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Enabling Electric Aircraft_Applications and Approaches

Dennis M. Bushnell
Langley Research Center, Hampton,Virginia

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Langley Research Center
Hampton, Virginia 23681-2199

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Abstract

Climate concerns have instigated serious research for weight-critical batteries to enable what are termed EVs, electric vehicles, initially for ground transportation. This research has advanced to the point where, at the system level, parity with combustion engines, via vehicle weight and drag reductions to reduce battery requirements, along with continued battery research, can conceivably be achieved in less than 10 years.. Concomitantly, renewable electric generation, which would enable essentially emission-less transportation, has via cost reductions, efficiency improvements and storage research advanced to the point of producing 25% of current electrical generation and 62% of new generation capability with continued rapid cost reductions and consequent rapid further adoption projected. The present report examines the resultant electric aircraft possibilities and opportunities including technologies to reduce requisite battery size and weight via airframe performance improvements, the benefits of electric propulsion and the enablement of a massive new aeronautics market for affordable, safe personal air vehicles that operate off of local streets.

Introduction

The Major initial driver for electric transportation, including electric aircraft, has been the reduction of emissions. Renewable energy for charging and operating electric transportation is developing rapidly. Renewable energy comprises 25% of all electric generation [ref. 1] and 62% of all new generation [ref. 2]. Costs are reducing rapidly and efficiency and storage technologies are improving across a wide range of renewable sources. Therefore going forward, to the extent that ever more electrical generation is from renewable sources, electric transportation should be nearly emission-less. What electricity replaces in transportation is largely heavy transportation fuels, mainly petroleum. Additionally, electric motors for transportation propulsion are far more efficient by a factor of two or more, lighter weight, contain far fewer parts, cost less and are easier to maintain than internal combustion (IC) and gas turbine engines (GTE) [ref 3]. The usual approaches to reducing aircraft emissions is via either improving performance to reduce fuel use or through using hydrogen fuel. The former is only a partial solution and would take decades of development to achieve incremental improvements. The latter produces water above the tropopause and forms thin cirrus clouds that reflect outgoing infrared radiation back to the surface of the Earth. Battery Electric Propulsion constitutes a solution to all of the emissions issues, NOx, CO_2 and water. The latter, estimated as the most worrisome climate impacting emission, would be eliminated by battery and airframe developments, market pull, the rise of renewable energy production and cost reductions.

Electric Aircraft propulsion can be envisaged for all classes of aircraft, from small drones and personal air vehicles to long haul and supersonic transports. The issue of long standing for electric aircraft has been what to do about the long extension cord: i.e. the size, weight, and functionality of the electricity source. The extensive battery research and development instigated by the development of electric ground vehicles has direct application to, and has created a renaissance in electric aircraft, both with respect to applications and design. The nominal battery goal for widespread electrification of aircraft is the energy density of chemical heavy transportation fuels. We are now approaching system parity via the extensive research on lithium-air, lithium-metal and solid-state batteries coupled with highly efficient electric motors along with vehicle weight and drag reductions. Research has now resulted in Li-Air batteries achieving 15 times the energy density of lithium-ion batteries [ref 4], and other research has achieved 750 recharge cycles [ref 5]. Also there is the announcement of a 500Wh/kg lithium-metal battery on the market in the nearer future. When coupled with electric motors that are two times more efficient and a more efficient airframe, system level parity can be envisioned. Therefore, in the current discussion it is assumed that the combination of greatly improved airframes via the concepts and technologies presented herein combined with the ongoing battery research could in a decade or less produce electric aircraft approaching system level parity with IC and GTE. This parity will open the entire speed range for electric aircraft transportation, up to and including supersonic speeds. Electric power does have the drawback of a fixed, or increasing, propulsion energy weight versus the weight reduction achieved as transportation fuels are burned. For long flights, this can produce up to a 20% range reduction unless mitigated by the many technologies and design approaches discussed herein [ref 6]. Indicated herein is a synopsis of technology approaches which could be applied to further improve the performance of electric aircraft, and reduce the required battery capacity to achieve system level parity.

There are two issues, besides battery capability, that will dictate the future of electric aircraft. First is the massive societal shift to tele-everything and virtual reality, including tele-travel. The second issue is the time scale to produce the required infrastructure, including certification, to accommodate the recharge capability and the air traffic control (ATC) and Information Technology (IT) capabilities required. The enabling ATC and IT systems for the extraordinarily large numbers of expected autonomous personal air vehicles is particularly challenging. Their numbers will also require designing for as near to "crash-proof" as possible while ensuring trusted autonomy for both the vehicles and the ATC system.

Advantages of Electric Propulsion

- No motor gear boxes
- Regenerative energy recovery during descent and landing
- Battery heat production could be utilized for cabin heating, deicing, or regeneration via thermoelectric generators
- Higher altitude operation feasible
- Reduced cooling drag
- Quieter
- Reduced vibration
- Fewer inspections
- No engine flameouts or restarts
- No fuel explosions during crashes
- Power train efficiency greater than 90%, nominally twice or greater than IC and GTE chemically fueled propulsion
- Much lower energy costs
- No power lapse with altitude at high temperatures
- Continuously variable transmission
- High reliability
- High efficiency over most of the power envelope
- Up to six times motor power to weight compared to combustion engines
- Reduced maintenance
- Far fewer parts
- Less expensive
- Higher torque
- No vehicle emissions
- Distributed, scalable propulsion

See ref 7 for a cogent discussion of the history and potential outlook for electric aircraft.

