IN-02
33-14
p. 1

NASA Technical Memorandum 109174

The Personal Aircraft--Status and Issues

Scott G. Anders, Scott C. Asbury, Kenneth S. Brentner,
Dennis M. Bushnell, Christopher E. Glass, William T. Hodges,
Shelby J. Morris, Jr., and Michael A. Scott
Langley Research Center, Hampton, Virginia

(NASA-TM-109174) THE PERSONAL AIRCRAFT: STATUS AND ISSUES (NASA. Langley Research Center) 126 p

N95-20688

Unclas

G3/02 0038874

December 1994

National Aeronautics and
Space Administration
Langley Research Center
Hampton, Virginia 23681-0001

Contents

Summary

The personal aircraft has been a recuring dream of mankind since the inception of the concept of human flight.The form of this vision has changed as the technology levels in the various aeronautical disciplines has improved.The current general aviation/private aircraft paradign is,in a limited sense,a realization of the personal aircraft vision.This [current] realization is characterized by separate air and ground vehicles,a requirement for use of airports/runways on the air side,the necessity of pilot training/proficiency with the attendant health,time and treasure which that entails,and an overall cost which exceeds the available transportation budgets of much of the population.What is needed is a personal aircraft transportation system which obviates these requirements;i.e. a combined/convertible air and ground vehicle capable of VTOL operation on the air side which is automatic in operation as well as navigation/ATC and which is affordable at least in the sense of a quality automobile.The latter necessitates and the other features enable very large production runs.The applicable paradign for this vehicle class is probably the automobile,as opposed to the general aviation industry with its' limited production runs.

The suggested personal aviation vehicle discussed in this report is therefore an automatic [on the air-side] VTOL-capable affordable converticar which meets,for both the air and ground sides,all applicable safety,environmental and nuisance regulations in terms of collision-avoidance/survivability,noise,emissions,
ground-vacinity operations and reliability as well as providing reasonable ride quality,all weather operation [in the same sense as current automobile operations] and minimal maintainance requirements/cost.The latter probably necessitates automatic vehicle health monitoring.

An obviously important issue is whether the requisite technology either exists or is in the pipeline to allow successful design and production/operation of such a class of vehicles.The answer is apparently positive,enabling current or emerging technologies include composite materials,advanced Wankel IC engines,the electronics revolution in terms of size/cost/capability of sensors/control systems/computing,the GPS system,the emerging global satellite-based personal communications systems,computational fluid mechanics and flow control.A spectrum of vehicle concepts is envisiged,anchored by a deployable rotary wing approach on the low end [in terms of cost],and by the Mollar vectored lift/cruise fan on the higher side.This spectrum would eventually provide,for the air side,analogous options in terms of cost,performance,etc.

to what now exists in the automotive world [e.g.,for Ford,from Escort to Lincoln].

The operational introduction of these vehicles would also be analogous to that of the automobile,with some initial versions characterized by limited production,high cost and restricted usage/usefulness,i.e. "a rich mans' toy".In parallel with the "model T" auto paradign,quite early on inexpensive and useful versions will be produced which will,again in analogy with the effects of the auto,revolutionize land use and transportation-related capitol investments,allowing expansion of the population over a much greater area,reducing population density and the tremendous capitol and environmental costs of long distance highways.The latter cost reductions are of especial importance to the developing world where such vehicles would uniquely provide 21st century transportation of personnel and high value goods without the requisite capitol costs of extensive highway systems/bridges etc.Railroads would still be required for long haul bulk cargo.Just as the auto allowed expansion of the population away from central cities into "suburbs",this class of vehicle will allow expansion into the countryside and a commute of up to 400 miles.This decentralization would obviously be conducive to,and enabled by,operation of these convertible vehicles in the air mode,they would convert to ground operation in built up areas such as current densely populated urban/suburban regions.

Introduction, Personal Aircraft History, and Advanced Personal Aircraft Mission Statement

by

Christopher E. Glass, Aerothermodynamics Branch, Gas Dynamics Division

Introduction

The primary source of short to moderate distance transportation in the United States is the automobile. For lower and middle class Americans, the automobile is also a primary source of long distance transportation. We in America cherish our cars and the freedom of movement afforded by this transportation mode. The automobile has evolved to become a necessity for nearly every segment of the population. It is common for an average family to have more than one vehicle--at least one for the daily commute to and from work and in some cases another for recreational use. However, the nation is today faced with a growing number of automobiles on the highways most of which are concentrated around the major urban centers. Hour long traffic delays on smog hazed highways are becoming a common sight in and around the large population centers.

As we enter the next century, the need for more highways will increase beyond the available surface area if the current trend remains unchanged. We are on a course that will soon cause our urban and suburban regions to become almost completely covered by either asphalt, concrete or buildings with little or no green area and with the air so polluted that both plant and animal life will be adversely affected. Although our city, county, state, and federal government planners are confident more highways can be funded with tax payer dollars and the automobile manufacturers are always willing to sell more vehicles to travel on the highways, is this the proper solution for the transportation needs that will face the nation in the next century? Diversity should exist in the type of transportation modes available to the traveling public. The Aerodynamics Technical Committee at the NASA Langley Research Center has this year chosen to study and report its findings on one such additional transportation mode. This transportation mode, although in concept as old as the automobile, may be right for the dawning of the new century--the advanced personal aircraft (APA).

Our nation stands at the cross roads of the next transportation revolution. The personal aircraft for the masses has long been proposed by some prominent aviation personalities. Private and public concerns have studied and produced working vehicles that have had great potential. In the following section some of the more well known of these vehicles will be presented. Why now is it important to take the task and exploit the technology necessary to produce this elusive vehicle? An answer to the question may be the potential positive impact on the nation's economy by creating a new industry, not just for a national market but for an international market; the need for an additional medium distance mode of transportation; aircraft are far more efficient at high speed than automobiles; or national pride of being the first country to create and produce for the public an advanced personal aircraft system for the future transportation needs.

The following sections of this chapter include a discussion of the personal aircraft's place in the history of transportation in the United States and a discussion of the mission of an advanced personal aircraft. Chapters that follow include more detailed vehicle discussions and options, critical issues, and conclusions. The discussions will include major overall issues and suggested ways to address these major issues.

Personal Aircraft History

To understand the role played by the personal aircraft in today's transportation system, one needs to review how the present transportation system evolved and how it has impacted the population density and land use in the United States. To this end, the section below will focus on the how the present transportation system developed in America, how the personal aircraft relates to the present system, and a brief history of the personal aircraft. Revolutions in transportation take place when a new form of transportation is introduced and accepted by the public. It is not enough to have a plan for a better transportation system; the public must understand and embrace the plan before a new transportation system can be successfully incorporated into the present system. Past revolutions in transportation occurred in the United

States when the steam powered locomotive and fossil fuel powered automobile were first introduced. These transportation revolutions have affected expansion of the population and the movement of commerce in the nation.[1,2,3]

The population density within the United States is not uniformly distributed. The early Europeans chose to settle in the New World in protected harbors along the eastern coast. Commerce in the country was first moved by ocean going vessels that needed protected waters to load and off load goods. As the country expanded west, river cities began to emerge as a transfer point between the interior and eastern distribution regions of the country.[1] Commerce was moved by horse-drawn wagon between river cities and interior regions. Also at that time, canals were planned and built to create water passages for the movement of commerce between the interior regions and the large eastern cities. When the locomotive was introduced a more efficient over land transportation alternative was available.[2] No longer were the major commerce centers restricted to coastal, river, and canal cities. The interior of the country was now easily accessible and population centers began growing at the intersections of and along the rail lines.

Although early transportation modes spread the population throughout the country, most of the population was clustered around the major commerce centers. Industrialization replaced commerce as the major economic activity in many northeastern cities as the industrial revolution began. The consequence of urban regions becoming industrial was an accumulation of people in the city searching for employment. The majority of the population in the country is urban and lives close to major commerce or industrial centers. However, the vast majority of the land area in the United States is rural and under utilized.

At the turn of the twentieth century, some labor unions and progressive businesses were influencing industry to increase wages and institute a standard 40-hour work week. Increased free time and spending power for the working class resulted. The time was right for the introduction of an affordable mode of transportation that could be enjoyed by all--the automobile. Henry Ford introduced the mass-produced, low cost Model T which was bought by the millions by consumers.[4] Freedom of movement with the crank of an engine was available to the public for the low price of a Tin Lizzy. The country began to enjoy an automotive revolution. Although street railways had created suburban regions surrounding the major urban regions by allowing people to commute to the job, with the automobile came a greater movement of people away from the urban centers into suburbia. Suburbia expanded outward and became a common place to live.[4] The automobile had found a use as a personal commuter vehicle. The commute was limited only by the time one could tolerate driving to and from work each day. This limited the radius of suburbia because a commute could range to only under a hundred miles.

Most of the early roadways produced a rough ride as the automobiles were constrained only to travel well-worn wagon routes. As the automobile became an accepted form of transportation, asphalt roads were laid first in the city, then into the suburbs and surrounding countryside.[4] Today our highway system has become a web of concrete and asphalt tying together all parts of the country; however, the automobile is still restricted to a relatively low maximum speed on these discrete ribbons of roadway. The automobile has taken suburbia as far from the city as possible. High speed trains now planned will further increase the radius of commute, but there will be a limit as to the capacity of commuters, speed of the trains, and the freedom of movement afforded by this form of daily transportation. There will always be a need by the public for flexible travel times which cannot be accommodated by scheduled high speed train routes. An alternative transportation mode is needed to fill this void and to further expand the outer reaches of the city and more fully utilize the vast expanse of rural area in this country.

When the automobile was first introduced, the physics of flight were being discovered and tested by Orville and Wilber Wright, Samuel Langley, and others. The early airplanes were flimsy creations made of cloth, wood, and a few bits of wire powered by inefficient early models of the internal combustion engine.[4] These powered air vehicles had no established airports from which to operate, were less than reliable, and would therefore be forced to land on just about any flat piece of ground in case of an emergency. Such emergency landings were common. The early aviators were a brave lot who put the pursuit of flight before their own safety as witnessed by the number of lives lost. Early airplanes were also expensive. The average person with the desire to fly could not afford to fly. It is not surprising that the early aircraft did not generate a great deal of interest within society as an alternate form of commuter transportation from the city center to the outer reaches of suburbia or as a weekend recreation type "get away" vehicle.

The first controlled, powered flight of a personal aircraft was made by Orville Wright just after 10:30 a.m., December 17, 1903 at Kitty Hawk, North Carolina.[4] Even by 1910 many people were still skeptical of the 1903 accomplishment of the Wright brothers.[5] The Wrights were soon not the only experimenters to test a personal aircraft. From the time of this first flight until the start of the Great War in 1914, the personal aircraft was merely a public curiosity flown at county fairs and carnivals by daredevils. The usefulness of the personal aircraft to the public was not apparent. Even miliary planners of the time had to be convinced of the usefulness of aircraft. The first military use of an airplane was as an aerial scout. The scout aircraft were soon carrying rifles and bricks as munitions. By the end of the Great War in 1918, the scout aircraft were armed with mounted machine guns and carried bombs.[4] These aircraft were becoming true military machines capable of great destruction. It is interesting that Orville Wright had a different outlook for the airplane than the military planners. "When my brother and I built and flew the first man-carrying flying machine," said Orville, "we thought that we were introducing into the world an invention which would make further wars practically impossible."[4]

In the years just after the Great War, the public perception of the airplane was as a savior of mankind. The war to end all wars was over and had been won by the Allies. The end of the war provided an opportunity for the aviation enthusiast to buy a war surplus personal aircraft. Surplus aircraft had greater speed and reliability then the pre-war models. These personal aircraft were used for barnstorming, stunt flying, racing, and carnival flying.[4] Local events brought the airplane into the public's backyard. Some pilots made a living by flying their personal aircraft into a open field, charging the gathering local townspeople for a ride, and moving on to the next town. Also, air racing became a national pass time. The race for the Pulitzer Trophy and Schneider Cup created much public enthusiasm.[6]

Other uses for the airplane in the early years were also being offered: life saving missions on the open seas, tracking schools of fish for commercial fishing fleets, filming movies, air mail, and passenger service.[7] Hollywood movies created interest for the airplane by bringing it to the big screen. Howard Hughes spent about four million dollars filming the early aviation classic "Hell's Angles."[6] Air mail service was also being explored as a use for the airplane.[8] Limited air mail service in the United States began in the late stages of World War I. The first commercial public use of the airplane in America came in the form of aerial passenger service from New York to Atlantic City that was offered by Aero Limited as early as August, 1919.[4] In the years that followed, passenger service gave the airplane's usefulness a great boost. The number of airline passengers had a 10 fold growth from about 50,000 to 500,000 from 1928 to 1930.[5] In the public's view, the general usefulness of the commercial airplane was coming into its own. However, the usefulness of a personal aircraft had not been well defined by the start of the 1930's.

Aviation distance and speed records were being made and surpassed regularly. On May 10, 1926, Lt. Commander Richard Byrd flew his aircraft, "Josephine Ford," near the North Pole.[5,6] The most memorable flight during the 1920's was when Charles Lindbergh flew a Ryan monoplane "The Spirit of St. Louis" solo from New York to Paris May 20-21, 1927. The Lindbergh flight across the Atlantic did much to increase public interest in the airplane.[6] Flying was not just for men, Emilia Earhart was the first woman to cross the Atlantic in an airplane June, 1928. Although she was just a passenger in the airplane, much praise was given to her.[4] These events are examples of the almost daily aviation firsts that were occurring during this time. The public's opinion of the airplane was changing, but still the personal aircraft was for those brave souls willing to risk it all.

As the airplane was finding more and more uses, safety became a greater concern. The Daniel Guggenheim Fund for the Promotion of Aeronautics promoted a safe airplane competition in 1927 that resulted in technology which decreased takeoff and landing speeds and shortened the landing distance.[5,6] The federal government through the Development Section of the Bureau of Air Commerce also promoted a "safe plane" competition. Eugene L. Vital, director of the Bureau at the time, was interested first in a "poor man's airplane" because he thought that an airplane for the masses had a great market potential. Vital planned to fund the program using monies from the Public Works Administration (PWA). Lawyers for the PWA argued successfully that the dream of a "poor man's airplane" should not be funded with public works dollars. Vital found a loop hole in the legislation that created the Bureau of Air Commerce allowing him to establish the Development Section to foster growth in commercial aviation.[6] John H. Geisse was appointed Chief of the Development Section. The Development Section called for bids on May 18, 1934 for twenty five airplanes to be used by the Section's inspectors.[9] The airplane would be a test bed for the airplane for the masses in disguise. Four factors were considered key: utility, cost, comfort, and safety, in particular, comfort and safety were considered the most important factors. Bids were opened August 27, 1934 and it was decided that the Bureau of Air Commerce would purchase first only one prototype airplane from each of the accepted bids for testing and evaluation. Contracts were awarded to the Hammond Aircraft Corporation, Mr. Waldo Waterman, the Autogiro Co. of America, the Kreider-Reisner Aircraft Corporation, and the Fahlin Manufacturing Company.[6]

The Hammond Aircraft Corporation produced the Hammond Y-1 and Waldo Waterman produced the Arrowplane, both of which had a pusher propeller with tricycle landing gear. The pusher propeller arrangement gave better pilot forward visibility but less performance than a tractor type. Emilia Earhart had a chance to fly the Waterman Arrowplane and said it handled "nicely."[6] Also, Waterman had designed the Arrowplane so that it could be easily adapted to become a roadable by removing the wings. Later Waterman aircraft incorporated the roadable feature. The Autogiro Co. of America produced the Roadable Autogiro which required a very short runway for takeoff and landing and was the only roadable aircraft of the group awarded contracts by the Development Section. By folding back the top blades and engaging a clutch, the rear wheel of the autogiro became a drive wheel. Autogiro technology was also a forerunner of helicopter technology development. The Kreider-Reisner Aircraft Corporation modified a Fred Weick designed Weick W-1 with new ailerons and flaps. Weick, a government engineer at the NACA Langley Aeronautical Memorial Laboratory, and his colleagues had earlier in 1931 designed and built in their spare time the "Ercoupe." Weick's design contributed spin-proof characteristics and tricycle landing gear technology to the aircraft industry. A Plymouth automobile engine was used in Fahlin Manufacturing Company's "Plymacoupe" entry. The automobile engine cost less than an aviation engine but produced less power per unit mass. Because of the weight penalty associated with the automobile engine, the concept of using the automobile engine for aviation use was put aside. The Vidal experiment that ended in 1936 had produced some very interesting designs which flew.[6,9,10] More than that, the experiment had infused a hope to the public that a personal aircraft for the masses was soon to become a reality.

Shortly thereafter however, international events in Europe and Asia that lead to World War II took the center stage. The country had a critical need to produce war material and supply young people for the Allies to fight Axis aggression. A Civilian Pilot Training Program was initiated by the Civil Aeronautics Administration in June 1939 to train pilots for America's entry into the war.[5] The military almost completely stopped private aircraft operations except for flight instruction during the war. Many people either worked in the aircraft and related industry, served aboard airplanes as either crew or pilots, or as civil defense spotters watching the coastal and border sky for enemy aircraft.[6] Dreams of owning a personal aircraft by the masses had to be set aside until the war was over. During the war years however, a debate was still taking place, "What and when will Mr. and Mrs. John Q. Public be flying after the war?"[6]

Because World War II was more aerial in nature than any previous engagement, the public was more airminded after the war than before. The airplane had been used successfully in a fighter and bomber role as an instrument of war to make the world safe again. With the close of the war, the public had a pent-up demand for consumer goods that were denied them during the war.[6] One such consumer good was a personal aircraft. Surveys conducted during that time showed the public was ready to take to the air.[11,12] A popular notion was that the near-future transportation system for the masses would be in the sky. Many veterans of the war, using the G. I. Training Program under the G. I. Bill of Rights, enrolled in pilot training schools. Communities built "airparks" for these and other new pilots. In 1946, over 33,000 personal airplanes were sold in the United States compared to the less than 3000 airplanes licensed in 1937.[6] One pre-war forecast held to a belief that by 1950 one million personal aircraft could be flying.[13] However, the airplane buying trend after the war did not live up to expectations. After one year of use, about one-third of the owners sold the aircraft. Among the primary reasons for selling their personal aircraft were financial, airport related, and general lack of utility.[14]

The personal aircraft proponents were however undaunted as positive expectations of future personal airplane use still abounded within the public. Some of the envisioned future personal aircraft for the masses would not be of a conventional design. Roadable aircraft, convertible aircraft, and helicopters were among the leading candidates for the personal aircraft market.[14,15] For a personal aircraft to be accepted by the public, it must be inexpensive, not bound to the airport, easily flown, fly in all weather, and be useful as a daily form of transportation.[15]

The roadable feature of the aircraft held great hope as the design for the air vehicle for the masses. Roadability would allow the vehicle to fly like an airplane and drive like a car. Many roadable aircraft designs have been built. As early as 1911, Glenn Curtiss said of his Curtiss Flying Boat, "Now if we could just take the wings off and drive this down the road, we'd really have something!"[5] Curtiss did just that. At the February 1917 Pan-American Aeronautical Exposition, the Autoplane, Curtiss Model 11 was displayed.[5] In 1922, a French built "Flying Automobile" was shown during the annual Aero Show in Paris.[16] Both of these early roadables were driven and flown. The Autoplane "flew briefly but not well"[17] and the Flying Automobile "proved to be entirely successful in both the flying and land tests."[16] Other roadable designs have been built and flown throughout the history of the personal aircraft.[6,15,17,18] Some of these are the Roadable Autogyro (1936), Waldo Waterman's Arrowbile (1937), Pitcairn Model PA-36 Whirlwing (1939), Spratt/Stout Skycar IV (1946), Robert Fulton's Airphibian (1946), Theodore Hall's ConVairCar (1947), the Zuck Plane-Mobile (1947), Moulton Taylor's Aerocar I (1949), and the Bryan II Roadable (1960). Although much ingenuity was used to devise the roadable aircraft designs, they never entered the mass market as a viable personal aircraft. The reasons are varied and many; however, the main reason was that the air-land vehicles did not excel as both an airplane and an automobile. The driving and flying qualities suffered by combining the two functions.

During the 1940's attention was given to the convertible aircraft as a candidate for the air vehicle for the masses.[19] Convertible aircraft combine the landing and takeoff qualities of the helicopter with the flight characteristics of a fixed wing aircraft. Various classes of convertible aircraft were proposed.[20] The classification was based on whether the rotor axis is fixed (Class I) or rotated 90° during transition from hover to fixed wing flight (Class II). Each classification was then further subdivided. Class I is subdivided depending if the rotor is retracted and stowed, fixed in a streamline position, or fixed to become the wing. Class II convertible aircraft are subdivided depending on if the rotor pivots and becomes the propeller or if the craft takes off and lands with its long axis vertical and turns 90° to engage fixed wing flight. Examples of early convertible type aircraft are the Herrick Convertoplane[21] and the Zimmerman type[22]. The name "convertible" has long been abandoned and replaced with Vertical/Short Take-Off and Landing or V/STOL. A recent operational V/STOL is the V-22 Osprey tiltrotor and conceptual designs such as the M-85[23] are being studied. The convertible or V/STOL type airplane offers the advantage of needing little or no runway for a low speed takeoff or landing similar to that of a helicopter but with the in flight performance of a fixed wing aircraft. One disadvantage of the V/STOL is however, complex mechanisms needed to achieve the helicopter-fixed wing combination cost in weight and money.

Helicopters were also considered to fill the role of the aircraft for the masses. The helicopter has a distinct advantage over the airplane in that no runway is needed for takeoff or landing. The helicopter also has an autorotate capability to bring the craft down safely if an engine out condition occurs. Any open area including an office building roof or parking garage roof will suffice as the helicopter's "airport." Sikorsky Helicopter Company in 1943 presented a promotional film which advocated the position that soon helicopters would whisk people from their home to the office.[6] Also, the February 1951 issue of Popular Mechanics Magazine proposed a jet-powered rotor helicopter as an upcoming personal transportation mode for the public. Helicopter development received much attention but primarily by the military. It was used during the Korean conflict as an air ambulance as popularized by a recent television series "MASH" and was used during the Vietnam conflict as an aerial jeep.[4] The helicopter has not seriously entered the personal aircraft market. Among some of the problems as addressed in

1970 are "poor flying qualities, undesirable vibration characteristics, high maintenance cost, high noise level, and low efficiency."[24] These problems are currently being addressed and some designs for personal transportation market do show improvement, for example the Robinson R22 and the ATI Ultrasport 254.

By the end of the 1950's the notion of a personal aircraft for the masses had all but lost its public appeal. The public had been waiting many years for a Henry Ford of the airplane to emerge and offer a low cost "Model T" of the sky and no one did. The personal aircraft for the masses was and still is accessible to only those individuals with the money to pursue the dream. The average American realized personal air travel "would likely remain a costly, inconvenient, and dangerous way to travel compared to driving"[6] and was therefore forced out of the market. The market today for the light to medium general aviation aircraft that could be used as personal aircraft is generally for commercial and business customers. Legal issues have also attributed to the decline of personal aircraft sales by artificially increasing costs. Manufactures of personal aircraft have been held responsible in court for accidents and required to pay large sums of money in litigation and damage costs.[25] Legal costs are passed on by the manufacturer to the consumer in the price of the product. Home or kit built aircraft are now becoming popular as a personal aircraft to a large extent because the kit builder assumes the legal risk, not the supplier of the kit.

The idea of an aircraft for a larger segment of the public is now being revisited. The federal government, through the NASA has begun a multi-year, $63-million dollar effort "to increase the utility of general aviation and create a demand among a larger group of people who are now put off by the complexity and cost of flying."[26] The activities of the effort during the 1994 fiscal year have been to establish an industry, university, and government team and to define goals for the program.[27] Not only is the federal government involved in the redefining the role of the personal aircraft, individual, private company, and university researchers are becoming involved. Conceptual designs for a number of advanced roadable aircraft from this second group have recently appeared. Stiles' CaRnard[28], Flight Innovation Inc.'s Sky Commuter[29], Crow's Starcar[30], Sarh's Advanced Flying Automobile (AFA)[31], Mollier's M400

Skycar[32], Sky Technology's Aircar[33,34], and others are proposing their designs as the next generation of personal transportation. Many of these designs have promise, however funding by the federal government or private investors is needed to keep many of the projects alive.

Advanced Personal Aircraft Mission Statement

Four factors that were first presented by the Chief of the Development Section of the Bureau of Air Commerce in 1935 are used as a basis to formulate a mission statement for the advanced personal aircraft now considered. Utility, cost, comfort, and safety were key issues that were lacking in early aircraft designs[9] and are still key issues that need to be addressed for the advanced personal aircraft (APA) to be successfully marketed to the general public. A brief discussion of each issue is presented next.

An APA must first be useful. Usefulness of the personal aircraft has been a recurring theme throughout the history of aviation starting just after the great war.[7,35] Door-to-door transportation for the daily commute to and from work, shopping, and weekend trips should be provided for by the vehicle. Of course, the automobile will not be displaced for short distance transportation (less than about 50 miles), but the APA should have the capability for short distance ground travel. However, the primary vehicle usefulness will be for medium distance flights carrying at least four people of between 100 to 800 miles. The APA must be faster and more fuel efficient on a medium distance trip than the car-aircraft-car transport alternative now available. The APA would help alleviate ground transportation congestion. Grid-lock in and around major urban areas would be reduced by the APA. The vehicle would be driven around non-destination areas on a controlled three-dimensional highway in the sky rather than on the one-dimensional discrete concrete and asphalt strips of highways on the ground that typically pass through non-destination urban areas.

Vast land areas in the United States (and throughout most parts of the world) are under utilized and rural. An adequate personal commuter transportation mode is presently not available to move people to and from these rural areas to major cities in a timely manner. Access to these regions would be provided by the APA. To best be useful for this role, the APA should have a maximum speed of between 200 to 300 miles per hour. Land that is now beyond reach of the city commuter would become available. This use of the APA would reduce urbanization and better utilize rural land by spreading the population away from the city. A similar, but smaller scale trend occurred after the introduction of the automobile. The outer portions of major cities were connected to the central city by horse-drawn or electric trolley cars. When the automobile became an accepted commuter vehicle, no longer was the commuter limited to the trolley route and the population spread even further from the central city into suburbia.[2]

The APA would be useful to the economy. In the short term, high technology employment to set in place an APA transportation system would have a positive affect on the national economy. A long term new industry to manufacture, maintain, refurbish, and recycle the APA would be created. This industry would be similar to the industry in place for the automobile. APA research and development would also generate spin-off technology. Commonality with an advanced transportation system could be built into the APA from the start. The APA should have an ability for automatic operation so that there is no need for a "pilot." APA hands-free flying technology with computer algorithms to pilot the vehicle using the Global Positioning System for location, direction, and velocity input and "seek and avoid" situation awareness logic to decrease the likelihood of an accident could be directly incorporated into other transportation modes such as automobiles and water craft. The national weather data base could also find an APA network useful. If each APA had an atmospheric detector tied to a national grid operated by the National Weather Service (NWS), thousand (or millions) more point readings of atmospheric temperature, pressure, humidity, wind velocity, and other parameters in real time along the APA flight path would increase NWS weather prediction accuracy by expanding the number of data collection sites for use in advanced weather modelling.

Part of the APA mission should be to reduce or at least maintain the cost of medium range transportation for the consumer. A complete cost analysis of the APA system including the required infrastructure should be made and compared with the total cost of other modes of transportation. The existing highway infrastructure repair and maintenance cost should be included in a cost comparison because the APA would need only use long distance highways to a limited extent. If the APA is to become a reality, the total cost of the vehicle and system must be low enough to create a mass market appeal yet profitable enough to encourage private investor participation. Although cost for manufacture, profit, and distribution of the APA must be included in the retail cost to the consumer, artificial increases such as those from high cost product liability insurance should be minimized by product liability law reform. Also, the unit cost of each APA must be formulated with mass production in mind. Ford was able with the Model T to lower the price of his automobile from $850 to $290 over the production run resulting in over 15 million automobiles on the highway.[4] Mass production of the APA should produce similar relative savings.

The third component of the APA mission is comfort. The APA must be "good neighbor" to those in the community. Issues such as noise, pollution, debris at take off and landing areas, and the environment impact must be studied and presented to the public for approval. The public must be comfortable with the issues. Operators and passengers must feel comfortable during APA use. Government agencies responsible for air operations must also be comfortable with the APA. For example, the FAA must be comfortable with Air Traffic Control policy changes to allow hundreds of thousands (ultimately millions) more aircraft in the sky.

