ABSTRACT

The ability to personalize air travel through the use of an on-demand, highly distributed air transportation system will provide the degree of freedom and control that Americans enjoy in other aspects of their life. This new capability, of traveling when, where, and how we want with greatly enhanced mobility, accessibility, and speed requires vehicle and airspace technologies to provide the equivalent of an internet PC ubiquity, to an air transportation system that now exists as a centralized hub and spoke mainframe. NASA airspace related research in this new category of aviation has been conducted through the Small Aircraft Transportation (SATS) project, while the vehicle technology efforts have been conducted in the Personal Air Vehicle sector of the Vehicle Systems Program. The PAV sector technology research conducted over the past several years is described, including intelligent avionics for ease of use, integrated low noise propulsion, advanced internal combustion engines, low cost variable pitch ducted propellers, lean design structures, quality assurance based certification regulations, a laminar flow fuselage with integrated aero-propulsion, advanced vehicle concepts, and high density airspace simulations.

INTRODUCTION

This paper provides the technology development portion of a trilogy of papers that report out the results of the Personal Air Vehicle (PAV) Sector of the NASA Vehicle Systems Program (VSP). The NASA VSP was cancelled over the past year as part of the Aeronautics Enterprise restructuring, being replaced by the Fundamental Aeronautics Program. Since no further investment is currently planned relating to small aircraft, transitioning this research to industry is imperative to maximize the potential societal benefit. These three papers present the project research, incorporating the overarching system of systems perspective of this vehicle sector (The Third Wave of Aeronautics: On-Demand Mobility - SAE paper 2006-01-2429), the technology portfolio investment required to enable PAV sector capabilities (NASA Personal Air Transportation Technologies – SAE Paper 2006-01-2413), and the integrated vehicle concept development required to achieve a balanced and complementary technology portfolio (Next Generation NASA GA Aircraft Concept – SAE Paper 2006-01-2430). The PAV Sector was the smallest of the six VSP vehicle sectors, with a full cost investment of $10 million dollars over the 3 years.
While not the solution to all travel, PAVs would provide a new, better choice for mid range trip distances of 50 to 500 miles where airlines and automobiles provide poor block speed service. Since this travel market accounts for almost half of all person trip miles in the U.S, it is more than a niche market that deserves effective cost to utility solutions to provide societal benefit. This supplemental personal air transportation network would do what car, airline, or rail could never do; combine on-demand access with high speed to yield a direct extension of the wireless, fax, and internet on-demand service age. At the same time, this new capability could maximize transportation capacity, robustness, and productivity. The first figure indicates how specific technology investments could yield integrated solutions which would offer increasingly distributed air operation capability. An analogy is presented to the computer industry which has transformed itself over the past 30 years from a highly centralized market solution, into an incredibly distributed market solution. This computer market revolution was driven by a combination of performance, packaging and cost technologies, which when combined with ease of use technologies (the Windows and Mac operating systems), the result was a much broader market with greatly increased revenues, while serving the customer better. The current aviation market offers an ‘innovator’s dilemma’ of trying to meet entrenched market needs through ever smaller incremental improvements to existing customers, instead of developing disruptive technologies that create new value networks. A detailed discussion of this potential ‘Third Wave of Aeronautics: On-Demand Mobility’ is presented in SAE paper 2006-01-2429.

At the commencement of the PAV sector efforts, an industry/academia/government working group was established to provide guidance on technology content and priorities. In addition, an independent review panel of industry ‘grey-beards’ provided continuous improvement of the technology project efforts. These meetings established a PAV sector GOTChA2 (Goals, Objectives, Technology Challenges, and Approaches – see Appendix) documentation set which decomposed efforts into a capability-based research plan with tracking metrics. These desired end state capabilities are listed below in Table 1, and are discussed in more detail within each technology approach section. The technology approaches were prioritized into near-term 5-year and far-term 15-year efforts, with available funding limiting current research to primarily the near-term set except for a few exploratory far-term efforts. An important distinction which occurred at the start of the research planning was defining the PAV as a self-operated vehicle meeting personal transportation needs; therefore a PAV is not necessarily personally owned or maintained, since fractional ownership offers dramatic benefits in cost through increased utilization. An important realization from this capability set is that the PAV technology efforts are not centered around achieving improved performance, but instead focus on improving the ‘ilities’ of the operational experience. In fact, as with most disruptive technologies, the focus is not on improving existing customer demands (established pilots) for improved performance, but instead meeting new customer requirements that would permit the current market to greatly expand, and reach greater economies of scale for all.

<table>
<thead>
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<th>Required Capability</th>
<th>SOA</th>
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<th>15-Years</th>
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<td>Haptic</td>
<td>Auto-like</td>
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<td>Community/Cabin Noise</td>
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<td>Motorcycle</td>
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<td>Field Length (feet to clear obstacle)</td>
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SEP-IFR = Single Engine Piston with Instrument Flight Rating

Table 1. Desired Near-term and Far-term PAV Capability Sets

The near-term 5-year Personal Air Vehicle (PAV) capability goals will achieve an ease of use equivalent to the automobile, a community noise level with a ten times reduction in noise energy levels, a 90% reduction in environmental emissions, and the ability to achieve a three times reduction in cost through the synergistic combination of new vehicle technologies, regulations, and manufacturing methods. These capabilities will enable a next generation General Aviation (GA) aircraft to travel distances of 500 miles as safely as commercial airlines, have a reduced overall door-to-door trip time compared to auto or airline while cruising at 200 mph, and fractional ownership affordability on par with a luxury automobile rental. This travel will be accommodated from the nearly 18,000 U.S. airfields that hosted FAA operations last year. In the past, small aircraft have been restricted to recreational or exclusive use vehicles that have not provided a significant impact to transportation, while these PAV sector technologies will provide a dramatic improvement for near-term rural and regional travel.