Technologies Which Could Reduce the Electrical Power Requirements via Lighter Weight and/or Lower Drag

Flow Control, or Designer Fluid Mechanics [ref 8] - Designer Fluid Mechanics subsumes a large number of flow control approaches and applications. These include laminar flow control (LFC): i.e. “natural”, pressure gradient induced at low sweep, and forced or controlled; mixing enhancement;, separated flow control especially for high lift, inlets, shock and boundary layer interactions; vortex control including managing the wake vortex hazard and maneuverability; turbulence control and drag reduction; favorable wave interference and drag reduction and designer fluids for internal systems. Flow control at cruise to allow inviscid performance optimization, smart controllers for load alleviation and trim drag reduction along with residual drag cleanup require additional study and optimization. A vast number of flow control methods are available that have been tried and sometimes applied to experimental aircraft designs. These methods include suction, injection, various body forces, surface motions, localized energy release, additives, surface permeability and heating or cooling. Research in this arena has for some two decades been moving from passive control approaches to first active and then reactive. Due to systems and applications considerations, by far the bulk of the flow control applications have been passive devices. The now decades long development of smart, multi-functional materials might alter this conventional propensity toward passive flow control for applications. Considering Laminar Flow Control, this has been under active research since the 1930‘s with most applications thus far being of the pressure gradient, “natural” laminar flow variety at relatively low chord Reynolds number on General Aviation (GA) aircraft. Until the 1960’s LFC was bedeviled by issues of insect remains and other roughness and waviness. As improved materials and approaches mitigated these concerns it was the relatively low fuel cost that prevented forced LFC from “buying its way” onto the aircraft in spite of numerous research flight experiments demonstrating feasibility and performance. With the advent of the issue of battery weight for electric vehicles, LFC is again under active consideration, to reduce the requisite battery capacity. Another issue, which has delayed the adoption and utilization of some flow control devices, has been facility capability shortfalls. In particular, except for the National Transonic Facility/European Transonic Wind Tunnel (NTF/ETW), a lack of Reynolds number to simulate the wake vortex hazard has hampered the further development of devices and approaches to mitigate the hazard. The vortex dissipation in the typical low Reynolds number facility causes quite a different vortex behavior and decay than in the high Reynolds number flight case. Also, the lack of low disturbance transonic facilities has been a problem not yet overcome for certification of LFC systems for long haul transports. For turbulent drag reduction, especially with respect to the fuselage, a critical flow control arena once drag due to lift (DDL), and wing friction drag, minimized via LFC are reduced, the options, aside from relaminarization, are few currently. Obviously shorter and wider fuselages, without incurring wave drag, reduce wetted area. Riblets have been flight tested and can provide an approximate 8% turbulent skin friction reduction. There is an opportunity to somehow operationalize the research observations that oscillatory transverse wall motions can reduce turbulent viscous drag in air flow up to the order of 45%. Overall, electric propulsion proffer the possibility of straightforward distributed energy and effector distribution and location, especially for flow separation control.

Aero/Propulsion Synergies [ref 9] – Conventional design practice in civilian aeronautics is to essentially separate the aerodynamics and the propulsion system. The military, for over half a century has in many cases utilized synergistic combinations of aero and propulsion to obtain improved functionality, often for enhanced high lift performance. Such synergistic combinations are equivalent to approaching the overall aero design problem in an open thermodynamic system where energy and mass properties are added to the overall design space. Examples of such aero-propulsive synergies include the following:

- Circulation Control Wings: produce up to a factor of four increase in Cl to nearly the theoretical 4Pi maximum, potential reduced cost and part count for high lift and improved control and maneuverability.
- Boundary Layer Inlet: Ingesting lower momentum air, where the fuselage and other aero skin friction reduction technologies has already produced up to 10% to 15% propulsion efficiency increase.
- Wing Tip Engines: As discussed in the subsequent drag-due-to-lift reduction section, placing the engines on the wing tip can for short span wings, reduce the drag-due-to-lift experimentally by up to 40%. The engine nacelle acts as an endplate, the engine energy and mass addition change, to first order, the dynamics of the wing tip vorticity rollup and also reduces the wake vortex hazard. Wing strut and truss bracing are conducive to wing tip engine placement. A related aero-propulsion interaction approach is wing tip injection, which also reduces the wake vortex hazard and drag-due-to-lift.
- Thrust Vectoring: Placing the engines at the rear of the fuselage and utilizing them for aero controls in lieu of the weight and drag of the empennage is a major performance enhancer.
- Goldschmied Thrusting Cowl: Goldschmieds' research indicated that placing a cowl around engines in the back, with boundary layer inlets, essentially puts potential flow sinks inside the body and increases the pressure on the back of the cowl, acquiring additional thrust in the process via aero-propulsion synergy. Research is underway to verify this assertion.

The submarine community, which utilizes such shrouded pump jets quite commonly, have accrued some additional performance benefits. The issues appear to be whether the benefits claimed by Goldschmied, up to some half of the fuselage friction drag, are obtainable. The boundary layer inlet propulsion improvements are the zeroth order effect of such a cowl.

- Hybrid Laminar Flow with leading edge suction utilized for high lift separation control: The suction from the engine used for Hybrid wing Laminar flow at cruise can be used for skin friction reduction during takeoff for flow separation control during the high lift configuration.

<u>Wave Drag Reduction</u> [ref 10] - The usual linear theory engendered approaches to wave drag reduction (WDR) include wing sweep, area ruling and reduced thickness as well as wing twist, camber and warp. More recently, computational fluid dynamics (CFD) nonlinear methods have been applied, resulting in further optimizations. Classical non-linear WDR techniques include use of nose spikes, either physical or via forward projection of energy, gases, liquids or particulates to extend effective body length. This is particularly useful for blunt nosed bodied vehicles for sonic boom reduction, and for base blunting which reduces the strength of the base recompression shock.