Safe operation is the final mission of the APA. The vehicle should be safe to a fault. The term "idiot-proof" may not be strong enough to describe the desired operational characteristics of the APA. Expert control systems should be included to over ride all erroneous actions of the operator. The vehicle should have a safe, nearly all weather capability similar to that of the automobile. The APA should also be crash proof and controllable during a critical engine out decent condition either by glide, parachute-glide, or autorotate capability. As mentioned earlier, "seek and avoid" situation awareness control logic is needed for the vehicle to safely avoid other vehicles and navigate around poor weather during flight operations.

The time is right for the APA. All of the system and vehicle components are available or will soon to be available. A multidisciplinary approach is needed to best piece together the puzzle of available components to define completely the APA system. Advanced high speed computers, software logic algorithms, and information transfer systems developed for other uses could be integrated with advanced smart and brilliant materials and newly explored advanced aerodynamic technologies to create the APA. The key issues to marketing the APA to the general public are utility, cost, comfort, and safety as briefly discussed above. However, more subtle issues should not be overlooked. The imagination of the public must first be captured. A ground swell of positive public opinion will give much political inertia to an APA transportation concept. Proper marketing from the onset will convince the public that the APA is a good idea whose time has come. The critical technologies are ready or will soon be ready to produce the APA. We as a country can either seize the moment and bring this transportation concept into a reality, wait another fifty or so years and revive the idea, or wait for a foreign interest in the interim to produce and market an APA for us (as has happened with other American ideas for products).

References

1 Green, Constance McLaughlin: *American Cities in the Growth of the Nation,* University of London, The Athlone Press, 1957.

2 Hanmer, Trudy J.: *The Growth of American Cities Issues in American History,* Franklin Watts, New York, 1985.

3 Mumford, Lewis: *THE CITY IN HISTORY Its Origins Its Transformations, and Its Prospects,* Harcourt, Brace & World, Inc., New York, 1961.

4 Firestone, Harvey S., Jr.: *MAN ON THE MOVE The Story of Transportation,* G. P. Putnam's Sons, New York, 1967.

5 Waterman, Waldo Dean and Carpenter, Jack: *WALDO: PIONEER AVIATOR A personal history of American aviation, 1910-1944*, Arsdalen, Bosch & Co., publishers, 1988.

6 Corn, Joseph J.: *THE WINGED GOSPEL America's Romance with Aviation, 1900-1950*, Oxford University Press, New York, 1983.

7 Finding New Uses for Airplanes. *Air Service Journal*, Vol. 4, No. 9 (Mar 1, 1919), New York, p. 14.

8 Air service develops airway program. Establishment of new transcontinental airways planned for service flying and civil aviation. *Aviation*, Vol. 13, No. 5 (July 31, 1922) New York, p. 127.

9 John H. Geisse (Chief, Development Section, Bureau of Air Commerce, U. S. Department of Commerce): Development Program Seeks to Improve Private Owner Aircraft in Utility, Cost, Comfort, and Safety, *Air Commerce Bulletin*, Vol. 6, No. 11, May 15, 1935, pp. 245-248.

10 John H. Geisse (Chief, Aeronautical Developments Section, Bureau of Air Commerce, U. S. Department of Commerce, Washington, D. C.): The Small Privately Owned Airplane and its Possible Future, Papers presented at the 1935 National Technical Aeronautic Meeting, Aeronautic Division of the American Society of Mechanical Engineers under Sponsorship of the St. Louis Section, St. Louis, Mo., October 10, 11, 12, 1935.

11 The Saturday Evening Post Aviation Survey. Curtis Publishing Co., 1946, Phila. Research Dept.

12 Aircraft Use in 1946. Research Division and Office of Aviation Information, Civil Aeronautics Administration, February 1948.

13 Cyril C. Thompson: 1,000,000 Airplane Owners in the United States by 1950. If Not, Why Not?, *U. S. Air Services*, Vol. 24, No. 4, April 1939, pp. 14-16, 38.

14 Grover Loening: The Economics of Personal Aircraft, Aeronautical Conference London 3rd-5th September 1947, Convened by The Royal Aeronautical Society and The Institute of the Aeronautical Sciences, The Royal Aeronautical Society, 1948, pp. 229-240.

15 T. P. Wright: Personal Aircraft - An American Appraisal, Aeronautical Conference London 3rd-5th September 1947, Convened by The Royal Aeronautical Society and The Institute of the Aeronautical Sciences, The Royal Aeronautical Society, 1948, pp. 547-578.

16 Flying automobile is folding biplane. *Popular Mechanics*, Vol. 37 (Feb. 1922), Chicago, pp. 164-165.

17 Peter M. Bowers: *Unconventional Aircraft*, 2nd Edition, TAB Books, Blue Ridge Summit, PA, 1990, pp. 205-216.

18 James R. Chiles: Flying Cars Were a Dream That Never Got Off the Ground, *Smithsonian*, Vol. 19, No. 11, February 1989, pp. 144-162.

19 Roland Rohlfs (Personal Flying Specialist for Assistant to Regional Administrator, 1st Region, C.A.A.): Will the Convertible Aircraft Break the Bonds of the Present Restricted Market for Private Aircraft, 1st Convertible Aircraft Congress Proceedings, Sponsored by Philadelphia Sections of the American Helicopter Society and the Institute of the Aeronautical Society, December 9, 1949, Philadelphia, Pa., pp. 95-98.

20 Louis de Monge de Franeau (Consultant, Pennsylvania Aircraft Syndicate, Ltd.): Configurations of Convertible Aircraft, 1st Convertible Aircraft Congress Proceedings,

Sponsored by Philadelphia Sections of the American Helicopter Society and the Institute of the Aeronautical Society, December 9, 1949, Philadelphia, Pa., pp. 99-108.

21 Gerard P. Herrick (President, Convertoplane Corporation): The Development of the Convertoplane, 1st Convertible Aircraft Congress Proceedings, Sponsored by Philadelphia Sections of the American Helicopter Society and the Institute of the Aeronautical Society, December 9, 1949, Philadelphia, Pa., pp. 83-89.

22 Charles H. Zimmerman (National Advisory Committee for Aeronautics): Performance and Stability of a Convertible Aircraft, 1st Convertible Aircraft Congress Proceedings, Sponsored by Philadelphia Sections of the American Helicopter Society and the Institute of the Aeronautical Society, December 9, 1949, Philadelphia, Pa., pp. 69-82.

23 Robert H. Stroub: Introduction of the M-85 High Speed Rotorcraft Concept, presented at the 48th Annual Forum of the American Helicopter Society, Washington, D. C., June 3-5, 1992.

24 Laurence K. Loftin, Jr.: Aeronautical Vehicles - 1970 and Beyond, AIAA Paper No. 70-1262, presented at the AIAA 7th Annual Meeting and Technical Display, Houston, Texas, October 19-22, 1970.

25 David Frum: Crash!, *Forbes*, November 8, 1993.

26 Michael A. Dornheim: NASA to Boost General Aviation, *Aviation Week & Space Technology*, August 16, 1993.

27 Flying Friendlier Skies. *NASA Magazine*, NASA Headquarters, Washington, D. C., Winter 1994, pp. 18-21.

28 Palmer Stiles: CaRnard - A New Roadable Aircraft Concept, SAE Aerotech '93, Costa Mesa, CA, September 27-30, 1993, SAE Paper No. 932601.

29 Steven C. Crow: Back to the Future of Personal Aircraft, *SAE 1990 Transactions, Journal of Aerospace*, Section 1, Vol. 99, Part 2, SAE Paper No. 901990, pp. 2150-2176.

30 Steven. C. Crow: Starcar Design and GPS Control, SAE Future Transportation Technology Conference, "The Flying Automobile" Session, Costa Mesa, CA, August 11, 1992, SAE Paper No. 921569.

31 Branko Sarh: Design Concepts and Market Opportunities for "Flying Automobiles," SAE Future Transportation Technology Conference, "The Flying Automobile" Session, Costa Mesa, CA, August 11, 1992, SAE Paper No. 921570.

32 The M400 SKYCAR Volantor. Moller International, Davis, CA, January 1993.

33 David A. Brown: Firm Designs Aircraft that Drives Like a Car, *Aviation Week & Space Technology*, November 1, 1993, pp. 67-69.

34 David Freeman: Blacktop to Blue Sky, *Popular Mechanics*, August 1994, pp. 33-35.

35 Turning Now to Peace Use of Airplanes, *Air Service Journal*, Vol. 4, No. 12 (Mar 22, 1919), New York, p. 11.

THE ADVANCED PERSONAL FIXED-WING CONVERTICAR

Scott G. Anders
Experimental Methods Branch
Fluid Mechanics Division
Research and Technology Group
NASA Langley Research Center

Abstract

This report looks at a personal fixed-wing vehicle that functions as a car on the ground and converts to an airplane configuration for air travel . This vehicle is intended to be used as a car for trips under 50 miles and as an airplane for trips between 50 and 500 miles. Several issues are presented and technological barriers and breakthroughs are discussed. Selected configurations of converticars are presented. Advantages and disadvantages of each are given.

Introduction

The idea of a roadable aircraft is certainly not a new one. The concept has resurfaced many times starting with the Curtiss Autoplane in 1917. There are currently close to 70 patents granted for roadable aircraft or flying automobiles (see Reference 1). Despite efforts, roadable aircraft and flying automobiles have never made their way into the market. Their failure has been mainly due to technological shortfalls. These include issues of safety, acoustics, ride quality, piloting requirements, complexity, propulsion requirements, cost, and environmental impact. Of course cost, which is a driving issue as well, is directly affected by technology also. The future holds promise in resolving these issues and creating a new marketing opportunity. The future will bring an environment where the "flying car" is an attractive mode of transportation compared to what conventional (automobile) transportation will offer. References 2-10 contain additional information on past flying automobiles and roadable aircraft.

This report looks at a personal fixed-wing vehicle that functions as a car on the ground and converts to an airplane configuration for air travel (thus the term converticar). This vehicle is intended to be used as a car for trips under 50 miles and as an airplane for trips between 50 and 500 miles. Several issues are presented and the technological barriers and breakthroughs are discussed. Finally, a few configurations of converticars are presented. Some advantages and disadvantages of each are given.

Personal Converticar Issues and Technology

One of the biggest issues for this vehicle is cost . The vehicle must, of course, be worth its cost for the paying customer. The cost of a flying automobile must be brought down to the cost of a luxury automobile (over $30,000 in 1994). At the same time, usefulness and desirability must be elevated to the same or higher level than a similarly priced item. Total cost includes initial cost, maintenance, depreciation, fuel, storage, and insurance. Initial cost can be managed by economics of scale and through new technologies that offer lighter weight, lower cost components. A quality four place general aviation airplane kit, including assembly, in 1990 cost $150,000. However, if 100,000 units a year are sold instead of a few hundred, costs should go down significantly. No product liability insurance except on for the engine is factored into that price. This could substantially increase the price and must be addressed. The use of today's new electronics (computers) to do health monitoring would reduce maintenance. Onboard computers could also handle new and upcoming collision avoidance algorithms to reduce insurance and repair costs and to address safety issues. The issues that follow will address the benefits of the converticar.

The time it takes for portal to portal transportation is much improved over other modes of transportation for the flying automobile for a wide range of travel distances. This range can be on the order of 50 to 500 miles. Below 50 miles the automobile may be better and above 500 miles the commercial aircraft may be better. At speeds of over 200 mph, the converticar can significantly cut travel time. It is important to note that even though commercial aircraft offers over two times the converticar cruise speed, the travel times are lengthened by airport to destination, destination to airport, and the hub and spoke system.

In order for a new transportation means to be accepted safety must be adequately addressed. The vehicle must be safe and provide a high 'comfort level'. Upon examination of the piloting requirements of today's general aviation aircraft it is obvious that a significant amount of work is needed in this area. Pilot error is the largest contributor to accidents (this is true for the automobile as well). The personal aircraft begs for automatic piloting and navigation. The technology is currently available to accomplish this through the latest electronics and the now available Global Positioning System (GPS). See references 11-16 for more on GPS and automatic control and navigation. Through electronics and automatic control the personal aircraft can be realized by the general public in contrast with today's high standards for pilots. This new computer controlled navigation system would also be capable of monitoring weather and preventive maintenance as well as a collision avoidance system. None of this requires new technology to be invented, only to be applied. As mentioned above, the personal aircraft must not only be safe it must make the passenger feel safe. This is the issue of rider acceptance which requires acceptable levels of acoustics, vibration, ride quality, reliability/safety, and operator requirements. The last one is added because if the operator is loaded down with too much responsibility that require extensive training and retraining, he/she will not feel comfortable using the vehicle. It must operate much like today's automobile in terms of complexity, safety, training and retraining.

A big cost driver and challenge in the design of the converticar is weight reduction. Automobiles are historically heavy. Increased aircraft weight implies that higher lift is needed. Since 45% of the total drag is drag due to lift this incurs a high penalty. A heavy vehicle requires higher wing loading for the converticar since adding span is not practical for an aircraft that is to convert back to an automobile on the ground. This means a larger and stronger wing structure which will drive up cost. A higher drag also increases costs due to a larger fuel burn rate and additional fuel weight. There must be a technical focus on strong light weight structures, high-lift devices, and induced drag reduction techniques. Much of this technology is already out there.

There are issues pertaining to enhanced performance also. These include high-lift devices, circulation control, separation control, laminar flow control, induced drag reduction techniques, and riblets. Many of these issues have been addressed and are documented for traditional aircraft and can be applied to the converticar where appropriate. Some offer substantial performance improvement and deserve a serious look. For instance, Jeff and Sally Viken are currently working on a NASA SBIR that promotes full chord laminar flow on the upper surface of the wing and 60% on the lower surface. For a Cessna Centurion size airplane with laminar flow wings this increases speed from 193 to 220 mph. In terms of increased range, the aircraft range will go from 880 miles to 1120 miles, traveling at the original 193 mph. However, these are not driving issues to get the converticar idea off the ground. They are issues of performance improvement (thus future marketability). I agree with Dr. Steven Crow in reference 17, "The market will not reward us for laminar boundary layers unless they happen to come on a safe, convenient, comfortable, fast, prestigious, good looking, sane vehicle." Though he specifically singles out laminar flow, this thought applies to other performance improvement issues as well.

The "threshold" issues and technologies for converticars include those for the general aviation aircraft. References 11,18, and 19 sum these up. They are, in general, the same as those listed in Table 3, page 11, of reference 18 in 1987 and are listed here: 1.) Substantial improvements in reliability, maintainability, and servicing, 2.) Substantial reduction in noise and vibration, 3.) Improved ride quality, 4.) Integrated pictorial instrument and navigation displays, 5.) On-board collision avoidance system, 6.) Simplified power management.

Other design issues not covered specifically in this 'chapter' but may be found in other chapters are the propulsion system (Reference 20 describes one approach), environmental impact, acoustics, safety, ride quality (Reference 21 and 22 offer a possibility) and liability.

The Converticar

Since the Curtiss Autoplane in 1917 there have been 68 patents granted for flying automobiles and roadable airplanes (see reference 1 for a complete list of patents). A few other examples to date are the Waterman Arrowbile, Pitcairn Whirlwing, Stout/Spratt Skycar, Fulton Airphibian, ConVairCar, Zuck Plane-mobile, Taylor Aerocar, and Bryan Roadable (short descriptions and photos available in ref. 1). Reference 7 sites that current work is being done by Dr. Steven Crow on his Starcar (references 17, 23, 24, and 25), A. J. Smith on his Aero Caballo, Joe Yasecko on a canard pusher, Branko Sarh on his Advanced Flying Automobile, Ken Fox who is working to start a Roadable Aircraft Association and is working on various concepts, and Gary Bullard on a canard pusher. This is not meant to be a complete listing of past or present work.

This paper has committed itself to the fixed-wing converticar option. The present choice for those who want to fly is the personal or rented/leased general aviation aircraft combined with the personal and rented automobile. This requires automobile transportation to the airport where the GA aircraft is stowed, flying the GA aircraft to the nearest airport of your final destination, and transportation via automobile to the final destination. This requires 3 vehicles at a minimum, imposing inconvenience and lost time. A successful converticar concept should reduce this cumbersome arrangement and reduce travel time. Converticars have been generally designed along three different lines. The way the design accommodates components that are unique to either the automobile or the airplane differentiates the designs. The design can 1.) use a modular approach, 2.) use a roadable aircraft approach, or 3.) use a "transformer type" approach. Though this paper concentrates on the fixed-wing converticar, these approaches are generally true for VTOL (Vertical Take-Off and Landing) concepts as well. The fixed-wing converticar is superior to the helicopter in speed by two to three times. Other issues unique to a VTOL concept must are increased piloting difficulties (though piloting difficulties may be alleviated through automatic piloting and navigation), noise, downwash, safety during power out (mainly for intermediate altitudes attained during take off and landing), and increased cost. The main disadvantage for the fixed-wing converticar is the requirement for a suitable runway. However, there are currently over 17,000 existing facilities in the US available for fixed-wing aircraft. In addition, runways could be built along existing highways at 30 to 50 mile intervals similar to the way current rest stops are placed.

The modular approach to the converticar design tries to isolate the components unique to the automobile and airplane and to combine the components that are common to both. The design assumes that parts of the vehicle will be left behind or towed after converting from one configuration the other. References 17, 23, and 24 by Dr. Steven C. Crow describe a vehicle that uses this modular approach. In these references Dr. Crow has done ground braking work with GPS control (References 25 and 26) and he has his own concept of a converticar. The design breaks the vehicle into three basic components. The only "owned" component would be the passenger module. The front end which contains the automobile wheels, suspension, and engine would attach to the passenger module for ground travel. For air travel this automobile only module would disconnect and a third airplane module would attach to the back of the passenger module. This airplane module includes all of the flight necessary components including the wings, tail, and powerplant. This design allows optimization of the flight components (including the powerplant) for the flight mode. Likewise, the front module containing the wheels, suspension, front chassis, and engine can be optimized for ground travel and crash worthiness without worrying about a large weight penalty. In reference 23 by Dr. Crow a vehicle is described that has a top speed of 230 mph with a range of 800 miles. The landing and takeoff distances over a 50 foot obstacle are less than 1500 feet. Reference 27, 28, and 29 describe a different design using the modular approach. This approach has been most successfully applied by Molt Taylor on his Aerocar. For this design the wings, prop, and tail are removable and storable on a trailer that the remaining car module towes. Molt Taylor's 1956 Aerocar was fully certified, meeting all of the standards for cars and airplanes at the time. Reference 30 is a video that shows his car during its operational phases. In an approach very similar to Molt Taylor's, reference 27 and 31 use a production type automobile that is attached to a flight module. The flight module consists of the powerplant, wings, and tail. It is designed to attach to the automobile and carry it to its destination. It is stowed at an airport and might be envisioned as a rent-a-wing concept. The disadvantages to the modular approach are serious in terms of convenience. Configurations that do not carry all of the components together suffer greatly in terms of their utility. If the flight module is remotely located and must be rented or leased this introduces too much restriction on travel. In addition, the user must allow time for assembly and disassembly of the hardware.

The roadable approach is to combine all of the automobile and airplane components into a design that requires only shifting the output of the engine from propeller to wheel(s). Nothing else is changed and all components are carried with the vehicle. This vehicle would have a very low aspect ratio and high drag due to lift. Reference 32 shows a concept of such a vehicle. The vehicle is an airplane made road worthy. Reference 32 describes an aircraft with a very short wing span of 10 feet for the production version. The design gross weight is 2800 lb.. Maximum speed is 266 mph with a 475 hp piston engine. Range is 600 miles carrying three passenger and pilot. The takeoff and landing acreage clearing a 50 foot obstacle is less than 1500 feet. The wings are short enough to permit ground travel without folding, telescoping, or otherwise being modified. The power of the one engine is transferred from propeller to wheels for ground transportation. A mockup of the proof-of-concept vehicle has been built and some wind tunnel testing has been carried out. The chord is very long for this vehicle. The aspect ratio is 0.75. Winglets extend below the wing for the full chord and extend above the wing near the rear. The lower winglets house the drive wheels for ground travel. The estimated priced tag is $100,000. This design will suffer performance wise in order to meet its roadable goal. However, the design offers a large increase in convenience over the modular design. All components for flight and ground travel are inherently with this vehicle. No special assembly or disassembly is needed to go from on mode of transportation the other. Only one vehicle is needed instead of several parts stored in different locations. Also, no renting or towing is required. In addition, one can add pride of complete ownership as a plus for this design. This design is a step in the right direction in terms of overall utility for the end user.

The telescoping or "transforming" converticar carries all components with it at all times. Reference 33, 34, 35 and 36 present such a design. This design looks like a car and transforms into an airplane. Reference 35 describes a four passenger "Advanced Flying Automobile" with a telescoping wingspan of 28 feet. The maximum speed is 200 mph with a 350 hp rotary engine. The range is 550 miles. Gross weight is 3000 lb.. Take-off and landing clearance over a 50 foot obstacle is less than 2000 feet. The wings, horizontal and vertical stabilizer telescope out for the airplane mode. The wings are stored in the automobile roof during ground travel. Reference 36 gives an analysis for the telescoping wing. The propeller is stored in the hatchback and folds out for the flight mode. The engine is used as the power source for ground and flight travel. The vehicle shown in References 33 and 34 is aesthetically pleasing as an automobile and as an airplane. In reference 33 Branko Sarh presents evidence for the marketability for this vehicle. This design will suffer performance wise, as did the roadable airplane design, compared to the modular approach but should perform better than the roadable. This design offers all of the advantages of the roadable aircraft and should perform better in both travel modes. Again, only one vehicle is required and no restrictions apply concerning the stowage, pickup, and retrieval of components. This design offers the most convenience and is the most eye-pleasing of all of the designs. Other "transforming" type vehicle designs might use folding wings or wings that pivot and fold into an automobile body. Reference 37 takes this approach with a road vehicle that folds out to a canard pusher. The difficulty with the "transforming" designs is their complexity and hence initial cost and maintenance cost.

Summary

The converticar is a promising new form of transportation. The vehicle should be no more complicated to maintain and operate than today's automobile and should maintain an equal or better record of safety. This requires a technological investment in ride quality, acoustics, reliability, maintainability, automatic navigation, collision avoidance, and propulsion systems. However, there are no technological "show stoppers" for this type vehicle. This vehicle will expand cities and improve quality of life by increasing leisure time due to decreased travel time. Converticars will not require large expanses of concrete that become choked with traffic as fast as they are laid down. The time to begin investing in this type of transportation is now in order to gain a strong upper hand on the future's transportation demands.

References

1.) Stiles, Palmer C.: "Flying Auto & Roadable Aircraft Patent Search", 1918-1991, 68 patents, 250 pp., Ed. Palmer C. Stiles, Custom Creativity Inc., Satellite Beach, FL.

2.) Borovec, Ron: "Roadable Aircraft", 338 8th Avenue South, Edmonds, Washington 98020-3412.

3.) Bowers, P.M.: "Unconventional Aircraft", pp. 207-216, TAB Books, Blue Ridge Summit, PA, 1990.

4.) Chant, Christopher : "1984 Fantastic Aircraft", W. H. Smith Publishers, Inc., New York, ISBN 08317-31893.

5.) Chiles, J. R.: "Flying Cars Were a Dream That Never Got Off the Ground", Smithsonian, Vol. 19, No. 11, pp. 144-162, Feb. 1989.

6.) Roby, John: Roadable Aircraft Literature list , Out-of-Print and Current, 3703Y Nassau Dr., San Diego, CA 92115.

7.) Stiles, Palmer C.: "History and Future of Flying Automobiles", SAE Technical Paper 921568, SAE International, Warrendale, PA, 1992.

8.) Taylor, M. B.: "Flying Automobiles, a Compilation of Articles, Reprints, and Stories." Aerocar Associates, Longview, Washington, April 30 1989.

9.) Woron, W.: "Of Wings and Wheels", An Investigation of flying cars. Smithsonian Museum literature.

10.) Zuck, Daniel R.: "An Airplane in Every Garage", Library of Congress.

11.) Holmes, B. J.: "U. S. General Aviation: the Ingredients for a Renaissance", Second AIAA/FAA Joint Symposium on General Aviation Systems, Wichita, Kansas, March 1992.

12.) Lechner, W.: "GPS in Germany", GPS World, Vol. 2, No. 4, pp. 25-29, April 1991.

13.) McNally, B. D.; Paielli, R. A.; Bach, R. E., Jr.; and Warner, D. N., Jr.: "Flight Evaluation of Differential GPS Aided Inertial Navigation Systems", Proceedings of AGARD Guidance and Control Panel Specialist Meeting on Integrated and Multi-Function Navigation, Ottawa, Canada, May 1992.

14.) Murray, C.: "Highway in the Sky", Popular Science, Vol. 240. No. 6, pp. 106, 107, 118, June 1992.

15.) Stewart, E. C.: "A Simulation Study of a Display and Control System Requiring Reduced Pilot Training and Proficiency", Second AIAA/FAA Joint Symposium on General Aviation Systems, Wichita, Kansas, March 1992.

16.) Studt, T.: "Smart Vehicles, Smart Highways-Roaring Down the Pike", R & D, Oct. 25, 1993, pp. 14-18.

17.) Crow, Steven C.: "Back to the Future of Personal Aviation", SAE Technical Paper 901990, SAE International, Warrendale, PA, 1990.

18.) Kraus, E. F.: "Technical Thresholds for Revitalizing General Aviation", AIAA-87-2933, Sept. 14-16, 1987.

19.) Grey, J.: "The Role of Technology in Revitalizing U.S. General Aviation", Report of an AIAA Workshop, Washington D.C., Dec. 12-13, 1989.

20.) Knepp, John E.; Mullen, Robert L.: "Conversion of Production Automotive Engines for Aviation Use", SAE Technical Paper 932606, SAE International, Warrendale, PA, 1993.

21.) Porter, R. F.; and Brown, J. H., Jr.: "Evaluation of the Gust-Alleviation Characteristics and Handling Qualities of a Free-Wing Aircraft", NASA CR-1523, April 1970.

22.) Porter, R. F.; Luce, R. G.; and Brown, J. H., Jr.: "Investigation of the Applicability Evaluation of the Free-Wing Principle to Light, General Aviation Aircraft", NASA CR-2046, June 1972.

23.) Crow, Steven C.: "Conceptual Design of a Starcar", SAE Technical Paper 911021, SAE International, Warrendale, PA, 1991.

24.) Crow, Steven C.: "Engineering Design of Starcar 3", SAE Technical Paper 932602, SAE International, Warrendale, PA, 1993.

25.) Crow, Steven C.: "Starcar Design and GPS Control", SAE Technical Paper 921569, SAE International, Warrendale, PA, Aug. 1992.

26.) Crow, S. C.: "Differential GPS Control of Starcar 2", Journal of the Institute of Navigation, Vol. 39, No. 4, pp. 383-405, Winter 1992-93.

27.) Sweeney, E.: "The AEROCAR - Its Past and Future", SAE Technical Paper 921567, SAE International, Warrendale, PA, 1992.

28.) Taylor, M. B.: The Aerocar "Flying Automobile", SAE 740393, Business Aircraft Meeting, Wichita, Kansas, April 2-5, 1974.

29.) Cox, J.: "Aerocar, Molt Taylor's Quest for a More Useful Airplane", Sport Aviation, Vol. 39, No. 1, pp. 11-21, Jan. 1990.

30.) Experimental Aircraft Association 1991, Molt Taylor's Aerocar - Giving the Automobile its Wings (video) Oshkosh, WI.

31.) Goldsworthy, Brandt: "The Convair Flying Automobile", SAE Technical Paper 921566, SAE International, Warrendale, PA, 1992.

32.) Brown, D. A.: "Firm Designs Aircraft That Drives Like Car", Aviation Week and Space Technology, Nov. 1, 1993, pp. 67-69.

33.) Sarh, Branko: "Design Methodology and Infrastructures for Flying Automobiles", SAE Technical Paper 932604, SAE International, Warrendale, PA, 1993.

34.) Sarh, Branko: "Design Concepts and Market Opportunities for "Flying Automobiles", SAE Technical Paper 921570, SAE International, Warrendale, PA, 1992.

35.) Weiss, Mierkel F.: "Design and Styling of an Advanced Flying Automobile", SAE Technical Paper 932603, SAE International, Warrendale, PA, 1993.