The far-term 15-year PAV capability goals will achieve lighter and more efficient vehicles that can even better address door-to-door travel needs. These capabilities will enable Gridlock Commuter aircraft, permitting 2 passenger vehicles that can travel 150 mph while achieving 40 miles per gallon. These vehicles would be capable of takeoff and landing distances of less than 300 feet (a football field) at local community airfields that are in close proximity to neighborhoods and businesses. The far-term vehicle technologies will address suburban and urban travel needs, permitting a 15 times improvement in daily mobility reach; that is, the ability to reach a destination within the same travel time for an area that includes 15 times more land resources than current methods. This improvement is based on achieving a door-to-door block speed of nearly four times that of automobiles which currently achieve
an average speed of 32 mph, and the mobility area being a function of the square of this block speed.

While the PAV capabilities provide an aeronautics vision as inspiring and bold as the NASA moon-shot, it is also a vision that provides the United States with an infrastructure advantage to compete in the new global economy. The digital and communications revolution over the past 30 years put many of these technologies at our fingertips, and an airspace control foundation for this mobility transformation has already been laid by NASA through the AGATE and SATS projects. But the vehicle technology-based mechanism for the next wave of the aviation PC has not been developed, and is an “as only NASA can” research objective beyond the reach of industry.

MAIN SECTION

The NASA PAV sector’s top technology priorities are the ability to achieve ease of use along with the direct coupling of improved operational safety, and a drastic reduction in community noise. The PAV sector will also benefit from applicable crosscutting technologies from the other NASA vehicle sectors, especially the HALE-ROA, ESTOL, and Subsonic vehicle sector. These crosscutting technologies include developments in autonomous flight control systems, gust loading alleviation, noise mitigation, and near all-weather operations. In addition, the PAV sector has conducted technology and system studies in cooperation with other NASA programs, such as the SBIR and Airspace programs, to leverage resources and develop the foundational breadth that is required to achieve a credible transportation solution. Each technology approach effort is described below and presented as a prioritized list based on near-term, to far-term, capability needs.

EASE OF USE HAPTIC CONTROL SYSTEM

An exciting alternative to fully autonomous or auto-pilot vehicle control concepts to achieve improvements in ease of use is being conducted in the Human Automated Vehicle System (HAVS) subproject. The concept employs a multi-modal user interface with a strong, bi-directional haptic component implemented through a force-feedback side-stick. Analogous to the reins of a horse, the interface allows a natural, variable autonomy relationship between an intelligent vehicle and its user. As desired, the user can allow the vehicle to operate in a “loose” rein mode, with a high degree of vehicle autonomy or can take a firm grip on the stick and operate in a “tight” rein mode providing the user with direct control. Even in the tight rein mode, the vehicle continues to provide hazard awareness and avoidance (i.e. self preservation instincts) functions. Through the force-feedback, the user can feel the vehicle’s desired actions and can allow them merely by relaxing his grip on the stick. A major advantage of this approach is the ability to achieve complementary failure modes between the operator and the machine, so that the combined system safety approaches the optimal safety statistic (as shown in Figure 2) of having an on-board instructor constantly teaching the user and making the pilot more proficient.

![Figure 2: Comparative Air Accident Rate (FAA)](image)

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![Figure 3: Horse Analogy to Sentient Vehicles](image)

Figure 3: Horse Analogy to Sentient Vehicles

Such a vehicle begins to simulate an intelligent transportation device that we have depended on for hundreds of years; providing the sentience of a horse in that it is an intelligent vehicle that “sees” the environment, shares its intent with neighboring vehicles, “feels” the flow over its wings, senses its internal health, and communicates with its user. Instead of a user being required to instruct the horse along a specific path, the user is able to provide the ‘intent’ while performing higher level tasks that the horse could never perform effectively (as visualized in Figure 3). From these perceptions, the sentient vehicle develops an integrated awareness of its situation and autonomously plans and executes a course of action that appropriately satisfies the user’s directives. The resulting vehicle’s capabilities will enable at least automobile levels of safety and convenience, while providing a balance between user control and security. At the same time, efficient community access will require operations with unprecedented traffic densities and proximity to hazardous obstacles. Many of these technologies are
rapidly evolving in the context of uninhabited vehicles and permits a leveraging of UAV work for a civil application that can benefit our daily lives. A Concept of Operations (CONOPs), along with 1-D, 2-D and 3-D simulations were completed this past year to validate the haptic control system, with results indicating that a 5 to 10 time reduction in pilot training could be demonstrated in the near-term, while still achieving improved safety compared to current small aircraft flight control systems.