All of the WDR methods mentioned thus far involve weakening the shock. There is another whole class of approaches, which utilize favorable shock interference. The fundamental approach is simple in concept – utilize shock waves, via reflection or interaction, to create a favorable interference either for body thrust or lift, or both. Generally volume distributions are utilized to synergistically create lift, and lift distributions are utilized to cancel volume drag. Realizations of favorable interference include ring wings and the related parasol wings; multiple bodies: fuselages, control surfaces, wing pods; and propulsion system interaction. For nonlifting bodies a ring wing can cancel, at the designed Mach number, the volume wave drag of the body, e.g. Busemann's Biplane. This is however, at the expense of an increased wetted area, weight, etc. For the lifting case the parasol wing provides both partial cancellation of the body and nacelle volume wave drag and an efficient lifting surface. The application of favorable interference would be facilitated by flow separation control and active controls facilitated by electrical actuation or pumping. Various experimental evaluations of favorable wave interference have resulted in far less than the expected inviscid performance levels due to the detuning and drag associated with flow separation caused by the concomitant shock wave-boundary layer interactions. The plethora of flow separation approaches currently extant, if employed at cruise conditions, should enable favorable nearly inviscid performance levels. One such approach is the use of passive porous surfaces. Flow separation control utilized during cruise could also greatly increase the percentage of lift carried on the upper surface as expansion waves, as opposed to the conventional lower surface shock wave rider approach. The use of active flow control would allow both enhanced on-design and improved off-design performance via shock locus tailoring. As an order of magnitude estimate, parasol favorable interaction Supersonic Transport [SST] wings can provide on the order of a 20% improvement in overall lift-to-drag ratio at cruise.

Drag-Due-to-Lift Reduction [ref 10] - Classical linearized theory indicates that elliptical loading, increased aspect ratio and span, lower lift coefficient values and reduced weight are the primary approaches to vortex drag-due-to-lift reduction (DDLR). Obviously increasing aspect ratio and span beyond a certain point becomes inefficient overall due to structural penalties. While decreased lift coefficient entails larger wings and both weight and wetted area as well as viscous drag increases. The application of the extensive alternative solution set for vortex DDLR has been relatively sparse, with the exception of winglets. This is due to many reasons including, depending upon the approach, structural weight, parasitic drag and/or power. This has been addressed in many cases via creative overall aircraft configuration design - e.g. truss braced wings. Relaxing the assumptions of classical linear theory (i.e. closed body, no energy addition, planar vortex sheet etc.) provides alternative vortex DDLR possibilities. In particular, the use of non-planar lifting surfaces, such as distributing the lift vertically through various approaches including upswept tips and multiple, vertically spaced wings can provide sizable reductions, on the order of 15% . In addition to conventional non-planar tips or span there are several interesting natural observations related to the morphology of Avians and Nektons. These observations which may relate to DDLR include serrated trailing edges, leading edge bumps, and shark caudal fin tips and sheared tips. The vortex which forms at, and downstream of, the wing tip, caused by the tip up wash from the high pressures on the lower surface, affects a smaller percentage of the wing as aspect ratio increases. A characteristic feature of this vortex formation is flow which is at an angle to the free stream. Devices can therefore be inserted into this flow to produce or recover thrust and/or energy from this tip flow. This is the fundamental rationale behind at least four devices which reduce DDL. These devices can obviously also have an influence upon the vortex formation process itself and thus may directly influence DDL. These devices include tip turbines for energy extraction, winglets, vortex diffuser vanes, tip sails and a plethora of other tip devices such as wing grids, spheroid and c-tips. The vortex diffuser vane is supported by a spar behind the wing tip to allow the vortex to concentrate before interception. These devices work quite well, depending upon wing design and tip region loading and produce on the order of 5% to 15% reductions in DDL at CTOL conditions. Major application issues for these include, along with the usual concerns stated previously, their possible utilization as control devices. The following DDLR techniques are based upon either eliminating the tip altogether or adding mass and/or energy in the tip region. Eliminating the physical wing tips can be accomplished either via use of ring wings or joined wings and tails. Mass addition at or near the tip can be carried out either via tip blowing or through the use of wingtip engines, resulting in a sizable DDLR of up to 40%, depending upon wing design. Passive tip blowing could possibly be approached via wing leading edge ingestion allowing for increased wing thickness, with subsequent tip blowing. This can be used to tailor the production of, and modulated to excite, virulent tip vortex instabilities at landing and takeoff in order to ameliorate the wake vortex hazard. Positioning engines at the wingtip requires aerodynamic theoretical developments in an open thermodynamic system since this is adding energy and species as well as mass. Also, the engine nacelle can function as a tip device. Oscillatory span load distributions have also been employed to reduce or obviate the wake vortex hazard. This same approach could well yield interesting levels of DDLR and should be investigated for such. Other design options that need evaluation and possible optimization for DDLR include distributed propulsion and circulation control of front and rear wing stagnation points, the latter to investigate the possibility of rotating the lift vector into the thrust direction. The truss braced wing, as currently conceived, reduces DDL 75% by the simple expedience of doubling the span. This is enabled by the structural characteristics of the external truss, creating a wholly new set of optimization parameters and approaches. Additional DDLR concepts include formation flight and utilization of alternative sources of lift including buoyancy, and thrust vectoring. The latter begins to be effective at high supersonic speeds and is beneficial at hypersonic cruise. Buoyant lift typically replaces DDL with a huge increase in wetted area and skin friction, producing an overall high drag with, due to the large sizes and areas, undue sensitivity to weather.