36.) Czajkowski, Mike: "Design and Analysis of a Telescopic Wing", SAE Technical Paper 932605, SAE International, Warrendale, PA, 1993.

37.) Stiles, Palmer C.: "CaRnard - A New Roadable Aircraft Concept", SAE Technical Paper 932601, SAE International, Warrendale, PA, 1993.

Propulsive Lift Vehicle Option For The Personal Aircraft

Dennis M Bushnell

There are three basic vehicle options for a personal aircraft, "fixed wing" [including folding/telescoping wing] configurations utilizing aerodynamic lift for takeoff/landing,[with or without special features to increase lift coefficient] and propulsive lift vehicles, either a helicopter or ducted/deflected [lift/cruise] fan [ref. 1].Many types of compound/combined approaches are also contained within the vehicle solution space including tilt rotor/tilt wing and x-wing etc.A fundamental difference between these options is whether or not an airfield is required for operation.Obviously the "fixed wing" class of vehicle would require an airfield whereas the powered lift approaches could probably operate from an open area of restricted extent with reasonably compacted soil.The fixed wing and helicopter options are discussed in separate chapters in the present volume,the purpose of this chapter is to consider the ducted fan class of vehicle,the assumption being that the tilt rotor and x-wing etc. are much to expensive an option for the personal aircraft mission.

The canonical example of the lift fan approach is the British Harrier and the U.S. variant,the AV-8.The major advantage of this type of powered lift approach compared to a rotary wing craft is cruise speed,up to order of 400 kn. vs. order of 160 knots for a helicopter.A probable disadvantage is cost.In general,compared to a helicopter the ducted fan requires greater horsepower and higher fuel consumption for hover,but allows lower system weight,greater cruise efficiency and higher altitude [ref. 2].Historically this class of air vehicle was developed for military purposes and has not yet entered civilian service.

The Harrier And AV-8

The Harrier aircraft concept dates from initial work in the U.K. in 1957.The interested reader should see ref. 3,an excellent historical review of the Harrier development and from which much of this section is abstracted [see also the Harrier discussion in ref. 2].The fundamental concept is simple,using rotating in-stream vanes,vector the engine exhaust down [at four positions,two on each side near the front and rear of the wing] to provide lift and then,once in the air,vector the thrust rearward for forward flight.The "transition" from vertical to forward flight is a critical and sensitive maneuver during which increasing forward flight speed allows aerodynamic lift to progressively replace direct/propulsive lift.Control during the vertical and transition portions of the flight is via directed high pressure jets at the wingtips and nose and tail of the aircraft.This is necessitated by the ineffectiveness of conventional aerodynamic controls in the case of low-to-zero forward speed.

The key design issue in the development of this aircraft were the various vehicle control [and associated flight safety] problems,especially during transition.The vehicle was adopted,with various application-specific modifications,in the Royal air force and navy and by the USMC as the AV-8.The aircraft has been in service since the 1960's performing multitudinous military missions [e.g. fighter,intercepter,patrol,reconnaissance,strike,close air support and anti-submarine operations,all without the necessity of airfield utilization.]They have operated successfully from roadways,forest clearings and fields and the decks of merchant ships.Their unique ability to nearly stop in midair make them very formidable opponents in a dogfight.Probably the most famous demonstration of Harrier prowess involved their excellent service in the Falklands war.Not only is the Harrier a VTOL aircraft,once airborne it is an excellent combat vehicle.The bottom line is we have some 35 years of very successful flight experience with this class of VTOL aircraft.

The Moller M400 Skycar

Given that the Harrier class of deflected exhaust,lift/cruise fan aircraft is the only,aside from the helicopter,VTOL aircraft for which we have extensive operational experience [ref. 2],how does/can this vehicle concept relate to the personal aircraft mission?Paul Mollar has spent considerable time and money investigating this question and is currently producing a prototype of such a vehicle,nominally capable of carrying four passengers with luggage at speeds of 350 mph with a range of 900 miles and a gross weight of 2500 pounds [see ref. 4].A key consideration is cost [for the personal aircraft application of the Harrier paradign] and turbine engines are simply too expensive,particularly in as much as a new turbine engine would have to be developed for the personal aircraft sized vehicle.Mollar 's approach to this problem was to shift to an internal combustion powerplant and to develop what amounts to a greatly advanced Wankel engine with much improved power density.The Wankel approach also provides significient increases in reliability due to their simplicity/paucity of moving parts compared to piston IC engines [3 vs. 44] and will run on conventional gasoline,see ref. 5.

The "Skycar" is powered by 8 engines in four nacelles located fore and aft of the cockpit analogous to the Harrier vectored exhaust nozzle locations.As in the Harrier the nacelles are fixed horizontally and vanes [two sets in each nacelle] are rotated to provide VTOL capability.The rotating vane,as opposed to the rotating nacelle/tilt rotor approach is a lower weight/more inexpensive approach.Safety-wise,Mollar has included parachutes for recovery of the entire vehicle and capability for VTOL operation with one engine out as well as considerable redundency throughout the flight-critical systems.The vehicle is aerodynamically stable and capable of gliding to an area suitable for parachute deployment.The control system,while simplified to allow ease-of-use by a pilot,is not fully automatic and pilot training is required for operation of the vehicle.

In the context of a spectrum of personal aircraft,the helicopter approach would probably become the "everymans"or "volkswagon" lower priced version,with significiently lower cruise speed than the lift/cruise fan approach.The latter would probably constitute the "cadillac" version,with improved performance etc.The "enabling technologies which make the personal VTOL lift/cruise feasible include Mollar's lightweight reliable Wankle engine,lite-weight composites and the electronics revolution in terms of size,capability and cost for sensors,controls and computers.

References

1.Deckert,W.H. and Franklin,J.A., Powered-Lift Aircraft Technology,NASA SP-501,1989

2. Campbell,J.P.,Vertical Takeoff And Landing Aircraft, The Macmillan Co.,N.Y.,1962

3. Fozard,J.W. ,The Jet V/STOL Harrier-An Evolutionary Revolution In Tactical Air Power,British Aerospace Aircraft Group,U.K.,1978,available as AIAA Professional Study Series Report "The British Aerospace Harrier-Case Study In Aircraft Design

4.Garrison,P., Will This Thing Fly?,pp.132,133,Flying,August,1991

5. Garrison,P, A Wankel In Your Future, pp. 94,96,97,Flying,March,1991

The Personal Helicopter

Dennis M Bushnell
NASA-Langley Research Center

INTRODUCTION

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 the order of hours-to-days/weeks, depending upon distance.In the closing years of the same century 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.In the process of supplanting older transportation systems,these newer approaches have had a profound influence upon the structure of modern societies.Cities have expanded out of 18th century seaports and 19th century railheads,where much of the developed region was within walking distance of the transportation terminals,into tremendous suburbs with attendant reductions in crowding/increased opportunity for individual home ownership etc.,etc.The existing transportation system fulfills a variety of purposes including travel to and from work and stores,and for various business,service and pleasure related activities.Transportation and related activities currently constitute the order of 1/5 of the U.S.GDP.

The present report will center upon future possibilities/options for a specific portion of the transportation spectrum,short-to-moderate range,nominally from 10's to 100's of miles.The current dominant transportation mode for this mission 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 and been responsible for the expenditure of truely prodigeous sums on roads and bridges,etc.The current status of the auto infrastructure is that we continue to clear and pave more of the watershed,contributing to flooding,dessication and the formation of heat islands.Also,the average trip time is increasing due to expansion of the suburbs and increased congestion,causing non-trivial changes in family life as travelers attempt to utilize non-traditional time slots,or suffer long/non-productive commutes.The interstate highway system is [finally] finished and is already clearly overburdened and in need of very expensive repairs and expansion.

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/are developing.Probably the most commonly advocated alternatives involve some form of mass transit,which have,along with tremendous capitol 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.Undoubtably,the future mix of short-to-intermediate transport systems will include both mass transit and automobiles of some variety,probably operated on "intelligent" highways to improve safety and throughput/trip time [ref. 1].

There is,however,both a need and an 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 has provided over the horse.Personal air transportation is both revolutionary and the next logical step in the development of human infrastructure and corporal communication.The increased speed of such a capability,along with the greatly reduced capitol requirements in terms of highways/bridges etc. should allow significient 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/less damaging co-existance of man and nature,along with improved transportation safety.The "vision" is of multi-level highways in the sky,controlled and monitored by inexpensive electronics as opposed to narrow,single level,exceedingly expensive "ribbons of concrete"[e.g. ref. 2]. Such air systems/vehicles could also obviously be used for longer haul,as are automobiles today.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 slower,but more direct,travel via personal aircraft [compared to the "faster"commercial jet].Various options exist for personal aircraft systems.The discussion herein will address one such option,a helo-converticar,and attempt to defend that particular recommendation.

PERSONAL HELICOPTER ISSUES

Certain requirements/desirements are common to any personal transportation vehicle/system.These include short transit time/speed,direct portal-to-portal,privacy and security,constant availability,personal stowage and a suitability for transport of the "non-pilot" with all that implies in terms of athletic prowess/physical and mental capabilities etc.From the outset an obvious [and probably attainable] goal should be an automatic personal air transport system,automatic with respect to navigation [e.g. refs. 3-5],air traffic control and operation.The technology to accomplish this is either currently employed by/for the long haul air transport application,or in the research pipeline,thanks to the microchip"electronics revolution" and GPS.Such automatic operation provides vastly improved safety,as the preponderance of accidents are due to operator error.In addition,it makes personal air vehicle transportation available to the general public,as opposed to the few who have the opportunity,money,and physical characteristics to become pilots.

Conventional wisdom holds that,to be successful,an alternative transportation system must be not only faster,but also relatively inexpensive,or at least not more expensive,or perhaps not significiently more so [depending upon which income strata one is targeting].The costs involved in any system include aquisition,operation,maintainance,and depreciation.To be competitive with the automobile a personal helicopter should have an acquisition cost in the vacinity of a quality automobile.In 1994,this is the order of 30k+.Although in terms of the current helicopter industry this is a ridiculous target,the advantages of a production run of millions instead of hundreds,along with a recent offering of a single seat helo for 30k [refs. 6 & 7] makes the outlook to achieve such a goal possible if not probable.Operational costs include fuel,insurance,parking fees etc.,and need not be greater than the auto.Maintainance is considerably greater for present helos than for autos,and therefore this issue would have to be addressed in the personal helo technology development program.

All-weather operation is also a requirement,the same all-weather capability one now has in an automobile,which is by no means absolute.Heavy rain,and extreme winds,ice and snow will all either slow or stop the auto ,and similar restrictions will hold for the personal helo.Obviously the evolving "detect and avoid" technology could be utilized by the personal helo [either on or off board] to increase safety vis-a-vis extreme weather.In terms of speed and range,the helo must provide a significient speed advantage or it is simply not viable.As compared to a fixed wing personal aircraft,the helo speed advantage is much less vis-a-vis the auto,but at a nominal factor of 4 [for the traffic case] still sufficient.We are currently spending significient sums to gain a factor of 2+ in the high speed civil transport program [vis-a-vis subsonic transports].Another key issue is rider acceptance in terms of acoustics,vibration,ride quality,and reliability/safety.All of these technical areas will require further work,although the helo community has made significient strides in these already and considerable further gains/technological advances are in the pipeline.A final major set of issues involve community acceptance in terms of acoustics and downdrafts during near surface operations.Again,more work is needed,but these could be addressed by operational as well as technological approaches.Previous approaches to the "personal helicopter" have mainly considered existing machines as opposed to the advanced technology/farther term vision discussed herein [e.g. refs. 8-10].There have been,however, calls for such an approach [refs. 11,12].

PERSONAL HELICOPTER TECHNOLOGY

Over the years,particularly since the 1930's,there have been suggestions,and in some cases strident calls,for the development and 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 and requisite technology readiness.History is replete with examples of concepts which are good ideas and which keep resurfacing until the technology base is ready.An obvious example is the gas turbine engine.Since the last personal aircraft campaign in the late 40's-50's,major strides have occured in several enabling technologies.These include light weight,miniature,inexpensive and tremendously capable electronics/computing,light-weight composite materials with essentially infinite fatigue life,computational fluid mechanics,smart-to-brilliant materials/skins,flow control of several types,active controls/load alleviation and direct energy conversion.Such advances significiently change the personal aircraft discussion,particularly for the helo."The helicopter looks,35 to 40 years after its invention,to be poised in the position the fixed wing aircraft were in the late 40's and early 50;s,again 40 years after the first flights were being made"[ref.13].In particular,the personal helicopter would profit from much of the sizable investment made in military machine research,albeit the civilian application is in many ways less severe in terms of "rough usage" etc.This is again directly analogous to the fixed wing situation where the 707 class of transport aircraft profited immensely from/was enabled by,the military investments in swept wing/jet propelled bombers/tankers/transports.

Key helo-specific technologies either available or in the pipeline include high reliability turbines with 100,000 hour time-between failures [allowing single engine operation],composite blades with 10,000 hour fatigue life,the hingeless-bearingless rotor with low drag hub,automatic health monitoring to allow significient reductions in maintainance costs,anti-vibration and anti-noise for enhanced rider comfort,automatic piloting and navigation/nap-of-the-earth operation,composite structure and skins and smart skins for flow and load control.Taken together these advances will address many of the issues identified in the previous section [see,for example,refs.14-21].

There are other key technologys which should probably also be addressed for application to the personal helo.These include the possibility of utilizing an electric drive via direct conversion and fuel cells.Such an approach may provide simplicity and reduced vibration,noise and emissions [refs.22-26].Another interesting farther term technology involves the development of "ice-phobic" surfaces,via surface chemistry tailoring,for anti-icing.Blade motion/flexing usually helps obviate ice buildup on the blades,but icing is a general problem in terms of all-weather operation.If speeds faster than 160+ mph are desired then several candidate techniques could be studied such as the tilt-rotor,x-wing,variable diameter rotor,stopped/stored rotor and the M-85 large hub fairing concept [e.g. refs. 27,28].Further work in active flow control holds the promise of reduced downwash effects,improved performance,improved ride quality and reduced vibration and acoustics.Also,a viable means must be worked to provide safe mission abort for a single engine machine below 500 ft. altitude.Parachute systems are an obvious candidate,as is autorotation.

Recent examples of personal helos include the well-known Robinson R22 Beta and the recently marketed Ultrasport 254 [refs. 6 & 7].The former is a two-place helo with an annual operational cost the same order as a GA fixed wing machine-11k.The rotor diameter is 25 ft.,the mileage is 15 MPG at 110 MPH,and the initial cost is the order of 100k for a production run of 300/year.The cost for the one-person ultralite Ultrasport machine [no pilot license required] is 30k,with a direct operating cost of $8/hr,which begins to sound affordable.The safe mission abort problem appears to be in hand for the Ultrasport.The bottom line regarding technology for the personal helo is that ,if we are not within striking distance we are at least very close.As in most cases of such systems,it is not one single technology which is enabling ,but an assemblage of technologies which will result in this revolution in personal transportation.

THE HELO-CONVERTICAR

There are several "systems level" issues and critical choices regarding the personal aircraft which served as key discriminators in the selection of the particular personal aircraft discussed herein,a helo-converticar.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 economicaly 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,engines,etc and therefore,if it is technically feasible to reduce the weight of an auto to what is reasonable for an air vehicle,then a single device should be considerably more economical [initial cost as well as maintainance-wise] than buying and maintaining two separate vehicles,particularly when one considers the present cost of autos [25k+ for a quality midsize].Simplex estimates of the flight-specific component weights indicates a value of less than 1000 pounds,indicating that,with shared utilization of common systems such as the engine,the "all-up" weight of the converticar could be in the [reasonable] range of 2600 to 3000 pounds.From an operational viewpoint,usage as well as maintainance-wise,a single vehicle should be much more convenient.Once the converticar option is selected,some decision/recommendation has to be made regarding the provision for the "air-unique" components,particularly the lift-producing surfaces which require,for resonable levels of drag-due-to-lift,non-trivial span/aspect ratio.Options include towed "trailored" wings [utilized in early versions of the converticar],fixed wings of inherently low aspect ratio for "roadability" [ref. 29],airport "rent-a-wing" concessions where the wings are attached prior to,and removed at the conclusion of,flight,and telescoping wings.The present author favors the telescoping option as offering the best compromise between convenience and performance.

The next critical choice is between conventional/"fixed wing" operation and a VTOL device.An essential difference is that the fixed wing machine/operation requires an airport and although there are many thousands of GA airports in the U.S.,one would still have to begin and end the air portion of the trip at an airport.In the opinion of the present author,this is simply too restrictive and contravenes several of the fundamental purposes of the personal air vehicle such as independence of/reduced requirement for large civil works,portal-to-portal transportation,and access to remote sites [remote from roads etc.].The VTOL option would allow development/usage of currently undeveloped nations/regions at a fraction of the cost of the roads/bridges etc. usually required for such development,and at much less disruption to the environment [ref. 30].Conversion from ground to flight and back again for a helo-converticar requires only a relatively hard surface with a diameter the order of 25 ft.,something which could be placed at intervals alongside the existing highway system to provide convenient ground-to-air "merging" away from existing builtup housing areas to minimize acoustic/downdraft etc, influences upon the population.Further advantages of the helo include the provision for both lift and propulsion in a single device during air operation and ATC "margin" [in the event of an ATC conflict the vehicles involved could "hover" or [vertically] land while the problem is addressed/resolved].

Another major option involves the extent to which the operation in the air mode should be automatic as opposed to pilot/human derived.While sport models could be somewhat human-controlled [within the confines of the ATC/safety regulations]the optimal solution is clear.The portion of the population physiologicaly capable of becoming pilots is not large and there is considerable cost and time involved in doing so,most accidents are due to pilot error [ref. 31],and the ATC system requires,for the large numbers ultimately envisiged,automatic operation.Therefore,a user-orientated personal air capability should,ultimately,be automatic in operation as well as navigation and ATC,as already suggested herein.

A personal transportation machine capable of both ground and [VTOL] air operation could be an automobile with an IC engine [ref. 32],probably initially a two-seater and at least somewhat pilot-controlled,which is light enough to also fly and which has built into its roof an erectable low drag,large taper [ref.33] rotatable hub with a diameter consistant with the vehicle width containing the order of four telescoping rotor blades.In addition,a rear deck vertical fin is required within which is a,perhaps electrically driven,tail rotor.An alternative approach would involve circulation control on the "afterbody" in liu of the tail rotor.As stated several times in this discussion,the central issue is COST [see the quote from Henry Ford in ref. 34] and usability.As a result of technological advances in several areas,many of them momentous,and the tremendous requirement/market for such an affordable/user-friendly capability,the issue of personal air transportation should be revisited.The probable course of development for personal air transportation is parallel to that of the automobile in the early 1900's.The initial machines were expensive ["rich man's play toys"] with many impediments to their operation such as poor roads,noise sensitivity and laws which were in many cases "anti-automobile".Once industrialists [e.g. Henry Ford] addressed the problem via "design to cost/PRICE",simplicity [any color as long as it's black] and mass production,the price dropped drastically and the resulting wide-spread sales/utilization of the product revolutionized,in many ways,our entire society.

REFERENCES

1.Studt,T.,"Smart Vehicles,Smart Highways-Roaring Down The Pike"pp 14-18,R & D ,Oct. 25,1993

2.Smelt,R.,"Looking Ahead In Aeronautics And Astronautics-A U.S. View",PP 501-529,"The Future Of Aeronautics",J E Allen & J. Bruce,ED.,St. Martins Press,N.Y.,1970

3.Crow,S.C,"Starcar Design And GPS Control" ,AME Research Report 92-18,1992,Univ. Of Arizona Dept. Of Aerospace & Mechanical Engineering

4.Kaufman,D.N. "Helicopter Precision Approach Capability Using The Global Positioning System",NASA CR-194037,1992

5.Kobayashi,T, "Automatic Flight Management System For Helicopters",15th European Rotorcraft Forum,1989,Amsterdam,Paper No. 24

6.Flynn,B. "They're Giving It A Whirl",Daily Press,New Port News,Va.,pg. B4,Dec. 13,1993

7.Smith,L.K.,"Everyman's Plane At Last! The UltraSport 254",Vertiflite,pg. 10,Sept./Oct. 1993

8.Lambert,M., "Personal Helicopters",Flight International,12 May,1979,pp. 1572-1582

9.Parrish,R.L. "Once Bitten,Forever Sold"Business And Commercial Aviation,March 1989,pp. H6-H10

10.Lert,P. "A Helicopter In Every Garage?", Air Progress ,V. 40,No. 11,Nov. 1978,pp. 40-45,65

11.Kelley,B. "Helicopter Evolution"J. Of The American Helicopter Society,V. 28,No. 1,Jan. 1983,pp.3-9

12.Drees,J.M. "Prepare For The 21st Century-The 1987 Alexander A.Nikolsky Lecture",J. Of The American Helicopter Society,V.32,No. 3,July 1987,pp. 3-14

13.Hamshaw-Thomas,C. "The Helicopter As An Element Of Air Transport Systems",Part 2,Proceedings Of The 14th International Helicopter Forum,1983,

14.Hooper,W.E.,"Technology For Advanced Helicopters",SAE Paper No. 87-2370,1987

15.Frommlet,H And Schick,C,"Modern Technologies For Future Light Helicopters",Paper No. 37,11th European Rotorcraft Forum,1985

16.Friedman,H.W. ,"Design And Fabrication Of An Advanced Light Rotor",Proc. 44th Annual Forum,American Helicopter Society,1988,pp. 347-354

17.Brahney,J.H. "Rotor System Design:An Adventure In Compromise",Aerospace Engineering,V. 5,July 1985,pp. 8-21

18.Logan,A.H."Light Helicopter Technology For The Year 2000",Paper No. 3-6,13th European Rotor Craft Forum,Sept. 8-11,1987

19.Carter,E.S. "Research-Technology Needs For Civil Helicopters",SAE Paper No. 83-1557,1983

20.Lachere,G.B.,Lamberti,R,And Berthier,J.M.,"Composite Helicopters",Aerospace,Dec. 1990,pp. 14-18

21.Amer,K.B."A New Philosophy Of Structural Reliability,Fail Safe Versus Safe Life",Paper No. 99,14th European Rotorcraft Forum,Milano,Italy,1988

22.McElroy,J.F. "Fuel Cell Power Plants For Automotive Applications",IEEE Transactions On Vehicular Technology,V. VT-32,No. 1,Feb. 1983,pp. 33-41

23.Galbraith,A.D. "Electric Propulsion For High Performance Light Aircraft",AIAA Paper No. 79-1265,1979

24.Lynn,D.K.,McCormick,J.B.,Bobbett,R.E.,Kerwin,W.J. And Derouin,C. "Fuel Cells For Vehicular Applications",Los Alamos Scientific Laboratory Report LA-UR-79-2826,1979

25.Strack,W.C. "Aeropropulsion Opportunities For The 21st Century,NASA T M 88817,1986

26.Kirchen,P.T.,Jacoby,D.R.,Galbraith,A.D. "Practical Feasibility Assessment Of Electric Power Propulsion In Small Helicopters Using Lithium Hydroxide Battery Technology",NASA CR-166455,1981

27.Fradenburgh,E.A. "The Variable-Diameter Rotor-A Key To High Performance Rotorcraft" ,Vertiflite,March/April 1990,v. 36,pp. 46-53

28.Stroub,R.H. "Introduction Of The M-85 High Speed Rotorcraft Concept",48th Annual Forum Proceedings,American Helicopter Society,V. 2,pp. 1081-1104

29.Brown,D.A. "Firm Designs Aircraft That Drives Like Car" Aviation Week And Space Technology,Nov.1,1993,pp. 67-69

30.Shapiro,J. "The Helicopter",The Macmillian Company,New York,1960

31.Powell,G.M. And Wagner,F.J. "A Design-Support Team Views Fourty Years Of Commercial Helicopter Value",42nd Annual Forum Proceedings,American Helicopter Society,1986,V.1,pp. 375-388

32.Knepp,J.E. And Mullen,R.L. "Conversion Of Production Automotive Engines For Aviation Use" ,SAE Paper No. 93-2606

33.Prouty,R.W. "Helicopter Aerodynamics",Rotor & Wing International [Text],PJS Publications,Peoria,Ill.,1985

34.Cohen,E.E., "What Small Turbine Engine Does The Small Helicopter Need,Or The Road To Hell Is Paved With Good Intentions",AIAA Paper No. 79-1324,1979

ENVIRONMENTAL IMPACT OF ADVANCED PERSONAL AIRCRAFT

Scott C. Asbury
Component Integration Branch
Aerodynamics Division
Research and Technology Group

Abstract

Personal aircraft have the potential for reducing exhaust emissions from transportation sources. Currently, the primary mode of transportation for short-to-moderate range trips is the automobile, which is the major contributor to air pollution in the United States today. Automobiles powered by internal combustion engines release large amounts of pollutants into the atmosphere at ground level where they often become trapped below thermal inversion layers and result in local air quality problems. Personal aircraft would operate between cities above inversion layers, where their emissions would have little impact on local air quality. To assure their success, personal aircraft must be powered by advanced propulsion systems specifically tailored for low exhaust emissions. The purpose of this paper is to discuss the emissions characteristics of potential propulsion systems for personal aircraft, methods for assuring low emissions, and the impact that these emissions may have on the environment.

Introduction

In response to growing public concern for the environment, Congress has enacted a series of laws requiring the transportation industry to comply with exhaust emissions standards. This legislative control is designed to restrict vehicle emissions and minimize ground level concentrations of pollutants, namely carbon monoxide (CO), unburned hydrocarbons (HC) and oxides of nitrogen (NO_X), which contribute to air quality problems in large metropolitan areas (ref. 1). While aircraft are relatively small contributors to overall national emissions burdens, their contribution to local emissions inventories is considered significant enough to warrant control by the Environmental Protection Agency (EPA) (ref. 2).

In late 1970, the United States Federal Clean Air Act was amended (ref. 3) to require the EPA to establish emissions standards for aircraft. In January 1973, the EPA responded by establishing emissions regulations (henceforth, known as the 1979 EPA Limit) for aircraft gas turbine and reciprocating engines manufactured after December 31, 1979 (ref. 4). In 1977 an amendment to the Clean Air Act required states to develop implementation plans to meet National Ambient Air Quality Standards (NAAQS) (ref. 5). Currently, states that are out of compliance with the NAAQS must, according to a 1990 amendment to the Clean Air Act (ref. 6), develop and implement control strategies that demonstrate specific degrees of emissions reduction. As a result of this legislation, the EPA California Federal Implementation Plan (FIP) was signed on February 14, 1994 to assist California in obtaining the NAAQS (ref. 7).

The California FIP consists of all-encompassing emissions regulations covering private, industrial and commercial pollution sources. Specific regulatory limits have been set for commercial aircraft that call for a 45% reduction, from the 1990 baseline emissions level, in CO, HC and NO_x emissions by the year 2010. As a result, commercial aircraft engine manufacturers are pursuing design modifications that will allow their engines to meet the 2010 California FIP requirements. However, no reductions have been proposed for general aviation (GA) aircraft, as the EPA considers the GA fleet turnover too low to experience significant benefits from new regulations intent on reducing engine emissions. What the EPA has done is to impose regulations that will limit GA operations in metropolitan areas where local air quality problems are severe.

The EPA's approach to GA aircraft emissions reduction results in a significant problem for the development of personal aircraft propulsion systems. At least initially, it is expected that the EPA will consider a personal aircraft to fall into the same category as the current general aviation fleet. At this point, designing a personal aircraft to meet a GA emissions target is not possible, as the emissions target for GA or personal aircraft does not exist. It is almost certain that CO, HC and NO_x emissions levels for personal aircraft would be regulated by the EPA if mass production were to begin. At a minimum, engines manufactured for personal aircraft will be required to meet the 1979 EPA limit for emissions. However, with growing concern over air pollution nationwide, many northeastern states are considering adopting emissions regulations similar to those in the California FIP (ref. 8). Therefore, by the time personal aircraft were to enter production, they would likely face emissions regulations much more stringent than the 1979 EPA limit. Based on current industry opinions it is felt that a target (henceforth known as the "design target") required for a reasonable assurance that production engines will meet EPA standards is 50% of the 1979 EPA limit (ref. 9).