INTEGRATED LOW NOISE-LOW COST PROPULSION

If small aircraft are ever to be acceptable to most people, environmental impacts need to be dramatically decreased. Emitted noise is the single greatest barrier to community acceptance of small aircraft today. A recent FAA comparison of aircraft noise showed that an average small aircraft today makes an equivalent perceived level of noise as commercial airliners, due to the closer proximity and time duration of the noise signature to communities. Currently there are very modest FAA noise regulations that are based more on legacy aircraft products than on acceptance, with the most modern small aircraft such as the Cirrus SR-22, emitting more noise than older aircraft. The indicated levels of agreeable small aircraft noise require a ten time reduction in the noise energy emitted to approach the public accepted noise metric of motorcycles. Even if aircraft engine systems utilized sound suppression systems, the propellers are still the noisiest part of the nois problem. Ducted propellers offer a method to significantly reduce the acoustical propagation characteristics through a combination of shielding, absorbing liners, elimination of asymmetric inflow, and the generation of higher frequency noise that dissipates more quickly in the atmosphere. System studies were first completed that indicated that ducted propeller systems, in combination with engine muffling, could achieve the proposed ten times reduction. These studies showed that there was also the potential to achieve a lower cost propulsion system, through the synergistic ability to utilize higher rpm automotive engines to drive the ducted propellers. Prior efforts, such as with Porsche and Toyota, have tried to use automotive-based engines for aircraft but without success primarily because they were attempting to retrofit these engines to the use of propellers. However due to the combination of propeller and crankcase impulse loads, along with the necessity of a gearbox, the main goal of utilizing a mass produced automotive engine core to achieve drastic cost reductions was not achievable. By using a ducted propeller these loads are compatible and the gearbox is not required due to the smaller diameter of ducted propeller. The final results of these studies, which were performed in collaboration with a propeller manufacturer, indicate that the noise goal is achievable, along with a reduction in cost by half of the total propulsion system. The critical follow-on work was then to develop an integrated airframe-propulsion system (such as visualized in the advanced concept in Figure 11) that could meet both noise and cost goals without adversely impacting other elements of the aircraft, while validating the ducted propeller characteristics with higher-order analysis tools and experimental methods.

The past year’s effort has concentrated on utilizing advanced aerodynamic methods (NASA Glenn ADPAC code) to analyze integrated propulsion concepts to minimize noise and efficiency interactions with the airframe. This analysis includes wake deficits from structural attachments such as the stators so that a very accurate representation of the flow is achieved for both the takeoff rotation design sizing condition, and the cruise condition. This analysis has permitted a significant improvement in efficiency over the initial reference conditions, with an optimization of the duct and centerbody shape to provide a balance between low-speed and cruise requirements. The results of this CFD analysis then permitted additional iteration with the propeller hub and blade analysis by the propeller company to further refine the design results. Acoustic and performance experimentation are now required to validate the analysis results, which have the potential to yield a major technology advance in small aircraft propulsion.

![Figure 4: Tail Mounted Ducted Propeller Flow Results from ADPAC (NASA Glenn).](image)

LOW COST DUCTED PROPELLER VARIABLE PITCH HUB AND BLADE SYSTESM

A simplified variable pitch hub and failsafe blade mechanism was developed that will met a 50% reduction in propulsion system cost goal. For low noise propulsors to be advanced into the market place, it is absolutely essential that cost is able to be shown as a benefit over existing propeller systems. Since the ducted propeller is inherently more complex than a simple propeller, a fresh perspective that looks at ways that not only achieves a drastic engine cost reduction, but also a reduced hub cost was required. This research was accomplished by working with a manufacturer of composite kit propellers, AeroComposites Inc., who developed a unique variable pitch hub system that is dramatically simpler, more robust, has a failsafe
retention system, and offers the opportunity for significantly lower costs. The blades are attached through dual composite ‘straps’ to a rotating rod system that achieves low pitch loads, eliminates counterweights, and is also lighter than a conventional variable pitch system. The hub system will accommodate many different blade numbers for a range of ducted propeller loading. Combined with the low noise duct analysis, the results of this hub and blade design indicate that 78% installed efficiency can be achieved, while still accomplishing the ten-fold decrease in noise energy (or 30 db reduction). While many will consider a 78% efficiency to not be impressive compared to advanced propeller efficiencies of 85% to 90%, this is a misleading comparison since the quoted propeller efficiencies are not installed. Nose mounted propeller suffer from significant installation losses, including scrubbing drag from the propeller slipstream over the body as well as body blockage. Rear mounted propellers suffer from inflow distortion losses that are typically equally as bad. Essentially the installed efficiencies are approximately equal, and this includes accounting for the duct drag. This is another reason why a complete system vehicle perspective is required as these individual technologies are developed, to insure synergistic complementation between technologies and the overall system. When all the elements of the ducted propulsion system are combined (including the automotive-based engine), the result is a complete 300 horsepower propulsor package at a cost of approximately $20,000, which equates to a cost reduction of approximately 50% from existing aircraft engine/variable pitch propeller combinations.

In order to understand the differences imposed by current Quality Control (QC) approaches versus QA, two case studies were performed of engine certification efforts that started with QA-based automotive products, but were turned into QC-based aerospace products. The Toyota Lexus-based FV-400 and Thielert Mercedes-based Centurion 135 are certified engines that provided valuable FAA certification datasets, and are unique in starting with an automotive engine as the initial core engine. While the Toyota engine never went into full production, it was a fully certificated engine with both a Type Certificate (TC) and Production Certificate (PC) granted to Hamilton Standard as the US partner supplier of the FADEC system for the engine. FAA records demonstrated that Toyota approached the certification of this engine with an aviation mindset, while attempting to utilize an automotive core. It is clear that almost no commonality between the original engine mindset and the aircraft version resulted. This was in part due to the propeller loads being carried on a relatively small crankshaft (compared to aircraft engines). But equally important is that the certification approach was as if a turbine engine was being certified, as Toyota/HS applied a higher standard to their effort, and induced many of their own certification cost problems. Many insights were developed from this example, as Toyota even
went so far as establishing a production line for the engine, which however, was completely separate from the Lexus engine line. In essence, this example showed the futility of attempting to start with a fantastic QA-based auto product, and attempt to retrofit it into an incompatible use, while turning it into a QC-based aerospace product. The result of this effort was a very expensive engine that was no better than the engines it was attempting to replace, and thus, full production was not justified.