Landing Gear Weight Reduction – To a first approximation, landing gear is 33% the weight of long haul transport fuselages and 63% the weight of SST fuselages. Therefore they constitute a target rich environment for vehicle weight reduction. Typically gear includes large, heavy brakes for refused takeoff. The military has evidently used parachutes to handle refused takeoff, thereby accruing sizable weight reductions. The structure of the gear itself is typically sized for high impact landings. Such landings could probably be minimized in frequency and impact strength via autonomous operations, slaving the lift system to the ground proximity and descent rate. Also, the revolutionary materials currently at a lower

TRL level would, along with reducing the weight of other structures, reduce gear weight.

Revolutionary Materials and Structures - There are several extant, but low TRL, approaches to significantly reducing the dry weight of aircraft via revolutionary materials and structures. Now that we are printing at the nano scale, the technology is developing to produce superb material microstructure, with far fewer dislocations and grain boundary problems, greatly improving the material performance. Thus far a factor of order five has been achieved in some metal alloy systems. These microstructure problems are largely produced during the historical materials processing approaches, which degrade performance by, in some cases, up to a factor of 20. Therefore a five time's improvement may not be the upper limit to the art of the possible. Another approach for ultra-performance materials is to attempt to merge nanotubes into a contiguous structural material. There are several approaches, with estimates of performance improvements in the 3X to 8X range. There are also continuing efforts, with respect to composites, claiming 10X the performance of aluminum. Also, there is work on storing electrical energy in structures and skins [refs 11, 12], thus far using capacitor approaches to turn the wing surface into an energy storage device. In addition, additive manufacturing can result in overall weight as well as cost reductions. Then there are the developments in multifunctional, morphing materials for controls as well as transitional flight modes along with materials with imbedded cellular micro structures. Finally, Inflatable wings might be an interesting approach for some configurations, especially with respect to the transition between vertical and forward flight but also for inner sections of largely unswept thin truss-braced transport wings. Revolutionary structures approaches include externally truss braced wings along with going windowless, using viewscreens instead of windows except for emergency exit locations.

Electric Aircraft Applications

Drone/UAS/ODM/UAM/PAV – The Nearly concomitant development of IT capabilities writ large - navigation, computing, automatics-to-autonomy, ubiquitous sensors, and now electric propulsion and additive manufacturing has spawned a rapidly growing market in electric aircraft drones and UAS for many applications and functionalities [refs 13]. This in turn has instigated the now very rapidly developing efforts for what has been termed On Demand Mobility (ODM), including Urban Air Mobility (UAM). On Demand Mobility is initially piloted but eventually becoming autonomous UAS carrying human passengers. The various approaches to accomplish this are nicely summarized in an UBER Elevate report of 2016 [ref 3]. The initial markets targeted are centered on the city commute and at least initially would be fee-for-service and multi-passenger. Beyond the current UAM efforts lie electric autonomous Personal Air Vehicles (PAVs) which operate out of the street in front of an individual holding. The estimated worldwide markets for PAV plus UAS, ODM, and UAM is in excess of a Trillion dollars/year, largely the current auto market.

The metrics for these include:

- acquisition and operation costs,
- safety,
- ease of use,
- acoustics,
- close proximity operations,
- reliability,
- ride quality,
- emissions,
- range and efficiency
- certification,
- all weather operation to the extent possible or feasible,
- crash proof

  In addition to the enabling autonomous operational and ATC systems to provide airspace access for many millions of vehicles.