Symbols and Abbreviations

EPAR $\dfrac{\text{engine emissions output}}{\text{1979 EPA limit}}$

Abbreviations:

BSFC	brake specific fuel consumption
CO	carbon monoxide
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
F/A	fuel-air ratio
FIP	Federal Implementation Plan
G	propeller gear reduction
GA	general aviation
HC	hydrocarbons
I	fuel-injected
LTO	landing and takeoff
NAAQS	National Ambient Air Quality Standards
NO_x	oxides of nitrogen
O	opposed cylinders
T	turbocharged

Effect of Emissions on the Environment

Damage caused by air pollution can be assessed in terms of effects on health and deterioration of inert materials (especially buildings), and degradation of the atmosphere itself. Pollutant emissions to the atmosphere can be broken down into two major categories: mobile and stationary sources. Mobile sources cover emissions from any source of transportation such as cars, trucks, ships, trains, aircraft, etc. Emissions of CO, HC and NO_X are considered to be the most serious threat to the environment due to their contribution to photochemical smog formation (ref. 10). Their effect is most evident in the Los Angeles basin area where, exacerbated by the local topography and climate, photochemical smog has become a serious health hazard. In an effort to improve the air quality in the Los Angeles basin, the EPA has introduced the California FIP regulating emissions from private, industrial and commercial stationary and mobile sources.

A breakdown of the national emissions inventory from 1990, shown in table 1, indicates that highway mobile sources are the most significant contributor to the overall national emissions burdens of CO, HC and NO_X. Relative to other sources, aircraft exhaust emissions are relatively small contributors to the air pollution problem. However, aircraft in use today operate from airports and, therefore, concentrate their emissions during the landing/takeoff (LTO) cycle in the vicinity of airports, magnifying their impact on the local air quality. Once away from the airport, aircraft quickly climb above local inversion layers and their emissions have little impact on local air quality.

Benefits of Personal Aircraft

Personal aircraft have the potential for alleviating air quality problems resulting from transportation sources. Significant emissions benefits are available through the careful selection of aircraft/engine combinations designed from the outset for low exhaust emissions. If successful, personal aircraft are likely to rapidly replace the aging general aviation fleet (designed with little or no emissions considerations) and may well reduce automobile use for short-to-moderate range trips, i.e., between cities. Automobiles powered by internal combustion engines release large amounts of pollutants into the atmosphere at ground level where they often become trapped below thermal inversion layers and result in local air quality problems (ref. 11). Personal aircraft would operate between cities above inversion layers, where their emissions would have little impact on local air quality. The current fleet of general aviation relies on long runways for LTO operations and, therefore, concentrate their emissions in the vicinity of airports. Developing personal aircraft with vertical/short takeoff and landing capability will be beneficial in alleviating air quality problems by dispersing the aircraft away from airports and eliminating concentration of pollutants.

Personal Aircraft Propulsion Systems

The potential exists for unprecedented numbers of personal aircraft due to reduced operational complexity that is available through "state-of-the-art" technologies. The wide range of personal aircraft concepts are capable of utilizing several different propulsion systems including reciprocating, rotary, gas turbine and turboprop engines. Alternative propulsion concepts such as fuel cells are possible, but not likely in the near future. Personal aircraft engine manufacturers will be required to demonstrate designs that, at a minimum, meet 1979 EPA emissions limits. It would be desirable to meet a design target of at least 50% of the 1979 EPA limit. The emissions characteristics of various propulsion systems are discussed, along with design modifications capable of reducing their emissions.

Reciprocating Engines

Horizontally opposed four and six-cylinder reciprocating engines are the most popular engine in use today for light conventional aircraft and helicopters. Their low cost and proven capability makes them a strong candidate for use as a powerplant for personal aircraft. Unlike their automobile counterparts, aircraft engines are required to operate at maximum power conditions part of the time during every flight. To ensure safe and reliable operation under these conditions, reciprocating engine manufacturers have traditionally employed rich fuel-air ratios to maintain safe cylinder head temperatures, keeping in mind that most modern reciprocating engines employ air cooling (ref. 12). These rich mixtures cause high carbon monoxide and hydrocarbon emissions. As shown in figure 1, current production engines without turbocharging generally meet the 1979 EPA limits (and are close to meeting the design target) set for HC and NO_x emissions, but exceed CO limits substantially (ref. 13). A solution to the CO emissions problem is required before the reciprocating engine can be utilized as a powerplant for personal aircraft.

Reciprocating engine emissions are amenable to some degree of control by either exhaust treatment (thermal and catalytic reactors) or engine modifications. A study carried out by the Bendix Corporation in the early 1970's indicated that exhaust treatment approaches were successful in reducing emissions, to varying degrees, but not without sufficiently greater effectiveness than engine modifications to offset their added expense, weight, and bulk (ref. 12). The study concluded that the most promising method for reducing emissions is to pursue engine modifications that allow operation at leaner fuel-air ratios. Operating at leaner fuel-air ratios will require an advanced fuel management system as the optimum mixture ratio will vary with atmospheric conditions and mission requirements. A discussion of promising techniques (including advanced fuel management systems, mixture enleanment, and secondary air injection) capable of reducing reciprocating engine exhaust emissions follows.

Advanced Fuel Management Systems

Currently, reciprocating engines are provided with a margin of richness to ensure safe and reliable operation over a wide range of operating conditions. Significant reductions in exhaust emissions can be realized by operating throughout the flight regime at the leanest mixtures possible. In order to do so, an advanced fuel management system consisting of a computer-controlled fuel-injection system to set a precise fuel-flow schedule and variable valve timing to optimize the engine power output is required (ref. 2). Because personal aircraft would likely utilize onboard computers to assist in piloting and navigation, use of the computer to operate a fuel management system is an attractive method for reducing emissions.

Advanced computer-controlled fuel-injection systems. A computer controlled fuel-injection system will be required in order to set a precise fuel-flow schedule during both steady state and transient conditions (ref. 14). Engine idle fuel-air ratios are traditionally set for operation at the coldest day to ensure adequate transient response and are richer than necessary for engine operation at higher temperatures (ref. 2). A computer controlled fuel-injection system will allow total density compensation (variation of the fuel-air ratio based on temperature and altitude) to set the leanest fuel-air ratio possible and will be a timed, airflow-sensitive system capable of supplying fuel at moderate pressure to the injectors. During low engine power conditions the injectors must provide a homogenous fuel-air mixture to the cylinders with little or no variations in fuel-air ratio between cylinders. During transient engine operation, cylinder to cylinder fuel-air ratio variations can cause momentary enleanment during throttle opening and result in poor engine acceleration. Current fuel-injection systems are low-pressure, continuous flow systems that frequently emit the fuel as a weak stream or dribble at low flow conditions. Curing this problem is critical to assuring adequate engine response to throttle movements. As indicated in reference 12, solving this problem is considered to be a straightforward matter of improving injector nozzle design and injection pressure ratios.

Variable valve timing. On current production engines, valve timing is optimized to highest specific output at high performance conditions to meet takeoff requirements, which leads to high CO and HC emissions at low power conditions (ref. 12). As indicated in reference 2, a camshaft equipped with movable lobes and gearing can be incorporated into the engine design to facilitate variable valve timing. Variable valve timing allows optimization of the engine power output at all conditions by assuring that maximum benefit of the fuel supplied to the engine is being withdrawn from each intake charge. Tests conducted by Continental Motors on an IO-520-D-type engine indicated a reduction in HC emissions from 97% to 48% of the 1979 EPA limit by utilizing variable valve timing (ref. 14). Emissions of CO and NO_X were unaffected by the changes.

Mixture Enleanment

Reciprocating engines typically operate at fuel-air ratios of 0.08 to 0.14 during the LTO cycle, resulting in high CO and HC emissions (ref. 2). As shown in figure 2, narrowing the fuel-air ratio range of operation offers substantial reductions in CO and HC emissions, at the expense of slightly increased NO_X emissions. A modal breakdown of CO and HC emissions during a conventional LTO cycle is shown in figure 3. As readily noted, reduction of emissions during the climb, approach and taxi modes is required. The potential for reduced emissions through operation at a leaner fuel schedule at maximum power settings (takeoff, climb) is limited by the extent to which cylinder cooling can be improved by other measures (ref. 15). The limitation in leaning idle, taxi and approach modes is the inability to accelerate from these conditions (ref. 12).

A series of tests conducted by the FAA's National Aviation Facilities Experimental Center to determine the effect of a lean fuel schedule on CO emissions was conducted. Several reciprocating engines manufactured by Textron-Lycoming and Teledyne Continental Motors were tested at sea level static conditions. As shown in figure 4, none of the engines as received could meet the 1979 EPA limits for CO in either the full-rich or production-lean fuel schedule configuration. When the engines were operated with the fuel schedule leaned to give optimally low emissions without encountering operational problems (fig. 5), all non-turbocharged engines met the 1979 EPA standards, and in some cases were close to meeting the design target (ref. 2).

In order to meet the design target for CO and HC emissions, further enleanment of the fuel schedule is necessary. As indicated in reference 15, engines operating at a leaner fuel schedule are likely to encounter significant operational problems including excessive cylinder head temperatures and/or poor ignition (misfiring, unacceptable acceleration, etc.). Solutions to these operational problems are possible through the use of improved engine cooling techniques and a stratified charge combustion system.

Improved engine cooling. As stated earlier, current reciprocating engines utilize rich air-fuel ratios to prevent excessive cylinder head temperatures during maximum power conditions. Surplus fuel in the combustion chamber consumes thermal energy during its vaporization and prevents overheating. Mixture enleanment to reduce emissions will increase cooling requirements. The solution to this problem is to increase the engine's ability to cool itself and/or improve the engines tolerance to high temperatures (ref. 12).

Improved engine cooling is possible through the use of a "low drag cylinder head" which features increased spacing between the cooling fins. Greater spacing between the cylinder cooling fins presents less resistance to the cooling air flow and will thereby increase the flow and improve cooling (refs. 2 and 12). Another method which offers significant potential for cooling would result from the adoption of an engine powered cooling fan. This change may result in weight, cost and reliability penalties, but these might be more than offset by the improved cooling and resultant improved power and fuel economy during LTO operations (ref. 12). Cooling fans are presently used in helicopters powered by reciprocating engines.

Another technique that has been shown to be effective at reducing cylinder head temperature is the use of exhaust port liners (ref. 2). A sketch of an exhaust port liner is presented in figure 6. Exhaust port liners may be either double walled with an air gap or may use insulative material. In either case, heat transfer from the exhaust port to the cylinder head is reduced allowing the higher combustion temperatures of lean operation. A concurrent benefit of exhaust port liners occurs at low power conditions where higher exhaust gas temperatures help to promote afterreaction of pollutants in the exhaust port, thereby reducing CO and HC emissions.

A technique for improving engine tolerance to high temperature would be to improve the heat-transfer characteristics of the cylinder barrel. Improving heat transfer from the cylinder barrel would help to conduct heat away from the cylinder head area where critical overheating problems occur. Cylinder barrels in aircraft engines are typically made from machined steel and, while having excellent wear resistance, they are poor heat conductors. Improved heat-transfer characteristics would be possible through the use of aluminum cylinder barrels (which have excellent heat-transfer characteristics) coated with a hard nickel alloy on the wear surfaces. This method has been employed by Porsche on their air-cooled Carerra automobile engines (ref. 12). This design offers additional cost benefits as the cast aluminum cylinder barrels would be significantly cheaper than machined steel cylinders.

Stratified-charge combustion. The stratified charge combustion system offers significant potential for reduced exhaust emissions and low fuel consumption by allowing an engine to operate at extremely lean mixtures (as low as half the ratio of fuel to air traditionally used in reciprocating engines), without encountering operational problems such as detonation, preignition, or poor acceleration. During stratified-charge combustion, the fuel-air mixture is divided inside the cylinder into two separate or "stratified" portions. One portion is sufficiently rich to ensure rapid ignition under all conditions; the other--the bulk of the charge--is lean enough to provide efficient operation with low HC and CO emissions (ref. 16). The potential of the stratified-charge combustion system for achieving low emissions is based on the idea of initiating the burning of the fuel in a rich zone where NO_X formation will be low, subsequently completing the combustion in a lean region where any remaining unburned fuel, partially oxidized hydrocarbons and carbon monoxide will be oxidized (ref. 17).

Stratification of the fuel-air mixture requires modified air intake and fuel injection systems, in addition to changes in cylinder design (ref. 18). The cylinders must be designed so that when the intake charge is drawn in, the fuel-air ratio is different in various parts of the cylinder, i.e. "stratified". The aerodynamics of the chamber causes the fuel-rich burning charge to encounter an advancing wave front of air, which supports continued combustion until all the fuel is burned. Detonation cannot take place on a significant scale, because there is no premixed mass of fuel and air to detonate. Because a stratified charge combustion system can successfully ignite and burn just about any mixture of fuel and air, the engine is indifferent to the octane rating of its fuel and can run equally well on avgas, jet fuel, diesel fuel or autogas (ref. 16). This is an immensely important characteristic for personal aircraft which may operate in such a manner that avgas would not always be readily available.

Secondary Air Injection.

Secondary air injection into the exhaust stream is an effective method to reduce emissions by promoting an afterreaction of HC and CO. The fundamental technique involves injecting air into the exhaust stream at the exhaust port to produce a combustible mixture. See figure 6. If the exhaust gas temperatures are high enough, unburned hydrocarbons present in the exhaust will burn, thereby reducing the amount of HC and CO in the exhaust. Enleanment of the fuel-air mixture can raise the exhaust gas temperature high enough to ensure afterreaction. Secondary air can be provided to the exhaust stream by an engine driven air pump or by negative pressure pulsations at the exhaust port to aspirate air into the exhaust stream (ref. 2).

A potential problem associated with secondary air injection systems is the increased temperature of the exhaust piping. A solution is to design the exhaust piping with double wall construction and insulate the area between the inner and outer piping.

Rotary Engines

The rotary-cycle (or Wankel) engine is a four-stage internal combustion engine with an excellent weight to horsepower ratio, which makes it an attractive powerplant for personal aircraft. It can be liquid- or air-cooled and consists of a triangular rotor that turns inside an elliptical chamber (ref. 19). A sketch of the rotary-cycle engine, taken from reference 19, is presented in figure 7. Since its inception in 1957, the rotary-cycle engine design has been refined (poor seals were a serious problem with early versions of the engine) to the point that it now surpasses the conventional reciprocating engines by all measures of size, weight and efficiency (ref. 16). To date, the rotary-cycle engine has been given the most attention by the automotive industry; both General Motors and Ford have paid for the rights to build rotary-cycle engines, and the Japanese automaker Mazda has sold over 1.5 million rotary-engine cars (ref. 11). The rotary engine has many advantages for use in aircraft, such as low-vibration, few moving parts, light weight and small size. NASA-sponsored research at Beech and Cessna have identified the rotary as the engine of choice for future general aviation aircraft (ref. 16). As indicated in reference 20, effort is underway in Russia to certify a rotary-cycle aircraft powerplant derived from a car engine design.

Because of the high surface to volume ratio inside the combustion chamber, the rotary-cycle engine has relatively high CO and HC emissions (ref. 1). However, the rotary-cycle engine is low in NO_X emissions and has a high exhaust temperature, which means that the CO and HC emissions can be reduced by thermal afterreaction (ref. 11). The most advantageous method for assuring low emissions in rotary-cycle engines is the adoption of the stratified charge combustion system, discussed previously. Stratified charge combustion has been successfully applied to John Deere rotary engines (the technology has been applied to piston engines, too, but not yet successfully) since 1976 (ref. 16). Alternative versions of the John Deere engine, such as the natural gas powered rotary engine discussed in reference 21, have the potential for extremely low CO and HC emissions, but special measures may be necessary to keep NO_X emissions down.

Gas-Turbine Engines

Small gas-turbine engines (8000 pounds of thrust, or less) are a potential alternative to either the reciprocating or rotary engine as a powerplant for personal aircraft. Gas turbine engines have the advantage of simplicity and can operate on such cheap fuels as kerosene or diesel fuel. Because a gas turbine engine burns fuel at a constant rate instead or in rapid explosions, it obtains good combustion efficiency and thus has low CO and HC emissions (ref. 11). Typical emissions characteristics for a gas turbine engine are presented in figure 8. As noted in figure 8, the shape of the emissions characteristics leads to a conflict of design requirements. Operating at a fuel-air ratio necessary for low CO and HC emissions results in high NO_X emissions. Design modifications are required to assure low NO_X emissions without increasing CO and HC formation.

Because the gas turbine engine is commonly utilized today in the business jet and commercial transport fleet, a significant amount of research and development has been undertaken by manufacturers to reduce gas-turbine engine emissions through advances in combustor design (ref. 22). Currently, "state-of-the-art" gas-turbine combustors have adopted conservative approaches at reducing emissions such as air-assisted fuel nozzles to enhance fuel atomization and improve performance. These combustors are shorter and more annular in shape than previous designs to reduce gas dwell time in the combustor and reduce NO_X formation. For example, by making the combustor of the CF6-80C2 engine 20% shorter than a similar unit in the CF6-50, General Electric was able to reduce NO_X production by 10% (ref. 22). However, gas-turbine engines with "state-of-the-art" combustors are marginal in meeting the 1979 EPA CO and HC emissions requirements, while NO_X emissions are well outside the limits (ref. 9).

To realize significant reductions in emissions, gas-turbine engine manufacturers are aggressively pursuing advanced combustors that will cut engine emissions by an additional 30-50%. One promising concept is the staged combustion system which, at low power conditions, operates only on a pilot zone with near stoichiometric fuel-air ratio to minimize CO and HC emissions. The main combustion zone is phased in at operation at high-power conditions in order to minimize NO_X emissions (ref. 23). Another alternative is the variable geometry combustor, which produces an infinite number of combustor variations to match engine conditions, reducing CO, HC and NO_X emissions (ref. 10). Despite a significant amount of work on these designs, many important issues remain to be resolved before the reliability of a staged combustion system or variable geometry combustor can satisfy operational requirements (ref. 23).

The effect of combustor modifications, including air assisted fuel nozzles and staged combustion systems, on CO, HC and NO_X emissions are presented in figure 9. The data points are coded to show the effects of modifications on combustor performance. The open symbols show emissions data taken from engines for which the combustion system has been shown to satisfy operational requirements. The cross-hatched symbols show emissions data that reflect an optimistic but cautionary attitude that modified combustors will satisfy operational requirements. The solid symbols show emissions data that reflect combustor modifications with uncertain operational performance (ref. 9).

As shown in figure 9, combustor modifications show promise for reducing gas turbine engine emissions. However, the apparent tradeoff between CO and NO_X emissions indicates that the design target may be difficult to achieve. Pratt&Whitney and General Electric have embraced the advanced combustor concepts as the best option for reducing emissions. The increase in environmental regulations is likely to keep their interest and may very well lead to a breakthrough in clean engine technologies in the future.

Turboprop Engines

The turboprop engine consists of a gas-turbine engine in combination with a reduction-gear assembly and a propeller. Figure 10 shows emissions characteristics for turboprop engines that are similar to turbofan engines. As expected, turboprop engine emissions can be reduced by techniques similar to turbofans such as air-assisted fuel nozzles and staged combustion systems (ref. 24). The increased fuel efficiency of the turbofan engine at Mach numbers below 0.70 makes it a viable alternative to the turbofan, since reduced fuel consumption means lower emissions for a given mission.

Fuel Cells

Fuel cells offer promise as a potential replacement for internal combustion engines in transportation applications. Fuel cells operate more efficiently than internal combustion engines, are capable of operating on non-petroleum based fuels such as methanol, ethanol, natural gas or hydrogen and have extremely low emissions (ref. 25). At the present, the United States Department of Energy has several major research and development programs underway to advance fuel cell technology. Application of fuel cells to vehicle use, however, poses some severe challenges. The challenges are to reduce the capital costs of the fuel cell power systems, to make the systems capable of meeting the dynamic power requirements of a vehicle, and to increase the systems' volumetric and mass power densities to enable their use within the space and weight limitations imposed by the vehicle (ref. 26). The Department of Energy is working towards demonstration of a fuel cell/battery powered bus by the late 1990's. Advancing the technology to the point where fuel cells would be a viable alternative for use as a powerplant for personal aircraft is, unfortunately, still many years away.

Concluding Remarks

This paper has briefly presented the emissions characteristics of potential propulsion systems for advanced personal aircraft. While the operational characteristics of personal aircraft may help to alleviate many problems associated with exhaust emissions from transportation sources, strict environmental regulations will require their powerplants to operate with low emissions of pollutants.

Powerplants considered as potential propulsion systems for personal aircraft include: reciprocating, rotary-cycle, gas-turbine, turboprop and fuel cells. While fuel cells would be the best choice from a strict emissions standpoint, their operational characteristics, expense and bulk prevent them from being considered as a viable propulsion system for aircraft in the near future. Likewise, the gas-turbine and turboprop engine would likely impose severe cost penalties on a small vehicle such as a personal aircraft. The choice is then narrowed down to either the reciprocating or rotary engine. Reciprocating engines are the most popular engine in use today for small aircraft and offer low cost and proven capability. Engine modifications are possible that should be able to reduce their emissions to acceptable levels. However, the rotary-cycle engine shows good promise as a replacement for the reciprocating engine in small aircraft applications. NASA-sponsored research at Beech and Cessna has identified the rotary as the engine of choice for future light aircraft. The rotary-cycle engines ability to operate with a stratified charge combustion system, which allows very lean mixtures and multifuel use, makes it a very attractive alternative to the reciprocating engine as a powerplant for personal aircraft.

References

1. Henderson-Sellers, B.: *Pollution of our Atmosphere.* Adam Hilger Limited, Bristol, England, 1984.

2. Kempke, Erwin E., Jr.; Houtman, William H.; Westfield, William T.; Duke, Larry C.; and Rezy, Bernard J.: *General Aviation Piston-Engine Exhaust Emission Reduction,* NASA CP-2021, pp. 243 - 275, 1977.

3. *The Clean Air Act,* as amended 1970.

4. Environmental Protection Agency. *Control of Air Pollution for Aircraft Engines - Emission Standards and Test Procedures for Aircraft.* Federal Register, vol. 38, no. 136, pt. II, July 17, 1973, pp. 19088-19103.

5. *The Clean Air Act,* as amended 1977.

6. *The Clean Air Act,* as amended 1990.

7. *1994 Environmental Protection Agency California Federal Implementation Plan.*

8. Fox, Jonathan W.; Heywood, John B.; and McRae, Gregory: *Aggregate Vehicle Emission Estimates for Evaluating Control Strategies.* SAE Paper No. 94-0303, 1994.

9. Steele, Montgomerie: *General Aviation Activities in Noise and Emissions.* AIAA-77-313, 1977.

10. Metcalfe, M.T.; Eaton, R.A.; and Snape, D.M.: *The Impact of Air Transport on the Environment.* AIAA-91-7021, 1991.

11. Lynn, David A.: *Air Pollution: Threat and Response.* Addison-Wesley, Reading, Massachusetts, 1976.

12. Tripp, David; and Kittredge, George: *Application of Automobile Emission Control Technology to Light Piston Aircraft Engines.* NASA CP-2005, September 1976.

13. Barriage, Joan; Westfield, William; and Becker Eric E.: *Emissions Data by Category of Engines*. NASA CP-2005, September 1976.

14. Rezy, Bernard: *Teledyne Continental Motors Aircraft Piston Engine Emissions Reduction Program.* NASA CP-2005, pp. 227 - 253, 1977.

15. Rezy, Bernard: *Teledyne Continental Motors Emissions Data and Analysis and Flight Test Results*. NASA CP-2005, September 1976.

16. Garrison, Peter: *A Wankel in Your Future.* Flying, Vol. 118, March 1991, pp. 94 - 97.

17. Edwards, John B.: *Combustion: Formation and Emission of Trace Species*. Ann Arbor Science, Ann Arbor, Michigan, 1974.

18. Henderson-Sellers, B.: *Pollution of our Atmosphere.* Adam Hilger Limited, Bristol, England, 1984.

19. Kroes, Michael J.; Wild, Thomas W.; Bent, Ralph D.; and McKinley, James L.: *Aircraft Powerplants*. McGraw-Hill, 1990.

20. *Rotary Powerplant Derived from Car Engine Design.* Aviation Week and Space Technology, Volume 140, Number 22, May 30, 1994.

21. Mack, J.R.: *Development of Natural Gas Rotary Engines.* Gas Research Institute Report No. 91-0290, 1991.

22. Kandebo, Stanley W.: *Advanced Combustors Under Development to Cut Emissions in Conventional Engines*. Aviation Week and Space Technology, Volume 135, No. 21, November 25, 1991, pp. 51-54.

23. Bruce, T.W.; David, F.G. and Mongia, H.C.: *Pollution Reduction Technology Program for Small Jet Aircraft Engines-Class T1*, NASA CP-2021, pp. 149 - 180, 1977.

24. Tomlinson, J.G.: *Pollution Reduction Technology Program for Turboprop Engines*, NASA CP-2021, pp. 125 - 147, 1977.

25. Patil, Pandit G.: *U.S. Department of Energy Fuel Cell Program for Transportation Applications*. Journal of Power Sources, vol. 37, Jan. 1992, p. 171-179.

26. Kumar, Romesh: *Requirements for a Fuel Cell for Transportation Application.* Proceedings of the Direct Methanol/Air Fuel Cell Workshop, Washington D.C., May 1990.

Table 1. National emissions estimates for 1991.

(a) Carbon monoxide

Source	Emissions, 10^6 tons/yr	Percent of total
Transportation	47.94	70.04
Highway vehicles	39.81	58.17
Aircraft	**1.16**	**1.69**
Railroads	0.18	0.26
Vessels	1.89	2.76
Non-highway use of motor fuels	4.90	7.16
Fuel combustion in stationary sources	5.15	7.53
Electric utilities	0.34	0.50
Industrial	0.73	1.07
Commercial-institutional	0.05	0.07
Residential	4.03	5.89
Industrial processes	5.17	7.55
Solid waste disposal	2.27	3.32
Inceneration	0.98	1.43
Open burning	1.29	1.89
Miscellaneous	7.91	11.56
Forest fires	7.30	10.67
Other burning	0.61	0.89
Miscellaneous organic solvent	0.00	0.00
Total	68.44	100.0

Table 1. Continued.

(b) Hydrocarbons

Source	Emissions, 10^6 tons/yr	Percent of total
Transportation	5.60	30.09
Highway vehicles	4.21	22.62
Aircraft	**0.20**	**1.07**
Railroads	0.12	0.65
Vessels	0.56	3.01
Non-highway use of motor fuels	0.51	2.74
Fuel combustion in stationary sources	0.74	3.98
Electric utilities	0.03	0.16
Industrial	0.15	0.81
Commercial-institutional	0.01	0.05
Residential	0.55	2.96
Industrial processes	8.66	46.53
Solid waste disposal	0.76	4.08
Inceneration	0.30	1.61
Open burning	0.46	2.47
Miscellaneous	2.85	15.31
Forest fires	0.98	5.27
Other burning	0.09	0.48
Miscellaneous organic solvent	1.78	9.56
Total	18.61	100.0

Table 1. Concluded.

(c) Oxides of nitrogen.

