircraft are also not limited by the FAA stall speed limit of 61 knots, so there are additional opportunities to use wheel-based pancake motors for takeoff and landing assistance to decrease maintain a 2000 foot field length, while going to higher stall speeds. Higher stall speeds would permit higher wing loading, which will directly improve passenger ride quality. Improvement of cabin noise would be a direct result of decreased noise, vibration and harshness from the elimination of piston engines with electric motors, which would likely not be located as tractor nose installations. Providing aircraft that non-pilot can safely interact with requires fundamental design changes, such as obscuring propellers from where people can access to avoid propeller strikes (which continue to occur every year as people unaccustomed to propellers simply walk into them). Ballistic recovery parachutes are a unique safety feature that can also be provided to small aircraft that can't be provided by larger aircraft.

Levels of safety equivalent to the car and airline that are ten times better than current GA operations would be targeted through autonomy and redundant electric propulsion. Re-design of aircraft for non-pilot operators will require providing auto like functionality and comfort.

Community Acceptance

Noise and emissions need to be aggressively targeted for improvement if communities to embrace the large number of predicted operations at costs of less than $1 per seat mile. Currently the SR-22 noise measurements indicate nearly a 85 dBA, 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 20 to 30 dBA reduction is required, which will require designing the aircraft with a strong bias for acoustic signature. Applying low tip speed propellers in combination with electric motors is a powerful combination that can likely achieve this goal, with a combination of variable pitch and variable speed motor operation (which electric motors offer without a gearbox) offering the possibility of operating an 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. Emissions likewise are drastically reduced (or eliminated, depending on whether the vehicle or energy lifecycle is considered). In particular electric provides an opportunity to break away from dependency on aviation grade 100 Low Lead fuel, which is single largest resulting of lead pollution in the environment today.

Noise reductions of 20 to 30 dBA, down to the 55 to 65 dBA certification level would be targeted through the use of electric motors in combination with low tip speed propellers that provide variable rpm and pitch capability. Dramatic emissions reductions would be targeted through electric propulsion provide zero community emissions, and dramatically lower lifecycle emissions than existing aircraft.

Year	Technology	Cruise Speed (m.p.h.)	Range (miles)	Utilization (hrs./year)	Fleet Mix (seats)	Number of Potential Airports	Cost (Year 2012 $/ passenger mile)
2012 Baseline	Piston/ Propeller, Gasoline (e.g. Cirrus SR22)	200	500	500	4	4,477 (existing public use)	$.20 to $.80
2015	Electric/ Autonomous ELV1	150	200	1500	1,2,4	10,680 (existing private and public use)	$.20 to $.80
2035	Electric/ Autonomous ELV2	200	300	3000	1,2,4	50,000	$.20 to $.80
2050	Electric/ Autonomous ELV3	250	500	3000	1,2,4	250,000	$.20 to $.80

Table 2. Vehicle Performance and Operating Characteristics

V. Conclusion

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, providing increased regional productivity and an alleviation of resource scarcity in established urban communities. The advanced technologies from autonomy and electric propulsion are presented as possible solutions for the many challenges experienced by the early adopter Air-taxi market. Specifically total operating costs that are decreased by a factor of four, greatly increased utilization, reliability, user access, and community acceptance, while providing a sustainable energy efficient and environmentally friendly solution that can at the same time provide high speed mobility for people and goods. Many additional and more detailed analyses are required to establish the feasibility of such a system, with elements of the current study looking at market demand, airspace impact, aircraft performance, advanced concepts, and life cycle emissions. Future studies would ideally look at markets from a regional basis to yield specific insights into regional transportation feasibility. Ideal regions for early adoption include areas with good weather, high property values, and geographical restrictions that limit ground transportation options. This paper has laid out an initial framework for understanding the concept of operations of future on-demand aviation systems, with the need for disciplines experts from vehicle and airspace technologies, regulations, and complexity sciences to provide increased levels of details across a broad and complex system of systems.

Acknowledgments

The author wishes to acknowledge all the participants of the Zip Aviation studies that have been conducted from a diverse set of perspectives to provide a breadth of understanding across the different feasibility questions. Jeff Viken and Jeremy Smith of NASA Langley, and their team of demand and airspace modelers that include Nelson Guerreiro, Sam Dollyhigh, Jim Fenbert, Chris Hartmann, and Teck-Seng Kwa, with support from Toni Trani of Virginia Tech. Ken Goodrich of NASA Langley for his support in scoping and guiding the autonomy discussions and goals. Jonathan Barraclough of NASA Dryden for his support relating to an understanding lifecycle emissions of electric aircraft. Brian German and Michael Patterson of Georgia Tech for their incredible support and efforts in modeling initial electric Zip aircraft concepts. Jack Langelaan of Penn State for discussions concerning the GFC electric aircraft concepts and future directions in electric flight. Bill Fredericks and Andy Hahn of NASA Langley for providing guidance on advanced electric aircraft concepts. Also Yuri Gawdiak and Bob Pearce for their vision and support for providing funding to scope out an initial understanding of how autonomy and electric propulsion technologies can provide a dramatic change to U.S. mobility. My apologies to any of the initial Air-taxi operators if my information on their operations is less than accurate; their pioneering work has laid the basis for any future aviation on-demand system.