The developed nations entered the 1900's with a transportation system, for people, centered upon the horse, the railroad and the steamship, with associated travel times on the order of hours-to-days or weeks, depending upon distance. The automobile has long supplanted the horse and the fixed wing aircraft has nearly driven the railroads and steamship companies from the long-haul passenger business. Travel times have shrunk to minutes-to-hours. These newer approaches have also had a profound influence upon the structure of modern societies. In the U.S., cities have expanded out of 18th century seaports and 19th century railheads, where much of the developed region was, by necessity, within walking distance of the transportation terminals, into tremendous automobile-enabled suburbs with attendant reductions in crowding and increased opportunity for individual home ownership. This section considers future possibilities/options for the nontransoceanic transportation spectrum, with emphasis upon the range from 10's to 100's, even thousands of miles. The current dominant transportation mode for this mission into the hundreds of miles range is the automobile, which, possibly more than any other single technical achievement, has enabled the current life style enjoyed by the developed nations. In this process, the auto has created massive safety problems, on the order of 40,000 deaths/year in the U.S. due to highway accidents - which is the order of the U.S. casualty count for the entire Vietnam War. - Additionally, the automobile has been responsible for the expenditure of truly prodigious sums on roads and bridges as well as being a source of pollution-induced health and material degradation requiring remediation and intervention of the legal system. The current status of the auto infrastructure is that we continue to clear and pave more of the watershed, contributing to air pollution, flooding, desiccation, the formation of heat islands and wildlife habitat degradation. Also, the average trip time is increasing due to suburban expansion and increased congestion, causing non-trivial changes in family life as travelers attempt to utilize non-traditional time slots, or suffer long, nonproductive commutes. Society cannot, easily or otherwise, continue to bear the costs imposed by almost sole reliance upon the automobile for short-to-intermediate passenger transport. Alternatives are necessary for the future, both for the developed societies and those that desire to or are actively developing. Probably the most commonly advocated alternatives involve some form of mass transit, which have along with tremendous capital costs, several other drawbacks such as passenger wait time, weather exposure and lack of privacy, security, pride of ownership and personal stowage. Additional drawbacks are the fact that they are not portal-to-portal and there is no guarantee of having a seat, as well as an inherent assumption and economic realism regarding required population density and concentration. Undoubtedly, the future mix of short-to-intermediate transport systems will include both mass transit and autonomous automobiles. There is, however, both a need and an emerging opportunity to include in the transportation mix a personal air vehicle which would provide, percentage-wise, the same increase in speed compared to the auto in traffic, as the auto provided over the horse. Personal air transportation usable by everyone is both revolutionary and the next logical step in the development of human infrastructure and corporal communication. The increased speed and potential safety improvements of such a capability, along with the greatly reduced capital requirements in terms of highways and bridges, should allow significant increases in the quality of life as well as reduced state and national public works budgets. Specific benefits include distribution of the population over a much larger area allowing a more peaceful and less damaging co-existence of man and nature, along with improved transportation safety. The vision is of multilevel highways in the sky, controlled and monitored by inexpensive and reliable electronics and communications as opposed to narrow, single- level, exceedingly expensive ribbons of concrete. Such air systems and vehicles could also obviously be used for long(er) haul, as are automobiles today, e.g., travel of 500 miles or less is currently usually accomplished via auto. With a faster personal air vehicle this distance could be the order of 1500 miles or more. This in turn would have a major impact on domestic scheduled commercial air travel, 90 percent of which is distances of 1500 miles or less. The various wait times associated with commercial air travel, along with the inefficiencies in terms of transit time of the hub and spoke system, mitigate in favor of reduced overall trip time for possibly slower, but more direct, travel via personal aircraft when compared to the faster commercial jet. Various options exist for personal aircraft systems. Certain requirements and desirements are common to any personal transportation vehicle/system. These include, besides affordability, short transit time, high speed, direct portal-to portal, privacy and security, constant availability, personal stowage, safety and a suitability for use by the non-pilot. The latter necessitates from the outset that an obvious, and probably attainable, goal should be an autonomous personal air transport system, autonomous with respect to navigation, air traffic control and operation. The technology to accomplish this is either currently employed by the long-haul air transport application, or in the research application pipeline via civilian investments in ODM/UAM and military investments in RPV's, AAV's, UAV's, UTA's, UCAV's, MAV's, Drones, UAS etc. Such autonomous operation could provide vastly improved safety, as the preponderance (70 percent to 80 percent) of air transport accidents have historically been due to human error [Ref. 14]. In addition, it makes personal air vehicle transportation available to the general public, as opposed to the few who have the opportunity, wealth, and physical characteristics and health to become pilots, as well as reducing the unit cost by an order of magnitude or more due to the concomitant vast increases in production rate and market. To be competitive with the automobile, a personal VTOL converticar, PAV, should have an acquisition cost in the vicinity of a quality automobile or less. Although in terms of the current main line helicopter industry, this is a ridiculous target. The advantages of a production run of millions instead of hundreds and printing; along with the current offerings of a single seat helo for $30K and a two-seat gyroplane for $20K, all at small production runs, makes the outlook to achieve such a goal possible, if not probable. The current ODM/UAM efforts could be greatly leveraged for PAV Application. As near as possible to all-weather operation is also a requirement, the same all-weather capability or better, via flow control, one now has in an automobile, which is by no means absolute. Extremely heavy rain, extreme winds, ice and snow will all either slow or stop the auto, and similar restrictions will probably hold for the PAV although technologies to greatly improve the current aviation weather impacts are certainly possible going forward via materials, flow control and AI. Obviously, the evolving detect-and-avoid technology could be utilized, either on or off board, to increase safety vis-a-vis extreme weather. Over the years, particularly since the 1930's, there have been suggestions, and in some cases strident calls, for the development and mass marketing of personal aircraft. Although general aviation has made considerable advances, the aircraft for the masses never really caught on for a variety of reasons, mainly involving cost, lack of requisite technology readiness and an absolute requirement that the operator be a pilot, e.g. non-automatic operation. History is replete with examples of concepts which are good ideas and which keep resurfacing until the technology base and market are ready. Since the last personal aircraft campaign in the late 40's-50's, major strides have occurred in several enabling technologies. These include light weight, miniature, inexpensive and tremendously capable electronics and computing hardware, lightweight composite materials with nearly infinite fatigue life, computational fluid mechanics, smart-to-brilliant materials and skins, flow control of several types, active controls and load alleviation, additive manufacturing, AI, and electric propulsion. Such advances significantly change the personal aircraft feasibility discussion. There are several systems level issues and critical choices regarding the personal aircraft which serve as key discriminators in the selection of a particular personal aircraft design. The first such issue is whether the personal aircraft, either fixed or rotary wing, should be a separate air vehicle, or a converticar, i.e., a combination automobile and air vehicle capable of economically performing both missions.

Economics and utility strongly favor the converticar option. There are numerous elements common to both the air and ground vehicles, such as passenger compartments, electric motors, etc. Therefore, since it is technically feasible to reduce the weight of an auto to what is reasonable for an air vehicle, a single vehicle should be considerably more economical in terms of initial cost and maintenance than buying and maintaining two separate vehicles. Simple estimates of the flight-specific component weights indicate a value of less than 1000 pounds, and therefore with shared utilization of common systems, the all-up weight of the converticar could be in the reasonable range of 3000 pounds or less. From an operational viewpoint a single vehicle should be much more convenient, obviating the need for a rent-a-car in the vicinity of one's destination. Once the converticar option is selected, some decision has to be made regarding the provision for the air-unique components, particularly the lift-producing surfaces which require, for reasonable levels of drag-due-to-lift, non-trivial span and aspect ratio. Options include towed trailored wings utilized in early versions of the converticar, fixed wings of inherently low aspect ratio for roadability, airport rent-a-wing concessions where the wings are attached prior to, and removed at the conclusion of flight and telescoping or folding wings. The present author favors the telescoping or folding option as offering the best compromise between convenience and performance. The next critical choice is between conventional fixed wing operation and a rotary wing device or compound machine. VTOL or Super STOL option would allow development and usage of currently undeveloped nations or regions at a fraction of the cost of the roads and bridges usually required for such development, and at much less disruption to the environment. To avoid the swarm problem the vehicle would probably be constrained to operate in the ground vehicle mode in currently highly congested areas and only allowed to go airborne in lower population density areas unless they are over-flying. Eventually such a vehicle could change current land use patterns and allow reduced population density, with an effect on the current built-up suburbs similar to that of the automobile upon the central cities.