Source	Emissions, 10^6 tons/yr	Percent of total
Transportation	8.00	38.69
Highway vehicles	5.92	28.63
Aircraft	**0.14**	**0.68**
Railroads	0.51	2.47
Vessels	0.26	1.26
Non-highway use of motor fuels	1.17	5.65
Fuel combustion in stationary sources	11.67	56.43
Electric utilities	7.40	35.78
Industrial	3.67	17.75
Commercial-institutional	0.23	1.11
Residential	0.37	1.79
Industrial processes	0.66	3.19
Solid waste disposal	0.11	0.53
Inceneration	0.02	0.10
Open burning	0.09	0.43
Miscellaneous	0.24	1.16
Forest fires	0.22	1.06
Other burning	0.02	0.10
Miscellaneous organic solvent	0.00	0.00
Total	20.68	100.0

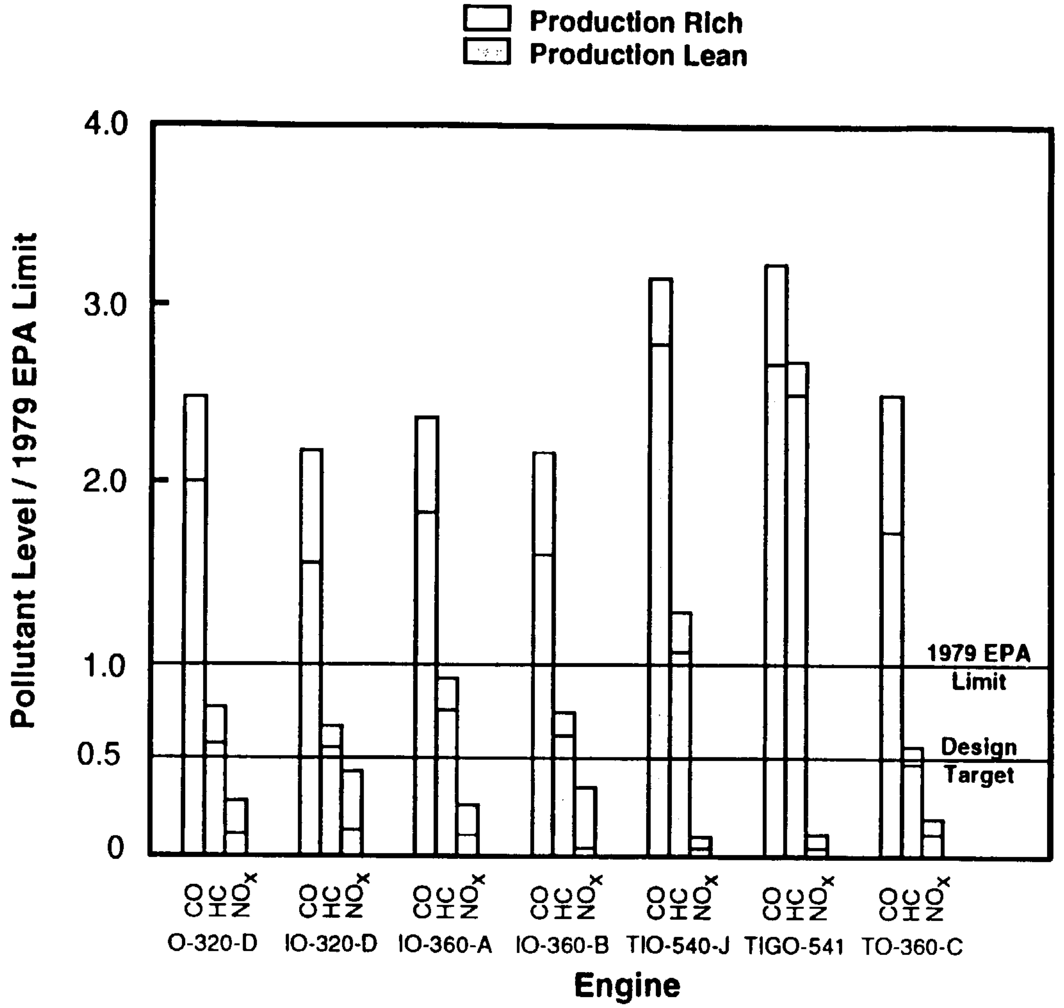


Figure 1. - Measured CO, HC and NO_x emissions for selected Textron-Lycoming reciprocating engines during a typical LTO cycle at the standard production-rich and production-lean fuel schedule configurations.

Engine Model Designations

T	Turbocharged
I	Fuel-injected
G	Propeller gear reduciton
O	Opposed Cylinders

Numbers following letters indicate displacement in cubic inches.

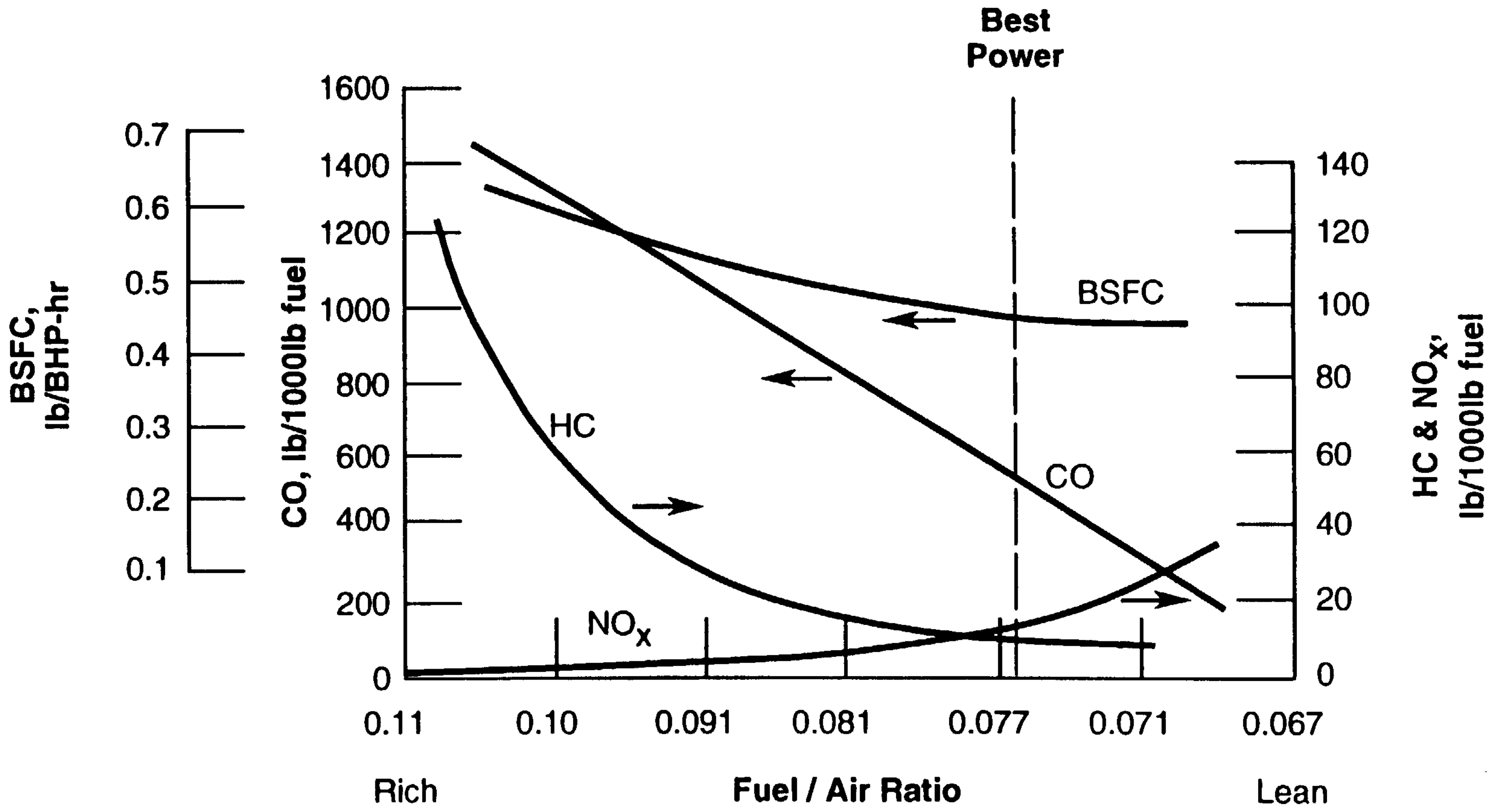
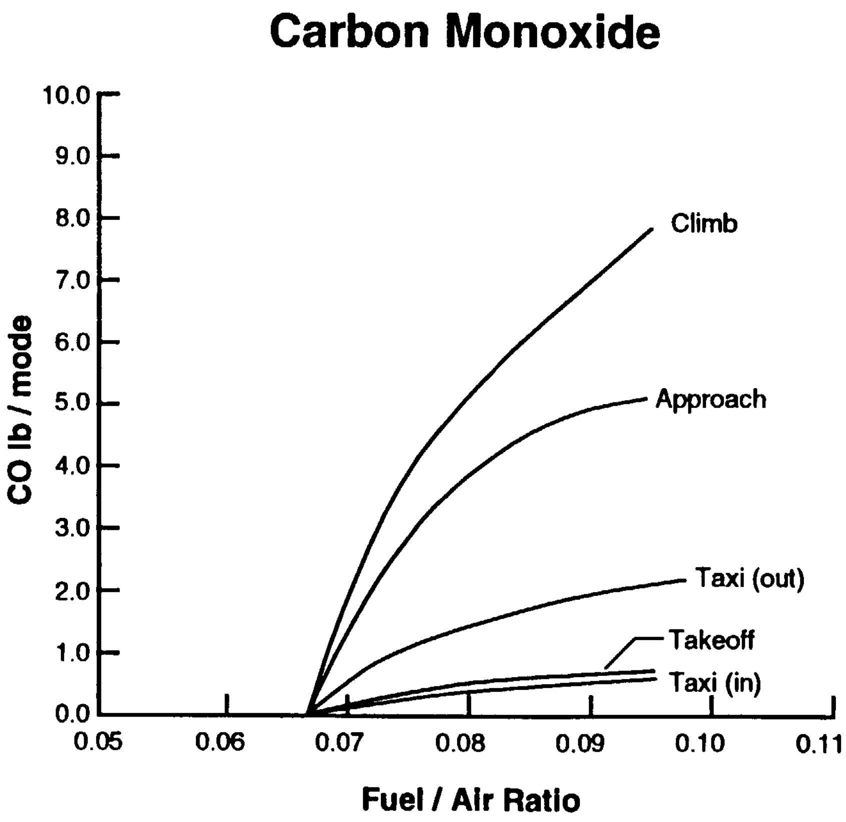


Figure 2. - Reciprocating engine emissions characteristics.

Power	Engine speed, rpm	Time at power, min.
Taxi (out)	1200	12
Takeoff	2700	0.3
Climb	2430	5
Approach	2350	6
Taxi (in)	1200	4



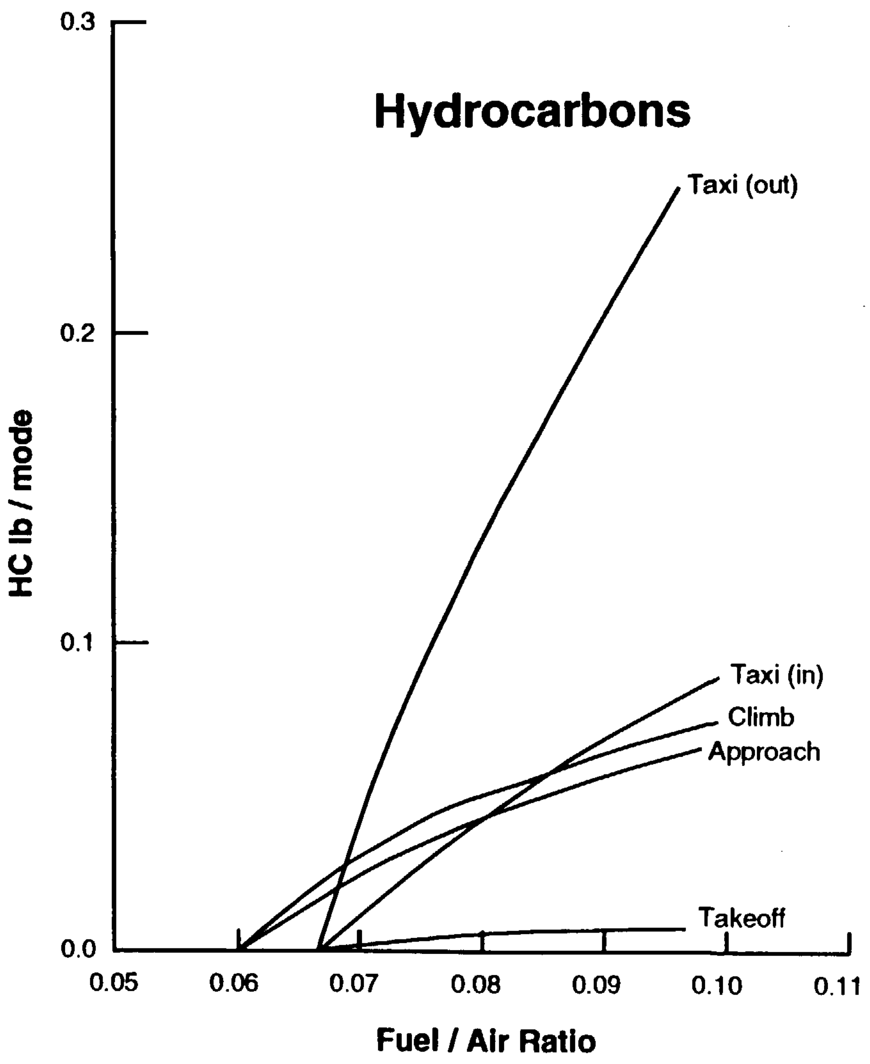
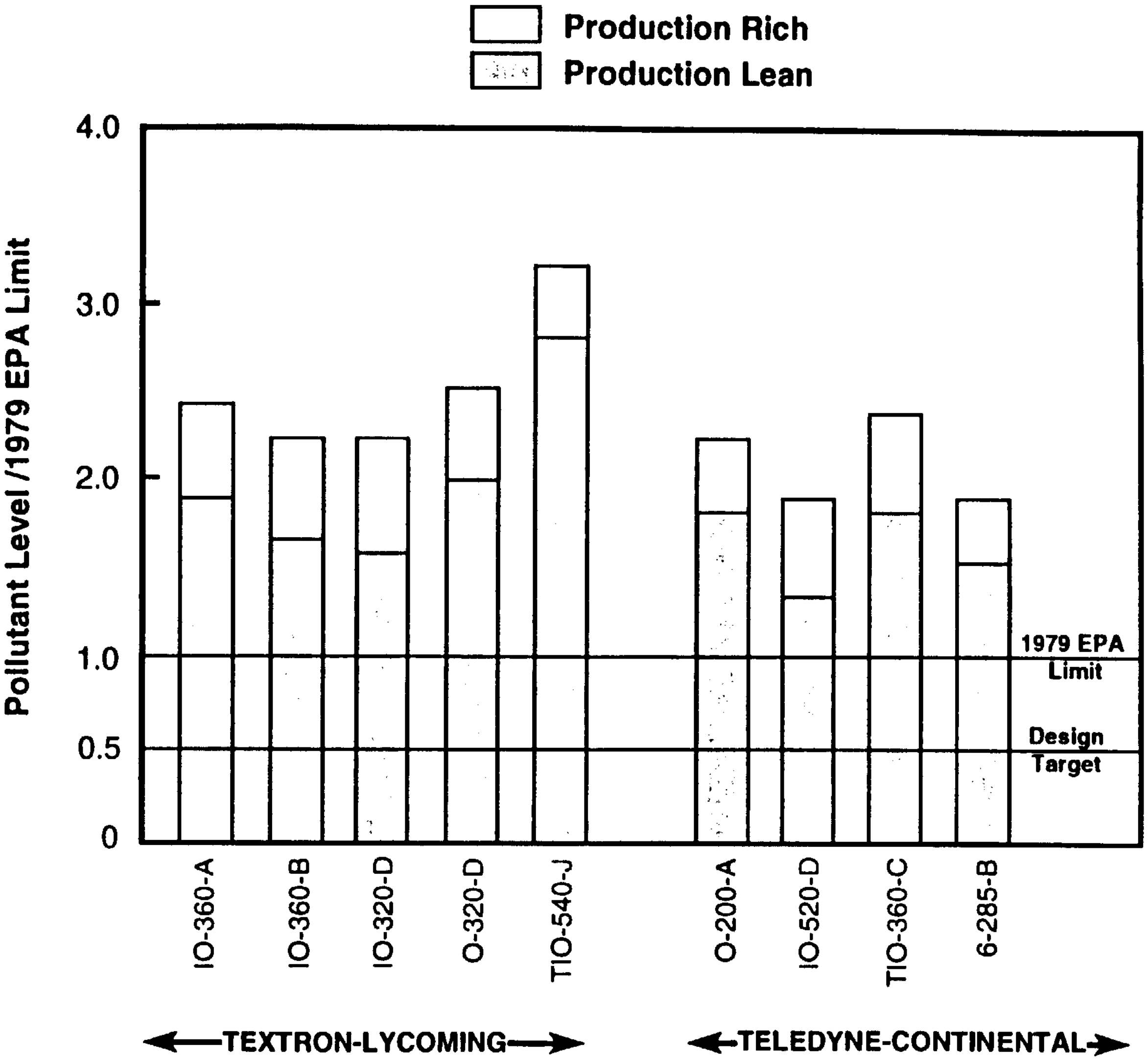


Figure 3. - Modal breakdown of CO and HC emissions for a Textron-Lycoming IO-360-A1B6D reciprocating engine during a typical LTO cycle. Induction air temperature of 85°F.

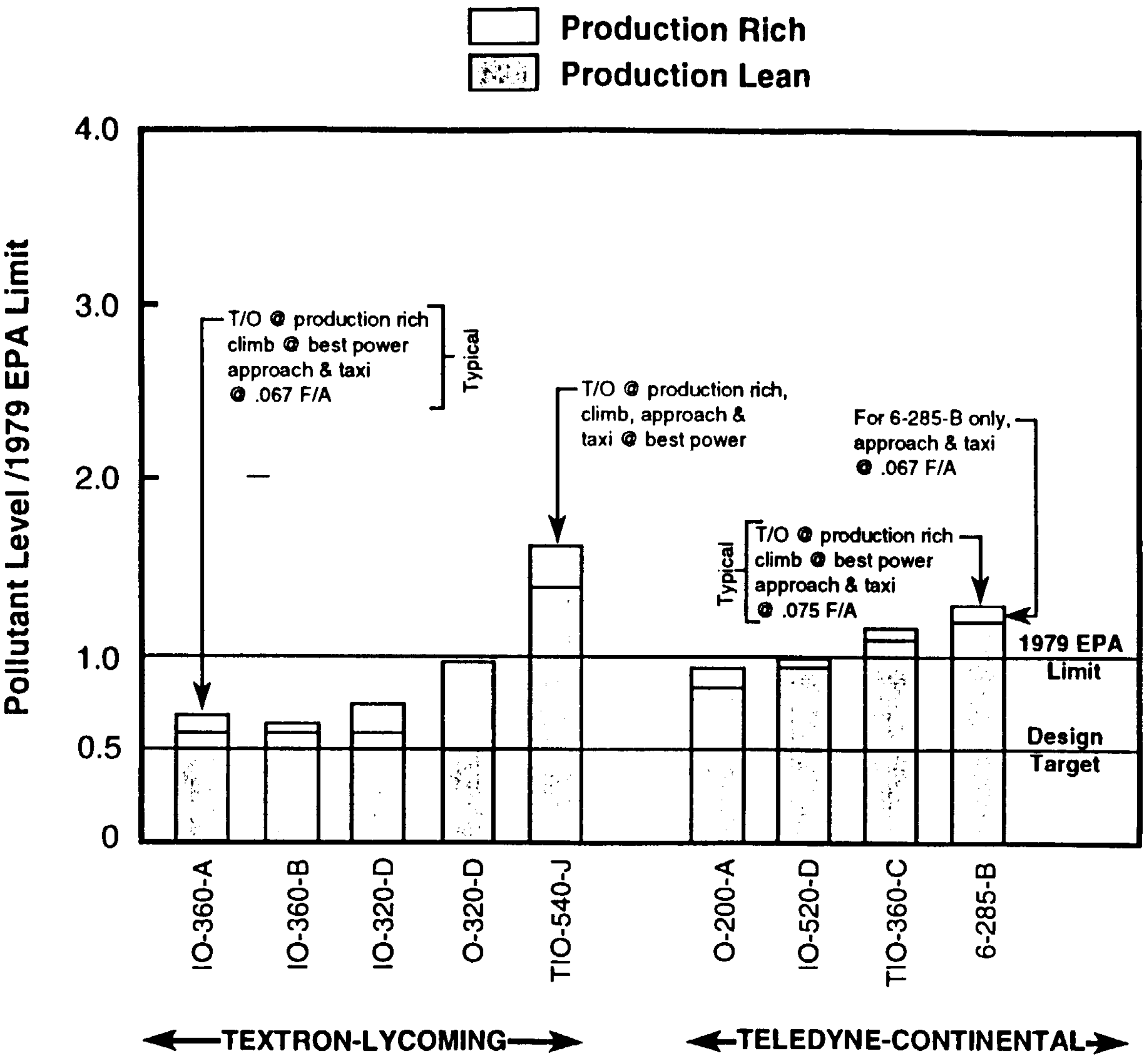


Engine Model Designations

T	Turbocharged
I	Fuel-injected
G	Propeller gear reduciton
O	Opposed Cylinders

Numbers following letters indicate displacement in cubic inches.

Figure 4. - Measured Carbon Monoxide emissions during a typical LTO cycle for selected reciprocating engines operated at the standard production-rich and production-lean fuel schedule configurations.



Engine Model Designations

T	Turbocharged
I	Fuel-injected
G	Propeller gear reduciton
O	Opposed Cylinders

Numbers following letters indicate displacement in cubic inches.

Figure 5. - Measured Carbon Monoxide emissions during a typical LTO cycle for selected reciprocating engines operated with mixture enleanment for reduced emissions.

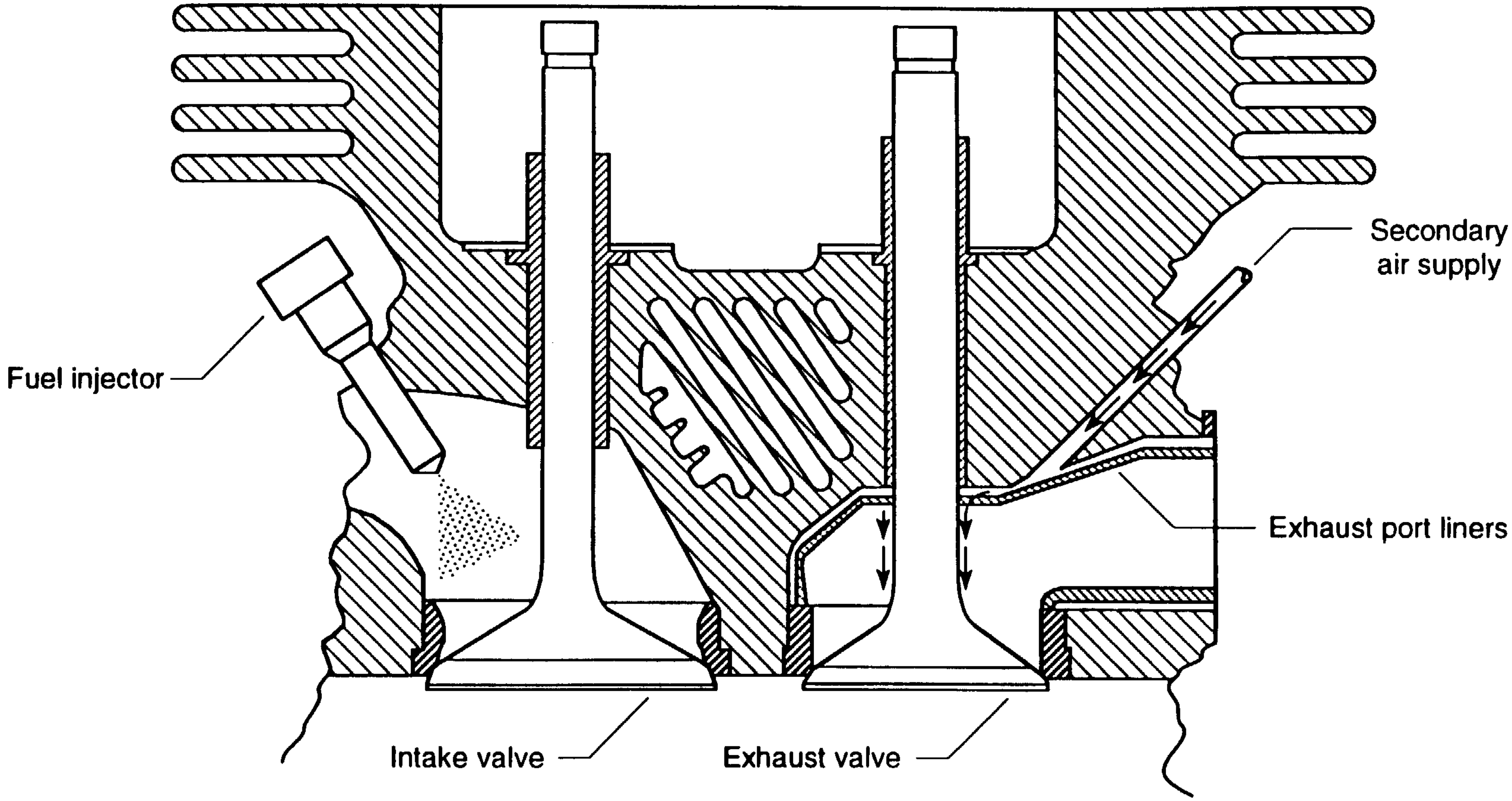


Figure 6. - Cutaway sketch of a typical cylinder incorporating exhaust port liners and secondary air injection.

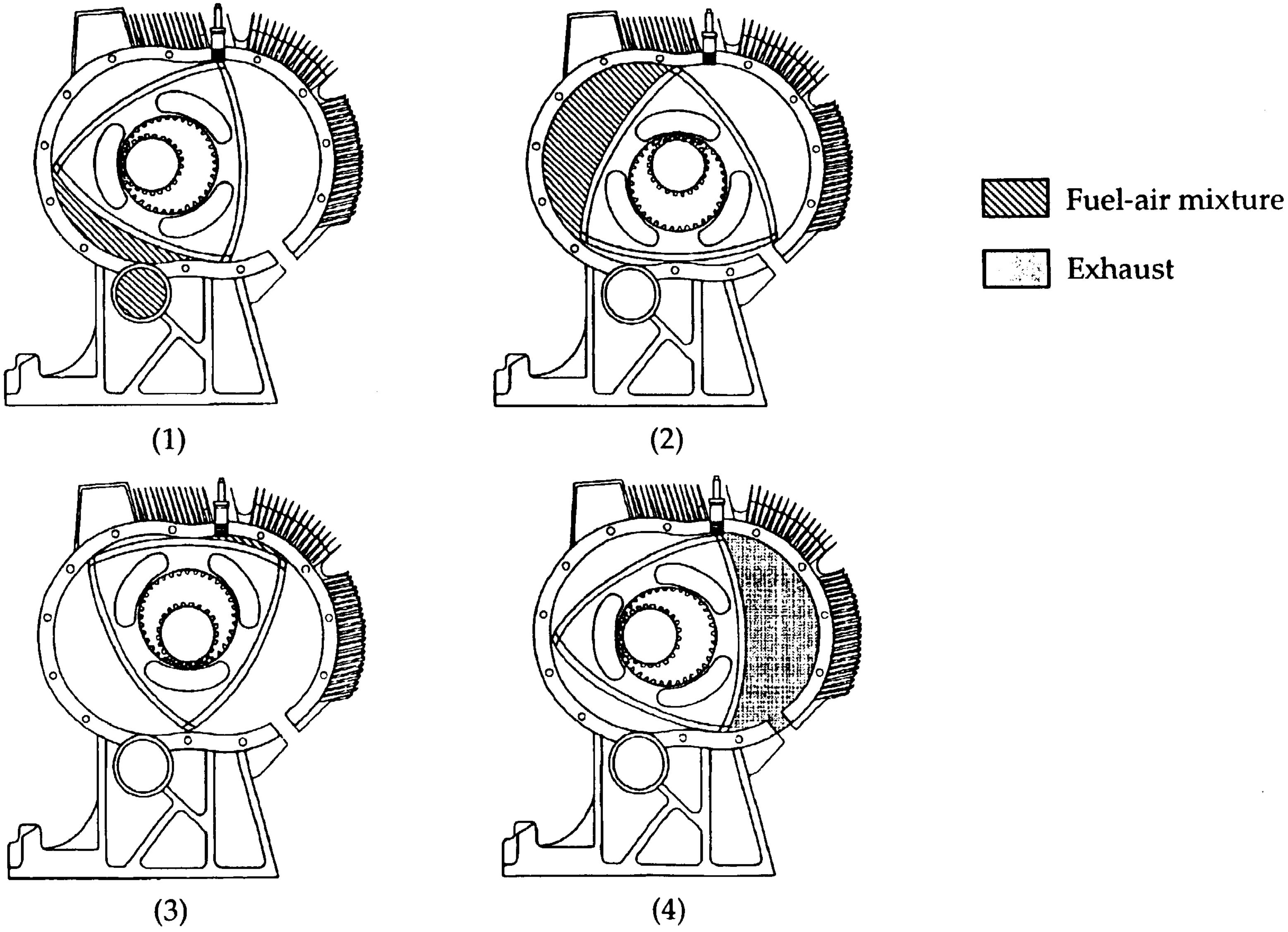


Figure 7. - Rotary-cycle engine. (1) Intake stroke begins when rotor tip uncovers intake port. (2) Compression starts as intake port is closed and rotor reaches highest point in front of spark plug. (3) Combustion takes place when charge is most compressed. (4) Exhaust begins as rotor tip passes exhaust port.