The Thielert certification effort was equally illustrative, but in very different areas of certification compliance. While starting with a Mercedes engine, and maintaining over 60% part commonality, Thielert has no control of the processes or production of the core engine, which is a requirement the FAA mandates for inspection compliance. The Centurion engine was fully certified with the German LBA prior to application in the U.S. with the FAA. The TC was readily accepted through the bilateral agreement between the FAA and LBA, however the FAA raised reasonable concerns over the PC issues of production control and conformity. In the end, the FAA (under some political pressure) accepted the LBA was qualified to make production control and conformity judgments, and certified the engine without access to supplier inspections. This is a very important issue since a precedent was established with this engine in terms of QA production practice acceptance (Mercedes and US automotive manufacturers use similar quality methods). However, no formal policy was written pertaining to US suppliers who wish to follow the same certification path as Thielert, providing an approved process that lacks repeatability, with questionable conformity compliance. This places U.S. manufacturers at a disadvantage to any foreign Tier 1 engine supplier (with a bilateral agreement with the FAA) who can follow the same precedent and readily certify a QA based auto engine, without providing access to the part suppliers – while a U.S. company could not.

Another element of the case studies was to understand how FAA regulations could be modified or adapted to meet the needs of high volume COTS parts certification. Fortunately, the FAA had recently finalized a new Light Sport Aircraft (LSA) rule set that parallels the intent of this requirement research. Important aspects of the LSA certification set is the ability to receive production certification through ‘consensus standards’ of quality assurance, and permits a new recreational airmen classification with reduced flight training requirements. While these rules are limited to a specific aircraft type (less than 1320 lbs all up gross weight, 2 place, single engine, private use), they are a prototype of what could be achieved with larger private aircraft by providing the FAA with operational impact data for future extrapolative rulesets. A key difference with the LSA regulations is that the FAA empowers the American Society for Testing and Materials (ASTM) as an agent for the FAA, allowing manufacturers to certify airworthiness without direct FAA oversight or plant access. Another important aspect of LSA is that the consensus standards are no longer considered a minimum only, but are effectively a contract between the manufacturer and owner/operator. The ASTM has provided these same types of consensus standards to other industries such as medical devices and amusement parks, and provided a reduction in litigation liability because the industry/government/public consensus standards hold up to better scrutiny than a government mandated minimum. Since litigation expenses have been presented as a major cost element of small aircraft, this is a key side benefit which was unanticipated, and is being further investigated.

![Figure 6: General Motors LS-1 Corvette Engine in Test Cell (Design Ideas Inc)](image)

The second element of this research involved a comparison of potential automotive engines, and FAA endurance testing of the best candidate to determine the engine durability at sustained high rpm operation and certification compliance. A comparison of 8 readily available all aluminum engines was performed within a range of 200 to 400 horsepower. Metrics including cost, weight, geometric packaging, efficiency, and aircraft compatibility indicated that the GM LS-1 Corvette was best suited for ducted propeller direct-drive integration. Unmodified the LS-1 engine provided 280 hp at 4000 rpm with a complete running engine weight of 530 lbs, while achieving better than .45 specific fuel consumption, at a retail cost (purchased one at a time) of less than $5000. This compares to a Teledyne or Continental aircraft engine of approximately the same horsepower costing about $32,000, with about a 100 lb lower weight. However, in many respects a pure weight comparison does not tell the complete story, since the LS-1 V-8 has counterweights to achieve drastically lower vibration, is water cooled to achieve significantly better fuel consumption, and avoids pre-ignition with lower grades of gasoline (thus eliminating the need to burn 100 low lead aviation gasoline), while achieving drastically lower emissions (the LS-1 is certified as an ultra low emission engine). A 150 hour FAA Part 33 test was conducted with the engine alone with an electric dynamometer. No simulated ducted propeller loads were introduced into the engine tests, which would be required for full compliance with this testing. However, ducted propeller loads are significantly lower than propeller loads since there are 7 blades (versus 3). Feedback from the engine into the ducted propeller is
also decreased due to the engine being a balanced 8 cylinder, instead of a large bore 6 cylinder. Since a torsional dampening system would be implemented with the extension shaft connecting the ducted propeller and engine, these shaft frequency issues were considered to be of less importance. The LS-1 engine fairied very well on this harsh test (which many equate to approximately 600 hours of normal use), with only a small drip leak from the water pump being observed. A complete teardown was performed both prior and after completion of the test, with wear measurements being negligible. Certification of this engine would mirror the Thielert engine in terms of the engine being life-limited and not rebuildable. The testing results indicated that with only minor external modifications (including a second engine controller with different software to eliminate simultaneous failure modes and a modified alternator pulley reduction ratio) would be required to meet the FAA regulation intent. One common misconception is that the FAA would require dual sparkplugs, however this is not the case, and the LS-1 does have 8 ignitors (one per spark plug) so that redundancy is built in and complete failure of the ignition system is not possible.

Current efforts continue with the collaboration of the FAA and NexTechnologies to review QA with industry to determine if such systems would be viable for FAA approval. Because of the desire to employ mass production techniques, while maintaining a very robust quality assurance (QA) system, the automotive QA system, TS-16949 was identified as the QA system directly applicable to this effort. Further the TS-16949 is a direct descendant of the ISO standard, which is the basis for the SAE AS9100 Quality Management system, currently employed by many aviation manufacturers today. This research activity will perform a trial TC and PC for a COTS automotive engine as an example that any U.S. company could follow.

HIGH PERFORMANCE HEAVY-FUEL ENGINE

Since the use of an automotive engine was initially perceived as high risk, an alternative low cost, moderate rpm reciprocating engine solution for quiet ducted propellers was also desired. Since the General Aviation Propulsion (GAP) program had previously investigated a Teledyne Continental turbo diesel and Williams EJ-22 turbofan engine (with far greater resources than our project, on the order of $60 million), the potential for solving this significant challenge with an all new engine design seemed very doubtful. However, in reviewing the original GAP engine proposals, we re-evaluated a relatively high risk effort after several years of private and Department of Commerce Advanced Technology Program investment. Significant risk reduction had been accomplished since the GAP program through single cylinder testing, and with only marginal additional investment it appeared possible to achieve a major breakthrough in small engine technology. The intent of this effort is a high specific output, omnivorous heavy fuel capable engine for PAV and UAV applications. Three engines are being developed in the 50, 100, and 125 horsepower sizes that will achieve lighter weight and lower fuel consumption than current small aircraft engines. These engines are also capable of burning any heavy fuel, because they are variable cetane and lubricity capable. This multi-fuel capability is a difficult problem as most diesel engines have significant problems with high pressure fuel injector maintenance with low lubricity fuels (such as JP-8), and compression knock with cetane variability (with significant variance across JP fuel types). Achieving a high specific output engine with .80 horsepower per pound ratings at 50 to 100 horsepower sizes, coupled to omnivorous fuel capability is therefore highly desirable, but has been extremely difficult to accomplish. Since low emissions is also a desired PAV capability, the ability to achieve zero ‘net’ carbon emissions when burning any bio-diesel fuel, and not be reliant upon 100 Low Lead fuel was also of primary importance. A unique cylinder head and Self Injection Engine Technology (SIETEC) permits these engines to have no electronic control, and achieves compression ignition with only the use of low pressure fuel injection (there is no high pressure fuel injection system present unlike other compression ignition engines). These characteristics lead to lower engine and certification costs, which are also primary PAV capability concerns. Multi-cylinder testing is currently being conducted to verify engine performance and longevity, with prototype engines being delivered as a compact hub integrated V geometry, and a horizontally opposed 6 cylinder, along with a turbocharged variant.

Figure 7: High Specific Output 6-Cylinder, Heavy-fuel 100 Horsepower Engine (GSE Inc)

BOUNDARY LAYER PUMPED PROPULSION

While it is the view of the author that only reciprocating engines can achieve the PAV cost goals in the near-term, many participants of the planning reviews felt that the current wave of small turbine engines could enable economically feasible turbine solutions. To accommodate this perspective, a technology approach was selected to enable a highly integrated turbofan engine, similar in low noise capability to the ducted propeller. This integrated propulsion concept incorporates an internal empennage turbofan engine configuration that uses fuselage boundary layer ingestion for intake air to promote laminar flow over the
aircraft body. Essentially the turbofan engine intake air acts as a pump for the boundary layer ingestion, and promotion of laminar flow over almost the entire fuselage. Results from a ½ scale Univ. of Washington wind tunnel test show that laminar flow was achieved over 90% of the fuselage length\(^1\), providing improved efficiency compared to a conventional rear pylon engine mount. The key to accomplishing low internal drag is a rapid deceleration of the internal flow (without separation), so that the internal tail volume acts as a low velocity plenum for the engine. This low velocity intake promotes higher propulsive efficiency, as well as uniform inflow characteristics which are highly important for the achievement of low noise. For this concept, it is conceivable that there would be a drastic reduction in the forward fan noise, as the internal volume acts as a noise baffling shield. There are many unknown issues that still inhibit the potential of this integrated propulsion concept, including door, window and hatch openings that will trip the laminar flow long before the fuselage inlet. However, these issues could be addressed in UAV concept applications where limited payload access is required. Additionally the inlet area may be sensitive to off design conditions, and variable inlet geometry may be required to accomplish a reasonable high speed to low speed capability. Unique positive characteristics of this concept include the ability to use low strength fan blades since bird strike issues are not present. The further possibility of using fixed pitch blades could result in a very low cost fan system.

Seabee demonstrated the longevity and robustness of skin-stiffened structures, with little evidence of corrosion, buckling or structural defects.\(^2\) Inherent to the skin-stiffened structure is the extensive use of symmetry (for instance the wings incorporate no taper) to achieve very low unique part counts and limited tooling requirements. Again, this research effort demonstrated that the structural technology could not be separated from integrated vehicle concept development. Across the entire vehicle design, there was a bias for trading off small amounts of performance, for large cost improvements.

Estimates based on the original Republic manufacturing processes and the revised skin-stiffened concepts indicated that labor reductions from approximately 2500 assembly hours to 300 was feasible. Reference assembly hours of current GA aircraft include the Mooney at approximately 4500 hours, and the Cirrus SR-22 at approximately 3500 hours (although the SR-22-G2 is reported as approximately 1800 after a focused redesign effort to incorporate lean manufacturing practices). Assembly labor still compares unfavorably to automobiles, with Chrysler averaging approximately 45 hours of assembly time per auto, and Mercedes averaging about 130 hours. While there is an obvious production scale and tooling difference between manufacturing 500 units per year and 100,000 units per year. Since tooling costs were an important factor in the trade-off with labor costs, finite element analysis results were packaged into manufacturing structural concepts, which were then provided to a manufacturing tooling company for comparative estimates across each of the concepts\(^3\). These detailed costing studies corroborated sparse Republic data that indicated that automotive type tooling of the skin-stiffened concept achieved break-even at production levels of less than 500 units. The assumed automotive assembly practices are those used for low to moderate production automobiles, such as the all aluminum Lotus Elise which have been manufactured at production volumes of approximately 3000 units per year, while still yielding a sub $40,000 sports car.

Labor currently accounts for the largest portion of manufacturing costs of small aircraft, comprising on average 29% of the total cost versus 25% for avionics and 18% for the propulsion system. A detailed structural system study was performed to compare seven simplified, lean design concepts including all aluminum and composites candidates. In conjunction with the study, a simple, skin-stiffened design from Republic Aviation was dismantled to calibrate the analysis and yield accurate labor and tooling cost estimates. The teardown of the 60 year old Republic Seabee demonstrated the longevity and robustness of skin-stiffened structures, with little evidence of corrosion, buckling or structural defects.\(^4\) Inherent to the skin-stiffened structure is the extensive use of symmetry (for instance the wings incorporate no taper) to achieve very low unique part counts and limited tooling requirements. Again, this research effort demonstrated that the structural technology could not be separated from integrated vehicle concept development. Across the entire vehicle design, there was a bias for trading off small amounts of performance, for large cost improvements.

Estimates based on the original Republic manufacturing processes and the revised skin-stiffened concepts indicated that labor reductions from approximately 2500 assembly hours to 300 was feasible. Reference assembly hours of current GA aircraft include the Mooney at approximately 4500 hours, and the Cirrus SR-22 at approximately 3500 hours (although the SR-22-G2 is reported as approximately 1800 after a focused redesign effort to incorporate lean manufacturing practices). Assembly labor still compares unfavorably to automobiles, with Chrysler averaging approximately 45 hours of assembly time per auto, and Mercedes averaging about 130 hours. While there is an obvious production scale and tooling difference between manufacturing 500 units per year and 100,000 units per year. Since tooling costs were an important factor in the trade-off with labor costs, finite element analysis results were packaged into manufacturing structural concepts, which were then provided to a manufacturing tooling company for comparative estimates across each of the concepts\(^3\). These detailed costing studies corroborated sparse Republic data that indicated that automotive type tooling of the skin-stiffened concept achieved break-even at production levels of less than 500 units. The assumed automotive assembly practices are those used for low to moderate production automobiles, such as the all aluminum Lotus Elise which have been manufactured at production volumes of approximately 3000 units per year, while still yielding a sub $40,000 sports car.
FLAT PANEL LEAN DESIGN STRUCTURAL CONCEPT

An alternative method of achieving drastic reductions in assembly labor was also investigated, however, with a completely different approach. While the prior approach involved a rather conventional wing and body configuration, this approach attempts to reduce components and assembly by merging an all lifting body with an all flat panel construction layout. Essentially this concept performs a modest trade-off of aerodynamic efficiency (achieving an L/D of 9.5 compared to conventional GA aircraft of 11.5) for a modest reduction in weight and a drastic reduction in vehicle complexity and cost. The lead researcher, Barnaby Wainfan, had already accomplished a flying prototype called the Facetmobile and has an extensive knowledge of faceted structure aerodynamics. Additional concept benefits verified through the prior flight demonstrator included benign flying qualities, stall and spin resistance, a large tolerance of center of gravity travel, a large volume cabin, superior occupant crash protection (which was actually put the test during an engine failure on approach), and a high useful load fraction (with an empty weight of only 55% that of a conventional aircraft configuration). The research results indicate that the cost reduction could result in a total aircraft cost reduction of 50%. In addition, the strength of this approach is that practically all structural elements can be produced through use of high-speed CNC machinery, resulting in a drastic reduction in up front tooling costs. Detailed efforts have included CFD study, a NASTRAN structural analysis, construction of joint specimens, and mock fabrication of some assembly elements with very promising results.

![Facetmobile Layout of Flat Panel Construction](image)

Figure 9: Facetmobile Layout of Flat Panel Construction (H.D. Neubert and Associates)

ADVANCED MISSION VEHICLE CONCEPTS

As pointed out across many of the technologies presented in this paper, the technology approach was tightly integrated into the vehicle concept itself and separation of the tech effort from the concept effort would have resulted in a futile attempt towards the capability goals. This is a constant theme discovered across the PAV research, that the combination of working the system of systems, concept integration, and technologies is essential to achieve meaningful results. This basic characteristic of technology investment portfolio management appears to be missing in many discipline specific technology efforts, and a primary reason for the lack of ability to transfer technologies into meaningful products, unless the tech advances are incremental in nature. “Organizational structures typically facilitate component-level innovations because … (they) mostly consist of subgroups that correspond to a product's components. Such systems work very well as long as the product's fundamental architecture does not require change.” While the majority of the concept development work was concentrated on the near-term capabilities, additional long-term mission concepts were developed to help guide the planning of future technology investment. Three primary missions were investigated, including Next Generation GA, Gridlock Commuter, and a SkyPony military variant mission to determine compatibility between civil and military PAV requirements. While benefiting from the near-term research (especially the Haptic control system), the far-term capabilities are much more suited to military missions of interest.

The near-term Next Generation GA concept is described in detail in paper SAE Paper 2006-01-2430. The capability intent was to achieve drastic improvements in cost, community noise, emissions, and ease of use, while also addressing critical public operational acceptance issues such as ease of egress, good visibility, low vibration and harshness environment, low cabin noise, safety, crash survivability, and comfort. While most GA aircraft tend to be biased for performance due to pilot customer desires, this vehicle is not designed for the existing pilot customer base, but as a transportation device for the general public. This is part of the current dilemma in GA aircraft sales transitioning to the mainstream market, that GA manufacturers are ‘held hostage’ by their current customers. Cessna did introduce a low noise version of its Model 172, but it didn’t sell well and was cancelled.