Similarities between the horse-to-auto transition and potential auto-to-PAV include occurrence in the early part of the century (~ 100 years apart), both provoke major changes in land use and ecology, lead to atrophy of concentrated population centers, revolutionize the nation's economy and builds upon nation's technological strengths, and have an equivalent percentage increase in speed and personal action radius or freedom of action and privacy. Differences between the two are favorable to the converticar, which should enhance safety and for which the infrastructure is largely in place. We do not have to clear and pave the watershed at prodigious cost, as required by the auto. The safety issue for the converticar can be approached via autonomous operation and a combination of vehicle parachutes and energy absorbing, crash worthy structural material design. It is not clear whether such a vehicle would make sense economically, technically and society-wise for those areas, such as parts of Europe, which are densely populated, and for that portion of the human race who prefer to live in crowded conditions. The IT telepresence revolution appears to be removing much of the economic rationale for such population concentration. Particularly enticing converticar markets include places with few intercity roads such as island nations Indonesia and Malaysia, Siberia, Northern Canada, Parts of Africa and Alaska. These machines will and in fact are being developed because the technologies are now ready, we can now do this, for cost avoidance in terms of infrastructure, because the telepresence emerging lifestyle requires such connectivity. The carnage on the roadways and increasing auto trip times and aggravation and the huge markets, extremely interesting business cases makes this potential future possible. Congress in the U.S. has allowed access into the NAS for UAS making the likelihood of PAV, UAS carrying passengers, access into the NAS likely in the near future.

The current ODM and UAM efforts are investigating, building and flying prototypes of alternative approaches to the VTOL needed for urban, focused ODM/UAM. With electric propulsion, distributed propulsion and flow control the literature is rife with large numbers of non-helo VTOL devices and approaches with several to many lift fans. The many issues and drawbacks of helo approaches are well known and documented. These newer, evolving VTOL approaches are an advance over helos, with some utilizing tilting components and utilizing some of the fans for cruise propulsion. Typical benefits include lower noise, drag, vibration, cost, maintenance, and greater safety. As the costs of renewables for electrical generation continue to drop and the batteries continue to improve, it is increasingly feasible to unload the lift fans for improved acoustics. Not yet evidently seriously considered for ODM/UAM or PAV for VTOL operation is a stacked, stopped rotor for efficient cruise lift fan. This could possibly reduce drag due to lift via a biplane effect, with the stacked, stopped rotors distributing the lift in the vertical direction. For super STOL operation there is the channel wing with circulation control, and for lower cruise speed STOL various flavors of auto gyro.

For PAV, electric propulsion eliminates engine exhaust noise, enables distributed propulsion and flow control and lighter engines, along with many more of the many benefits of electrics stated earlier.

Another serious metric for PAV, UAS and ODM is safety. In particular, scheduled airlines are a very well developed system, have a very low accident rate. If that low accident rate is applied to the number of PAV, UAS and ODM vehicles, an increase in number from thousands to millions, there will obviously be many more crashes. If now we discount the increase in the crash rate from scheduled airline experience for vehicles which may not have the same extreme design and maintenance and regulation lavished upon commercial transports to the PAV, UAS, and ODM vehicles then even more crashes would be expected. Therefore some means of economically ensuring functional crash proof operation for such vehicles needs to be developed. There are two obvious mitigation approaches to conditions which could result in a crash, either somehow enable the vehicle to keep flying or enable a successful landing that is not a crash. To keep flying or even to land successfully in a suitable location requires thrust and controllability. So some redundancies would need to be included in the vehicle designs. The current approach involves the historical solution space of using a parachute for the vehicle, which does not provide thrust, but does supply the other functionalities of drag, speed reduction and controllability and provides a modicum of capability to keep flying, for some period of time, along with reducing impact velocity.

The ATC system required for the anticipated huge growth in the number of smallish flying things, well into the many millions from the thousands, will have to be quite different. To avoid the cost and latency of human controllers and provide the requisite raw capacity, it will have to become autonomous, and going forward it will control autonomous aircraft. The system will probably initially be developed as a simulation to check out all the component parts and their system of systems interactions, using data from, but not interacting with, the existing ATC system. The simulation could then be utilized to run a physical test out in controlled airspace and after such successful demonstrations the simulation hardware becomes the ATC system. The existing system must work constantly, as such trying to do a massive change to it is not really feasible. An entirely new system must be developed. Such a new, autonomous ATC system is essential going forward to enable PAV. The simulation would be utilized to develop and prove out and incorporate into a usable system the critical components. Communications, sensors, actuators, navigation, software, computers, AI, architectures, and redundant capabilities will be necessary to ensure resilience in the face of weather and equipage malfunctions of both ATC and vehicles. The NASA Smart NAS approach is a start on such a simulation.