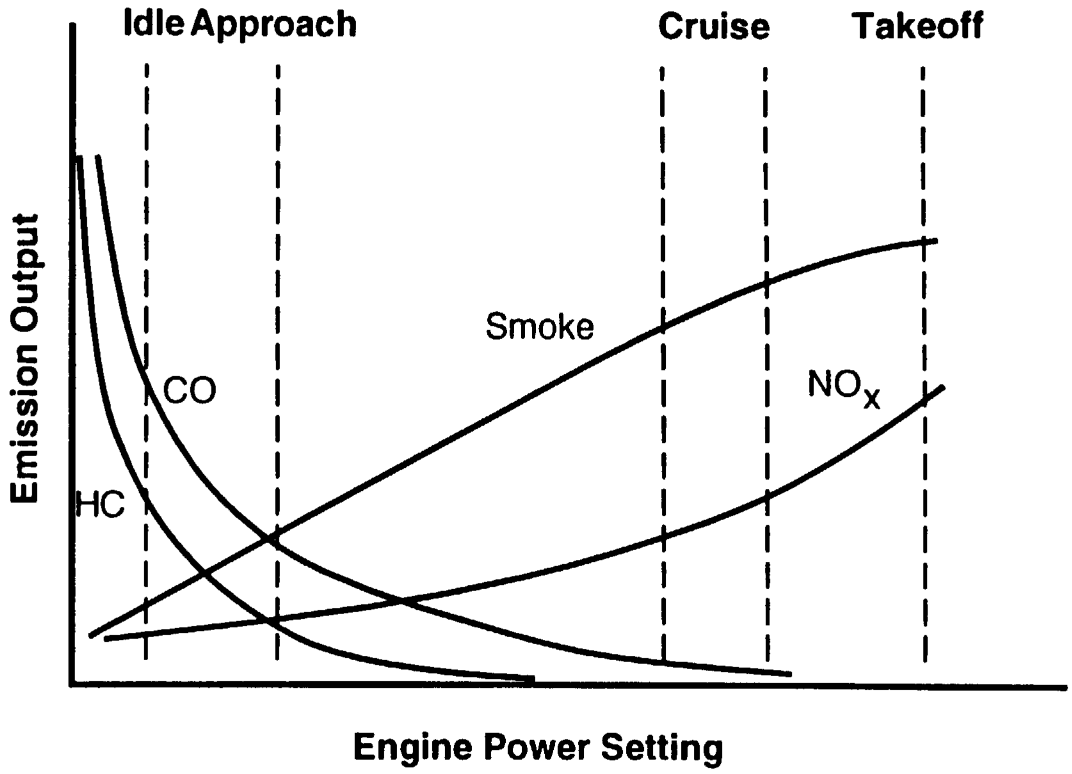


Figure 8. - Gas-turbine engine emissions characteristics.

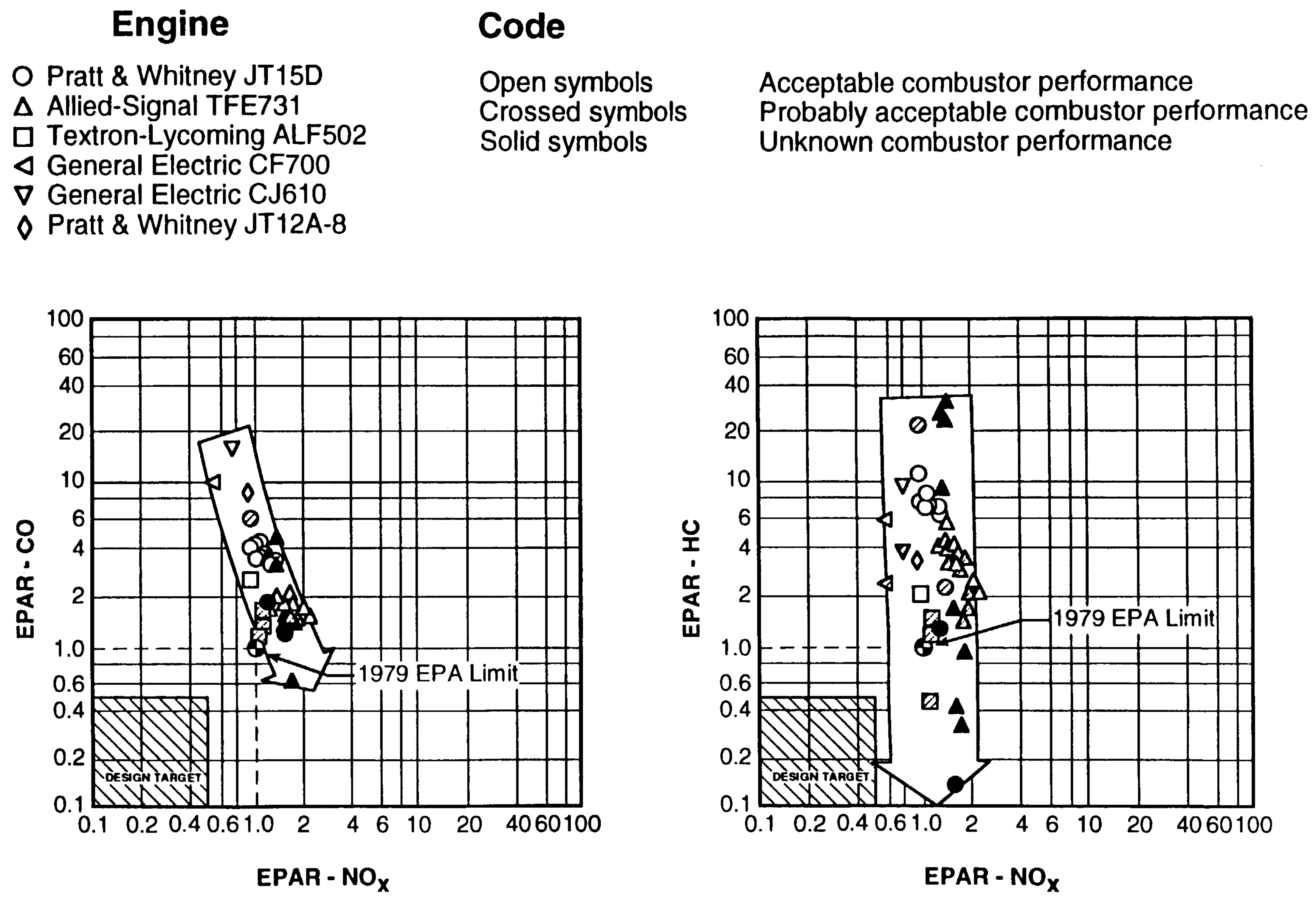


Figure 9. - CO versus NO$_x$ and HC versus NO$_x$ emissions for general aviation turbofan and turbojet engines.

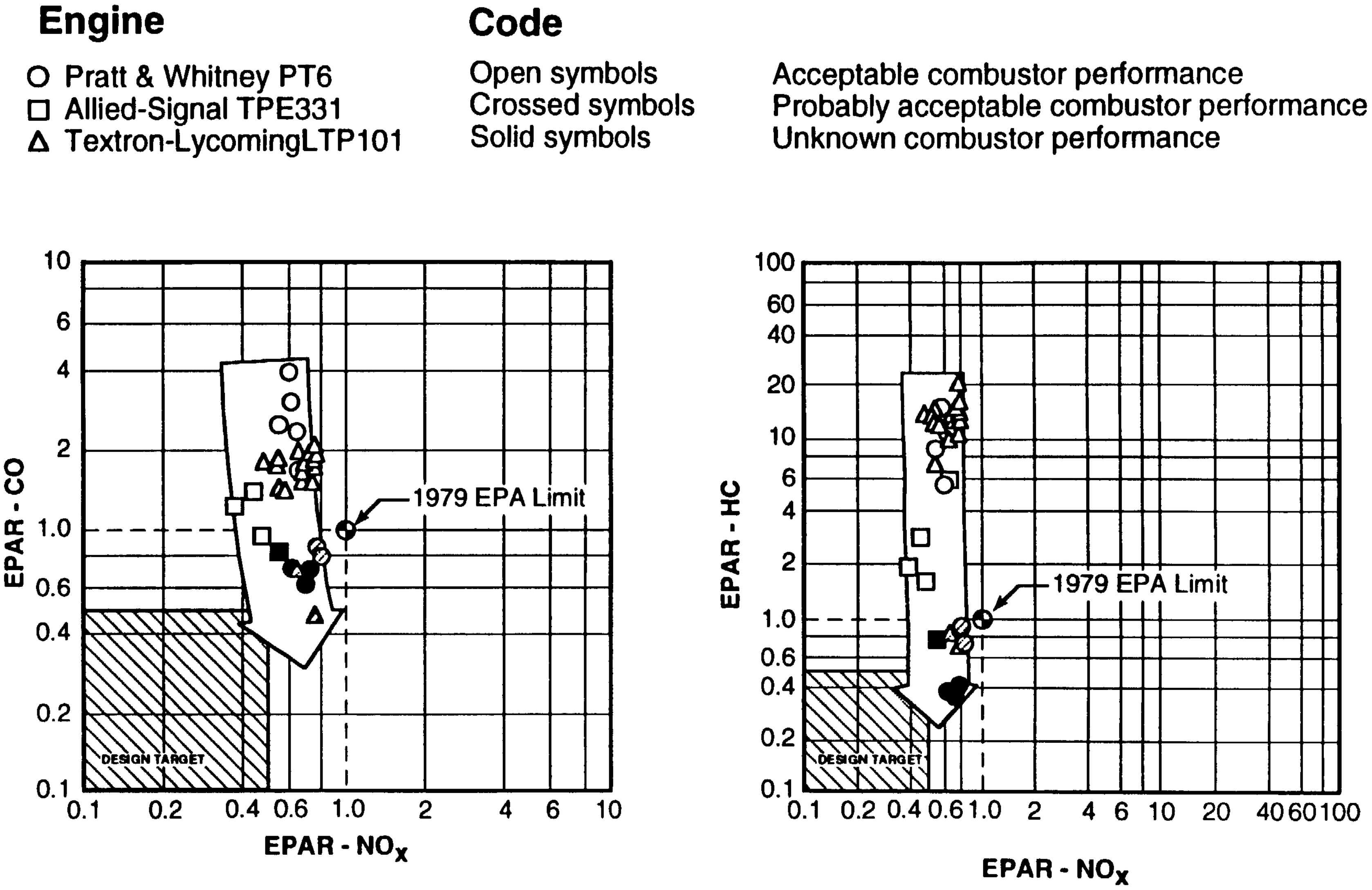


Figure 10. - CO versus NO_X and HC versus NO_X emissions for general aviation turboprop engines.

SMALL AIRCRAFT ENGINES

By Jack Morris

The purpose of this section of this report is to summarize the state-of-the-art in small engine technology. The engines to be considered are those which might be used to power a typical General Aviation or personal aircraft. We will limit the size of the engines to be considered to approximately 500 horsepower. The considered engines will include both intermittent combustion (piston or rotary) engines and gas turbine engines (see reference 1 for a survey of this class of engine) as well as some of the alternative engine concepts. First we briefly consider alternate engine concepts. These alternate engines include fuel cells, battery powered electric motors and novel thermodynamic cycles. The novel thermodynamic cycles include the Stirling and Erickson cycles. Unfortunately all of these alternate candidate engines have not matured to the point that they can be seriously considered as practical power sources for a man-rated aircraft. However the battery powered electric motors have been used extensively in small model aircraft and solar powered electric motors have been suggested for special applications which are not at present man-rated. The fuel cell has been used for many years as a power source for various space craft. Experimental Stirling and Erickson engines have been tested in the laboratory.

For the present we should not seriously consider fuels other than gasoline or Jet-A since none of the alternate fuels have matured sufficiently to be competitive (when used with general aviation aircraft engines) with these hydrocarbon fuels and any comparison with alternate fuels such as hydrogen or natural gas or batteries brings up fuels storage and supply issues, as well as cost issues, that complicate comparison of these alternative fuels.

The measures of merit for this class of engines include the acquisition cost per unit of power, the weight per unit of power, and the efficiency of the engines. We will measure the acquisition cost per unit of power in dollars per horsepower ($/hp), the weight per unit of power in pounds per horsepower (#/hp) and the efficiency by the thermal efficiency of the power plant. It should be noted that the thermal efficiency can be related to the brake specific fuel consumption (BSFC). The BSFC is a measure of fuel consumed per unit power and is customarily quoted as pounds of fuel per hour per horsepower. For the typical hydrocarbon fuel (gasoline or Jet-A) the relationship between thermal efficiency and BSFC is "thermal efficiency equals 0.1383/BSFC" where the BSFC is measured in pounds of fuel per hour per horsepower.

The fuel cell has been suggested as a source of power for various general aviation aircraft but the weight (in pounds per horsepower) and complexity of this source of power has so-far eliminated this interesting power source from any practical general aviation applications. The typical fuel cell also uses fuels other than aviation gasoline or Jet-A so that fuel storage, supply and cost become issues. To quote the status of fuel cells from page 238 of reference 2: "Fuel cells are not a mature technology. If they are to make a major impact on tomorrow's energy markets, innovation in design and materials is required. Fuel cells use hydrogen fuel, so today's technology is a very ineffective design compromise to allow them to use fossil fuels. Stationary systems operating on reformed fossil fuels are expected to improve by evolutionary change, so that they will become increasingly competitive compared with, for example, gas turbine combined cycles (particularity for stationary power plants which are not weight sensitive). When hydrogen fuel is available, 60-80% of the cost of a mature fuel cell is eliminated, and they should be very competitive. However, they must not find their applications restricted by materials supply. A case in point is the platinum catalyst. Even though the cost per kilowatt can be reduced to acceptable levels, reliance on such materials will restrict fuel cells to niche markets. Innovation is therefore required in materials, particularly new catalysts and new electrolytes, perhaps of the solid type, which can operate in temperature ranges which are unavailable to fuel cells today. A breakthrough in this area may even allow the direct use of carbonaceous fuels." In summary, the fuel cell is a promising power source, particularly where a ready source of hydrogen and oxygen is available. Most of the present effort in fuel cell research is focused on space applications and ground-based transportation (cars, trucks, buses). The use of the fuel cell to power general aviation aircraft is at present limited by the cost, weight and the lack of maturity of this interesting source of power. If, in the future, we go to a hydrogen-based energy distribution system to minimize the carbon and hydrocarbon emissions and to reduce the NOX emissions these power sources would become even more interesting. Additional research, which would focus on the weight and cost limitations of present fuel cell designs, would seem to be justified. The fuel cell would seem to be of particular interest, at the present time, for unique missions where the hydrogen and oxygen might be available or where the fuel cell's unique capabilities would be of use. These missions would include applications where the supply of power in space was necessary and perhaps a very high altitude unmanned vehicle, such as that suggested in reference 3, which would use solar collectors during the day to collect energy which could be used to power the vehicle and to reduce water into hydrogen and oxygen which would be used during the night to power a fuel cell which would produce power and, as a byproduct, water, which would be used to complete the cycle. This bold venture, which presses the technology to the limit or beyond, might produce a very long endurance, high altitude, platform for scientific work or as a spy-in-the-sky. Excellent popular summaries of the state-of-the-art in fuel cell technology are included in references 4 and 5.

The general aviation market can be divided into several different segments or market types. For example the general aviation market could be divided into the ultra-light or powered hang glider aircraft market, the light single engine piston aircraft market, the multi-engine piston aircraft market, the single and multi-engine gas turbine aircraft market, the jet engine powered business aircraft market, the kitbuilt aircraft market and the commuter aircraft market. Each of these market segments cater to a different type of customer and have different market requirements. We will focus our discussion on the light single and multi-engine piston and the single and multi-engine gas turbine aircraft market which typically has one or more pilots using a single aircraft for personal or a combination of business and personal use. This segment of the market is very price sensitive and has suffered a severe decline in numbers of aircraft manufactured per year. We will arbitrarily call this market the "general aviation market" although it is in reality a subset of the general aviation market. Some of this discussion of engine technology could also apply to the kitbuilt market which is growing rapidly and tends to overlap the above described "general aviation" market. Currently the principal sources for the "general aviation" class of engines are the piston engines manufactured by either Textron Lycoming or Teledyne Continental or the small gas turbines manufactured by Allison (see references 1 or 6). The piston engines are typically 300 horsepower or less, cost about $100/hp, weigh about 2 #/hp and have a thermal efficiency of about 25%. These piston engines are typically air cooled and many have turbochargers to reduce or eliminate the power lapse created by the lower atmospheric air density at the higher altitudes. The gas turbine engines produce between 400 and 500 horsepower, cost about $300/hp, weigh about 0.5#/hp and have a thermal efficiency of about 20%. The piston engines typically burn 100 octane low-lead (100LL) gasoline and the gas turbine engines burn Jet-A. The Environmental Protection Agency (EPA) has been discussing the elimination of fuels containing lead and if these leaded fuels were restricted, most of the current piston engines would need to be replaced or redesigned for the lower octane unleaded fuels that could replace the 100LL fuel (references 1 and 6).

Recently a new segment of the general aviation market has been growing rapidly. This market includes ultralight aircraft and the lower end of the kitbuilt aircraft. These aircraft are typically uncertified or certified under the FAA "Primary" class and use a variety of small piston engines as sources of power. One of the largest of the engine manufacturers for this class of vehicle is an Austrian-company "Bombardier-Rotax" which according to the 1993-1994 Jane's (page 603) has sold over 50,000 small piston engines in the last 10 years for aircraft propulsion. Some of these engines are certified under the European JAR Very Light Aircraft and the US FAA Primary Aircraft regulations. A typical engine in this category, the Rotax 912A (figure 1), cost about $100/hp, weighs about 1.8 #/hp, produces 80 horsepower, and has a thermal efficiency of about 25%. Many of these engines (but not the Rotax 912) are two-stroke and are lubricated by mixing oil into the gasoline. These engines are typically air-cooled. Other manufacturers of this class of engine include the German-based Hirth, Konig, Limbach, and Pieper; the Italian-based Arrow, IAME, Offmar, and VM; the British-based Emdair, MWAE and Norton; and the US-based AMI, Moller, Rotorway and Nelson. This active and often ignored market segment is very dynamic and interesting.

There are also companies which are designing engines to compete directly with the engines manufactured by Lycoming and Continental. These companies include the German-designed Zoche, the Italian-designed VM, the Polish-designed WSK-PZL RZESZOW, the American-designed Dyna-Cam, and the Russian-designed DN-200. Many of these engines are very novel and advanced but most have not yet reached the marketplace. Several of these engines are based on the Diesel cycle. For example, the German-designed Zoche engine (figure 2) is an air-cooled, two-stroke diesel engine which is supplied in either a four-cylinder 150 horsepower single-row radial version or a twin-row eight-cylinder 300 horsepower version. The 150 horsepower engine weighs about

1.3#/hp, would costs an estimated $100 to $150/hp, and has a thermal efficiency of about 36%. The 300 horsepower engine weighs about 0.88#/hp, costs about $100 to $150/hp, and also has about 36% thermal efficiency. These engines are in an advanced state of development and according to the manufacturer should be available to the public soon. The Russian-designed DN-200 (figure 3), which is in an early prototype stage of development, is a two-stroke, liquid-cooled diesel piston engine. According to the 1993-94 Jane's All the World Aircraft, this engine is " hoped to be the most economical in the world. It is being designed to replace American engines in light aircraft, though it is beginning with the Yak-112. Five single-cylinder test engines had been built by 1991 to assist in reaching the target fuel consumption. The first DN-200 ran in 1991, and certification is due in 1994-1995." The target BSFC is 0.27 #/hr/hp which translates into a target thermal efficiency of 51.3%. The projected weight per horsepower is 1.82 #/hp. The cost and present status of this engine are not known. This engine's thermal efficiency is spectacular for a general aviation engine, but it should be noted that NASA Lewis has, at the present time, a contract to develop a truck engine which is to have a thermal efficiency of 55%, which translates to an BSFC of about 0.25. The engine has already operated at thermal efficiencies over 50%. The Italian-designed VM (figure 4) is also a diesel engine, which is a four-stroke, horizontally-opposed, turbocharged engine in three different versions: a four-cylinder, 206 horsepower version, a six-cylinder, 315 horsepower version, and an eight-cylinder, 424 horsepower version. These engines, according to Jane's, "offer cruise BSFC 40 to 80 percent lower than for a petrol engine and are designed for operation to 29,000 feet and with a Time Between Overhaul's (TBO) of 3,000 hours." Other novel engine designs include the American-designed Dyna-Cam engine (figure 5) which is a "barrel" engine with a history that dates back to 1916. This engine produces 250 horsepower , weights about 300 pounds and has a thermal efficiency of about 35%. According to the 1992-93 Jane's this engine is fully certified and installed in a Piper Arrow increased the rate of climb from 900 to 1500 feet per minute. The engine's production depends on the arrangement of funding. Another interesting engine is the American-designed Moller RC or rotating combustion engine (figure 6) which is described in the 1992-93 Jane's. This engine's manufacturer has claimed that this engine will have a weight-to-power ratio of 85 pounds for 150 horsepower or 0.56 pounds per horsepower. According to Jane's the development of this engine slowed or stopped in 1992 and the future of this engine is not clear.

Another segment of the aircraft engine market are the so-called "Derivative or Derived" engines which are aircraft engines that have been "derived" from an engine which has been manufactured originally for a different purpose. Most of these engines are modified from automobile engines. Automotive engines which have been used for this purpose include the Porsche and Offenhauser Racing engines on the high end of the power requirements and the Buick V-6, the Chevrolet V-8, the Volkswagen, and Subaru engines at the lower end. These engines often use cogged belts to reduce the engine RPM down from 5000 to 6000 RPM at the drive shaft to 2000 to 3000 RPM at the propeller. According to reference 7 it is possible to get up to 370 horsepower from a fully-developed Buick 3.8 liter V-6 which might weight about 285 pounds after all the street equipment had been stripped from of the engine. According to this reference there are aluminum racing engine blocks available for most of the popular engines including the Buick V-6 which could reduce the engine weight even more. Since the typical automobile engine can costs as low as $10/hp, the advantage of these modifications is obvious. These engines are not designed or certified for aircraft use so the risks are also obvious. It should also be mentioned that many of these engines (but not all of them) are liquid cooled so the additional complications of the liquid cooling system and the radiator must be included in the design process.

It is interesting to hypothesize about the future of the small general aviation or personal aircraft engine. If we ignore the personal liability and legal problems which are creating havoc with the manufacturers of these engines and just consider the technical issues and limits it is very easy to argue that the present typical mainstream general aviation engine could be improved substantially. For example, if the Russian DN-200 is able to deliver a BSFC of 0.27 (or the equivalent thermal efficiency of 51%) which is about one half of the BSFC of an existing Lycoming or Continental engine then the ranges and fuel economy of aircraft using this new technology would be radically increased. If this hypothetical engine could also have a reduced weight of say 0.5 to 1 pound per horsepower instead of the current typical 2 pounds per horsepower and if this engine could be manufactured in volume so that the price could fall then it might be possible to produce a revolutionary new light aircraft. One possible candidate for such an engine is described in reference 8. This novel cycle, which is based on a proprietary cycle, might produce almost 2.5 times the power per unit airflow as that of a simple gas turbine. Typical small simple gas turbine engines can produce engine weights of about 0.5#/hp. Some of the new cycles are projected to have an airflow over 50% less than the simple gas turbine engine for a given horsepower. The simple gas turbine engine typically scales (in weight) with airflow. Therefore it might be reasonable to hope that the new proprietary "Coleman Cycle", proposed in reference 8, could have a considerable weight advantage over the simple gas turbine (such as the Allison 250 which already has a weight to power ratio of 0.5#/hp). If this proposed new engine could produce the power of the Allison 250-17C (about 420 horsepower) at about half the weight (say 100 pounds instead of about 200 pounds) and if at the same time the BSFC was reduced by 50% from 0.65 to 0.3 (thermal efficiencies from 21% to 46%) as suggested by reference 8 then a most interesting engine might be possible. Unfortunately the "Coleman cycle" engine, which is currently under extensive study under the Advanced Concepts program at NASA Lewis, requires additional hardware, compared to the simple gas turbine cycle, to achieve the projected performance levels. Therefore the "Coleman" engine may not scale down in weight as argued above. The additional hardware may also increase the cost of this engine even higher than the current $300/hp of the Allison 250. It would be a major contribution to general aviation if these engines were manufactured in sufficient quantities and with cost-effective design so that these cost would scale down substantially. If the cost could be reduced to reasonable levels (to perhaps $30/hp or less) by innovative design and the use of advanced composite materials and by increasing the number of engines manufactured, this engine cycle could be a real winner.

The challenge to the designer of a new general aviation or personal aircraft engine is to produce a engine design which combines the low cost of the "derived" or converted engine (say $10/hp) with the weight per horsepower of the gas turbine (say 0.5#/hp) and the efficiency of the proposed Russian DN-200 (thermal efficiency of about 51% or greater). The TBO (Time Between Overhauls) or cost of maintenance should also be addressed. Typical large gas turbine engines have TBO's up to about 10,000 hours. If the new engine could get half of this it would be much better than the typical 1500 to 2000 hour TBO's of existing piston engines. The tools that the engine designer would have to accomplish these goals are the new composite materials currently under development and the exciting new cycles (including the "Coleman" cycle) which have been proposed. The enhanced demand that such an engine could generate should create a market sufficiently large to reduce the development cost per engine. If compromises were necessary it might be reasonable to compromise the thermal efficiency and weight of the engine while holding the cost per horsepower goal. A better option might be to design four engines at some fixed horsepower (say 300 hp), one optimized for minimum cost per horsepower, one optimized for maximum thermal efficiency, one optimized for minimum weight and the fourth engine combining the most appealing features of each of the previous designs to result in the best combination or compromise for a new general aviation engine. Such an engine could revolutionize the personal aircraft market, if the litigation issues were solved. NASA's aid and resources could be used in the development of such revolutionary technology and if NASA decided to commit to such a venture it would be time and money very well spent. The application of this technology could extend far beyond the general aviation market and could affect the automotive and truck marketplace as well as the stationary power plant market.

Finally, excellent summaries of the history of the light piston engines are given in references 1, 6, 9, 10 and 11. A summary of the battery technology is presented in reference 12. A table summarizing the weight per horsepower, the cost per horsepower, and the thermal efficiency for the power sources discussed above is shown as figure 7. This information should be taken as guidelines or rough estimates since each technology is the subject of current research and breakthroughs are possible especially in the fuel cell technology and battery technology which are less mature than the piston engine technology or the gas turbine technology.

REFERENCES

1. Gunston, Bill, "The Development of Piston Aero Engines" Patrick Stephens Limited, 1993.

2. Appleby, A. J. and Lovering, D. G., "Fuel Cells 2", Proceedings of the 2nd Fuel Cell Symposium, London, September 24-27, 1991, Elsevier, Amsterdam/London/New York, 1992.

3. Brown, Stuart F., "The Eternal Airplane", Popular Science, April 1994.

4. Anonymous, "The Different Engine", The Economist, February 5, 1994.

5. Williams, Robert H., "Fuel Cells, The Clean Machine", Technology Review, April, 1994.

6. Gunston, Bill, "World Encyclopedia of Aero Engines", Revised Second Edition, Patrick Stephens Limited, 1989.

7. Finch, Richard, " Converting Auto Engines For Experimental Aircraft", Second Edition, Finch Books, Inc. (Published By Finch Books Inc. 340 Birch Street, Titusville, Fla. 32780), 1986.

8. Acurio, John, "Small Gas Turbine Engines In The 21st Century", Aerospace Engineering, August 1993.

9. Heywood, John, "Internal Combustion Engine Fundamentals", McGraw-Hill, 1988, New York.

10. Heron, S. D., "History Of The Aircraft Piston Engine", Ethyl Corporation, Detroit Michigan, 1961.

11. Schlaifer, Robert and Heron,S.D., "Development Of Aircraft Engines and Development Of Aviation Fuels", Graduate School Of Business Administration, Harvard University, 1950.