![Near-Term Next Generation General Aviation Aircraft Concept](image)

Figure 11: Near-Term Next Generation General Aviation Aircraft Concept

A number of vehicle concepts were developed for the Gridlock Commuter mission requirement set, which includes the capability to takeoff and land in extremely short distances of less than 300 feet. This facilitates use from communities to support shorter trip distances (and therefore more trips). In order to accomplish the same overall door-to-door block speed, the cruise speed requirement is decreased since the inter-modal ground legs are now shorter. Once again noise is a major capability goal so that such operations from a
community-based access portal permit compatible operations. Both rotorcraft and 'elegant' (versus the current brute force) powered-lift concepts were developed, along with a portfolio of required technologies. Since these technologies aligned with far-term goals, only modest investment was made in this research area, and these efforts are not described in this paper. The technologies included a circulation control nacelle to permit variable thrust dislodging, a Multi-Gas Generator driven Fan (MGGF) propulsion system to allow single engine failure with limited sizing penalties, a Pulsed Ejector Thrust Augmentor (PETA) distributed propulsion system, a hybrid electric powerplant to improve engine-out sizing, a low cost, low pressure ratio turboshaft engine, a Hansen matched stiffness rotor to allow a drastically simplified rotocraft hub, a newly devised variant of the Custer channel wing to achieve a Cimax of 12 (demonstrated in small-scale wind tunnel tests) through circulation augmentation, wingtip vortex turbines to provide auxiliary power for a blowing system during landing approach directly from the tip vortex energy and removing engine dependency, and even roadable aircraft technologies that would enable dual-mode operation with limited ground street use. While this research area offered the most potential for radical change and improvement over the status quo, it was very difficult to attract funding for these efforts due to their ‘disruptive’ nature. This research is to be reported out in a future paper that will concentrate on the far-term mission concepts, and the technologies required enabling them.

A military variant of the Gridlock Commuter mission was also investigated. The intent of SkyPony was to achieve a highly agile, small mobility platform that could be operated by any soldier for a variety of missions, including Special Operation replacement of horseshoeback/ATV/motorcycle/watercraft, squad resupply, fast couriers, military police surveillance, auto-evac of wounded and downed pilot rescue. This capability was tested in a Special Operations Force wargame exercise and ranked as 3rd highest of 50 capabilities to maximize effectiveness. Inherent to this mission is a vertical takeoff and landing capability, however, a unique difference was that no hover requirement was imposed.

This was a very important requirement decision that drastically opened up the feasible design space region for the concepts, as the hover requirement imposes many additions burdens that causes significant vehicle growth. As sizing studies were performed, it became clear that for the vehicle to achieve high agility and appropriateness for close proximity combat operations, the vehicle payload must be as small as useful operations would permit. Therefore a 350 lb payload was utilized, with a 400 mile range as the requirement. This led to Concept of Operations that included linked ‘mule’ caravanning, so that multiple vehicle units could be used in combination to augment the payload. Another significant element that pushes the payload to the lower bounds is the linking of the vehicle growth factor to the cost goal. While conventional aircraft have growth factors of around 3 (the amount the gross vehicle increases in weight for each additional pound of payload), vertical takeoff aircraft have growth factors in the range of 6 to 9, with the cost typically being directly proportional to the vehicle weight. In order for the cost to be equivalent to a HUMV, or under $100,000 acquisition cost, the vehicle gross weight by necessity must remain less than 1500 lbs, considering the expensive VTOL technologies that will be utilized. One of the most promising concepts was a Tilt-Nacelle based on the work of the Grumman 698 concept in the 1970’s and 80’s, achieving a good balance between the cruise efficiency of a fixed wing vehicle, with a compact and relatively robust vertical propulsion system. Rotorcraft concepts fairied poorly in these areas, with cruise efficiencies of less than half, while requiring twice the clearance footprint in proximity to ground obstacles. The key research areas to enable this capability set include the vehicle control system, the aero-propulsive powered-lift system, the high specific output heavy fuel propulsion system, the integration of these elements into viable concepts, and clearly understanding the rugged customer use along with an implementation strategy into Net-Centric battlefield operations.

DYNAMICALLY-SCALED RESEARCH FLIGHT MODEL

The ability to achieve risk reduction across the technology investigations is a prime motivation in these research experiments. While most of these research efforts were conducted at Technology Readiness Levels (TRL) of 1 to 4, it is essential that TRL’s of 6 can be
achieved so that these efforts can be transitioned to private industry and market use. By definition a TRL of 6 requires flight demonstration, which is typically an expensive endeavor. One method of accomplishing a degree of flight demonstration is to perform testing with sub-scale unmanned flight demonstrators that can simulate the appropriate environment and testing conditions. This desire led to the collaboration with a small UAV company and academic partnership to develop the Next Generation Airplane Demonstrator (NGAD). A critical element of this effort is that the flight model is dynamically scaled to allow for valid scientific flight experiments of advanced technologies, such as lift augmentation, gust load alleviation, and noise control. With the relatively large 1/3 scale of the model currently being developed, it is quite likely that both aerodynamic and dynamic control testing of the critical design elements can be accomplished.

Figure 14: One-fifth dynamically-scaled predecessor to the one-third scale experimental flight test model (ACR, Univ of Arizona-Tucson)

PAV CENTENNIAL CHALLENGE

While the PAV Sector research was a highly structured capability-based plan, it was recognized that many technology innovations occur through chaotic inspiration, outside of a well managed project. For this reason, and to promote increased flight demonstration that could capture the public imagination of future PAVs, a competition-based research element was also developed. As part of the NASA Centennial Challenges program office, the Personal Air Vehicle Challenge was established with a $250,000 annual prize for flight demonstration of advances in all of the technology areas already discussed in this paper. It is hoped that prizes such as this will follow in the example of the Orteig (Lindbergh), Kremer (MacCready), and X prizes (Rutan), yet also provide useful technological advances. This competition is being managed through the Comparative Aircraft Flight Efficiency (CAFÉ) Foundation with detailed rules available through their website at www.cafefoundation.org. This competition will promote the popular use of self-operated, personal aircraft for fast, safe, efficient, affordable, environmentally-friendly, and comfortable on-demand transportation as a part of America’s need for future mobility solutions.

AGENT-BASED HIGH DENSITY AIRSPACE OPERATIONS SIMULATION

While not within the domain of vehicle technologies, an agent based simulation was conducted of the large-scale use of PAV’s within specific geographical areas. Since the concept of having hundreds of thousands of PAVs in the air is foreign to most individuals, this is key area where a credibility gap seems to exist prior to this on-demand vision being accepted within the aerospace community. Simulation tools developed for DoD battlefield operations are being used for two specific modeling regions, a 100 mile radius around New York City and the Silicon Valley. The study will determine flight control rule sets for high density operations, along with throughput feasibility to the over 400 airports in each region. The study includes agents with highly diverse characteristics such as cruise speeds, and will include utilization of both existing airports and assume new community-based small access portals. An initial result that is very promising demonstrates that with very simple ‘rules of the road’, and relatively simple on-board sensor sets, a large number of vehicles can be accommodated.

Figure 15: Agent Based Simulation of PAV High Density Operations Around New York City

One tracking metric during the phase of investigation is the number of attempted collisions when no evasive action is taken by the PAVs. The aircraft simply fly the set course which was generated by random trips calibrated to the population densities of the localities while avoiding major airports, airspace, and downtown restrictions. The simulation includes takeoff and landings based on typical travel trends, with higher density operations in the morning and evening peak
hours. Additional study elements look at the creation small river barge-based fields to supplement the high demand for downtown access. Through the use of simple altitude banding in association with the flight heading, the number of collisions was reduced to a level that could be managed by reasonable avoidance procedures. Early study results indicate that it is quite feasible to have on the order of 100,000 PAVs operating within the 100 radius of a major city, without chaos or air to air collisions. Obviously this is only a first step, with many sensitivities and rule-based sensitivities required before accurate assessments of operation densities can be determined.

ANALYSIS TOOLS

A very important part of any innovative technology or systems development effort is the development of computational and experimental tools for analysis. Since much of the technology effort was in areas where prior investment had not occurred for many years (such as ducted propellers), or had not been attempted. (such as agent-based high density airspace operations). A significant portion of the PAV sector research included the generation of tools to meet the specific analysis needs of these small aircraft. Some examples of successful tools include;

- Vehicle SketchPad concept to analysis modeler
- Haptic Naturalistic Flight Deck bi-directional experimental control stick and simulator
- Mobility analysis tool with lifecycle cost analysis and web-based analysis
- PAV manufacturing cost tool based on labor assembly hours
- Ducted propeller performance and noise tool
- Empirical circulation control aerodynamic prediction tool
- Multi-Gas Generator Fan cycle analysis tool
- Circulation control nacelle experiment methods
- Simajin agent-based high density simulation tool
- Skin-stiffened structure analysis procedure

Another important realization throughout this research was that, just as technologies can’t be developed effectively without the concept integration studies, tool development without specific technology, vehicle and market based application intent is not nearly as productive. The development of tools for the sake of better pioneering fundamental aerodynamic concerns should certainly be performed, but only as a portion of the portfolio of tool development, with the majority of effort applied to specific problem sets that would lead to specific capabilities. As an example, developing an easy to use, intuitive concept geometry modeler could have (and has been) done for years without applying to actual systems studies that quickly incorporate higher-order analysis; but it is the act of applying the tool to applied problems that identifies the critical tool efforts that maximize the effectiveness of the tool in a relevant environment. An analogy would be expecting to develop flight capable technologies that are relevant to products, without ever performing flight tests to understand the behavior in a relevant environment.

CONCLUSION

A number of significant technology advances across many areas of expertise are required prior to the ability of PAVs to provide a benefit to a more significant portion of the public, than current General Aviation aircraft. With the results obtained from the PAV sector research activities, significant progress was made across many of the critical required capabilities. Achieving drastic improvements in ease of use and community noise are the two most critical steps towards the future feasibility of this market, as agreed upon by industry members in the PAV workshops that defined the sector goals. Working across many technology disciplines, this research is providing support for improved aerodynamics, quiet propulsion, zero emission engines, lower cost certification, lower cost structures, and the ability to understand the societal and airspace needs as these vehicle technologies bring about a new age in on-demand aviation. Much of this PAV research is also directly attributable to future UAV and military mission needs.

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CONTACT

Mark D. Moore was the Personal Air Vehicle Sector manager in the NASA Vehicle Systems Program until the the recent redirection of NASA Aeronautics into the Fundamental Aeronautics Program. Most research activities relating to both SATS and the PAV sector have been concluded and no new research into these topic areas is currently planned by NASA. After the conclusion of the final contracts next year, NASA will continue to encourage small aircraft related research through the NASA PAV Centennial Challenge yearly competitions. This research effort has in many ways mirrored the research path of other disruptive technologies as discussed in ‘The Innovator's Dilemma’ by Clayton Christensen and has once again shown that “disruptive projects stalled when it came to allocating scarce resources among competing product and technology development proposals”. While large institutions such as IBM and Bell Labs often initiate disruptive research that has major societal impact, it appears that “firms that lead the industry in every instance of adopting disruptive technologies are entrants to the industry, not its incumbent leaders”. The author remains committed to NASA's important role in disruptive technology development and continues to work on independent research in this topic area through his current PhD studies and may be contacted at mark.d.moore@nasa.gov.