Electric Long Haul Transports – A truss braced wing design is proffered an example of what may be possible for an electric long haul aircraft design [ref 15], use of an external wing truss provides major structural benefits, and allows reduced wing weight, thickness and sweep, resulting in a tremendously enhanced and easily maintained, with reduced sensitivity to roughness, insect remains, ice clouds, and reduced cross flow extent of natural-to-easily forced low drag laminar flow, along with increased span. The latter allows a reduction in wing chord, further enhancing the extent of laminar flow, as well as a reduced vortex hazard. Plenninger's designs for such aircraft yielded L/D values in the 40's, over twice current levels with one of his studies which included a laminar fuselage yielding a machine with L/D = 100, 700 Pax and 200,000 Km range. The concept was not, however, adopted primarily because the extensive wing span did not fit the FAA 80-meter box requirement for airport gate compatibility, and the disbelief that a transonic strut or truss braced wing could be designed with acceptable shock drag and obtain laminar flow on the strut or truss. Obviously strut-bracing is routinely employed on lower speed aircraft. The latter objection is probably not valid in light of today's CFD capabilities. In general, we build what we can compute and we have been too long constrained in aircraft design to linear theory and the consequence is linear thinking. Indeed, lack of adequate or believable first principles estimation methods for not only performance but cost, maintenance and operability, etc. are a major reason why work on advanced aero concepts has lagged. Much of our current systems methodologies are essentially extrapolation and interpolation procedures based upon, and therefore largely restricted to, empirical data from the current paradigms. Improved computing machine capabilities and mod-sim developments are changing such considerations and judgements in real time. The span of a truss-braced configuration can probably be doubled and a hinge already studied and applied in industry could be utilized to conform to the 80-meter gate requirement. Doubling the span would halve Reynolds number on the wing and reduce drag due to lift on the order of 75%. Combining this DDL reduction with the extensive wing laminar flow results in most of the remaining vehicle drag being fuselage friction drag. Such drag can be addressed in several ways. The most dramatic is to apply boundary layer relaminarization just downstream of the cockpit or forward door. The aircraft nose region with the radome, probes, windshield, wipers etc. will be turbulent, and therefore need to ingest or take aboard greater than 150% to entrain the turbulent superlayer of the local fuselage turbulent boundary layer and reestablish laminar flow. The increasing use of personal view screens versus windows greatly eases the task of maintaining laminar flow downstream. The air taken aboard can be slot injected into the wing-fuselage turbulent flow wedge to accrue local skin friction reduction. The electric motors can be moved to the rear of the fuselage, surrounded by a Goldschmied shroud. This would enable several interesting and useful functionalities. The propulsion exhaust flow could be thrust-vectored, obviating the weight and drag of the empannage. The shroud provides copious volume for acoustic treatments. The propulsion system ingests the fuselage boundary layer accruing a sizable propulsion improvement. Then there is the oft mentioned but still under study Goldschmied effect [ref 16] that purportedly could cancel a sizable portion of the fuselage friction drag. The thought is that possibly putting sinks inside the body using the cowl could convert the back of the cowl into a stagnation region, thereby producing what Goldschmied called favorable interaction static pressure thrust.

The gear weight could be reduced in several ways. One is to utilize parachutes instead of super heavy brakes for refused takeoff. Another is to utilize wholly autonomous landings with the controls slaved to the altitude or ground proximity and decent rate to take out the impact loading. Yet another is to employ imbedded hydraulics in the gear structure to provide rigidity only when needed versus carrying the weight throughout the mission. All of these benefits reduce overall vehicle weight, which along with clever vortex flow control can reduce the wake vortex hazard. The advanced materials mentioned previously could be applied, further reducing dry weight. The computed L/D for these configurations is in excess of 40 or higher, vice the current values the order of 20 or less. It should be noted that we have no detailed studies of truss braced wing truss optimization. The studies thus far have been at the systems, not the detailed design level. We have never been here before. Obvious options include pre-stressing, hydraulic dynamic internal pressurization, laminar elements, arching, Y-intersections with the wing to avoid supercritical flow regions, optimizing the overall number, nature, positioning of the elements, etc. The truss could be carried out beyond the wing hinge position; all of these options and far more are forward work.

Electric Supersonic Transports – Electrics for SSTs is a major enabler. They fly above the tropopause where, even using bio or hydrogen fuels, the water in the exhaust is a major climate problem, in fact is thought to be more serious such than CO_2. The only realistic way to solve emissions for SSTs is to go fully electric. Also, the increased efficiencies enabled by electric propulsion could provide the requisite solid economic case, especially when compounded by the several other concomitant breakthroughs, including materials, manufacturing, and supersonic through-flow fans. Compared to existing SST aero designs, with an L/D in the 10 range, a strut braced extreme arrow configuration could provide the order of 16 L/D.

Thus far SST's have not been particularly successful, either conceptually or in actual realizations. The Concord was a technological marvel for its time but not commercially successful. Similar remarks hold for the TU-144. The basic SST issues are confounded by the addition of serious wave drag, higher fuel fractions, higher temperatures, and greater weights, all driving up vehicle cost. Then there are the high-altitude emissions problems, far more incident radiation, and the sonic boom, the latter causing anti-SST legislation. The sonic boom affects both people and things. There has been success in reducing the N-wave peaks that affect people but reducing the low frequency rumble that affects buildings, etc. is a much more difficult task. Taken together, the various and in some instances rather extensive studies over the years since Concord of SST potential viability, especially economic viability, have not been optimistic. There are concentrated studies ongoing of SST Business jets as such smaller vehicles both reduce the massive investment level required to field such machines and also reduce the sonic boom, which is first order dependent upon weight. Advanced Configuration SSTs come in five major categories, unswept, thin natural laminar flow wings, parasol wing with favorable interference, multi stage aircraft, yawed wings and the Pfenninger extreme arrow strut braced wing [ref 17]. The multi-stage approach usually involves a stage which includes the capability to get off the ground with acceptable noise and high lift and then separates and returns to the airfield. The portion of the aircraft that lands at the end of the flight weighs far less, allowing carriage of lighter weight gear and high lift systems. In-flight refueling is another multi-stage aircraft option. The yawed wing approach uniquely provides a low supersonic Mach number option that is nearly boomless and extremely efficient. Of these, the Pfenninger extreme arrow strut braced wing appears to have the greatest SST potential, essentially doubling the Concord L/D of 7.3ish. The best NASA did in the HSCT/HSR program of the late 90's was an L/D in the range of 9.5. The Pfenninger designs proffer values in the range of 14 to 16 plus. The extreme arrow wing minimizes wave drag due to lift and wing wetted area as well as providing a credible span for vortex drag minimization. The short wing chord aids suction laminar flow control. There are mid-wing fuel canisters for favorable wave interaction and load alleviation with the possibility of natural laminar flow on the forward regions of the fuel canisters and the fuselage. Several approaches utilized to optimize the truss braced CTOL design can also be applied to this SST including gear weight reductions via automatic landings and parachutes for refused takeoff and C-Wing tips to reduce DDL. The serious takeoff jet noise issue can be addressed via an essentially new approach by disabling or reducing the causative turbulence dynamics versus reducing the jet velocity via entrainment using heavy mixer-ejectors. Experiments and some theory indicates that the injection of liquid water jets, suitably tailored for effectiveness and minimal water mass flow can place water droplets in the mixing region of the external jet which reduces turbulence intensity and noise. The water injection produces additional thrust versus the mixer-ejectors that reduce thrust and is a way of staging the aircraft, the water is only utilized during takeoff, and does not have to be carried throughout the flight as does the mixer-ejector. Having such a high L/D provides the margins necessary to address the myriad SST problems. Probably next-in-line in terms of efficient SST configuration approaches would be the oblique or yawed wing and work on a bi-directional flying wing concept and the NASA N+3 SST studies. The former is due to R.T. Jones and is well discussed in the literature. The bi-directional approach is circa 2011 [ref 18] and involves a design based upon 90-degree rotation of the configuration for supersonic versus subsonic flight. The design thereby provides major alterations in aspect ratio for each speed range, enabling true bi-modal performance with excellent aero performance for both supersonic over water and subsonic over land. The overall approach is similar in philosophy to the variable sweep and yawed designs, but executed in a wholly novel fashion, with efficacy still to be determined. Such bi-modal aero performance improves the overall performance for the mission and reduces required energy.

Electric propulsion for SST's could involve a quite different approach from that for fueled aircraft. Instead of a combustor and a turbine to drive axial flow compressors, very light weight, very efficient electric motors would drive them. The initial stages of compression could involve supersonic through flows. Rather than combustion providing the cycle enthalpy increase, batteries would provide such, primarily as compression, with thrust produced via subsequent flow expansion out the nozzle. Such engines should be more efficient than GTEs, with many other benefits as discussed previously. To further increase efficiency the heat produced by the compression, the stagnation of the supersonic free stream and the motors could be regenerated and used to produce additional electricity to propel the aircraft. There are a plethora of extant energy conversion approaches to enable this including thermal electrics, pyroelectrics, sterling cycle heat engines, etc. It also may be possible to efficiently radiate heat from the wing surface to cold space via specific wavelengths [ref. 19].

Electric propulsion for SSTs is in an early research stage, with ideation, and R&D optimization required especially for such as propulsion cycles, boundary layer control, including shock-boundary interactions to increase compressor stage loading and to obtain favorable shock wave interference, minimization of shock losses in the inlet and compressor stages, along with further work on supersonic through flow fans and possibly morphing blades. A selected precis of research opportunities includes the revolutionary materials, e.g. the 5X, 1300 C MIT materials, which would both reduce the requisite cooling and weight. The combination of greatly improved materials and aero performance, coupled with electric propulsion could conceivably successfully address all of the extant major SST issues, emissions, efficiency, cost, and due to the resultant battery weight and dry weight reductions even sonic boom.

Concluding Remarks

As is the case with the current acceleration of renewable energy development, the combination of cost reductions, and serious climate impacts is an accelerator for electric transportation writ large, including electric aircraft across the speed range. There are a plethora, cited herein, of very sizable cost and operational benefits which accrue from switching to electric propulsion for air travel. The emission benefits include obviation of water addition above the troposphere, the most serious current aircraft emission with respect to climate impacts, along with eliminating CO_2 and NOx. Given the rapid development of renewable energy to recharge the batteries, electric aircraft would be increasingly emission-less. The single most serious impediment to electric aircraft development is the energy density of batteries. Recent research indicate the potential for 750 recharges and 15 times lithium ion battery energy density for lithium air batteries. Also, there is the announcement of a 500 Wh/kg lithium-metal battery on the market in the nearer future. This research has, advanced to the point where, at the system level, parity with combustion engines coupled through mechanical drive trains can conceivably be achieved over the next decade.

Contained herein, are a large number of approaches to reduce energy requirements and battery weight by reducing aircraft empty weight and reducing drag. Revolutionary aircraft concepts, configurations and technologies would make electric aircraft even more feasible and desirable and their development enabled sooner.

Overall, gas turbine engines, heavy transportation fuels may be approaching a pivotal game changing moment in their history, enabling in the process the UAS/ODM/UAM/PAV revolution in human and material transportation, this time on the personal level, as well as enabling viable SSTs, while also greatly reducing the climate impact of aviation...

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14. ABSTRACT

Climate concerns have instigated serious research for weight critical batteries to enable what are termed EVs, electric vehicles, initially for ground transportation. This research has now advanced to produce lithium air batteries, which are essentially at chemical energy density, with thus far 750-recharge capability. Concomitantly, renewable electric generation, which would enable essentially emission-less EVs, has via cost reductions, efficiency improvements and storage research advanced to producing some 25% of electrical generation and some 62% of new generation capability. The present report examines the resultant electric aircraft possibilities, opportunities across the speed range including the many , besides emissions reduction, benefits of electric propulsion and the enablement of a new massive Aero market for affordable, safe personal air vehicles that operate off of local streets.

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