11. Woodruff, David, "Electric Cars, Will They Work? And Who Will Buy Them?", Business Week, May 30, 1994.

12. Knepp, John E. And Mullen, Robert L., "Conversion Of Production Automotive Engines For Aviation Use" SAE Paper 932606, Aerotech '93, Costa Mesta, Calif. September 27-30, 1993.

SUMMARY OF THE ROTAX FAMILY OF SMALL ENGINES

ENGINE MODEL	277	377	447	503	582	912
LAYOUT	1 CYLINDER PISTON PORT	2 CYLINDER PISTON PORT	2 CYLINDER PISTON PORT	2 CYLINDER PISTON PORT	2 CYLINDER ROTARY VALVE	4 CYLINDER ROTARY VALVE
BORE/STROKE (INCHES)	(2.83/2.60)	(2.44/2.40)	(2.66/2.40)	(2.83/2.40)	(2.99/2.52)	(3.13/2.40)
CAPACITY IN CU INCHES	16.397	22.475	26.637	30.310	35.44	73.912
WEIGHT IN POUNDS	41.9	60.6	60.6	66.6	62.4	132
RATING (HP)	25.5 HP @6,500 RPM	34.9 HP @6,500 RPM	29.4 HP @6,500 RPM	36.2 HP @6,500 RPM	63 HP @ 6,500 RPM	79 HP @ 5,500 RPM

Figure 1. The Bombardier-Rotax Family of Engines (including the Popular Rotax 912).

THE GERMAN "ZOCHE" TWO-STROKE DIESEL ENGINE

- TYPE: TWO-STROKE AIR-COOLED DIESEL ENGINE
- POWER: 4 CYLINDER @ 150 HORSEPOWER AND 8 CYLINDER @ 300 HORSEPOWER
- WEIGHT: 4 CYLINDER=196 POUNDS; 8 CYLINDER=265 POUNDS
- SFC: BOTH HAVE SFC=0.385 LB OF FUEL PER HP HOUR
- STATUS: NEARING PRODUCTION

Figure 2. The German-designed Zoche Turbocharged Two-Stroke Diesel Engine.

THE RUSSIAN DN-200 TWO-STROKE DIESEL ENGINE PROTOTYPE

- TYPE=TWO-STROKE LIQUID-COOLED DIESEL PISTON ENGINE
- PROPOSED HP RATING: 200 HP @ T/O
- SFC: CLAIMED TO BE 0.27 LB OF FUEL PER HP HOUR
- WEIGHT: 364 POUNDS
- STATUS: SINGLE CYLINDER TEST ENGINES HAVE BEEN BUILT TO TEST CONCEPT
- PRESENT STATUS: UNKNOWN

Figure 3. The Russian-Designed DN-200 Turbocharged Two-Stroke Diesel Engine.

THE ITALIAN "VM" SERIES OF DIESEL ENGINES

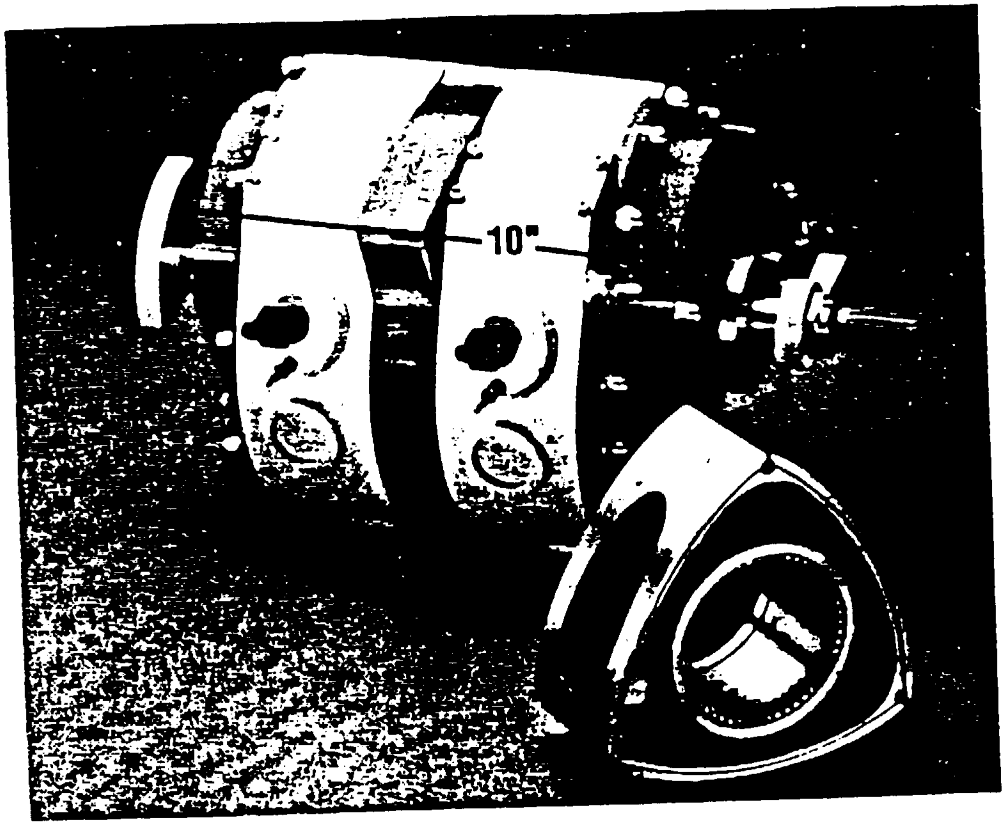
- MAKER: VM MOTORI SpA
- TYPE: 2,4 AND 6 CYLINDER HIGH SPEED LIQUID COOLED DIESEL ENGINES
- WEIGHT: 4 CYLINDER=408 POUNDS; 6 CYLINDER=536 POUNDS AND 8 CYLINDER=657 POUNDS
- HP: 4 CYL=206 HP; 6 CYL=315 HP; 8 CYL=424 HP
- SFC: ABOUT 0.63 LB PER HP HOUR

Figure 4. The Italian-Designed VM Turbocharged Four-Stroke Diesel Engine.

THE DYNA-CAM ENGINE

- TYPE: A "BARREL" ENGINE
- HP: 250 HP @ 2000 RPM
- SFC: 0.40 LB/HP HOUR
- WEIGHT: 300 LBS.
- STATUS: PROTOTYPE HAS BEEN FLOWN IN PIPER ARROW

Figure 5. The American-Designed Dyna-Cam Engine.



Moller MR 530 HT High-Performance Two-Rotor Engine

	Moller Rotary(1)	Standard Piston(2)
Power	150 hp	160 hp
Weight	75 lbs	255 lbs
Volume	1.0 ft^3	8 ft^3
Frontal Area	0.6 ft^2	3 ft^2
Major Moving Parts	3	44

(1)Moller MR 530 HT, (2)Avco Lycoming 0-320-A

Comparison of Moller Rotary and Standard Piston Engine

Figure 6. The American-Designed Moller RC Rotary Engine.

SUMMARY OF ENGINE CAPABILITIES

ENGINE TYPE	WEIGHT PER HORSEPOWER	COST PER HORSEPOWER	THERMAL EFFICIENCY	COMMENTS	SOURCES
GAS TURBINE	0.5 LBS/HP	$300/HP	20%	TYPICAL VALUES (ALLISON 250)	ALLISON
LIGHT GENERAL AVIATION PISTON	2 LBS/HP	$100/HP	25%	THE CURRENT "STANDARD" GENERAL AVIATION POWER SOURCE	JANES
AUTOMOBILE PISTON	2 LBS/HP	$10-$20/HP	25%	CAN VARY DEPENDING ON MANUFACTURER AND TECHNICAL SOPHISTICATION	FINCH
FUEL CELL	30 LBS/HP (BUT ESTIMATES VARY WILDLY DEPENDING ON TECHNOLOGY ASSUMPTIONS AND FUELS USED)	$1000/HP (BUT AS LOW AS $5/HP MAY BE POSSIBLE FOR HYDROGEN/OXYGEN CELL)	50%	TECHNOLOGY NOT MATURE	APPLEBY AND LOVERING ED. FUEL CELLS 2 ELSEVIER 1991.
BATTERIES WITH ELECTRIC MOTOR	5-50 LBS/HP	$300-$1000/HP	VERY HIGH BUT BATTERIES MUST BE CHARGED FROM ANOTHER SOURCE	CURRENT SYSTEMS ARE HEAVY AND BATTERIES MUST HAVE EXTERNAL POWER SOURCE TO CHARGE THEM.	BUSINESS WEEK MAY 30, 1994, PAGE 110.

Figure 7. A Summary Of the Various Engine's Capabilities

Personal Aircraft Operations And Safety

William T.Hodges

NASA,Langley Research Center

The operation of an aircraft has always required a high level of skill. As a result of the increasing complexity of aircraft and airway systems, the piloting workload and skill level has steadily increased. The result of this evolution has been increased costs of operations, training and purchase price of aircraft. As costs were spiraling upward, the usefulness of the aircraft as a transportation device was basically stagnant,and actually becoming more restrictive in some respects. However, the continuing revolution in computers and micro electronics is providing an opportunity to reverse this trend of ever increasing costs. This revolution in electronics also holds the promise to trigger a revolution in the usefulness and safety of the aircraft as a transportation device. In the near term this will manifest itself in a generation of vastly improved avionics and air traffic management procedures which should greatly improve aircraft. utility.In the future [beyond 2010],this revolution could allow completely automated operation of an aircraft, provided that a significant investment in airway management infrastructure is made. In both near and far term, safety and comfort will be greatly enhanced by advanced systems management, sophisticated collision avoidance, digital flight controls, fault tolerant systems, self diagnostics and degradation management of systems that malfunction.

In the past, whenever a pilot wanted more information on the current state of the aircraft and its flight path, another dial, gage or instrument readout would appear in the cockpit. Along with these displays another array of associated controls to operate the new instruments would also appear.In 70 years of General Aviation flying we have gone from an airspeed indicator, altimeter, compass, magneto switches and an engine tachometer, to a dizzying array of over a hundred displays, knobs, readouts, instruments, gages, needles, switches and circuit breakers. Each time a new device appeared in the cockpit, it was simply added to the other devices already crowding the cockpit, with little concern given to any optimal integration. Today, pilots are required to keep track of all of these devices todetermine their flight situation. Human factors expert George Hoover captured the essence of the problem in his statement: "The natural world consists primarily of visual cues. Nature does not use symbols, letters or numbers to convey information. As a result, the human being has evolved as an effective differentiator, but a poor integrator. Yet, pilots still are forced to read and interpret hundreds of hieroglyphics, most of which are relatively unimportant to the task at hand. Research has proved that good pictorial visual information is a powerful counter to vertigo and will rapidly restore a pilots situational awareness". It is easy to understand why flight training takes so long, is so expensive and requires so much recurrency training to maintain proficiency.

Despite all of the effort and expense that goes into training, confusion in the cockpit is still occurring too often with current technology. Accidents related to human factors, such as controlled flight into terrain, simply should not occur. These accidents, often referred to as "pilot error" account for more the 80 percent of the total.In reality, the so-called pilot error accidents occur when the pilot is attempting to operate a system that is mismatched with human capabilities.There is a great need to properly simplify and integrate the information displayed to the pilot, with human factors considerations guiding the way. With todays computer technology it is now possible to provide this integration and simplification of displays, at low cost, while increasing the level of alertness to critical flight information and overall situational awareness. Currently entering the market are separate map systems, trip calculators, facilities directories and other flight management tools.In the future, these tools will be integrated into a user friendly package that has been optimized by human factors considerations.Many of these techniques will come from the computer industry that has transformed itself from user hostile banks of switches and blinking lights to an icon and graphics based interface that is quickly becoming natural and intuitive to operate. In the far future, beyond 2010, further integration into a fully automated system could occur if an air traffic management system infrastructure is in place to support it.

With an increasing reliance on computers to operate flight critical systems, computer system reliability will have to effectively become perfect.Computer redundancy can greatly help the situation, but additional measures will need to be taken in the areas of fault tolerance, graceful failure degradation and automated run-time self diagnostics. Both hardware and software fault tolerance is being studied at universities and government laboratories. Numerous fault tolerant techniques have been developed and demonstrated. Graceful failure degradation is also an effective technique to deal with the failures that ultimately occur.If a manageable increase in workload and decrease in performance occurs as a result of failures, then a safe abort to landing can be executed. A very powerful safeguard would be to diagnose a problem before you takeoff, or in its earliest stages while in flight. Increasingly sophisticated diagnostic routines will need to be developed to assure reliability in increasingly complicated computer systems. By combining modular construction with accurate fault isolation, repair of the system would simply involve a module swap of the failed component.

In addition to monitoring the health of the electronic systems, computerized diagnostics can also be applied to structural, mechanical and propulsion systems. Diagnostic systems are currently under development that measure vibration and acoustic spectra to compare with known oscillation spectra to determine if there are any problems. Other strategically placed sensors, such as temperature, pressure, or load transducers aid in the detection of problems at their earliest stages. Once a problem is detected, additional analysis will be used to further isolate the cause of the problem.With the addition of some systems intelligence, action items could be suggested to the operator that would eliminate or manage the problem in a manner that would maximize safety. Some items could get automatic action, such as the triggering of a fire suppression system by heat sensors.

If a critical problem was to develop so quickly that corrective action could not be taken, a ballistic parachute system for the entire aircraft could be deployed. Ballisticly deployed parachute systems can be effective in as little as 200 feet of altitude. Systems have been developed for many different aircraft from ultralights to aircraft as large as 4 passengers and 3000 pounds. Initial crash tests of an airbag system around instrumented dummies in a helicopter have demonstrated an improved ability to withstand impact loads.Such loads on aircraft passengers can also be greatly attenuated with energy absorbing seating and structures. Coupled with the parachute system, an airbag system, impact absorbing seating and energy absorbing floor structures will greatly enhance the survivability of a crash.

Weather conditions have always greatly effected aircraft operations. One concept for gathering weather data that has a great deal of potential for weather forecasting would be to place weather sensors onboard aircraft as they fly their routes. The sensors would send back weather data to forecasters on the ground as the aircraft fly through various weather conditions,generating a superlative central,real time,data base which should greatly improve localized forecasting .In addition to the airborne sensors, a new generation of atmospheric sensors will also be located on the ground and on satellites. The new GOES weather satellite now has an atmospheric water vapor sensor.The new doppler

C-2

radar stations that will be set up in the future will be able to sense strong wind currents as they are forming in thunderstorms. A system of ground based and satellite based atmospheric profilers are also in development. These profilers will be able to gather data rapidly and often enough to greatly aid weather forecasting. With such a rich, accurate and timely data base to work with, forecasters should be able to blend the data into their system in a way that should increase the accuracy of near term predictions. These improved forecasts will be made for the entire United States, large portions of Canada and Mexico on a grid spacing of every 60 kilometers (36 miles). Once the weather predictions have been made, it is then the task of the communications systems to place the forecasts and any appropriate warnings into the aircraft in an easy to understand format for action by the aircraft operator or his expert system[s].. In the near term this will come through terrestrial communication systems, such as the FAA's mode S weather data links already in development [but not yet in wide spread operation]. Ultimately, communications will come through satellite links as their costs approach current terrestrial based communications systems. Once the information enters the cockpit, it needs to be presented to pilots in a way that they can easily interpret. Advanced graphical displays are being developed at the National Center for Atmospheric Research that are intuitive and quickly impart complete situational awareness to a pilot. All of this weather forecasting infrastructure will also be needed for any fully automated aircraft systems in the future.The onboard computers could automatically plot a route around icing and severe storms. On those rare occasions when it will be unsafe to fly because of severe icing or thunderstorms, it will also probably be unsafe to drive a car.

Air traffic management can be greatly improved in both efficiency and safety with the proper application of emerging technologies in the areas of communications and satellite navigation systems. Today, pilots operate aircraft using the practice of "See and Be Seen". In reality, this practice is a myth, with very few airborne aircraft being visible to each other for traffic safety. In the future, aircraft will report positions and intentions based on GPS locations and flight management computer data displayed in graphical form on each others instrument panels. With these capabilities, "See and Be Seen" will become an electronic reality. With some added computer intelligence, conflict alerting could be implemented, including avoidance trajectory negotiation between the computers on each of the aircraft. With world wide adoption of the direct aircraft to aircraft air traffic management system, operations over the open ocean and third world countries would have the same level of collision avoidance as in the United States. Again, the information will have to be displayed in a way that is intuitive and easily understood. By coupling the GPS position to computerized terrain and obstacle data bases, collision with fixed objects could also be avoided. Advanced air traffic management will involve communications from aircraft directly to other aircraft, and to the ground through a direct link, and later through satellite links.

Sizable infrastructure expenditures will need to be made by the Federal Aviation Administration (FAA) to support advanced air traffic management. However, these investments could actually lower operating costs for the FAA because of the decreased number of air traffic controllers needed for aircraft collision avoidance. A greatly reduced number of controllers will be needed with an air traffic management system that relies on the distributed processing capabilities of airborne and ground based computers networked together. A kick-off meeting in August 1994 between the FAA and the NASA-AGATE (Advanced General Aviation Transport Experiments) program officials laid the initial ground work for a series of research experiments and demonstrations that could ultimately lead to an orderly transition from the current National Airspace System (NAS) to the type of air traffic management system that will be needed in the future. A phased approach envisions that by 1998 a series of data link demonstrations would have ATC clearances, traffic and weather information delivered to a display in the cockpit. It is not sufficient that the information arrives in the cockpit. The display and it's information has to be very intuitive to operate and intuitive to interpret for the pilot to have complete situational awareness at a safe workload. The National Weather Service, National Center for Atmospheric Research, private weather information sources and the FAA will be working together to develop new formats for weather information display that will be much more useful to aircraft operators. It will also be necessary to display traffic information in a way that can be quickly and correctly interpreted for the pilot to properly react for collision avoidance. Another demonstration goal to be accomplished via GPS will be direct routing-area navigation for classes D and F airspace. Direct optimal routing will be much more fuel and time efficient than the current practice of following designated airways between VOR stations. By the year 2000, the experiments could be extended to class C airspace with separation criteria and procedures being established for collision avoidance. Around 2005, class B airspace could be included and a set of "Rules Of The Road" developed for enroute and terminal area operations.

In the long term future, beyond 2010, cockpit automation for pilots could be joined by autonomously operated aircraft. This will require a fault tolerant, multiply redundant, automatic aircraft control system. Such a system in its ultimate form would only need the passengers to designate a final destination and activate a "go" button. Automatic routing and air traffic control could be handled by ground computers that keep track of airborne vehicles by their GPS based position reporting transponders. A high level of fault tolerance and redundancy would be as necessary in the ground based computers as it is in the airborne computers. Communication systems would also have to be as reliable as the computers, perhaps by using spread-spectrum broadcasting techniques.

In summary, the technological revolutions taking place in electronics, aircraft systems, safety technologies, communications and aircraft operations infrastructure will lead to operations that are far more useful and safer than air travel today. These technologies will also lead to a reduction in the costs of pilot-operator training because the aircraft will be easier to operate. Operations costs will also be reduced because of more efficient flight profiles and the impact of advanced diagnostics and condition monitoring on maintenance costs. With direct operating costs reduced and usefulness greatly improved, the increased volume of aircraft sold should hold the purchase price of aircraft below the cost of currently available, relatively inefficiently produced [old technology] aircraft.

Ensuring Flying Cars are Quiet

Kenneth S. Brentner
NASA Langley Research Center

INTRODUCTION

The acoustical characteristics and noise should be evaluated in the consideration of any new transportation system. Noise is a primary concern since it is associated with human annoyance. In the past, people have complained about noise generated by new vehicles because little if anything was done to reduce the noise. Often the annoyance was also related to a concern for safety and a fear of the machines themselves. Undoubtedly this was true with the introduction of both locomotives and automobiles, yet the need for these new machines effectively overshadowed any consideration of their unfriendly nature. Today people are much less likely to accept new technology if it comes with significant negative side effects. Passengers do not want to travel in noisy vehicles, communities will not accept acoustically intrusive activities, and governments now regulate allowable noise levels (especially aircraft). Hence a vehicle which is not "friendly" in terms of noise may never be allowed into production. The sonic boom problem, for example, is at least partially responsible for the absence of a U.S. supersonic transport and the restriction of supersonic overland flight. For this reason it is important to characterize the potential challenges and noise reduction strategies to minimize the acoustical impact of new vehicles.

Over the years aircraft and rotorcraft have been designed with little regard for the noise until late in the design cycle or after noise related problems forced redesign. Although this has been changing recently, designers often do not have much acoustic intuition to guide their designs. Many things can be done to reduce noise levels if noise is considered from the beginning. To ensure that the vehicle can be "designed for low noise," it is appropriate to investigate the noise characteristics in every stage of the design process of conceptual vehicles. Such an investigation is made in the context of personal aircraft[†] ("flying cars") in this chapter along with a discussion of the challenges and opportunities of low noise design.

THE HUMAN SIDE OF NOISE

The first aspect of noise to be considered in this chapter is the human response to noise. Unlike performance, safety, cost, manufacturability, and other aspects of design, noise is important because of its direct effect on and the response of people. The perceived annoyance or unpleasantness is determined by many factors, some of which are directly related to the sound generated (i.e., frequency content, duration, number of exposure events, time of day, etc.) and some which are not related to the sound itself (i.e., concern for safety, importance of noise source, perceived ability to reduce noise, etc.). During the past 30 years considerable information has been learned about annoyance due to aircraft noise. This information has been generated through both laboratory studies and community response surveys.

A study by Powell[1] is particularly relevant in the consideration of human response to noise generated by personal aircraft. In the study, the annoyance to both traffic and aircraft noise sources was considered along with the effect of their interactions. The study also provided guidance for the appropriate weightings or penalties to account for evening and night noise exposures. This guidance is important since personal aircraft are envisioned as being distributed throughout the community and operated very much like automobiles are today. Finally, comparisons were made between the annoyance responses obtained in laboratory situations and for typical community indoor-noise surveys. Powell found that people are generally more annoyed by a combination of aircraft and traffic noise

---

[†] The terminology personal aircraft and flying cars will be used interchangeably in this chapter — without any prejudice toward the actual type of vehicle, but rather the general idea of a combined flightworthy and roadworthy vehicle.

than by either noise source alone. Another interesting aspect of the study was that noise events occurring in the evening and at night were rated about 5 dB and 10 dB more annoying, respectively, than similar events during the day.

With the introduction of personal aircraft there would be more aircraft noise, especially in areas away from airports which are not accustomed to aircraft noise, hence there may be a penalty associated with having both traffic and aircraft. Nevertheless masking of noise from one source by the other can also occur and the combined annoyance can be less. Thus it is not exactly clear what the final impact will be and it is probably very dependent upon individual neighborhoods. Some consideration of vehicle operation time of is prudent.

In a study of helicopter noise annoyance, Fields and Powell[2] had the unique opportunity to conduct a community survey on helicopter noise while they where able to control the types and numbers of exposures each day of the survey. The participants were unaware that the focus of the survey was on helicopter noise or that their exposure was being controlled. Fields and Powell found that the helicopter noise was perceived as more annoying than road traffic noise and they were able to quantify some of the reasons people were annoyed. The perception that some danger was involved in the overflight of helicopters accounted for a 7 dB noise penalty. The respondents attributed a 8 dB penalty to their belief that the aircraft noise was in fact preventable. In other words, people who felt that helicopters were unsafe rated their noise as more annoying as did people who felt that the noise could be prevented. People who felt helicopters and their mission are important rated the noise 3.5 dB less annoying that those people who did not. Another interesting finding, characteristic of the sometimes acoustically unrelated nature of annoyance, was that people who did not like their local neighborhood felt that the noise was 3.5 dB more annoying that those who were happy with their neighborhood. The annoyance to helicopter noise increased steadily when the level increased above 45 dB (LEQ, 9 hour – a measure which accounts for the total noise energy in a 9 hour period).

These results confirm that the annoyance to noise is a very complicated matter influenced by emotions and opinions. Aircraft and rotorcraft noise can be more annoying that road traffic noise, but masking of noise sources can reduce the annoyance level. Some factors that can reduce annoyance to personal aircraft/helicopter noise are: 1) design the vehicles to be very safe; 2) demonstrate to people that they are as safe as automobiles; and 3) ensure a wide access to these vehicles so that people will accept their importance. Until personal aircraft are widely used there will probably be an additional noise penalty because they will be viewed as a luxury available only to the rich. Later, as personal aircraft become widely utilized this penalty will diminish, but care must be taken to minimize the noise to the greatest extent possible initially so that the annoyance level is comparable to current automobiles and motorcycles. Powell and Fields have written a chapter reviewing the human response to aircraft noise in a very comprehensive reference edited by Hubbard.[3]

THE PHYSICAL CHARACTERISTICS OF NOISE

Nearly all of the candidate propulsion systems appropriate for a personal aircraft (propellers, fans, and helicopter rotors) involve rotating blades as a significant or even dominate noise source. Noise generated by rotating blades is known to arise from many different mechanisms. A rudimentary understanding of these mechanisms is needed as a basis for comparing the potential noise challenges of each of the vehicle classes that will be considered in the rest of this chapter.

Low-frequency rotor noise is comprised of two main components: 1) thickness noise due to the blade pushing the still air out of its path, and 2) loading noise due to steady and unsteady loading on the blade. Thickness noise radiates mainly in the plane of the rotor while loading noise radiates predominantly along the rotor axis. Reducing the tip speed of the rotor is the strongest parameter in reducing both thickness and loading noise. This effects the performance of the rotor and in the case of a helicopter, the autorotation capability of the rotor also depends upon sufficient rotor rotation rate. Hence the tip speed cannot be lowered arbitrarily. Blade design can also reduce low-frequency noise. For example increasing the number of blades to reduce the loading on each blade is a means of reducing loading noise. Using thinner airfoil sections or tapering the rotor blade helps to reduce thickness noise when the tip speed is relatively high (by delaying transonic effects). For a helicopter rotor any changes made to reduce the noise from the high-speed advancing rotor must also be acceptable on the retreating side of the rotor disk when the blade operates at high angle of attack.

Although the main component of rotor noise is composed of low-frequencies, when impulsive noise is generated it dominates all other noise sources because of its large amplitude and relatively rich harmonic content. For helicopters, impulsive rotor noise is generated by two distinctly different mechanisms: 1) blade-vortex interaction; and 2) high-speed compressibility effects.

Blade-vortex interaction (BVI) noise occurs whenever the tip vortex of a previous blade is encountered by a subsequent blade. BVI noise is a special case of loading in which the blade loading varies impulsively due to the close passage or collision of the tip vortex. Interactions of this type occur both on the advancing and retreating sides of the rotor. BVI noise is intense, highly directional (below the rotor and forward on the advancing side, below the rotor and rearward on the retreating side), and occurs primarily during descending flight as the rotor wake is swept back through the rotor plane. The most severe BVI noise occurs when the collision between the vortex and the blade is parallel and hence occurs nearly simultaneously along the entire length of the blade. BVI noise can be reduced by changing the rotor trim conditions to reduce the vortex strength at the point of interaction, increase the miss distance between the vortex and the blade, and reduce the lift on the blade during the interaction. Fans and propellers also have a large increase in loading noise when the inflow into the rotor is not uniform. If a wing or a strut is placed directly upstream, the rotor blades experience a rapid change in loading as the blades cut the wake of the obstruction. This rapid change in loading usually generates intense noise.

High-speed impulsive (HSI) noise is normally only associated with the appearance of shocks on an advancing helicopter rotor during high-speed flight. HSI noise radiates primarily in the rotor plane and forward of the rotor and can be of the same order as thickness noise. Yu *et al.*[4] have found that the nonlinear transonic field of the helicopter rotor can suddenly extend many rotor radii, or "delocalize", when the rotor speed is increased sufficiently. When this occurs HSI noise is the most dominant and annoying noise source present. HSI impulsive noise can be alleviated by either avoiding high-speed flight or through sweeping the blade tips and using thinner airfoil sections to delay the onset of shocks. Propellers and rotors used for a personal aircraft would probably be designed to avoid shock formation.

Another type of noise which is important is the non-deterministic component of loading noise known as broadband noise. Any turbulent phenomena associated with the flow near or on the blade surface can generate broadband noise. Turbulence ingested by the rotor can produce both narrow-band and broadband noise. This turbulence can occur naturally in the atmosphere or come from blade wakes. The random pressure fluctuations on the blade surface due to turbulence within the attached or separated boundary layer generate noise known as blade self-noise. Other self-noise mechanisms include tip vortex formation, laminar vortex shedding and trailing edge noise. The stochastic nature of broadband noise make it equally difficult to predict accurately and control. Hubbard has compiled an comprehensive set of articles on aircraft noise sources and aircraft noise control.[3] A recent review of the state-of-the-art of helicopter rotor noise prediction is given by Brentner and Farassat[5].

POTENTIAL NOISE CHALLENGES

The goal of introducing a personal aircraft with noise emission levels comparable to current ground-based, personally-operated vehicles will be as challenging as it is important. The acoustic characteristics of personal aircraft will vary widely depending upon the configuration and type of vehicle. Proposed personal aircraft designs range from fixed-wing, propeller propulsed cars to automobile-like helicopters to vehicles which utilize vectored thrust to provide both lift and thrust. Since each of these vehicle types has several unique aspects, they will be considered separately in this section. It will be assumed that the vehicles will operate on the ground in a mode similar to current automobiles and that advanced automotive technology is available to ensure quiet ground operation. One problem that may invalidate this assumption is that automotive technology may have a weight penalty which is unacceptable for a flying vehicle. Nevertheless it is likely that this problem can be managed and therefore no further consideration to automobile-like ground operation noise will be given.

Personal Helicopter

The personal helicopter is a very attractive vehicle type for several reasons. As a helicopter, this vehicle does not require a runway and hence is a true portal-to-portal vehicle and could therefore be used as a replacement for the automobile. In fact if the configuration is an automobile-like helicopter it could be driven on the road for trips in the neighborhood without any noise penalty whatsoever. A personal helicopter also offers some flexibility as it is incorporated into the air-traffic control system since it has hover capability and can fly very slowly – both of which also add safety since hovering flight can be utilized by a pilot or by an automatic piloting system in situations which would otherwise lead to inflight collisions. It is important to point this out because helicopters have not been widely used by the general public, hence many people have the perception that they are not as safe as fixed wing aircraft. Changing this perception is a big challenge which may eventually be accomplished by demonstrating safety in widespread use.

The relatively slow speed of a helicopter is one concern since the personal helicopter must sufficiently reduce travel time over that of an automobile to warrant the additional complexity and cost. High-speed helicopter flight is usually attained at the expense of significant increases in vibration and noise. Tiltrotor aircraft can travel faster, since the rotors operate in a propeller mode during the cruise portion of the flight, but these vehicles are significantly more complicated and are not well suited for ground travel. The additional complexity required to tilt the rotors would potentially increase the cost of a personal tiltrotor significantly as compared to a personal helicopter. The noise challenges for a tiltrotor vehicle are similar to those of a helicopter. The convenience of the helicopter probably makes it the best alternative of all the personal aircraft designs.

The noise from helicopters is unique due to the complex, unsteady flow environment in which the main rotor operates. Helicopter rotor noise is characterized by low frequency tone noise, impulsive tone noise in some operating conditions, and broadband noise. The largest acoustic pressure fluctuations are the low-frequency tone noise generated by the main rotor, but since the human ear is not as sensitive to low frequencies this noise source not necessarily the most annoying. Tail-rotor noise, which generally contains higher frequency content, is often very annoying and can dominate noise in the frequency range of importance. For the same reason, engine noise can be a significant noise source for small helicopters if it is not attenuated in some manner. The variety and complexity of noise generation mechanisms associated with rotating blade noise make noise reduction a challenging task. Nevertheless, progress has been made in reducing helicopter noise in the last decade and it is illustrative to consider the noise characteristics of a modern, quiet helicopter.

Example helicopter: MD 520N

A good helicopter to use as a baseline for comparison with a potential personal helicopter is the MD 520N. The MD 520N is a modern helicopter which entered into production in 1991 with significantly lower noise levels than FAA noise certification requirements. This helicopter has an empty weight of 1586 lbs., a design gross weight of 3350 lbs., and carries four passengers in addition to the pilot. The 520N is roughly the size of an automobile. It uses a gas turbine engine to drive a five-bladed rotor and uses the NOTAR antitorque system rather than a more conventional tail rotor. The NOTAR antitorque system uses a circulation control boom, vertical surfaces, and a direct-jet thruster to balance the torque of the main rotor.

The MD 520N is a quiet helicopter. This is due in part to its relatively low weight, the reduced blade loading per blade with a five-bladed main rotor, and the absence of a tail rotor. The NOTAR system has a fan inside the base of the tail boom which generates noise, but the housing around the fan provides shielding of the fan noise. The fan noise is also attenuated by the atmosphere more readily than tail rotor noise since the fan fundamental frequency is higher (1167 Hz.) than a tail rotor(97 Hz.). The helicopter noise certification procedure for FAA Stage II certification for helicopters uses the EPNdB noise metric for three operating conditions: take-off, level flyover, and approach. The EPNdB metric is an temporal integration of noise, with weighting to account for frequency. The radiated noise measured during the noise certification of the 520N was 80.2 EPNdB for level flyover, 85.4 EPNdB on take-off, and 87.9 EPNdB during a six degree approach. It is reasonable that the approach noise is the highest because this is the operating condition in which BVI noise is expected. To gain some perspective about the noise level generated by this helicopter, the noise level during level flyover (72 dBA directly overhead at a nominal altitude is 500 feet) is comparable to a Cessna 180 propeller-driven general-aviation aircraft[6] at the same flight condition. The MD 520 and Cessna 180 are comparable in size and flight speed. The MD 520N is quiet helicopter and a reasonable upper bound for the allowable noise of a personal helicopter, nevertheless it does not really approach the target of automotive noise levels. More details of the noise characteristics of the MD 520N and a comparison with other helicopters has been given JanakiRam and Currier.[7]

Propeller-Driven Winged Cars

An alternative to a personal helicopter is to have a flying car which uses fixed wings for lift and a propellers for thrust. A flying car would require some sort of runway to take-off and land, hence it would be operated in a automobile mode in residential areas. Although this may be less convenient than a helicopter, take-off and landing noise would not be as critical for a flying car.

Propeller noise is similar to helicopter rotor noise with the main difference being that the loading on the propeller is steady and hence generates less noise. Usually propellers are not operated at speeds sufficiently high to generate shocks, so high-speed impulsive noise is not much of a concern. Also since propellers rarely interact with their own tip vortices, blade-vortex interaction is not a problem. Propeller noise can be dramatically increased, however, if the propeller operates in the wake of other objects. If the propellor is placed in a pusher configuration as Sahr has proposed,[8] the wake and boundary layer from the passenger compartment flow directly into the propeller. Another example would be if a pusher propeller is mounted on an aft mounted wing then the wake from the wing would immediately enter the prop. This type of inflow distortion causes an unsteady loading on the propeller which generates an intense noise similar in nature to BVI noise.

Another disadvantage of having the propeller located on the centerline of the vehicle is that the propeller loading noise radiate most strongly along the axis of rotation of the prop. Hence the most intense noise is radiated into the passenger compartment. This is one of the reasons single-engine general aviation aircraft often have high interior noise levels. The loading noise can be reduced somewhat by using higher numbers of blades and designing the load per blade to be less.

Directed-Thrust Vehicles

Another vehicle type which has potential as a personal aircraft is a vehicle which uses powered lift for take-off and landing but has wings to produce lift in cruise. This type of vehicle has the convenience of portal to portal flight like a helicopter, but is able to cruise at significantly higher speeds. One such design by Moeller[9] has several ducted fans to propel the vehicle in flight and to provide powered lift in take-off and landing conditions. The power lift is accomplished through the use of turning vanes to redirect the fan exhaust downward. This particular configuration is not well suited for ground travel, but this mode of travel could be incorporated into the design.

The acoustic characteristics of this configuration would be somewhat different from a propeller driven car or a helicopter. Fan noise is a rotor noise, but the duct around the fan alters the radiation pattern. If the duct are sufficiently long, fan tones can be "cut off" in which case they do not radiate. Ducted fans also offer the opportunity to include liners to further attenuate the noise radiation. Unfortunately ducts on a personal aircraft would probably be very short and light weight. This means they probably wouldn't be long enough to cut off propagating modes and liners may not feasible due to weight considerations. Even if passive duct liners proved to be excessively heavy, active noise control technology might offer some noise attenuation capability and any duct should provide some shielding of the fan thickness noise in the passenger compartment. Fan noise can be reduced through the proper design of the duct and fan blades. The number and location of any support struts in the duct is critical. Struts must be placed to minimize inflow/outflow distortions to the fan or noise levels can be very large. Counter-rotating fans may have some performance advantages, but generally produce more noise than single stage fans. If multiple fans are utilized in a duct, they should be coupled together so that the interaction tones can be controlled.

Using vectored or directed thrust for powered lift is potentially the greatest acoustic challenge for this vehicle class. If the turning vanes are in close proximity to the fan blades, the flow distortion would increase the fan noise greatly. Also the unsteady, turbulent flow acting on the turning vanes would cause them to act as efficient noise radiators. Military aircraft with blown flaps or vectored trust are very noisy. This noise would primarily occur on take-off and landing and since ground travel is limited, it would be difficult to avoid high noise levels in residential neighborhoods.

NOISE REDUCTION STRATEGIES

Even without specific details it is possible to offer the designer some guidance for a low-noise personal aircraft. This section will discuss several considerations to ensure that acoustic performance requirements can be met.

Weight Reduction

One of the most effective design parameters for minimizing aircraft noise is vehicle weight. The more the vehicle weighs the more lift and thrust required to make it fly. For a wide range of aircraft the noise goes like:

$$dB \sim \log_{10}(W)$$

where W is the vehicle weight and dB is the radiated sound level. This simple rule of thumb points out that anything that can be done to reduce aircraft weight, especially for a smaller vehicle, should yield a payoff in noise reduction. This may be challenge to the designer of flying cars since any vehicle that is both roadworthy and flightworthy must carry components that are only utilized during portions of the operating envelope. Nevertheless any weight reductions through the common use of components, utilization of advanced lightweight materials, or innovative designs will provide improvements in both vehicle performance and noise reduction.

Source Noise Reduction

In describing the physical characteristics of rotating blade noise earlier in this chapter several possibilities were mentioned to reduce the noise at the source. One of the most important design parameters is the blade tip velocity. When tip speed is reduced both deterministic and broadband noise are reduced. The number of blades in the rotor has a strong effect on the radiated noise. If the lift per blade can be reduced or the loading moved inboard from the tip, then loading noise will be reduced. Finally, blade radius is an important factor. If the blade radius is small, this often implies a high blade loading and high tip speed – both of which are bad for noise. While these fundamental configuration changes can reduce the noise they cannot be made independently from performance and safety considerations.

The blade planform is the next important parameter that can be utilized to reduce noise. Blades with either tapered or swept tips can be used to reduce both thickness noise and HSI noise. Reductions in BVI noise should also be possible if the blade planform is chosen to avoid parallel interactions between the tip vortex and the blade. Such planforms may include both aft and forward sweep.[10] Rotor noise prediction technology is currently capable of analyzing these types of changes, therefore rotor blades designs could be tailored significantly more than the blades currently used on present day helicopters. Porous blade designs[10] and rotor blades with active flaps[11], individual blade control, higher harmonic control[12], and smart skins/structures'[13] also hold promise for BVI noise reduction. Rotor blades incorporating these technologies would reduce BVI noise through modification of trim and ultimately the tip vortex structure and strength or through modification of the interaction event itself. Sophisticated blade designs may be a challenge for current industrial manufacturing methods and materials, but with state-of-the-art materials and the very large production runs envisioned for a personal aircraft, significant noise reduction should be possible.

The technology is also currently available to design fans that have good noise characteristics. It is important to minimize any inflow and outflow distortions to the fan blades. Flow distortion for a fan is primarily determined by the number and location of struts. The number of struts should be minimized and located as far from the fan as possible. Counter-rotating fans can be noisy because the second fan row does not see a clean, uniform inflow. Varying the number of blades on each row can improve the noise, however. Airfoil shapes, twist distribution, and blade sweep are other parameters for fan noise reduction.

One other source of noise that should not be ignored is engine noise. Engine noise on piston engine aircraft and helicopters can dominate rotating blade noise. If exhaust temperatures and velocities are high, jet noise can become a problem. Since these noise sources can be controlled in small aircraft, they should not be neglected.

Active Noise Control

While reducing the source noise through proper design is the best approach, it is not possible to design a silent vehicle. Some sort of noise attenuation is usually needed to reduce the noise exposure to passengers and the community. In current aircraft and automobiles passive treatment is used to dampen the noise entering the passenger compartment. Passive treatment is effective but it comes with a substantial weight penalty. An attractive alternative to passive interior treatment is active noise control of interior noise levels. State-of-the-art active control systems have been develop in a research environment which can attenuate from 10 to 20 dB.[14, 15] Active noise control systems are attractive because they have the potential to provide significantly more performance over a larger frequency range with substantially less weight than a passive system. In a flying car it might be desirable to build an active noise control system into a high-tech sound system. The passengers might not even be aware of its presence.

Low-Noise Operational Procedures

Noise can also be reduced through operational procedures. Today large aircraft operate using take-off and landing procedures designed to reduce noise in the airport community (cutback of engine thrust on take-off for example). Helicopter operators also are beginning to "fly neighborly" by following roadways, rivers and flying over industrial areas when possible. Procedures like these can be utilized by personal aircraft to reduce community exposure. Similarly, the infrastructure which must be developed can be designed to reduce the community noise exposure without much additional cost. Some ideas along these lines will now be presented.

Roadside Take-Off and Landings

Personal helicopters or other vertical take-off vehicles which operate in residential communities offer portal-to-portal travel. This is a attractive benefit over a fixed wing vehicles that operate from a local airport, but it creates a noise problem directly in the community. This is potentially a severe problem since residential communities normally have not been exposed to significant aircraft noise levels. A true flying car – a vehicle which is both roadworthy and flightworthy – could potentially avoid some residential noise emission by simply driving to a nearby take-off/landing pad located strategically along a existing highway. Hence for short local trips, where flight is really no advantage, the vehicle would be driven as a car with only automobile noise levels. A short drive to the nearest take-off pad would have little impact on transit time on longer trips. Roadside take-off and landing pads (air access points) could be distributed at regular intervals along almost any existing road, highway, or freeway. Community noise would be reduced for two reasons: 1) The take-off and landings would be a little farther away from homes, and 2) masking of aircraft noise by traffic noise should result in an effective lowering of annoyance due to aircraft noise. Placement of these pads would be regulated by local governments to provide even greater regional control of noise exposure.

Automatic Piloting

The widespread use of personal aircraft depends heavily upon the technology for the vehicle to be automatically piloted with little passenger intervention and certainly without trained pilots. This paradigm can also yield a payoff for low noise aircraft operation. Especially in the case of helicopters, noise reduction is possible through steady and accurate flight control. Rapid maneuvers and even small perturbations in vehicle control increase the generated noise. The automatic piloting system could be designed with low-noise control laws and would therefore be more capable than a human pilot of flying in a steady, deliberate, low-noise manner. The automatic piloting system would also be able to fly much more complicated trajectories. For example, segmented approaches (multiple descent angles) are now being proposed to reduced helicopter noise during landing. An automatic piloting system could effectively approach with a continuously varying descent rate.

The air-traffic control system, which is at the heart of the automatic piloting paradigm, could also incorporate noise considerations. For example, the vehicle flight path could be directed to avoid noise sensitive areas. Local regions could impose noise budgets so that once a certain level of exposure was reached less overflight would be allowed until a prescribed recovery time had passed. Finally, the noise considerations in the automatic flight path determination could be based upon time of day and day of week, etc.

SUMMARY

Personal aircraft offer great potential to revolutionize the way people travel, but this potential will not be realized unless people accept them. Design of ***low noise*** vehicles will be important to gain widespread acceptance. Much of the technology needed to "design for noise" is currently in hand or clearly within reach. Prediction methods are available and the noise sources are broadly understood. There are a wide variety of design options to make these new vehicles quiet and even further possibilities for noise reduction through automated "flying neighborly". Hence any new design should seriously "design for noise" rather than try to "fix the noise".

REFERENCES

1 Powell, Clemans A., "Laboratory Study of Annoyance to Combined Airplane and Road-Traffic Noise," NASA TP 1478, September 1979.

2 Fields, James M. and Powell, Clemans A., "A Community Survey of Helicopter Noise Annoyance Conducted Under Controlled Noise Exposure Conditions," NASA TM 86400, March 1985.

3 Hubbard, Harvey. H., editor, "Aeroacoustics of Flight Vehicles: Theory and Practice," Volumes 1: Noise Sources and Volume 2: Noise Control, NASA RP 1258, August 1991.

4 Yu, Y. H., Caradonna, F. X., and Schmitz, F. H., "The Influence of the Transonic Flow Field on High-Speed Helicopter Impulsive Noise," *Proceedings of the Fourth European Rotorcraft and Powered Lift Aircraft Forum*, Paper 58, 1978.

5 Brentner, Kenneth S. and Farassat, F., "Helicopter Noise Prediction: The Current Status and Future Direction," *Journal of Sound and Vibration,* Vol. 170, No. 1, pp. 79-96.

6 U.S. Department of Transportation, Federal Aviation Administration, Advisory Circular AC No: 36-1E, Noise Levels for U.S. Certificated and Foreign Aircraft, Appendix 7, Aircraft Noise Data for U.S. Certificated Propeller Driven Small Aircraft, June 30, 1988, page 7.

7 JanakiRam, Ram D. and Currier, Jeffrey M., "Noise Characteristics of Helicopters with the NOTAR™ Anti-Torque System," presented at the conference on "The Quiet Helicopter," organized by The Royal Aeronautical Society, London, UK, March 1992.

8 Sahr, Branko, "Advanced Flying Automobile," presentation to NASA Langley Aeronautics Technical Committee, December 1993. (See also "Design Concepts and Market Opportunities for "Flying Automobiles" ", SAE Technical Paper Series 921570, presented at the Future Transportation Technology Conference and Exposition, Costa Mesa, CA. August 10-13, 1992.

9 Moeller, Paul, presentation to NASA Langley Aeronautics Technical Committee, January 1994, and "The M400 Skycar (Volantor)," Moller International publication, Davis, CA, January 1993.

10 Brooks, Thomas F., "Studies of Blade-Vortex Interaction Noise Reduction by Rotor Blade Modification," NOISE-CON 93, Williamsburg, VA, May 2-5, 1993, pp. 57-66.

11 Marcolini, M. A., Booth, E. R.,.Jr., Tadghighi, H., Hassan, A. A., Smith, C. D., and Becker, L. E, "Control of Blade-Vortex Interaction Noise Using an Active Trailing Edge Flap," to be presented at the 1995 American Helicopter Society Vertical Lift Aircraft Design Conference, San Francisco, CA, January 18-21, 1995.

12 Brooks, T. F. and Booth, E. R., Jr., "The Effects of Higher Harmonic Control on Blade-Vortex Interaction Noise and Vibration," *Journal of the American Helicopter Society*, Volume 38, Number 3, July, 1993, pp. 45-55.

13 Prasad, J. V. R., Sankar, L. N., Park, W. G., and Corban, J. E., "Active Control of Rotor Noise Using Blade Airfoil Shape Changes," presented at the American Helicopter Society International Specialists' Meeting on Rotorcraft Multidisciplinary Design Optimization, Atlanta, GA, April 27-28, 1993.

14 Stevens, J, and Ahuja, K., "The State-of-the-Art in Active Noise Control," AIAA Paper 90-3924, October, 1990.

15 Active Structures Technical Committee, "A State-of-the-Art Assessment of Active Structures," NASA TM 107681, September, 1992.

Costs, Benefits, and Needed Changes for Realizing the Personal Aviation Dream

Michael A. Scott

An important factor effecting the commercial success of any personal aviation vehicle developed is the cost. Obviously cost will be a function of the quantity sold, which in turn is a function of the purchase price. The true cost of ownership includes the initial purchase price, operating costs(taxes, maintenance, insurance, fuel, and other life cycle costs), as well as any specialized training required. If the sum of these costs is too high, or the training too complicated there is little chance of a large scale success. This chapter presents a brief overview of some costs and related issues that affect making widespread personal aviation a reality.

The single largest one time cash outlay is the initial purchase. If the vehicle is designed as part of a completely automatic flight system there will be minimal need for training. The vehicle can be made more affordable by manufacturing millions of vehicles like automobile makers have done but building them to aircraft type weight specifications. To examine the initial purchase price you must look at the expenses incurred by the manufacturers and distributors of the vehicle. One major cost to manufacturers is the cost of raw materials. There are strong incentives to use advanced composites in any personal aviation vehicle. At the present time both the cost of manufacturing and the initial material cost of these materials is excessive in many cases. This is not always true as can be seen by the price of composite helicopter blades being cheaper than comparable metal blades. Such parts are lighter and have the potential for longer useful life.

An additional expense incurred primarily by manufacturers and their suppliers is pollution controls and other state and federal laws regulating how a company operates on a daily basis. While many of these laws and regulations are needed, these same measures taken to extremes can be prohibitively expensive for companies. This can be seen by the number of companies leaving California. Many companies move to other states due to the high cost of complying with California's anti-pollution laws and other costs higher in California than elsewhere. In an attempt to help the existing small aircraft general aviation market there have been many requests for tax credits and other investment credits to ease the burden on manufacturers and purchasers.

A cost that affects the manufacturers, distributors, and owners is taxes. The costs incurred by each are usually from different types of taxes but since they all go to some federal, state, or other local government they can be looked at simultaneously. During the design and development of any personal aviation system the people doing the work must keep in mind the cost of building and maintaining any new infrastructure. Since this infrastructure may be built, and will be regulated, by the government in some way, care must be taken to minimize the impact of new construction and development on already tight budgets. One factor that should lower the cost of this infrastructure is the use of existing systems such as GPS and the new personal communication systems. The infrastructure must be much less expensive to maintain than the many miles of interstate highways and other roads currently in use. This lower cost feature is not enough in and of itself since this new cost will be in addition to existing costs not instead. If sufficient people use the new system the maintenance costs for roads may decrease because of a decline in the number of people using them every day. Another advantage will be with decreased traffic flow on existing roads and therefore fewer new roads may be needed. Also the improved productivity allowed by the increased speed and decreased transit time of these vehicles is a significant cost offset issue.

While credits would help a company, the one cost incurred by the manufacturers that requires the most attention is not a technical or production issue but a societal issue, liability. The liability issue has been one of the single greatest contributors to the decline of the small, personal type, general aviation manufacturer. There are numerous examples of how a person doing something that most people would consider obviously unsafe gets hurt and then they or their family sues anyone they can see any possibility of getting money from. One such example was reported in the Wall Street Journal. In this case a man mounted a camera facing backwards in a small aircraft with the camera operator and the camera partially blocking the instrument panel. The man removed the front seats from the aircraft and proceeded to try to fly the aircraft from the rear seat. The airport operator blocked the runway in an attempt to prevent the man from taking off, he had a questionable safety record. The man continued his takeoff attempt and hit the van blocking the runway causing extensive and permanent brain damage to himself. The man's family sued both the airport operator and the aircraft manufacturer and won. This case shows how a good lawyer can use the jury system to win a case that most people looking at only the facts without emotional involvement would consider ridiculous. The need for torte reform to address the liability issue has been recognized by many people. One reason for the lack of progress on the issue is the strong lobby against any form of torte reform by many lawyers. If a personal aviation vehicle is to be a widespread reality some method of avoiding or reducing the liability issue must be found.

There are several strategies for limiting vulnerability to liability lawsuits. One is to not sell and explicitly prohibit the selling of the vehicle in the United States. This method is not one we want to consider since it prevents the benefits of personal aviation from coming to the US. Another method is to manufacture outside the US. This method is not desirable either; while the benefits of personal aviation will come to the US the economic boost would not directly aid the US economy. A strategy that works well has been used in part by some companies is to aggressively litigate every case and never settle the case merely to end the litigation. This could be combined with the "deep pockets" approach very effectively where the company uses the fact that it has a large cash or credit reserve and just out spends and out lawyers any opposition until they can not afford to continue the case. The opposite strategy from the "deep pockets" approach is to have little or no net value in the company; rent all capital equipment and pay share holders and employees based on any profits immediately so there is no cash value for someone to claim against in a lawsuit.

Another way to avoiding problems with liability can be found by examining how liability is applied to car manufacturers. In most cases courts have been consistent on liability cases brought against automobile manufacturers based on failure to warn. The principle defense in failure to warn cases is based on the fact that the cited danger is open and obvious to most consumers. With a trial by a jury of your peers in these type cases perhaps the defense lawyers should have insisted on at least a few people with private pilot training and good safety records. This would be logical since private aircraft are not sold to be operated by the typical member of the general public, rather by a person who has received special training and authorization to operate this type of vehicle. Whether or not this approach would have helped the general aviation industry, or even been allowed by the courts, can not be easily judged. Studying the ramifications and legal technicalities related to this approach is best left to legal philosophers.

Determining the best mix of these and other methods to address the liability issue will be a critical factor in the success of any personal aviation system. If liability continues to be such an overwhelming obstacle no real chance exists for small craft general aviation to continue let alone expand into the future with a personal transportation system. Once an approach is chosen to keep the liability issue under control the technical design of the system can proceed.

Once the vehicle is purchased there are operational and life cycle costs that must be paid by the owner/operator. Many expenses for this type of vehicle can be compared with those currently incurred by automobile owners. The general issues related to parking, maintenance, fuel, licenses, and taxes are very similar. While the actual dollar amounts may be different, the sources and many of the methods for controlling these expenses are the same. Insurance may be cheaper because of the use of advanced electronics for health monitoring of vehicle systems and automatic flight control will greatly reduce the two dominant sources of accidents and other safety issues -- human error and equipment malfunction.

One of the keys to the widespread realization of personal aviation is controlling the cost. The detailed cost analysis for many life cycle aspects such as maintenance and fuel consumption is highly dependent on the exact vehicle design and other systemic parameters. The many vehicle systems that are common for both ground and flight vehicles when combined with the price of electronics suggests that it may be reasonable to build a personal aviation vehicle for the price of a sports car. The technical issues and problems are solvable but no matter how eloquent the resultant vehicle may be, without considering all the cost issues from the beginning the odds are against success on the scale being sought.

REFERENCES:

"Gama Targets Tax Credit, Liability", Aviation Week & Space Technology, February 8, 1993.

Gannon, Mary T., "An Automobile Manufacturer's Duty to Warn of Common Hazards", Federation of Insurance & Corporate Counsel Quarterly, Summer 1990.

Proctor, Paul, "Rising Liability Insurance Costs Affect General Aviation Companies", Aviation Week & Space Technology, July 28, 1986.

Proctor, Paul, "U. S. General Aviation Aircraft Manufacturing Slump Deepens", Aviation Week & Space Technology, January 19, 1987.

Shapiro, Stacy, "Tort Costs Hurt Aircraft Manufacturers", Business Insurance, June 10, 1991.

Shapiro, Stacy, "Aircraft Firms in Tailspin", Business Insurance, May 25, 1992.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY ***(Leave blank)***

2. REPORT DATE
December 1994

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
The Personal Aircraft--Status and Issues

5. FUNDING NUMBERS
WU 232-01-04-01

6. AUTHOR(S)
Scott G. Anders, Scott C. Asbury, Kenneth S. Brentner,
Dennis M. Bushnell, Christopher E. Glass, William T. Hodges,
Shelby J. Morris Jr., and Michael A. Scott

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-0001

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
NASA TM-109174

11. SUPPLEMENTARY NOTES
Scott G. Anders, Scott C. Asbury, Kenneth S. Brentner, Dennis M. Bushnell, Christopher E. Glass, William T. Hodges, Shelby J. Morris, Jr., and Michael A. Scott: Langley Research Center, Hampton, VA.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Unclssified-Unlimited

Subject Category 02

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

Paper summarizes the status of personal air transportation with emphasis upon VTOL and converticar capability. The former obviates the need for airport operations for personal aircraft whereas the latter provides both ground and air capability in the same vehicle. Fully automatic operation, ATC and navigation is stressed along with consideration of acoustic, environmental and cost issues.

14. SUBJECT TERMS
Aeronautical vehicles, transportation, VTOL, general aviation, personal aircraft.

15. NUMBER OF PAGES
126

16. PRICE CODE
A07

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT