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Hot Topics in General Aviation: Sustainable Aviation Gasoline Alternatives

By

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Acknowledgements & Dedication

A heartfelt thank you to the many members of the general aviation community including regulatory agencies, interest groups, manufacturers, experts, oil and fuel additive companies, and potential fuel formula holders. You were all accessible and extremely generous with your time and I would never have been able to draw any conclusions without your participation. This 30-year-old plus situation is a very complicated and likely expensive one for all stakeholders involved, and I have tried to present its many facets at a beginner pilot's level to be able to reach the novice: the future generation of pilots. The dynamics and risks at stake are not easily identifiable to the outsider, and even for those directly involved in the process, it seems possible that politics and competition to retain one's market positioning could have added to the complexity. That is to be expected on a free market and cannot be avoided. Regardless of why we are in the situation we are in, the fact remains that the leaded aviation gasoline that we have been using and available to us for decades and where high performance piston-powered spark-ignition engines have been designed to harness this fuel's potential is on the verge of extinction. Safety and reliability must not be compromised, yet speediness of approval in whichever format that certification comes about must take precedence. Time is of the essence and resources must be aligned to accommodate this next major shift in the general aviation industry. If a true drop-in fuel solution arises, amen, but it still appears to have the potential of costing the industry billions. Expediency in the standardization and certification process must adapt to this new environment in order to keep our planes and pilots flying, and thus continue to experience the positive economic impact these operations beget.

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Dean of the International School of Management, Dr. Mark Esposito, my thesis advisor who put in several precious hours of Skype chats with me. Thank you to Amy Fienga, friend and former colleague, for being an extra set of eyes to read this thesis and for correcting my mistakes. Lastly, and definitely not least, thank you to my very wonderfully supportive family for all their help, patience, and excellent humor. This is dedicated to you.

Glossary of Terms and Abbreviations

1. AGE 85 – Aviation-grade ethanol at 85 percent.
2. Air taxi – on-demand operations under FAR Part 135.
3. AKI – Anti-knock Index; the octane rating found at automotive gasoline pumps that takes the average of the RON and MON ratings.
4. AOPA – Aircraft Owners and Pilots Association; a 70-year-old association with approximately 415,000 members and a group that lobbies for general aviation interests (Dancy, 2010).
5. API – American Petroleum Institute; trade association covering all players in the oil and natural gas sectors with corporate members numbering 400 (*About API*, 2010).
6. A&P mechanic – a mechanic that works on aircraft and has passed an Airframe and Powerplant certificating exam under FAR Part 65.
7. Aromatics – a class of hydrocarbons that identifies its carbon and hydrogen arrangement; monoaromatics exist in aviation gasoline like benzene (Hemighaus, Boval, Bacha, Barnes, Franklin, Gibbs, Morris, et al., 2006, p. 85-86).
8. ASTM International – American Society for Testing and Materials International; sets the standards for petroleum and oil specifications.
9. Avgas – aviation gasoline; aircraft fuel for mainly piston-powered spark-ignition reciprocating engines that abide by ASTM D910 standards and Defence Standard 91-90 from the United Kingdom Ministry of Defence.
10. BA – Business Aviation; general aviation flights used for business purposes (National Business Aviation Association, 2010).
11. BDC – Bottom Dead Center; the furthermost position the piston travels when it is at the bottom of its stroke.

12. Binary fuel – a fuel that uses two main hydrocarbon components.
13. BTU – British Thermal Unit; a measure of a fuel's energy or heat content that can be translated into the amount of work it can perform in foot-pounds (De Remer, 1996, p. 49). Otherwise defined as "the quantity of heat required to raise the temperature of 1 lb of water 1 °F... equivalent to 778 ft-lbs of mechanical work." (De Remer, 1996, p. 49).
14. Carburetor – a device used in low performance aircraft to meter the correct amount of fuel into the entering air where the fuel and air are mixed and then travel to the engine via the intake manifold to be combusted (Hemighaus, et al., 2006, p. 70; Lombardo, 1999, p. 79). It uses a venturi system to create a vacuum within the carburetor to draw the fuel out of the carburetor bowl through a jet in the venturi throat where the fuel vaporizes and mixes with the air (Hemighaus, et al., 2006, p. 70; Lombardo, 1999, p. 79). The throttle controls the airflow entering the carburetor via the throttle valve and the mixture control lever manages the fuel flow within the limits of the set maximum rich and lean settings for the particular carburetor (Lombardo, 1999, p. 79).
15. Carburetor icing – this occurs when ice forms in the venturi of the carburetor or around the throttle valve causing engine roughness or even making the engine quit if the problem is not remedied. There are three types of carburetor icing and they depend on ambient air temperatures, humidity, and various physics properties such as loss of heat from vaporization and low pressure in the throat of the venturi (De Remer, 1996, p. 101-102). Thoroughly understanding the causes of this phenomenon and learning how to apply carburetor heat properly should eliminate or reduce this problem.
16. Cetane number – an important quality measure of diesel fuel that describes "the fuel's tendency to ignite" (C. Gonzalez, personal communication [telephone call], March 4, 2010).

17. Compression ignition – an internal combustion engine which does not use a spark plug to ignite the fuel-air mixture in the combustion chamber but uses the heat produced from compression to start ignition. Diesel engines work off this principle.
18. Compression ratio – "the ratio between the volume in a cylinder when the piston is at BDC to the volume of the cylinder when the piston is at TDC." (Hemighaus, et al., 2006, p. 68). The higher the compression ratio, the higher horsepower it should be able to produce (De Remer, 1996, p. 44). As compression ratio increases, cylinder head temperatures get hotter, and higher octane fuel becomes necessary for proper operations (De Remer, 1996, p. 50).
19. CRC – Coordinating Research Council; an "industry collaborative research program" (*Coordinating Research Council*, 2008) that for the purposes of this discussion organized two panels designated to find unleaded avgas alternatives that met octane requirements starting in the 1990s.
20. Def Stan 91-90 – The United Kingdom Ministry of Defence standard for aviation gasoline equivalent to ASTM D910.
21. Detonation – an abnormal combustion condition in which instantaneous burning of the remaining unburned fuel-and-air mixture in the combustion chamber ignites causing damage to the engine from excessive pressure and forces (Hemighaus, et al., 2006, p. 46- 47; U.S. Department of Transportation Federal Aviation Administration Flight Standards Service, 1980, p. 22).
22. Displacement – "the total swept volume of all cylinders." (Hemighaus, et al., 2006, p. 68). The swept volume is the region from TDC to BDC for a piston in a cylinder (Hemighaus, et al., 2006, p. 68).

23. Distillation profile – the range of temperatures at which the various hydrocarbons in a fuel blend boils or distills (Hemighaus, et al., 2006). Used "for the identification and purification of a compound." (*Distillation*, n.d.).
24. Duty cycle – a term used to describe what an engine was designed to do. More specifically, it is "the engine's typical expected operating range of rpm, power output and so on." (Mac McClellan, 2009).
25. EAA – Experimental Aircraft Association; association that is over 50 years old and has around 160,000 members who are dedicated aviation enthusiasts especially for homebuilt and sports aircraft and whose leaders lobby for GA (*Oshkosh 365*, 2010).
26. EIA – Energy Information Agency; a 30-year-old independent statistics and analysis agency attached to the U.S. Department of Energy to provide unbiased information on energy to Congress and the public (*About EIA*, n.d.).
27. Elastomeric – a polymer that has elastic, rubber-like characteristics (*Elastomeric*, 2010).
28. EPA – Environmental Protection Agency; U.S. agency granted power under the Clean Air Act of 1970 to protect human health and the environment (*History*, 2008; *Our mission*, n.d.).
29. ETBE – Ethyl Tertiary Butyl Ether; an oxygenate that boosts octane (*Q & A*, n.d.).
30. Ethylene dibromide – scavenging agent to rid engines of lead buildup creating a chemical called lead bromide which exits aircraft engines as exhaust, is toxic, and moreover has been banned since 1987 by Montreal Protocol (Malone, 2006).
31. Experimental – a class of aircraft that fall under FAR Part 21 certification mainly for amateur-built aircraft, exhibitions, racing, or test flights.
32. FAA – Federal Aviation Administration; regulating agency for aviation attached to the U.S. Department of Transportation.

33. FADEC – Full Authority Digital Engine Control; an electronic (EEC: electronic engine controller or ECU: engine control unit) unit that controls aircraft engine performance by adjusting spark-ignition timing in each cylinder, controlling fuel-air mixture, cylinder head temperatures, exhaust gas temperatures, manifold pressure, power, and starting aimed at maximizing efficiency for a given power setting (FADEC, 2010; Smith, 2007).
34. FAR – Federal Aviation Regulations; rules dictated by the FAA for aviation operations.
35. FAST – Future Avgas Strategy and Transition Plan; a GAMA group that should help industry implement unleaded avgas solutions (Rumizen, 2009). Comprised of GAMA, EAA, AOPA, NATA, and API with the participation of the EPA and FAA (anonymous, personal communication [telephone call], February 26, 2010).
36. FBO – Fixed Base Operator; service providers on airports often covering fuel, hangar space, maintenance, flight instruction, and charter operations.
37. FOE – Friends of the Earth; environmentalist group that appealed to the EPA to reconsider national ambient air quality standards for lead in 2006.
38. Fuel boil-off – a condition where a fuel's vapor pressure reaches atmospheric pressure at a given temperature and it boils (Hemighaus, et al., 2006, p. 49). Aviation gasoline is made up of different components, so when boil-off occurs, the lightest components evaporate first which results in a change in fuel composition (Hemighaus, et al., 2006, p. 49). Boil-off will occur as an airplane goes up in altitude where the atmospheric pressure decreases, and although pressure differentials between the pressure in the fuel tank and the atmosphere equalize relatively quickly thanks to the fuel vent, the fuel's temperature takes longer to decrease relative to the ambient air temperature (Hemighaus, et al., 2006, p. 49). The temperature decrease with the rise in altitude and

the cooling achieved from evaporation help cool down the fuel and allow it to reach a new equilibrium reducing fuel boil-off (Hemighaus, et al., 2006, p. 49).

39. Fuel injection – a system that delivers vaporized fuel via fuel injectors directly into the intake ports to be mixed with the air just prior to or at the moment of entering into the combustion chamber. Advantageous over carburetors for more even fuel distribution and no carburetor icing (Hemighaus, et al., 2006, p. 70). However, there tends to be a greater risk for vapor lock in these systems (Hemighaus, et al., 2006, p. 70).
40. G – Stands for GAMI in its G100UL fuel.
41. GA – General Aviation; all flights not designated as military or scheduled airline (National Business Aviation Association, 2010).
42. GAMA – General Aviation Manufacturers Association; an association that represents the interests of "over 60 of the world's leading manufacturers of fixed-wing general aviation airplanes, engines, avionics, and components." (*About: GAMA*, n.d.). It disseminates information on GA statistics and educates the public about the benefits of GA.
43. GAMI – General Aviation Modifications, Inc.; a company that has a pressure sensitive spark-ignition management system in the process of certification. They also recently unveiled their own unique 100 octane unleaded fuel blend called G100UL.
44. Heptane – a reference fuel compared against isooctane that has zero percent octane (Hemighaus, et al., 2006, p. 46).
45. High performance airplane – a plane which has an engine with more than 200 horsepower (*Title 14: Aeronautics and space*, 2010).
46. Horsepower – a measure of power to show how much work a machine can perform in a given amount of time. One horsepower is equivalent to 33,000 ft-lbs per minute (De Remer, 1996, p. 7).

47. Hydrocarbons – defined best in Chevron's *Aviation Fuels Technical Review*: "organic compounds composed entirely of carbon and hydrogen atoms." (Hemighaus, et al., 2006, p. 85). There are four main classes identified by the number and arrangement of carbon and hydrogen atoms they contain: "paraffins, olefins, napthenes, and aromatics." (Hemighaus, et al., 2006, p. 85). Parrafins and aromatics are elements found in the highest percentage in aviation gasoline (Hemighaus, et al., 2006, p. 85).
48. IA – Inspection Authority; a qualified A&P mechanic that can carry out specific aircraft inspections.
49. IAOPA – International Aircraft Owners and Pilots Association; it is "a nonprofit federation of 66 autonomous, nongovernmental, national general aviation organizations," (*International Aircraft Owners and Pilots Association*, 2010) that has been in activity for 35 years and represents more than 470,000 constituent members (*International Aircraft Owners and Pilots Association*, 2010).
50. Isooctane – a reference fuel compared against normal heptane that has 100 percent octane (Hemighaus, et al., 2006, p. 46).
51. Lead bromide – toxin that exits aircraft engines when ethylene dibromide, a scavenging agent, combines with tetra-ethyl lead so as not to leave lead deposits in the engine. Banned by 1987 Montreal Protocol (Malone, 2006).
52. Lean-mixture rating – octane rating tests of a fuel in a high air-to-fuel ratio similar to cruise flight (De Remer, 1996, p. 90; Hemighaus, et al., 2006, p. 46).
53. LL – low lead; referring to 100 low lead aviation gasoline which is colored blue and contains about two grams of lead per gallon. It is called low lead because it has half as much lead per gallon as 100 octane fuel, but compared to automotive gasoline when it was leaded, it contains twice as much (B. Visser, personal communication [telephone interview], February 19, 2010).

54. LSA – Light Sport Aircraft; a "new" class of aircraft designated since 2005 that cannot weigh more than 1320 pounds on takeoff (or 1430 pounds if the aircraft is used on water), go faster than 120 knots, have a stall speed no greater than 45 knots, seats two people, single-engine reciprocating, non-pressurized, and fixed gear unless the aircraft is used for water (Smith & Buchanan, 2008).
55. Magneto – self-contained ignition system that is independent from the electrical system of the airplane (De Remer, 1996, p. 221). There are two on piston-powered reciprocating engines today and each are connected to one spark plug each per cylinder.
56. Mixture – an aircraft engine control that allows the pilot to manually set the fuel-air mixture going to the engine.
57. Mogas – pilots' jargon for automotive gasoline used in aircraft and follows ASTM D4814.
58. MON – Motor Octane Number; a laboratory test with a high load configuration to determine the amount of octane in a fuel and its value is always less than RON (Barber, R., Carabell, K., Freel, J., Fuentes-Afflick, P., Gibbs, L., Gooch, H., et al., 1996, p. 5).
59. MTBE – Methyl Tertiary Butyl Ether; a cheap oxygenate that boosts octane that has been banned in some U.S. states due to a history of ground water contamination (*Fuel ethers*, n.d.). It is not classified as a human carcinogen by the EPA or in the EU although it is on the EPA's contaminant candidate list (*Fuel ethers,* n.d.; *Overview*, 2008). The Blue Ribbon Panel designated by the EPA to study the benefits of oxygenates and provide recommendations on their use, decided MTBE should be phased out as an oxygenate in the U.S. in 2000 (Blue Ribbon Panel, 1999).

60. NAAQS – National Ambient Air Quality Standards; standards for air quality mandated by the EPA.
61. Napthenes – one of the classes of hydrocarbons that occur at “less than one percent” (Hemighaus, et. al., 2006, p. 85) of avgas, but are major components for jet fuel (Hemighaus, et. al., 2006, p. 85).
62. NATA – National Air Transportation Association; provides national certifying safety seminars for aircraft fuel servicing and more.
63. NBAA – National Business Aviation Association; an association that serves the needs of the business aviation community in the U.S.
64. NEI – National Emissions Inventory; collects air quality data for the EPA.
65. NFPA – National Fire Protection Association; U.S. organization that sets standards for aircraft fuel servicing.
66. Nozzle – a tube through which fluids or gases flow. In the case of a carburetor, the venturi is a nozzle that is convergent, then divergent, and has a throat in-between the two ends.
67. Octane – determined to be the most important parameter in an aviation fuel for safe and reliable operations as it provides anti-knocking characteristics (Ciurczak, 2006). It is the measure of the volume percentage of two reference fuels called normal heptane and isooctane (Hemighaus, et. al., 2006, p. 46).
68. OEM – Original Equipment Manufacturer; term used when speaking of any part of a plane (for example the engine, propeller, or the airframe) that was originally designed, manufactured, and then approved for use by regulatory agencies.
69. Olefins – one of the classes of hydrocarbons not usually found in either avgas or jet fuel (Hemighaus, et. al., 2006, p. 85). Less desirable in avgas or jet fuel as they cause gumming of the fuel (Hemighaus, et. al., 2006, p. 66).

70. 100 – One hundred octane leaded aviation gasoline with about four grams of lead per gallon of fuel and is green in color. No longer in great circulation as it has virtually been replaced by its lower leaded counterpart: 100LL.

71. 100LL – One hundred octane low lead aviation gasoline that has around two grams of lead per gallon of fuel and is blue in color.

72. Paraffins – one of the classes of hydrocarbons that are a major component in both avgas and jet fuel, isooctane being an example of this type of constituent (Hemighaus, et. al., 2006, p. 85).

73. Part 135 – FAR regulations covering on-demand operations such as “air taxi, charter, and aero-medical” (GAMA, 2008, p. 27) services.

74. Performance Number – the measure of octane in a fuel when it is above 100. It is a mix of isooctane and tetraethyl lead (Hemighaus, et al., 2006, p. 46).

75. Pipeline – the most economical method of transporting a finished petroleum product (Trench, 2001, p. 2-3). This cannot be used for avgas as the lead content could contaminate other products that pass through the pipeline afterwards.

76. PMA – Parts Manufacturer Approval; authorization from the FAA for a company to manufacture parts.

77. Power – a measure of how much work can be performed over a period of time: it is the “rate of doing work.” (De Remer, 1996, p. 7). It is expressed in foot-pounds per minute (horsepower) or in watts (joules per second) (De Remer, 1996, p. 7-8). The conversion is the following: “1 hp = 746 watts” (De Remer, 1996, p. 7).

78. Preignition – an abnormal combustion condition in which hot spots in the cylinder head cause ignition prior to proper timing and results in major damage to the engine to the point of complete loss of power (Hemighaus, et al., 2006, p. 70; U.S. Department

of Transportation Federal Aviation Administration Flight Standards Service, 1980, p. 22).

79. Reduction gearbox – mechanical method which uses sets of gears to reduce the rotations per minute engine output to a range acceptable for propellers (Bertorelli, 2009d).
80. Refiner – a branded oil company or broker that usually extends other services including additional insurance coverage, credit card loyalty card systems, and marketing support. They are not necessarily integrated with refineries, although in 2002, 78 percent of refiners in the U.S. were so (Kleit, 2003, p. 13).
81. Refinery – the production facility where crude oil is processed into a finished product. Not necessarily vertically integrated with the companies that sell their product although 78 percent were in the U.S. in 2002 (Kleit, 2003, p. 13).
82. Reid Vapor Pressure (RVP) – a measure of fuel volatility expressed in pounds per square inch (psi). Aviation gasoline specifications require its RVP to be from 5.5 to 7 psi maximum (T. Petersen, personal communication [telephone call], February 19, 2010). In comparison, automotive gasoline's RVP can be from 7 to 15 psi (T. Petersen, personal communication [telephone call], February 19, 2010). The higher the RVP, the more volatile it is as it evaporates more readily and can thus be ignited more quickly.
83. Rich-mixture rating – octane rating tests of a fuel in a high fuel-to-air ratio similar to a takeoff mode (De Remer, 1996, p. 90; Hemighaus, et al., 2006, p. 46).
84. RON – Research Octane Number; a laboratory test with a low load configuration to determine the amount of octane in a fuel (Barber, et al., 1996, p. 5).

85. Service ceiling – "the altitude at which the airplane is unable to climb at a rate greater than 100 feet per minute." (U.S. Department of Transportation Federal Aviation Administration Flight Standards Service, 1980, p. 309).
86. SF – Abbreviation for Swift Fuels in the name of their 100SF octane unleaded fuel.
87. Spark-ignition – an internal combustion engine that uses (a) spark plug(s) to ignite the fuel-air mixture in the combustion chamber.
88. STC – Supplemental Type Certificate; an official document called a Type Certificate from the FAA authorizing an aircraft to be modified from its original design (*Supplemental type certificate*, 2008).
89. Stoichiometric – a balanced chemical mixture in which all the air and all the fuel are used up (De Remer, 1996, p. 85-86; Hemighaus, et al., 2006, p. 41). For small aircraft engines it is "a ratio of fifteen pounds of air to one pound of gasoline" (De Remer, 1996, p. 85).
90. TAME – Tertiary-amyl-methyl-ether; an ether-based oxygenate that boosts a fuel's octane (*Q & A*, n.d.).
91. TDC – Top Dead Center; the uppermost position the piston travels in the cylinder.
92. Terminal – a key distribution point in the supply chain of a finished petroleum product (Trench, 2001, p. 15). It may be connected to the refinery or it may be at the end of a pipeline at the point of service or on a fuel farm where products may be blended and then shipped via truck, barge, or rail car (Trench, 2001, p. 15). Terminals may or may not be owned and controlled by integrated refiners (Kleit, 2003; Trench, 2001, p. 15).
93. Tetraethyl lead – toxic yet cheap and effective octane boosting fuel additive found in aviation gasoline.
94. Throttle – an aircraft engine control that sets the power level. It either controls the volume of air entering the cylinder heads if the aircraft is fuel-injected or it controls

the air entering the carburetor where it mixes with the fuel and then travels to the cylinder heads to be combusted.

95. Turbine engines – engines that produce "power by the force of reaction." (Otis, 1997, p. 12).
96. Turbocharge – the act of using the exhaust gases on a normally air aspirated piston engine to drive a compressor that adds more air to the intake manifold so that an engine can create more power without increasing the size (or the weight) of its powerplant (Knuteson, 1999).
97. Turbojet – an engine that uses a "compressor, combustor, and turbine" (Otis, 1997, p. 14) to produce power by means "of reaction to the flow of hot gases." (Otis, 1997, p. 14).
98. Turbo-normalize – the same idea behind turbo charging only with the intention of maintaining the power output of the engine at sea level pressure rather than boosting the power of the engine as with turbo charging (Knuteson, 1999).
99. Turboprop – a "turbine engine with a propeller" (Otis, 1997, p. 15).
100. Type certificate – authorization from the FAA after validating tests that a part, engine, airframe, etc., have approved safe and reliable operating characteristics and performance criteria.
101. UADG – Unleaded Avgas Development Group; name of the panel on the CRC of "60 members from 40 different organizations including AOPA, EAA, Cessna, and the FAA." (*The future*, 2008).
102. UL – unleaded.
103. Valve – on a reciprocating engine, there are usually only two per cylinder head. One serves for induction and opens during the intake stroke of a four-stroke piston-powered reciprocating engine. The other is the exhaust valve that allows combusted

gases to exit the combustion chamber (a.k.a. cylinder head) during the exhaust stroke. Due to exposure to the high temperatures from the exhaust gases, the exhaust valve is made from and treated with sturdier, higher temperature-resistant materials than the intake valves (De Remer, 1996, p. 31).

104. Valve Seat – best described by Dr. De Remer in his book *Aircraft Systems for Pilots* (1996): “The valve seats are circular rings of hardened metal which protect the relatively soft metal of the cylinder head from the hammering action of the valves and from the exhaust gases.” (p. 29).

105. Valve Seat Recession (VSR) – an occurrence in which the valve travels beyond its seat into the cylinder head usually because the valve and valve seat are either not lubricated enough to avoid deteriorating each other, the metal alloys the valve and seat are made of are too soft, and/or due to normal wear and tear for the life of the valve and seat. Although today’s engines use harder valves and seats as compared to pre-1950s models (*Engine overhaul*, 1996), it is still recommended by OEMs to break-in newly overhauled engines using leaded avgas to properly lubricate the valves and seats and avoid VSR (*Engine overhaul*, 1996; S. Johnson, A&P and IA mechanic at Wisconsin Aviation, personal communication [telephone call], February 2, 2010).

106. Vapor Lock – evaporation of fuel in the fuel lines because they are too hot causing a disruption in fuel flow and resulting in possible fuel starvation that stops the engine. Occurrence that is especially dangerous while in flight.

107. Venturi – a nozzle that is convergent and then divergent. Its shape is what creates a low pressure area at the throat that speeds up the flow of the fluids going through it. A venturi system is found in carburetors to draw out fuel and vaporize it in the throat of the venturi so that fuel and air can mix and then be combusted in the engine.

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Executive Summary

Background

In the 1910's and 1920's after much experimenting with various fuel formulations, a special metal additive was introduced that provided anti-knock resistance that would enable larger and more technologically advanced engines to exhibit better performance (Kovarik, 1994/1999). Engine and by extension aircraft manufacturers during these early stages in both motorized automotive and aviation history realized that power and speed were limited, but they didn't exactly comprehend why (Kovarik, 1994/1999). It was also not known what caused the damaging knocking noise the engines made and was thus mistakenly attributed to electric motor starters or to heat absorption difficulties in engines with too high of compression ratios (Kovarik, 1994/1999). A petrol researcher named Charles F. Kettering and his assistant Thomas Midgley, and later Midgley's colleague Thomas Boyd, did about ten years of research on various fuel formulations and additives to both address the pinging noises heard in engines and to find a way to elongate the petroleum crude oil reserves (Kovarik, 1994/1999). Shortly after its discovery, tetra-ethyl lead became "'Kettering's magic anti-knock fluid'" (Kovarik, 1994/1999) that would provide the anti-knock margin necessary for engines to be designed both more efficiently to burn the fuel more fully in the combustion chambers and to generate more horsepower (Kovarik, 1994/1999). Lead was added to lower quality petroleum in low percentage volumes and this in combination with more effective combustion in the engines was recognized as an effective method for stretching the usage of refined crude oil products to help address oil shortage issues (Kovarik, 1994/1999). Without going too much into detail about its advantages over other fuel additives to reduce knock, tetra-ethyl lead did not have a high freezing point, did not gum while in storage, did not lower the overall energy content or BTUs, and very little of it was needed to provide the benefits it was designed to deliver (Kovarik, 1994/1999). Tetra-ethyl lead did attack parts of the engine if too much was left behind after combustion, thus the need to use a scavenger such as bromide which achieved market dominance to meet this purpose (Kovarik, 1994/1999). Overall, tetra-ethyl lead became the low percentage additive of choice to help alleviate demands on oil reserves and to prevent knock even though health concerns over its manipulation had already been brought to the public's attention from its onset (Kovarik, 1994/1999).

In the 1940s, turbine technology started rapidly surpassing its piston counterparts with the birth of the modern jet engine (Otis, 1997). These engines could use aviation gasoline (avgas), but only in the case of an "emergency alternate" (Otis, 1997, p. 262) as jet engines react more properly with kerosene or jet fuel without gasoline (Otis, 1997, p. 261). As jet powered aircraft took precedence on the market, particularly in military operations, demand for leaded avgas declined dramatically. Where once there were very precise fuel grades from 73 octane to 145, in approximately a 20-year period, roughly three main grades of avgas remained: 80/87, 91/98, and 100/130 (Hemighaus, et al., 2006, p. 43-44). The quantity of lead in each fuel varied with very little on the bottom of the scale at around 0.5 grams per gallon to more than four grams per gallon on the top end (De Remer, 1996, p. 90). By 1964, leaded avgas fuel grades' continuing disappearance caused concern among piston aircraft owners and operators, in particular the 11-year-old interest group called the Experimental Aircraft Association (EAA) (*Who we are*, 2010; *About us*, 2010). EAA began developing a test program to allow for lower octane rated aircraft engines to be able to consume either ethanol or premium grade unleaded automotive gasoline called mogas the latter for which they succeeded in receiving authorization for its use from the Federal Aviation Administration (FAA) in a Cessna 150 with a Continental 0-200 engine in 1982 via a Supplemental Type Certificate (STC) (*EAA aviation fuels*, 2010). Petersen Aviation, a private agriculture airplane spraying entity, followed suit creating 150 different mogas STCs in just ten years from the winter of 1982 to 1993 (T. Petersen, personal communication [telephone call], February 19, 2010).

In the 1970s, 100/130 octane fuel came under scrutiny since it had a high lead content at around four grams of lead per gallon - four times more lead than that found in leaded automotive gasoline (Hjelmberg, 2004; anonymous, personal communication [telephone call], February 25, 2010). Lead in automotive gasoline damaged the catalytic converters which were used to reduce exhaust emissions in motor vehicles and thus smog, resulting in its progressive phase out from the 1970s to its final ban on January 1, 1996 (*Petition requesting*, 2007). The United States Environmental Protection Agency (EPA) allowed for off-road vehicles and engines, marine crafts, and airplanes to continue using leaded fuels in disregard of the Clean Air Act of 1990 until further testing would allow for them to find an unleaded solution that would not affect safety and have an overbearing negative impact on the economy (Ciurczak, 2006; *Petition for rulemaking*, 2006). The aviation community responded to this Act by creating two committees in an organization tasked with research and development for all types of fuels and gasolines for various sectors, the Coordinated Research Council (CRC), called the Unleaded Avgas Development Group (UADG) and the Aviation Engine Octane Rating Panel comprised of 60 different members from 40 organizations (Ciurczak, 2006; Coordinating Research Council, 2008). Just prior to these panels' creation, avgas 80/87 octane fuel's availability began to be compromised, resulting in its discontinuance in the early to mid-1980s (U.S. Department of Transportation Federal Aviation Administration, 1984). State's legislature required empty, abandoned, and especially underground fuel tanks to be removed and disposed of to comply with environmental and health regulations or at least abate risks that could affect them (anonymous, personal communication [telephone call], February 25, 2010). The 80/87 fuel tanks were removed, as were any other unneeded tanks that had been used for various grades of leaded avgas, and the general aviation market began seeing just one tank and grade for sale at Fixed Base Operators (FBOs) – 100 low lead (LL) as was intended, according to Hemighaus, et al. (2006, p. 44).

This blue-dyed fuel contains half the lead its green-dyed near equivalent at around two grams of lead per gallon. As 100LL in all intents and purposes except for lead content complied with the American Society for Testing and Materials (ASTM) specification D910 for aviation fuels, the FAA granted an across the board approval for all engines and airframes to use this fuel instead of the 100/130 grade all their type certification had originally been tested on (multiple anonymous contributors, personal communication [telephone calls], February 22 to March 1, 2010). Some large radial and very high performance engines had previously carried out the necessary testing and certification to be de-rated from 115/145 grade to the 100/130 grade, so that operations on the lower leaded 100 octane fuel did not negatively impact them considerably much more than when they had started using 100/130 (anonymous, personal communication [telephone call], February 26, 2010). The aircraft and engines that could not support the additional reduction in octane boost became displaced, meaning they found other markets that allowed for the use of more heavily leaded fuels (C. Gonzalez, personal communication [telephone call], March 4, 2010).

Current Situation

Fast forward to the present and the Friends of the Earth's (FOE) petition to the EPA to either carry out further ambient air quality testing to determine whether the remaining sources of leaded emissions were hazardous enough to discontinue or reduce their operations because of their impact on human health and safety, or to simply accept that any source of lead needed to be eliminated based on prior health impact studies and to end their operations (*Petition for rulemaking*, 2006). The EPA has acted on this petition and has been coordinating with the general aviation industry to try and find an alternative propellant. However, having completed more than fifteen years of research, the CRC concluded that after laboratory testing more than 200 different blends of unleaded aviation gasoline, 75 of which were performed in full-scale engine tests, that there is no clear drop-in 100 octane unleaded fuel that would allow for safe and reliable operations the same way leaded 100 octane fuel does without further polluting the environment with even more lethal additives (anonymous, personal communication [telephone call], February 23, 2010; Coordinating Research Council, 2008). Despite these findings, in October of 2008 the EPA announced a reduction in the National Ambient Air Quality Standards (NAAQS) for lead from 1.5 milligrams per cubic meter to 0.15 milligrams per cubic meter to be enforced in full by January 1, 2017 (*Fact sheet*, 2008). On December 30, 2009, the EPA announced a further reduction in lead emissions monitoring from potential sources to a half a ton per year from the previous one ton per year in a notice of proposed rulemaking (Environmental Protection Agency: Revisions to Lead Ambient Air Monitoring Requirements Proposed Rules, 2009). The general aviation community has not opposed this ruling and therefore has not submitted any remarks during the comment period even though an additional 50 airports will have to be monitored from the original five that fell into the one ton per year emissions criteria (anonymous, personal communication [telephone call], February 26, 2010). Keeping things in perspective, 55 airports are only about one percent of the general aviation paved public airports in use in the United States (General Aviation Manufacturers Association, 2009). Once the air quality testing is completed, the EPA will decide whether the sources either cause or contribute to the non-attainment NAAQS for lead and whether operational practices will have to be imposed at these airports (two anonymous contributors, personal communication [telephone calls], February 25 & 26, 2010).

Industry continues to try to find other solutions and substitute formulas, yet standardization, certification, and convincing companies to produce and distribute alternate fuels will be the greatest and most expensive hiccoughs the community will be forced to address in the next few years. It is clear that the general aviation sector cannot continue to exist in its current form producing engines and aircraft certified for a fuel that industry leaders accept will soon disappear, and therefore must act in a manner which will set the foundations for a sustainable GA future.

ASTM Standards

Developing and introducing new types of fuels is not a quick process as it requires much study, testing, and ultimately approval from the ASTM board. This 112-year-old organization has several standard setting committees including the Petroleum Products and Lubricants section that would cover aviation gasoline (*About ASTM*, 2010). It is a consensus-driven member society made up of any stakeholders “with a material interest” (*About ASTM*, 2010) like oil companies, additive producers, original equipment manufacturers (OEM), STC providers, and any other concerned participants (Hemighaus, et al., 2006, p. 54). They derive aviation fuel grade specifications such as the D910. ASTM standards are internationally accepted as is their U.K. equivalent for aviation fuels called the United Kingdom Defence Standards where aviation fuel grades fall under Def Stan 910 (Hemighaus, et al., 2006, p. 54). The D910 specification sheet defines the fuel’s performance properties as well as permitting certain additives or making other items mandatory, like it is the case with tetra-ethyl lead content (Hemighaus, et al., 2006, p. 54). The D910 does not require that an aviation fuel have a minimum amount of lead, but it does cap its maximum content depending on the grade (Hemighaus, et al., 2006, p. 55). If a fuel formula is proposed to the board and it does not follow D910 to the letter, its members then decide which types and how long certain tests must be performed in order to ensure consistent performance characteristics (two anonymous contributors, personal communication [telephone calls], February 24 & 26, 2010). The testing required to accumulate the necessary data in order for the board to either approve a fuel to the D910 standards or to create a new set, depends entirely upon the degree to which the proposed fuel deviates from the existing standard and how much additional data the ASTM members demand on the proposed fuel's unique properties (anonymous, personal communication [telephone call], February 26, 2010; L. Hjelmberg, CEO Hjelmco Oil, Inc., personal communication [telephone call & email], January 29 & February 24, 2010). Pooling responses from the various phone interviews conducted on this subject, the ASTM specification process could take anywhere from one to six years depending on the fuel's composition and the consensus the board arrives at for the testing procedures (multiple anonymous correspondents, personal communication [telephone interviews], January 29 – March 1, 2010).

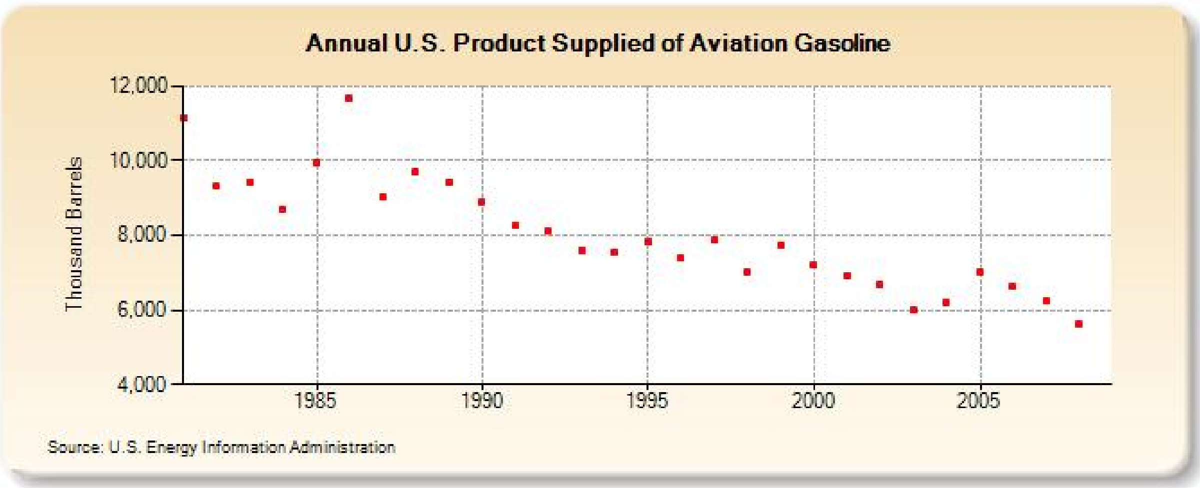
FAA Certification

The FAA does not certify fuel grades; it allows the ASTM board to carry out this function (anonymous, personal communication [telephone call], February 24, 2010). Although some have alluded to the fact that the FAA could take over fuel certification as it is apparently allowed to do so under its agency's mandate (anonymous, personal communication [telephone call], February 25, 2010), it probably does not due to lack of manpower to carry out these additional functions and because the ASTM board system is an accepted and proven process for regulating fuel composition and performance specifications. As the FAA is positioned to approve the operational performance limitations of a part or machine manufactured by an OEM or company designated under a Parts Manufacturer Agreement (PMA), any modification to the operating and performance measures documented during a product's type certification require additional approval in a format accepted by the Administrator (two anonymous and separate contributors, personal communication [telephone calls], February 24 & 26, 2010). This is how the FAA indirectly controls fuel certification, as a new or modified formula from that which is already endorsed by the ASTM board and other than that under which the original product was type certificated, would require further testing to verify whether the operational performance characteristics have changed (two anonymous and separate contributors, personal communication [telephone calls], February 24 & 26, 2010). Changes to performance limitations may include higher fuel flow rates, reduced range and endurance, longer takeoff distances especially under high altitudes and hot temperatures, reduced durability of a part, changes to exhaust gas temperature and cylinder head temperature normal operating ranges, etc. (anonymous, personal communication [telephone call], February 26, 2010). The type of testing required to determine changes to operational performance limitations could go from a standard 150-hour endurance and climbing flight tests with a complete breakdown of the engine or fuel system, to full lifecycle testing of a product’s proposed durability such as 2,000 hours for an engine to reach its time before overhaul (TBO) (two anonymous and separate contributors, personal communication [telephone calls], February 24 & 26, 2010). Each test must be done for each engine and aircraft model and its funding is entirely private as the FAA’s role is to approve the data from the testing and not to carry it out themselves (anonymous, personal communication [telephone call], February 24, 2010). This is done after a proposed fuel has been approved by the ASTM board and a specification sheet has been derived for it. Therefore, the potential for any change from the status quo could potentially cost the industry and its users billions of dollars (anonymous, personal communication [telephone call], February 24, 2010).

Production and Distribution

Aside from deriving appropriate fuel standards and certifying all parts whose operating performance limitations depend on it, production and distribution are key components in the general aviation picture. Each element depends upon the other and, so long as there is demand for a refiner’s products, production and distribution should continue (anonymous, oil refiner salesperson, personal communication [telephone call], February 2010). Members of the GA community recognize that avgas is in fact a “boutique fuel,” (multiple anonymous correspondents, personal communication [telephone interviews], January 29 – March 1, 2010; *Other fuels*, 2009), and it risks carrying an even more expensive specialized price if volumes continue in its current descent. Avgas production equated to approximately 235 million gallons in 2008, and these numbers should decline with 2009 data showing 219 million gallons as published on the U.S. Energy Information Administration's (EIA) website (anonymous, personal communication [telephone call], February 25, 2010; *Supply and disposition*, 2009). Aviation gasoline production and consumption have been dropping since the early 1980s as shown in the EIA's *Petroleum Navigator: Annual U.S. Product Supplied of Aviation Gasoline* table in Figure 1 (*Petroleum navigator*, 2009).

Figure 1. "Petroleum Navigator: Annual U.S. Product Supplied of Aviation Gasoline"



Note. From the U.S. Energy Information Administration's website, *Petroleum Navigator: Annual U.S. Product Supplied of Aviation Gasoline*, 2009. Available on the public domain. Permission not requested.

The latest decline is attributed to the difficult economic context the U.S. is recovering from and the high fuel prices, that according to Dave Hirschman, Senior Editor of AOPA Pilot magazine, in an interview he hosted during the Aircraft Operators and Pilots Association (AOPA) Summit in November 2009 has had the most negative impact on GA:

> …a couple summers ago when the oil prices spiked and avgas prices were five to six dollars a gallon to seven dollars a gallon in some places… the flying activity stopped, essentially. It had a more immediate and harmful effect on GA flying than any regulatory change there's ever been.

As avgas by definition is a boutique fuel since it has "a specialized fuel formulation that is unique to a particular market… and that cannot be obtained from other markets in the same regional distribution system," (*Other fuels*, 2009) its production volume would probably need to decrease even more before its prices reached comparable levels with others in its class. For example, car racing fuels that require similar octane levels as that which is found in avgas, have much higher prices to the consumer starting at seven dollars a gallon to 27 dollars a gallon depending on the blend (M. Miller, Head of racing fuels at Sunoco, personal communication [telephone interview], January, 2010). Car racing fuel's production volumes are still much lower than avgas' at around 10 to 20 million gallons per year (M. Miller, Head of racing fuels at Sunoco, personal communication [telephone interview], January, 2010) compared to avgas' 235 million gallons 2008 figures (*Supply and disposition*, 2009). Keeping an avgas replacement's price point as low as possible is crucial to maintaining demand and thus higher production and consumption volumes to help position it away from comparative specialized fuel prices in its classification.

Other factors must be taken into consideration besides volume when pricing the fuel: price of tetra-ethyl lead; price of other additives such as toluene, butane, isopentane, ethylene dibromide, dye, and any other additive allowed by the D910 specification that a refinery may want to include (Hemighaus, et al., p. , 2006); size of the refinery and thus the number of crude oil runs done in a year to extract the comparatively small percentage of light alkylates needed for avgas which also compete for automotive gasoline production (Hemighaus, et al., p. 66-67, 2006; L. Hjelmberg, CEO Hjelmco Oil, personal communication [email], February

19, 2010); method and frequency of distribution; the cost of complementary services provided by the refiner or broker to the retailer; taxes; and any other extra costs not included in this non-exhaustive list. Much of this information is proprietary and thus quite difficult for an outsider to put a price tag on without being privy to the details concerning these elements. Current day avgas prices vary from out of the refinery at about $2.00 a gallon to a wholesale price of $4.00 per gallon for a shipment of 1,000 gallons for a consumer (anonymous, personal communication [telephone call] February 8, 2010; G. Braly, Co-founder General Aviation Modifications, Inc., personal communication [email], February 24, 2010). Wholesale prices depend on the quantity and frequency of deliveries plus the related transportation costs, state and federal taxes, the latter value which is around 19.4 cents on the gallon (*Fuel tax refunds*, 2003).

Today's aviation gasoline cannot benefit from the relatively lower costing pipeline infrastructure as the lead may contaminate other products that would pass through after it besides becoming contaminated itself with particulates, water, or lower quality gasoline blends whose interface could mix into the aviation gasoline (Trend, 2001); thus one of the reasons why this fuel is slightly more expensive than jet or mogas. Transportation methods can be categorized by price with truck being the most expensive followed by rail and barge (Trench, 2001, p. 2-3). Another reason is that holding tanks and transportation containers must be dedicated specifically to the use of leaded avgas, again due to contamination risks. One might hypothesize that blending of the toxic elements for avgas could be done at terminals so that the fuel could utilize the pipeline structure. This method, however, is not very practical for refiners as it multiplies the amount of risk associated with lead handling including additional opportunities for spills (*What drives*, n.d.). An additional cost lies in the cleaning and purging each refinery must accomplish after each run of leaded avgas production in order to ensure no cross-contamination with any other petroleum products. How much all of these costs amount to is not easily verifiable, but one source estimated leaded avgas transportation to equal three dollars a mile (Ells, 2006, p. 1). If an unleaded 100 octane fuel formula is approved and it doesn't contain any other toxic components that could contaminate fuels in the production and transportation supply chain, some of the costs related to the issues just listed may be alleviated in the future.

Impact on General Aviation

What is clear from this exercise is that industry members are in disagreement as to the best solution to pursue in order to cover the largest proportion of the existing GA fleet with a new fuel formula without the lead content which would simultaneously ensure a sustainable future that manufacturers could design for and fuel production oil companies would agree to secure. Some conclude that a two-fuel system is the best solution since at least 70 percent of the fleet would be covered with either a lower-octane unleaded aviation gasoline version or mogas, leaving the minority to continue consuming leaded avgas at lower volumes, perhaps appeasing the EPA. Others believe the economics are not there to be able to support a two-fuel system as avgas consumption and production volumes are so low today compared to 20 years ago that refiners and refineries will not want to produce even less avgas unless they were able to increase their margins correspondingly, plus today there is normally only one tank available for an aviation gasoline at FBOs. The best solution would be to find a high octane lead-free drop-in substitute, but in fact technically it is still not proven to exist although certain new fuel formulations are in testing phases today. Even if the new fuel formulations prove to work appropriately, there is still the ASTM certification and FAA type certification loop holes to jump through which will both take years to implement and potentially millions to billions of dollars of testing and certificating. This is because any new fuel formula not already exactly like the current ASTM D910 will logically have dissimilar properties from this specification which will lead to differing operations characteristics and performance data that someone will have to accumulate and pay for before delivering it to the FAA for approval. Infrastructure for production and distribution must not be ignored either, for if a new fuel formulation uses bio inputs, processing is not the same as with crude oil and the set-up costs linked to new production facilities will need to be financed.

To address these issues and assist the industry in moving ahead on the best approach for all players is the Future Avgas Strategy and Transition (FAST) committee headed by GAMA representing its manufacturers, with members from the operators' side, the fuel producers, and the EPA and FAA (anonymous, personal communication [telephone call], February 26, 2010). It is quite clear that not everyone agrees on the next best step forward, but hopefully through GAMA's leadership and inclusion of all the stakeholders, the future fuel will be sustainable for more than the next 80 years.

The second section of part two of this paper enumerates a number of alternatives the GA industry could pursue to solve the avgas conundrum. A SWOT analysis is carried out for each using as much detail as possible and compiling both industry insights collected through informal telephone interviews of the most respected members in the general aviation community who have played an active role in equipping the industry with solutions and information readily available in popular general aviation media and on regulatory agency websites. From this more exhaustive list is derived a short list of possible venues industry could pursue in order to move forward on the avgas dilemma. The recommendations section further points to only a few logical, safe, reliable, and cost-effective sustainable avgas 100LL alternatives.

Option 1 – 100 Octane Unleaded "Drop-In Fuel" That Uses Current Production and Distribution Infrastructure

As there is no real drop-in 100 octane unleaded fuel that exists today, this option and the discussion that ensues is currently only hypothetical. The advantages to having a seamlessly implemented 100 octane unleaded fuel using current production and distribution infrastructure are numerous: it would keep the refiners and refineries happy as they would continue to sell a niche market product at the same volumes, the consumer would not ‘feel’ the pass-down effects of paying for any infrastructure set-up costs, the consumer would not have to pay for any engine modifications or hardware installations incurring acquisition costs for these so they could keep their flying hours up painlessly, and the industry would finally obtain a good corporate citizenship image for getting rid of the lead and being concerned about public health. The downside to the story could be the following: if the fuel formulation differs greatly from today’s D910, the ASTM specification process could be time-consuming and expensive; the FAA certification procedure could be equally lengthy and costly depending on operations performance data, but the data could likewise prove to be satisfactory and a blanket approval could then be issued. The costs accumulated in the specification and certification process would most likely be passed down to the consumer distributed among the price of engines, airframes, and the fuel itself. Maintenance projections running on this fuel could be altered, hopefully for the better, but it could go the other way too affecting inspection times and TBOs. As for production, no one knows what the price of the components would be and whether they would require expensive processes to make them, nor how much of those costs would go through to the consumer. For example, in the case of G100UL, George Braly in a video interview with Paul Bertorelli on Avweb, hints that the components in his fuel formulation are well-known by the industry, can be produced in refineries but they don’t currently do so (Bertorelli, 2010c). Lastly, as the fuel formulations and their components for this category are unknown, no one can attest to just how long the shelf life of these fuels would be. If they happen to be shorter than 100LL which lasts about a year (Visser, 2005), those costs would too be transmitted to production expenses and ultimately to the consumer at the pump.

Option 2 – 100 Octane Unleaded "Drop-In Fuel" That Creates New Production Facilities and a New Distribution Supply Chain

As in option one, this fuel does not exist and the following pros and cons list is an exercise in conjecture. The types of fuel formulas or additives that would fall into this category would be of the bio-derivative sort as producing fuel components from renewable feed stocks requires an entirely different production process and facility set-up to accommodate its creation. This could result in the possible loss of the current refiners support network FBOs enjoy today. The cost of implementing all new infrastructure, minus many of the FBO-owned tanks, refueling trucks, and pumps already on the airfield, would certainly show up at the pump price. Production costs related to the price of the fuel's components would ultimately find its way on the customers' bill as it would with any fuel, only bio-processes have been rumored to be more expensive probably due to the fact its pricing is based on smaller facilities with lower production runs that would need to be ramped up in order to enjoy economies of scale to reduce their price. As in the previous example, the shelf life of this product would need to be taken into consideration since it would find itself included on the list of costs. Durability of engine parts on this fuel would need to be confirmed including indications of any maintenance adjustments operators would need to make to their operations projections. Furthermore, choosing renewable feed stocks that would have the least impact on food displacement should also be taken into consideration. Backing up a little, these types of fuels would still need to go through the ASTM specification and FAA approval process and given the fact the fuel formulation is very nearly sure to have qualities not defined in the D910, it could be a long pricey road.

There would be an upside, of course. If this fuel were a drop-in solution, no engine modifications should be required for operators. The aircraft's engines wouldn't have to have any extra hardware installed to manage ignition timing or fuel flows to prevent detonation. As with hypothetical option one, getting the lead out positions GA users and industry under a positive corporate citizen limelight. Moreover, using a renewable energy source that is both more environmentally friendly and assists in meeting energy security and independence goals are two very positive points.

Option 3 – Certification of an Ultra Low Lead Content in 100LL Plus ETBE Retaining Current Production and Distribution Infrastructure

Option three includes the use of the existing standard D910 but without all of the lead, which is legal so long as it meets octane requirements that the baseline fuel could not do without some sort of additive. To reach octane levels while keeping a portion of the lead so as to retain some of the positive combustion properties lead provides, ETBE will be proposed as an oxygenate replacement. However, like its counterparts described in options one and two, there is no existing aviation fuel specification that allows for the use of ETBE as an octane booster, nor is there a separate ETBE specification. So, option three would also need to jump through the procedural hoops the same as the two options previously described. This fact brings a lot of criticism from industry members who feel investing in the testing for this formula only diverts attention and money away from long-term, fully unleaded solutions. Therefore, approach three could ultimately be thought of as being more expensive for industry overall. Likewise, industry members would have to be convinced that ETBE does not have a lower energy content that could affect various performance characteristics when using this additive. Still, the motivation behind such a method has solid reasoning too: it is a conservative, step-by-step, and safety-centric approach that allows for industry to gain experience with lower lead fuel blends without removing any previous infrastructure in case the new blends don't work (C. Gonzalez, personal communication [telephone call], March 4, 2010). Furthermore, if the ultra low lead fuel formulation does work, it could set the grounds for completely removing the lead (C. Gonzalez, personal communication [telephone call], March 4, 2010).

One might argue that the single lead providing facility will shut its doors if even more lead is taken off the market. When put to the question, Innospec, formerly Octel/Actel, asserts that even if the United States were to cut its lead use in half, it would still continue producing and distributing it to them (personal communication [telephone call], March 1, 2010). This is not to say that they do not think that they will one day discontinue their lead production; they know it is going to happen (anonymous, personal communication [telephone call], March 1, 2010). However, so long as there is a market for their product, they will continue its manufacture (anonymous, personal communication [telephone call], March 1, 2010).

The ETBE additive is derived from bio-components which would require infrastructure investment for production and distribution, and also raise concerns about possible food displacement from its culture much like in option two. Shelf life, maintenance changes and bottom-line costs related to them must be considered as well; then again, one could hypothesize that they would be less dissimilar from current day levels as a partial quantity of lead would remain in the fuel warding off microbial growth and gumming (Hemighaus, et al., 2006). Finally, and probably the most difficult potential obstacles this fuel might find are overcoming the negative public perceptions concerning oxygenates in the ether family as the MTBE ground contamination scandals are not so far back in U.S. history (Blue Ribbon Panel, 1999). As these problems took place primarily in California, and as California happens to be the state with the largest GA fleet (General Aviation Manufacturers Association, 2009, p. 34), they could be the biggest opponents to buy into using this fuel.

Option 4 – Production and Distribution of 94UL Causing Engines That Require 100 Octane to Either Be Tested on This Fuel and Be De-rated, or Requiring Them to Use a Hardware Solution to Keep from Detonating, or Forcing Them to Become Obsolete/Offering an Overhaul Option

Option four would put in place a lower octane unleaded fuel that essentially is 100LL but without the lead. It would probably find the quickest implementation if it creates market demand as it conforms to D910 except for the lead, and it would retain existing production and distribution infrastructure. The last reason would keep the refiners and refineries content, and likely preserve marketing support and other benefits for their retailers. An ASTM specification for 94UL is expected to come out in the summer of 2010. The 94UL fuel would not be able to cater to the entire GA fleet, but it could potentially meet the demands of roughly 90 percent of the engines on the market today (Misegades, 2010; multiple anonymous contributors, personal communication [telephone calls], February 8 to March 1, 2010). In addition, this strategy has already gained much industry support and engine manufacturers seem to be testing current engines for octane ratings, as well as designing future models that will be able to run on this fuel. Removing the lead revisits the corporate citizenship advantage as it makes the fuel more environmentally acceptable.

The disadvantages to this line of attack are that a portion of the GA fleet would have to find other alternatives to manage operating in a lower octane environment like with the purchase of spark-ignition management systems, FADEC, de-rating the engine via an STC, or purchasing a new engine certified for the new fuel and airframe, all of which can add up quickly. This raises concerns about the longevity of engines and parts, increased maintenance inspections, and ultimately safety as there is not yet enough data to draw these types of conclusions. The shelf life of this avgas that no longer contains its preserving lead additive could impact the price of the fuel as well. Lastly, as it was judiciously remarked by Mr.

Gonzalez, respected industry expert on the aviation gasoline matter, in a telephone interview, that removing the lead infrastructure would eliminate all opportunities for reverting back to this structure should an unleaded environment prove ineffective or unsafe (March 4, 2010).

Option 5 – A Two-Fuel System Using Any Combination of Unleaded Fuels and 100LL

This solution would require major investment in FBO infrastructure, which at approximately $100,000 per average-sized 12,000 gallon tank (two anonymous Fuel Tank Inc. & Garsite employees, personal communication [telephone calls], February, 2010), makes it difficult to get a ready return on investment, particularly for small structures. Depending on the grade of unleaded fuel used, related STCs or blanket FAA approvals for these fuels would need to be achieved. The unleaded fuels could have the potential of being cheaper as they maybe could utilize lower-cost transportation methods, a.k.a. pipelines. The reverse to this coin is that pipelines could expose aviation fuels to less stringent quality controls and fuel blending at the interface could take place (Trench, 2001), which might raise concerns among industry members about liability. The advantage to this type of system would be that if the infrastructure were put in place, 30 percent of the current leaded fuel consumption could be proportionally reduced with the positive impact that could bring on the environment. One begs the question as to whether the refiners and refineries would appreciate a corresponding drop in 100LL demand, further diminishing production with a fuel that represents only 0.2 percent of the total automotive supply (*Supply and disposition*, 2009; *U.S. product supplied,* 2010a). As most of the industry stakeholders aver, the economics for a two-fuel system are just not there (C. Gonzalez, personal communication [telephone call], March 4, 2010; L. Hjelmberg, CEO Hjelmco Oil, personal communication [telephone call], January 29, 2010; multiple anonymous contributors, personal communication [telephone calls], February 1 to March 10, 2010).

Option 6 – The Jet-A Consuming Retrofit Solution: Scrap the Avgas Engine, Find a Light Jet-A Capable Piston or Turbine One, and Ask the OEMs to Type Certificate It Into a Particular Aircraft Model

The last option selected from the list of 13 described in greater detail in section 2.2 of this paper, is one focused on using engines that can consume an entirely different fuel that does not suffer from the threat of extinction (Bertorelli, 2010c), is produced in much larger quantities than avgas at around 16 percent of total motor gasoline supply volume (*U.S. product supplied*, 2009a; *U.S. product supplied*, 2009b), requires no fuel specification standardization constraints since it has had one for years, and will soon be produced using bio and synthetic components making general aviation users automatic good corporate citizens concerned about public health safety and energy security and independence. What's more is that the piston versions tend to get longer ranges thanks to lower fuel burn despite the fact the fuel is a bit heavier than 100LL, and routine maintenance is lower than with its avgas-consuming piston equivalents (Bertorelli, 2010c).

Looking at the piston-driven diesel technology, it has its disadvantages: it's typically heavier than its spark-ignition equals due to more durable metallurgy to support the high pressures experienced within the combustion chamber, and it needs tough reduction gearboxes and robust pulse-dampening equipment to bring down the high engine RPMs to normal propeller operating speeds and protect the metal propellers (Bertorelli, 2010c). Also, as efficiency in the combustion chamber for piston-driven diesels is reliant on the ignition quality of its fuel called its cetane number, and as cetane numbers are not controlled in jet fuel specifications, this could lead to potential efficacy and safety issues for the use of these engines (C. Gonzalez, personal communication [telephone call], March 4, 2010). Turbine technology is fairly light and competes well against either piston categories. Turbines produce a lot of horsepower at between 300 to 500 shp for this class, so there needs to be the right aircraft model to put them in. Which leads to the last two points: diesel piston engines and small turbines need to be designed into more airframes through STCs or original type certificates to help increase their demand, raising production volumes that would help to reduce their inhibitive acquisition costs.

Recommendations

The general aviation industry is at the brink of a new era of innovation. Like when the Wright brothers initiated powered flight in 1903 and the rapid ascension of technological advancements and design innovations that that event produced all over the world thereafter (TED Talks, 2006), today there are real opportunities for the general aviation market to exploit existing knowledge discovered over years of engineering and testing to build the way towards a sustainable GA future. It is no longer a question of whether leaded aviation gasoline is hazardous for the environment (anonymous, personal communication [telephone call], March 1, 2010). It is an industry-wide recognized fact that the aviation gasoline that is pumped into the tanks in its current form will be discontinued in a not so distant future (C. Gonzalez, personal communication [telephone call], March 4, 2010; L. Hjelmberg, personal communication [telephone call], January 29, 2010; multiple anonymous contributors, personal communication [telephone calls], February 8 – March 1, 2010; T. Petersen, personal communication [telephone call], February 19, 2010; B. Visser, personal communication [telephone call], February 19, 2010). As many stakeholders involved in the research, development, and testing for finding an unleaded aviation gasoline agree that none of the options listed above are ‘silver bullet’ alternatives, the next best option should be chosen until time, experience, and moreover design features allow the industry to transfer progressively to a sustainable, possibly unleaded avgas solution. Much has been learned through the CRC testing achieved under the Aviation Engine Octane Rating and UDAG banners at the FAA’s William J. Hughes Technical Center, as well as at Cessna and other independent organizations, that now is the time to apply this knowledge to realize practical and realistic progress while focusing efforts on retaining the one stakeholder the entire industry is reliant upon: the customer. Industry must act in the pilots', the commercial operators', and society's best interests. This analysis points to accomplishing any of the first four options with a more practicable, less costly, and safety-centric method for the immediate future achieved through option three, while option six may be a possibility given airframe and engine manufacturers cooperate on this approach and jet fuel standards incorporate cetane specifications. Although one could argue that general aviation piston-powered reciprocating engines have reached the end of their product lifecycle, on the contrary, one must remain positive and confident that industry will choose the most cost-effective and safest solution that will incorporate both the legacy fleet and new releases to bring GA into the new unleaded fuel era. To quote both the largest pilots association, AOPA, and a popular aerobatics return performer at EAA Airventure Airshow, Sean D. Tucker, let's not lose hope and let's not give up, "let's go flying."

Hot Topics in General Aviation: Sustainable Aviation Gasoline Alternatives

Introduction

The general aviation industry is on the verge of a major revolution. Whereas piston-powered reciprocating aircraft have been using a leaded fuel for more than 80 years (Hemighaus, et al., 2006, p. 43), and whereby these aircrafts' engines have been developed to take advantage of this fuel's capabilities, the amount of lead found in aviation gasoline in its current form will soon be discontinued (C. Gonzalez, personal communication [telephone call], March 4, 2010; L. Hjelmberg, personal communication [telephone call], January 29, 2010; multiple anonymous contributors, personal communication [telephone calls], February 8 – March 1, 2010; T. Petersen, personal communication [telephone call], February 19, 2010; B. Visser, personal communication [telephone call], February 19, 2010). It may not seem to be a very difficult problem to resolve as the automotive industry has already removed lead in gasoline; however, aircraft engines have a longer useful life than automobiles. Herein lays the root of the problem: "airplanes don't run out" (K. Kenville, professor at the John D. Odegard School of Aerospace Sciences University of North Dakota in Grand Forks, personal communication [telephone call], February 9, 2010) and today's GA fleet has an average age of 39 years (General Aviation Manufacturers Association, 2009, p. 36). Although this aspect in itself should be considered green, society is no longer willing to tolerate possible contributions to known public health concerns in the form of leaded exhaust emissions.

The following composition identifies various current and possible alternatives to leaded avgas in order to ascertain which options would best suit the general aviation piston-powered legacy fleet in terms of safety, reliability, and economic viability to bring the industry into a more environmentally friendly and therefore sustainable age. First definitions and statistics related to general aviation and the benefits this industry provides to society are discussed. Part two provides a summary on regulatory actions taken to rid the environment of lead. Next, explanations on the importance of octane levels, why aviation fuel needs lead, including an overview of the types of traditional grades of aviation gasoline are given. The number of aircraft affected by the removal of lead in avgas is portrayed including figures concerning these aircrafts' fuel consumption and annual flight hours. The second part of Part two carries out a SWOT analysis of a number of possible alternatives to 100LL that are currently available or in developmental stages on the GA market. Finally, the Executive Summary presents a short list of substitutes that appear to best cover the entire GA piston fleet followed by recommendations to produce the most logical, the safest, the most reliable, and the most economically viable alternative to aviation gasoline 100LL.

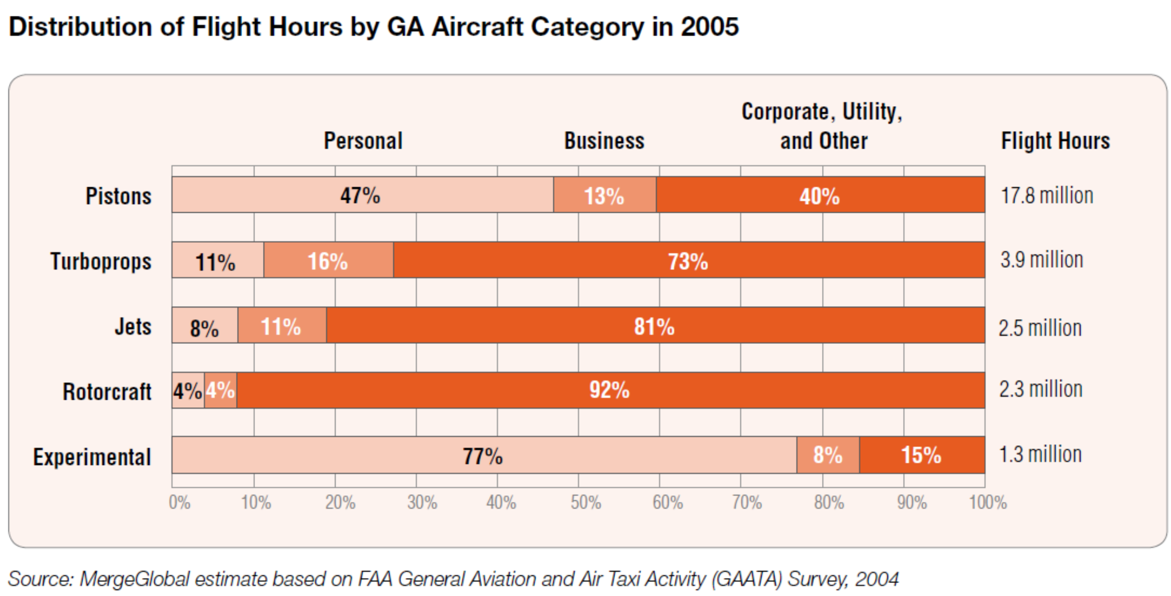
Part 1: Types and Utility of General Aviation

1.1 Types of General Aviation

General aviation is the part of civil aviation, meaning non-military, that is not scheduled air carrier service (General Aviation Manufacturers Association, 2009, p. ii). It can be used in the furtherance of business via business jets with a paid crew or by a business person flying the aircraft herself. General aviation covers on-demand types of services under the FAA's regulations called FARs Part 135. These rules refer to operations that are on-demand for "air taxi, charter, and aero-medical" (General Aviation Manufacturers Association, 2009, p. 29) flights. Other categories include sightseeing, instruction, and recreation (General Aviation Manufacturers Association, 2009, p. 29). GA activities can be referred to in three simple categories as presented in a 2006 study *General Aviation's Contribution to the U.S. Economy* by MergeGlobal for the General Aviation Manufacturers Association (GAMA) and the National Association of State Aviation Officials (NASAO):

personal which is for recreational use; business which is an owner-pilot that does not pay a professional crew; and corporate, utility, and other which uses one or more paid professional pilots (Allen, Blond, & Gellman, 2006, p. 10). A breakdown of the types of aircraft and their uses, including the number of flight hours they perform derived by this same study based on 2004 data can be seen in Figure 2.

Figure 2. "Distribution of Flight Hours by GA Aircraft Category in 2005"



Note. From *General Aviation's Contribution to the U.S. Economy*, by W. B. Allen, D. L. Blond, and A. J. Gellman from MergeGlobal, 2006, p. 10. Copyright 2006 General Aviation Manufacturers Association. Available on the public domain. Permission not requested.

According to GAMA, there are more than 320,000 GA aircraft flying over 35 million hours per year around the world today (General Aviation Manufacturers Association, 2009, p. 29). In the U.S., more than 228,000 of these GA aircraft are based in the country and fly around 26 million hours a year (General Aviation Manufacturers Association, 2009, p. 29). Two thirds of these operations are done for business (General Aviation Manufacturers

Association, 2009, p. 29). Regardless of the types of operations being accomplished by the GA sector, they are in one way or another contributing to economic growth wherever they go.

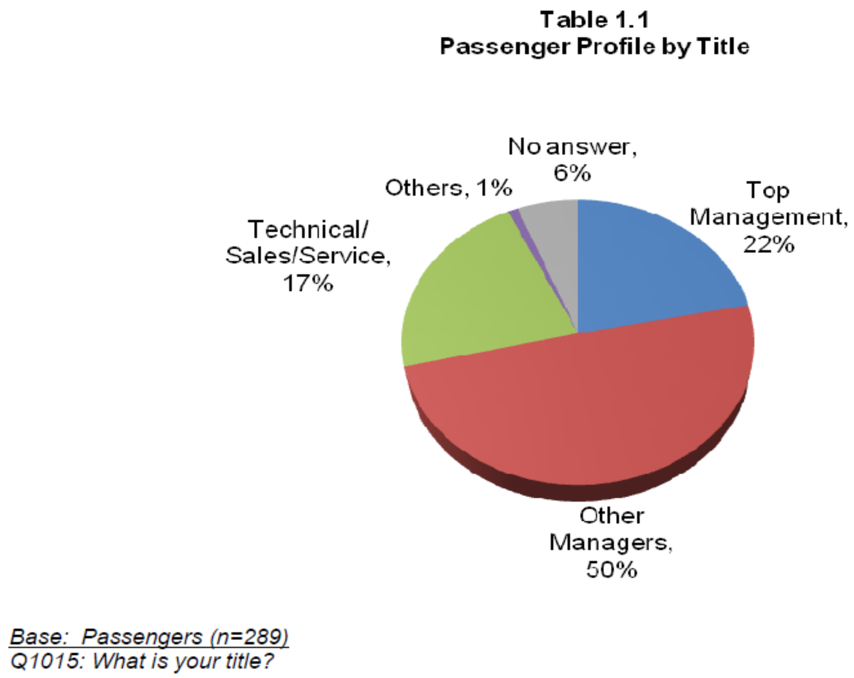
1.2 Utility of General Aviation

GA positively impacts companies, local communities, and nations in a variety of ways and in the U.S. has been tabulated as providing more than $150 billion in direct, indirect, and induced economic benefits (General Aviation Manufacturers Association, 2009, p. ii). The GA sector employees over one million people in the U.S. in highly-skilled and high-paying jobs (Allen, et al., 2006, p. 2; *GA: A vital tool in our economy,* n.d.). A number of studies have been carried out in recent years like MergeGlobal's *General Aviation's Contribution to the U.S. Economy* (2006), NEXA Advisors' *Business Aviation: An Enterprise Value Perspective* (2009), or Harris Interactive's *The Real World of Business Aviation: A Survey of Companies Using General Aviation Aircraft* (2009) with the goal of measuring the ways in which GA utilization impacts society. There are also several websites sponsored by aviation associations such as *No Plane, No Gain* and *GA Serves America* that have been released or updated in order to better inform the public on the variety of uses and services general aviation provides. Even the Cessna Aircraft Company has taken it upon itself to release a dedicated website for promoting the use of general aviation aircraft on its *Cessna Rise* site. GA assists in connecting isolated communities to the rest of the world, it provides indispensable emergency medical flights, it extends assistance in humanitarian flights, and helps businesses get their jobs done quickly and efficiently.

For example, from an airport standpoint alone, the U.S. has some 20,000 public- and private-use airports (General Aviation Manufacturers Association, 2008, p. 46) of which only around 4,000 are paved and regularly utilized by both GA and scheduled airlines (General Aviation Manufacturers Association, 2009, p. ii). However, an even smaller percentage of these are exploited by the airlines: 381 for scheduled large carriers plus 91 more airports for regional airline service for a total of 472 airports providing access to airline services (Federal Aviation Administration, 2010). GA aircraft are able to interconnect communities ten times more than commercial airlines. In fact, Krane & Orkis (2009) found that 80 percent of business flights using turbine aircraft were made to secondary airports that had little to no airline service (p. 6). GA websites report that there are only 70 major hubs that are serviced by the airlines and total airports servicing U.S. cities is declining (*Business aviation*, 2010). *No Plane, No Gain* recounts that 100 American cities have experienced a reduction in airline services while 30 communities have had their airline service eliminated just last year (*Business aviation*, 2010). In comparison, European airports amount to just under 2,100 for airports that had at least one instrument departure in the year 2006 according to EUROCONTROL, the European air traffic management organization (Marsh, 2007). Other sources give different statistics about the number of airports in the E.U. An independent study used a much smaller figure at 429 airports that had at least 2,000 passengers annually in a 2005 comparative study among 13 different EU nations (Williams, 2005). The Central Intelligence Agency (n.d.) reports 2,677 airports either paved or unpaved airports for those same thirteen European states, but some of the airports may be used or unused (see Appendix A).

Businesses that use their own aircraft tend to do "'better'" (Allen, et al., 2009, p. 14) than those that do not (Allen, et al., 2009, p. 14). In the *Business Aviation: An Enterprise Value Perspective* report covering 423 S&P 500 companies owning 1,400 aircraft, Allen, et al., (2009) found that "companies that use business aviation out perform their peers in almost every financial category, including revenue growth, profit growth and asset efficiency." (p. 7). These companies also prove to build up intangible benefits for their enterprises by positively impacting customer and employee satisfaction, "innovation and risk management and compliance." (Allen, et al., 2009, p. 27). Allen, et al. (2009) measured these values using respected magazine "'Best of the Best' lists'" (Allen, et al., 2009, p. 27) and found a correlation between the number of S&P 500 companies found on these lists and the percentage using business aircraft (p. 27). It is interesting to note that the types of business passengers these aircraft carry consist of a majority of managers and technical or sales personnel much more than top management at 50 percent and 20 percent respectively compared to 22 percent for the latter (Krane & Orkis, 2009, p.5) as shown in Table 1.

Table 1. "Passenger Profile by Title"



Note. From *The Real World of Business Aviation: A Survey of Companies Using General Aviation Aircraft*, by D. Krane & K. Orkis, 2009, Harris Interactive, Inc., for the National Business Aviation Association and the General Aviation Manufacturers Association. Available on the public domain. Permission not requested.

Although it is more likely that businesses in the S&P 500 use turbine powered aircraft, they may also be using piston-powered rotorcraft that consume aviation gasoline 100 LL and as such are equally affected by the upcoming changes in fuel formulation or hardware solutions necessary to implement a discontinuation of leaded avgas.

Part 2: Sustainability and Alternatives to leaded Avgas

Removing the Lead: Background

In the United States on January 1, 1996, the banning of lead in gasoline for on-road vehicles came into full effect (7545, 2008). Regulatory control of lead in air pollution in the United States started in 1955 with the Air Pollution Control Act followed by the Clean Air Act of 1963, the Air Quality Act of 1967, and finally the various Clean Air Acts of 1970, 1977, and 1990 (*Ethanol-blended*, 2008; *History*, 2008). Amendments continue to be made to these laws to carry out the Environmental Protection Agency's (EPA) mission established in 1971: to implement the many facets of the Clean Air Acts (*History*, 2008). Since then, the EPA has been actively working to rid the air of six major pollutants: particulate matter, "ground level ozone, carbon monoxide, sulfur oxides, nitrogen oxides, and lead." (*Cleaning up*, 2008) and has had some success in its purpose. For example, the transportation sector has experienced a reduction in lead emissions of 96 percent between the years 1981 to 2005 (*Petition requesting*, 2007).

The EPA is currently targeting General Aviation to reduce lead in the atmosphere as it has been found to contribute "29 percent of the air pollution emissions for lead and is overall, the largest source category." (*Petition requesting*, 2007). Other sources have claimed that GA adds upwards of "45 percent of the ambient air lead inventory." (*Assessment and Standards Division*, 2008, p. 8-9; Atwood, 2009). Lead has not yet been completely banned from all of its uses such as with airplanes, marine crafts, off-road vehicles, construction equipment, and other stationary platforms (*Avgas*, 2009; *Petition for rulemaking*, 2006). However, the trend is moving towards its elimination. The EPA's most recent standards for lead in fuel for non-road vehicles and engines were changed in October 2008, and stipulate a reduction from the previously accepted lead levels of 1.5 micrograms/m³ to 0.15 micrograms/m³ to be enforced in full by 2017 (*Fact sheet*, 2008). The environmentalist group that played a key role in achieving this revision in lead acceptance levels is the Friends of the Earth (FOE). In their letter to the EPA in 2006 to appeal for it to adjust its lead standards, they targeted GA estimating that it makes up 88 percent of lead emissions from total mobile sources according to 2002 data (*Petition for rulemaking*, 2006). The National Emissions Inventory (NEI) estimated 491 tons of lead emissions came from the use of leaded avgas in 2002 (*Petition requesting*, 2007). The Department of Energy reported that 281 million gallons of leaded avgas were supplied domestically for that same year (*Petition requesting*, 2007). Unfortunately the 2002 NEI figures were underestimated. The EPA had to revise these numbers in their *Lead Emissions from the Use of Leaded Aviation Gasoline in the United States Technical Support Document* in 2008 because they had received more precise data on how much lead remains within aircraft engines (the EPA had used a historical value of 25 percent lead retention since that was the value for automotive gasoline but only 5 percent lead residue is left inside airplane piston-driven engines), thus re-evaluating the total quantity of leaded emissions emitted by GA to be 623 tons in 2002 (*Assessment and Standards Division*, 2008, p. 3).

The above figures on lead emissions due to avgas use are not encouraging considering studies have shown that the toxins from the combustion process of fuels incorporating lead cause damage to brain development in babies resulting in a demonstrated reduction in IQ in children (*Avgas*, 2009; *Fact sheet*, 2008). Lead effects on adults have also been found to cause an increase in blood pressure, cardiovascular disease, and kidney malfunction (*Fact sheet*, 2008). It is evident the GA community must quickly find a solution to replace leaded aviation gasoline to fully comply with the upcoming 2017 regulation.

Industry has not ignored the leaded avgas dilemma and has spent many years searching for alternatives. In the 1990's two subcommittees were assembled to address this problem under the control of the Coordinating Research Council (CRC), a non-profit organization that directs major research projects bringing together industry players who are concerned with "the interaction between transportation equipment and petroleum products" (Coordinating Research Council, 2008, p. 2). They are the CRC Aviation Engine Octane Rating Panel and the CRC Unleaded Aviation Gasoline Development Panel (Coordinating Research Council, 2008, p. 2). They were tasked specifically with facilitating the research, development, and testing of "a high octane unleaded aviation gasoline as an environmentally compatible, cost effective replacement for the current ASTM D910 100LL fuel." (Coordinating Research Council, 2008, p. 2). The first committee looked at finding the best way to consistently and realistically test aircraft engines for minimum octane requirements since the general aviation fleet had never had such a standard to conform to previously (Coordinating Research Council, 2008, p. 3 & 7). It derived two testing specifications called ASTM D 6424 for normally air aspirated engines and ASTM 6812 for turbocharged ones (Coordinating Research Council, 2008, p. 7). The Aviation Engine Octane Rating Panel also found that for the legacy fleet's engines that require high octane, that even avgas 100 LL did not have enough octane and that an unleaded equivalent needed to be greater than 100 MON for both normally air aspirated and turbocharged engines (Coordinating Research Council, 2008, p. 7). The second committee concentrated on testing various fuel formulations against a minimum octane criteria: 99.6 MON which is the minimum found in avgas 100 LL (Coordinating Research Council, 2008, p. 3). Throughout this research, the panel laboratory tested more than 200 different unleaded blends and did further full-scale testing on 75 unleaded fuel formulations (Coordinating Research Council, 2008, p. 3-6). What they found was that even if unleaded blends had equivalent octane ratings as their leaded counterparts, they did not perform the same way in full engine tests demonstrating a difference of three MON (Coordinating Research Council, 2008, p. 6). The committees acknowledged that there are more than 200,000 engines that consume avgas around the world half of which are the most flown and actually need the high octane fuel (Coordinating Research Council, 2008, p. 7). Unfortunately, after more than ten years of testing, they did not find an unleaded "transparent replacement for the 100LL AVGAS product" (Coordinating Research Council, 2008, p. 9).

Some solutions may exist and others are still in testing phases which could contribute to resolving the avgas problem; however not all of the alternatives are able to cover the entire GA fleet and in some cases it is still unclear whether the newest propositions will one day be able to do so either. Besides raising the question as to which fuel or fuels will replace the leaded avgas, multiple other factors must be taken into consideration including how much they will cost, by whom and how will they be distributed, what infrastructure needs to be adapted to incorporate the new fuels, what regulatory issues must be considered while using the alternatives, and what, if any, engine and fuel system modifications including supplemental type certificates, must be made and obtained in order to use the alternative fuels. Finally, what type of incentives are available in order to encourage either existing or new oil companies to produce and distribute unleaded avgas while convincing retailers to invest in updating equipment if need be in order to make it accessible to users.

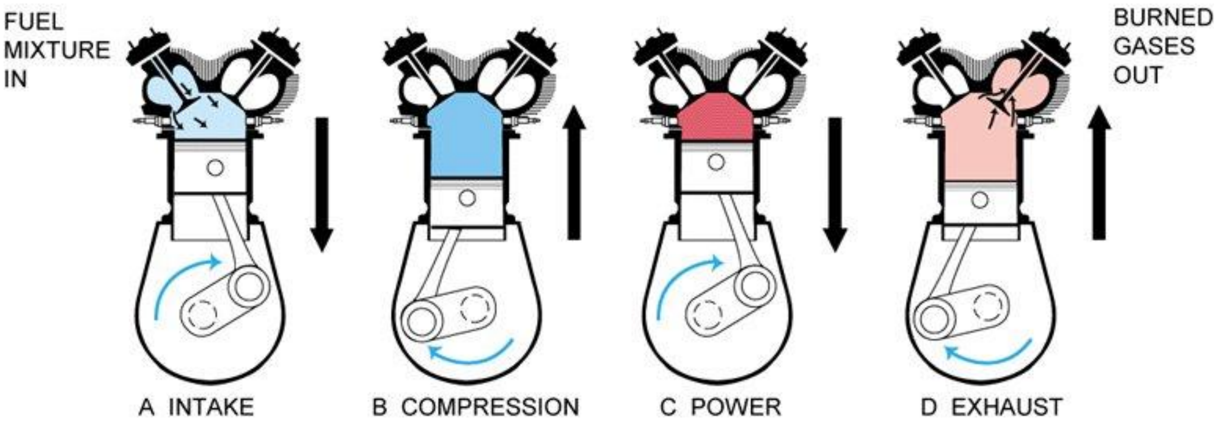
The next section will identify and describe the grades of fuel that have traditionally been used in general aviation including an explanation of why lead is still used in it, the importance of octane, how it affects engine performance, and an estimation as to how many aircraft use leaded aviation gasoline including the number of hours they fly annually. Note that the focus is on the U.S. market as it has the largest piston-driven GA fleet in the world and statistics are easily accessed and updated every year. Then current unleaded fuels that are on the market or possible future alternatives that could constitute as drop-in fuels (fuels that require little to no engine modifications to be able to use it) to replace today's leaded version of aviation gasoline will be specified including a look towards the future with increasing popularity of Jet A certified engine retrofit kits taking into account Jet A's imminent bio or synthetic replacement, and an overview of up-and-coming electric hybrids and solar planes. Alternate hardware solutions that could be used in combination with existing unleaded fuels shall be looked at as well. A SWOT analysis is then carried out for each alternative to determine the most logical and if possible, cost-effective approaches industry should pursue in order to ensure a seamless implementation of solutions to leaded aviation gasoline for piston-powered, spark-ignition reciprocating aircraft.

2.1 Traditional Grades of Fuel Used in General Aviation, Octane, Lead, and Number of Aircraft using Avgas

2.1.1 Traditional grades of fuel used in General Aviation. Powered flight has been possible for more than one hundred years and in the beginning engines used the same fuel as car motors (Hemighaus, et al., 2006). Several types of aviation-specific fuel grades have been developed over time to accommodate more powerful and better performing "specialized" (Hemighaus, et al., 2006) aircraft engines. There are two main types of fuel used in civilian aircraft: aviation gasoline referred to as avgas, and kerosene-based fuel called Jet A or Jet A-1. The latter is most significantly used in turbojet, turbofan, and turboprop engines, and for a minority number of piston-powered engines. Avgas has several grades and is the conventional type of fuel used in piston-powered, spark-ignition reciprocating engines. The following types of aviation gasoline are traditional grades: avgas 80/87 octane which is dyed red and contains low levels of lead at approximately 0.5 grams per gallon although no lead is required; avgas 100/130 octane with a minimum 100 MON and RON ratings which is green in color and has a high lead content at four grams of lead/gallon; avgas 100 Low Lead (LL) has similar MON and RON octane ratings to 100/130 fuel but contains half the lead at around two grams per gallon, is needed for higher-compression engines like those found in newer aircraft such as Cirrus' SR22, Diamond DA50, or Cessna's Corvalis 400 and is blue in color; avgas 115/145 octane fuel which is used in WWII and the Korean conflict aircraft with high performance engines, is purple in color, and can only be obtained on special order (*Avgas: Grades*, 2009; *Common aviation*, 2009). These traditional grades are presented here using their lean- and rich-mixture antiknock ratings. Other intermediary grades did exist prior to 1950 as described in Chevron's *Aviation Fuels Technical Review* by Hemighaus, et al., (2006) including avgas 73, 91/98, and 108/135 (p. 44). Today the assortment of avgas choices listed above are no longer offered as since the early 1940s advances in turbine technology took over (Hemighaus, et al., 2006) drastically reducing the demand for avgas variants and replacing it with aviation turbine fuels Jet A and Jet A-1. Now 100LL is the most widely-available avgas fuel and reference to the antiknock rating has been simplified to include only the lean-mixture one.

Lean- and rich-mixture antiknock ratings, MON and RON octane ratings, AKI rating, and performance number are terms used to identify a fuel's ability to protect the engine from abnormal combustion that would create a knocking or pinging sound in the cylinder due to a phenomenon called detonation (Hemighaus, et al., 2006, p. 46; U.S. Department of Transportation Federal Aviation Administration Flight Standards Service, 1980, p. 22). Normal fuel burn occurs when a mixture of fuel and air that was drawn into the cylinder head during the intake stroke and then compressed during the compression stroke is ignited by the spark plugs, typically around 20 degrees before the piston reaches top dead center (TDC) of a four-stroke spark-ignition reciprocating engine as shown in Figure 3 (To see a schematic and description of a cylinder, see Appendix B).

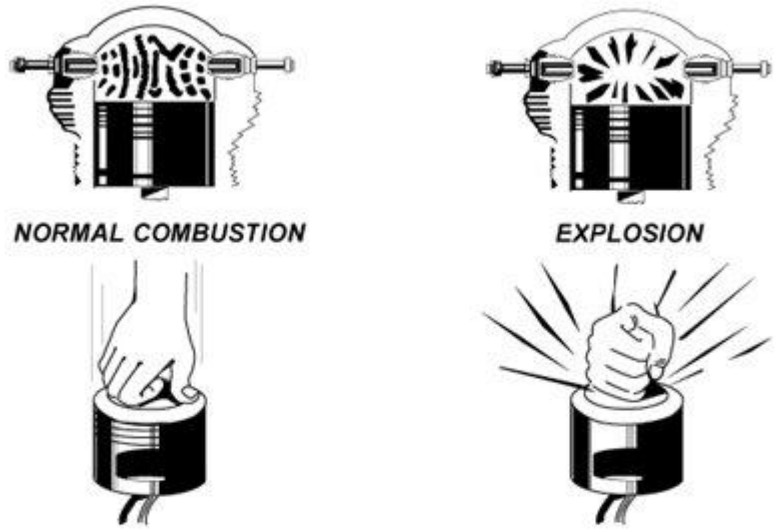
Figure 3. "Four Strokes of a Piston in a Piston-Powered Reciprocating Engine"



Note. From *Pilot's Handbook of Aeronautical Knowledge* (p.2-7), by U.S. Department of Transportation Federal Aviation Administration Flight Standards Service, 1997, Newcastle, WA: reprinted by Aviation Supplies & Academics. Permission not requested.

The fuel and air do not ignite homogeneously immediately within the cylinder head but in fact begin what is called a flame front starting from each spark plug and spreading across the combustion chamber to reach the middle of the chamber when the piston arrives at TDC (Hemighaus, et al., 2006, p. 46). The subsequent expansion of the burning fuel and air drives the piston down in what is called the power stroke (De Remer, 1996, p. 41). Not all of the fuel-air mixture is completely burned in the power stroke before it is pushed out of the cylinder during the exhaust stroke in normal operations. Detonation occurs when this unburned fuel-air mixture left over from the normal flame front ignites spontaneously exerting excessive pressure and heat forces on the piston head which forces it down having an effect "equivalent to a sharp blow with a sledge hammer," (U.S. Department of Transportation Federal Aviation Administration Flight Standards Service, 1980, p. 22) as shown in Figure 4.

Figure 4. "Normal Combustion Versus Explosive Combustion"



Note. From *Pilot's Handbook of Aeronautical Knowledge* (p.2-12), by U.S. Department of Transportation Federal Aviation Administration Flight Standards Service, 1997, Newcastle, WA: reprinted by Aviation Supplies & Academics. Permission not requested.

Conditions such as very high temperatures and pressure within the cylinder would be a prime environment to give rise to detonation (Hemighaus, et al., 2006, p. 46; U.S. Department of Transportation Federal Aviation Administration Flight Standards Service, 1980, p. 22).

Preignition can occur when "'hot spots'" (U.S. Department of Transportation Federal Aviation Administration Flight Standards Service, 1980, p. 22) within the cylinder cause ignition prior to normal timing (U.S. Department of Transportation Federal Aviation Administration Flight Standards Service, 1980, p. 22). The hot spots might be on exhaust valves, from carbon deposits, or from the spark plug's parts overheating and are usually in consequence of detonation (U.S. Department of Transportation Federal Aviation Administration Flight Standards Service, 1980, p. 22). Whether the engine experiences detonation or preignition, the excessive pressure and heat they produce is not good for the engine as structural limitations for the cylinder, piston, and other engine parts can be met. The result is enough damage to cause a loss of power if corrective action is not taken expediently

(U.S. Department of Transportation Federal Aviation Administration Flight Standards Service, 1980, p. 22).

Although this type of occurrence is not wholly uncommon in automobile engines, it is of greater threat to an aircraft engine because it is difficult to detect the knocking in such a noisy setting (Hemighaus, et al., 2006, p. 46; U.S. Department of Transportation Federal Aviation Administration Flight Standards Service, 1980, p. 22). Preventing conditions conducive to this type of environment is key to safety namely via the usage of appropriately rated antiknock aviation grade gasoline. This is where lead takes its lead: it is an effective and relatively inexpensive additive that improves antiknock characteristics (Hemighaus, et al., 2006, p. 46).

2.1.2 Octane. Aviation grade fuels have stringent specifications in order to provide the necessary power to engines and enable them to operate smoothly while being exposed to harsh atmospheric conditions. The American Society for Testing and Materials (ASTM) International establishes the standards for fuel for aviation use namely ASTM D910. Properties such as energy content, "knock resistance, volatility, fluidity, stability, non-corrosivity, and cleanliness" (Hemighaus, et al., 2006, p. 45) are the main focal areas for quality performance of an aviation gasoline. After energy content, knock resistance is an "essential" (Hemighaus, et al., 2006, p. 46) performance criteria to ensure "reliable engine operation[s]." (Hemighaus, et al., 2006, p. 46). This characteristic is identified via its octane and performance number (Hemighaus, et al., 2006, p. 46).

Octane is detected via the measurement of "the volume percentage of isooctane" (Hemighaus, et al., 2006, p. 46) in a blend of fuel with two pure reference fuels called normal heptane and isooctane (Hemighaus, et al., 2006, p. 46). Normal heptane has zero octane while isooctane has 100 octane. When octane is above one hundred, the term used is performance number and higher antiknock resistance is reached via additives like tetraethyl lead being mixed in the fuel (Hemighaus, et al., 2006, p. 46). Octane, and performance numbers above one hundred octane, provide an engine with the opportunity to produce more power while avoiding knocking and increasing performance (De Remer, 1996, p. 90; Lombardo, 1999, p. 130).

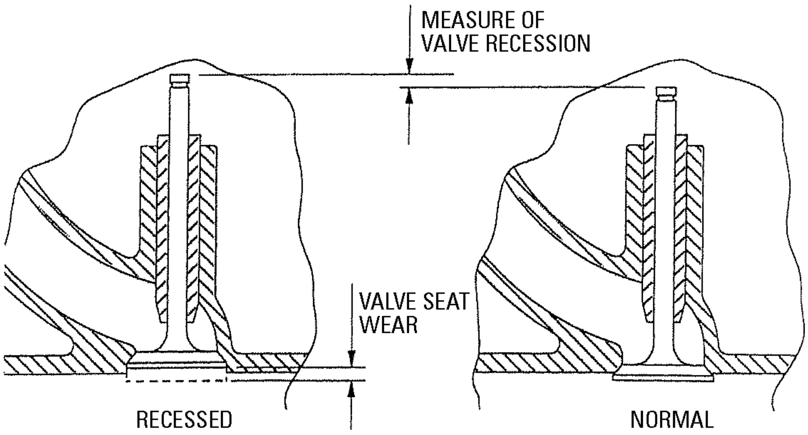
There are several types of laboratory tests that evaluate the level of octane in the fuel two of which are the ASTM motor octane number (MON) and the ASTM research octane number (RON). In comparison, automobile gasoline displays the average of the RON and MON called the antiknock index number (AKI) (Barber, et al., 1996, p. 5; *Detonation, AKI and octane number*, 1996). Aviation grades will refer to the MON number as it most resembles a fuel’s lean-mixture rating (Barber, et al., 1996, p. 5; *Detonation, AKI and octane number*, 1996). The lean-mixture rating measures the level of octane in a high air-to-fuel ratio situation which would resemble cruise flight conditions (De Remer, 1996, p. 90; Hemighaus, et al., 2006, p. 46). The rich-mixture rating measures the amount of octane using a high fuel-to-air ratio that resembles a takeoff configuration (De Remer, 1996, p. 90; Hemighaus, et al., 2006, p. 46). For example, fuels graded 80/87 octane display numbers that refer to these last two tests respectively (De Remer, 1996, p. 90; Hemighaus, et al., 2006, p. 46). Today, however, the rich-mixture rating is no longer mentioned and fuels are referred to using the lean-mixture rating to indicate the octane content (De Remer, 1996, p. 90).

2.1.3 Lead. Lead or tetraethyl lead (TEL) is an octane-boosting additive found in aviation gasoline like avgas100LL with 2.12 grams per gallon for piston-powered spark-ignition aircraft (*Petition requesting*, 2007). It can also be found in other grades of avgas such as avgas 100 at around 4 grams per gallon, but this fuel is not as accessible as 100LL in the U.S. (J. Hennig, Vice President of Operations GAMA, personal communication [e-mail], January 25, 2010; *Petition requesting*, 2007). Lead’s infamous career was launched in 1923 when it started being added to gasoline as an anti-knock agent that raised the octane of gasoline more cheaply than via petroleum chemical reactions during the refining process (Barber, et al., 1996, p. 30). It was banned in automobiles in the United States progressively from 1979 onwards to its final prohibition in 1996 (7545, 2008). Lead additives continue to be utilized in aviation as there is yet to be found a safe, cost-effective, less pollutant alternative to obtain proper octane levels. Lead helps to boost performance in piston-powered aircraft particularly in high-compression air-cooled engines, to prevent detonation and pre-ignition, and to prevent "valve seat recession" (*Petition requesting*, 2007) which would result in a loss of compression and engine power (*Common aviation*, 2009; *Petition requesting*, 2007; Ruley, 2004; Sparrow, 2008).

Valve seat recession (VSR) occurs when the valve and its opposing seat stop providing the seal they are required to make during the four-stroke cycle in a piston-powered reciprocating engine (See Appendix C for an example schematic of valve, rocker arm, and tappet plus valve part description). Damage is incurred to the seat allowing the valve to recede past the seat and into the cylinder head towards the rocker arm or tappet (Sparrow, 2008) as shown in Figure 5.

Figure 5. "An Illustration of Exhaust Valve Recession into the Cylinder Head"

Figure 1 An illustration of exhaust valve recession into the cylinder head



Note. From "The lead ban, lead replacement petrol, and the potential for engine damage," by P. L. Barlow, 1999, *Industrial Lubrication and Tribology, 51*(3). Copyright Emerald Group Publishing. Figure on public domain via Google search. Permission not requested.

Keeping things simple, one valve opens for the air and fuel mixture to enter the cylinder in the intake stroke, both are closed during the compression and power stroke, and the second valve opens so that the combusted gases can evacuate during the exhaust stroke (U.S. Department of Transportation Federal Aviation Administration Flight Standards Service, 1980, p. 18). In actuality, timing is such that both valves are open at the same time for efficiency purposes at the end of the exhaust stroke and at the beginning of the intake stroke (De Remer, 1996, p. 31). When VSR happens, the exhaust valve is unable to carry out part of its function which is to allow for pressure to build during the compression stroke and to create a contained environment for combustion during the power stroke. The result is a loss in compression and power. VSR will eventually happen due to regular wear and tear during the life of a valve and seat, but it may occur prematurely if the valves are not properly lubricated to inhibit their erosion particularly if the valves are made of a soft metal alloy (Sparrows, 2008). Lead provides this lubricity to keep these parts from creating friction and wearing away at each other (S. Johnson, A&P and IA at Wisconsin Aviation, personal communication [telephone call], February 2, 2010).

Lead is not good for all aircraft engines. In fact, a large number do not fancy it at all as too much will cause spark plug fouling (lead deposits on the spark plug that keeps it from performing its job) in a relatively short period of time if lead scavengers are not added to the fuel. Some planes even have to use specialized spark plugs in order to utilize leaded avgas to operate normally. One example of such planes is the Cessna 152. According to Steve Johnson, experienced Airframe and Powerplant (A&P) mechanic and inspector at Wisconsin Aviation in Madison, Wisconsin, although the Cessna 152 continues to function normally prior to its routine inspection, as much as three grams of lead buildup must be removed from all eight spark plugs (personal communication [telephone call], February 2, 2010). Ethylene dibromide is the scavenging agent that is added to the fuel and combines with the lead to create lead bromide to pass out of the engine as an exhaust gas (De Remer, 1996, p. 90). This is a toxic emission that is not good for the environment nor human health and has been rated by the EPA as a potential carcinogen (U.S. Environmental Protection Agency, 2009). Moreover, the Montreal Protocol of 1987 has banned this scavenger due to its effect on the ozone layer (Malone, 2006).

2.1.4 Estimated number of aircraft using avgas today, consumption data, and total hours flown annually. According to the 2009 General Aviation Statistical Databook and Industry Outlook publication distributed by the General Aviation Manufacturers Association (GAMA), there are 228,663 general aviation and Part 135 aircraft in the U.S. Around 84 percent of the total GA aircraft figure is made up of piston-powered airplanes, turboprops, turbojets, and rotorcraft (see Appendix D, *Table D1*) (General Aviation Manufacturers Association, 2009, p. 30). The remaining 16 percent represents gliders, lighter-than-air, experimental, and light sports aircraft (LSA) which have virtually no Part 135 participation and are mainly used for personal use with only a very small number used for business flying and some for training (See Appendix D, *Table D1*) (General Aviation Manufacturers Association, 2009, p. 30). Experimental and LSA categories are not insignificant, however, with over 23,000 aircraft in the former and more than 6,000 in the latter (See Appendix D, *Table D1*) (General Aviation Manufacturers Association, 2009, p. 30). Both of these categories consume avgas although a large majority of Experimental aircraft utilize Jet A fuel while LSAs primarily use motor gasoline (See Appendix D, *Table D6*) (General Aviation Manufacturers Association, 2009, p. 36). The discussion that follows covers only the first categories mentioned: piston-powered airplanes, turboprops, turbojets, and rotorcraft as the types of engines used and the kind of fuel they consume is clearly delineated in FAA statistics whereas in Experimental and LSA categories they are not. Finally, the first categories that make up the 84 percent of the total GA and Part 135 aircraft in the U.S., operate at more than 24 million annual flight hours (See Appendix D, *Table D3*) (General Aviation Manufacturers Association, 2009, p. 32).

Breaking down the aircraft statistics within the aforementioned 84 percent majority, only 14 percent or 26,326 aircraft make up the turboprop, turbojet airplanes, and turbine-driven rotorcraft which generally use Jet-A fuel (See Appendix D, *Table D4*) (General Aviation Manufacturers Association, 2009, p. 32; Hemighaus, et al., 2006). The other 86 percent or 166,511 airplanes and rotorcraft are piston-powered which customarily use aviation grade gasoline for spark-ignition reciprocating engines for either high or low compression although some piston aircraft may have motor gasoline STCs or compression-ignition engines that use Jet A fuel (See Appendix D, *Table D4*) (General Aviation Manufacturers Association, 2009, p. 32).

To put things further into perspective with regards to fuel consumption, 92 percent of fixed-wing piston aircraft use 100LL avgas or 100 octane fuel compared to two percent mogas and six percent Jet A fuel (See Appendix D, *Table D6*) (General Aviation Manufacturers Association, 2009, p. 36). However, Jet fuel, mogas, and 100 octane statistics are not altogether reliable for this category of aircraft due to the relatively low sampling sizes in the survey collection method with 13.9 percent, 11.5 percent, and 11.4 percent standard error margins respectively compared to 2.7 percent error margin for 100LL (See Appendix D, *Table D6*) (General Aviation Manufacturers Association, 2009, p. 36). Turboprops use very little avgas, 100LL and 100 octane combined, at only 2.1 percent of its total fuel consumption whereas the rest of this fleet uses Jet A fuel (See Appendix D, *Table D6*) (General Aviation Manufacturers Association, 2009, p. 36). Turbojets use Jet A fuel although the data collected by the FAA indicate that a small percentage does actually use avgas 100LL and 100 octane at 5.3 percent of its total fuel consumption (See Appendix D, *Table D6*) (General Aviation Manufacturers Association, 2009, p. 36). Here again one must be wary of the accuracy of this data as the standard margin for error for these two categories, although acceptable for 100LL at 4.2 percent, the figures are a little less reliable for 100 octane at10.9 percent (See Appendix D, *Table D6*) (General Aviation Manufacturers Association, 2009, p. 36). It should be noted, however, that turbojets do not typically consume avgas as it would not be good for their engines (J. Hennig, Vice President of Operations GAMA, personal communication [e-mail], January 25, 2010). A high percentage of rotorcraft piston-powered engines consume both avgas 100 grades at 94 percent of its total fuel consumption (See Appendix D, *Table D6*) (General Aviation Manufacturers Association, 2009, p. 36). Turbine-powered rotorcraft prefer Jet A fuel, yet the FAA reports rotorcraft with turbine engines consuming 1.5 percent of its total fuel consumption as 100 grade avgas although the margin error is rather high again at 14.6 percent (See Appendix D, *Table D6*) (General Aviation Manufacturers Association, 2009, p. 36). Finally, it must be noted that statistics concerning turboprops, turbojets, and rotorcraft are generally rather accurate as the number of these aircraft operating in the U.S. is smaller than for piston-powered fixed-wing planes and thus sampling sizes are 100 percent for these categories every year compared to only 10 percent for the latter category (Federal Aviation Administration, 2009, p. A-10).

Total hours flown by piston-powered aircraft have decreased significantly according to the most recent 2009 General Aviation and Part 135 Activity Survey which went from between 16.5-17 million hours flown in 2005 to 15 million hours (Federal Aviation Administration, 2005; Federal Aviation Administration, 2008). Although total number of hours flown by piston-powered aircraft has fluctuated over the last decade, the general trend has been declining with significant dips in 2001 and 2008 (Federal Aviation Administration, 2008). The former drop was due to the aftermath affects of September 11, 2001, terrorist attacks on the U.S. where GA aircraft flying under visual flight rules (VFR) were grounded for approximately one month as the author of this thesis can confirm. The latter decline reflects what Senior Editor of AOPA Pilot magazine Dave Hirschman in an AOPA live video during the last AOPA Aviation Summit held in Tampa, Florida, in November 2009, claims was due to high oil prices that were manifested at the avgas pumps which ultimately grounded a lot of the GA fleet.

Imposing a reduction in or complete elimination of the amount of lead permissible in aviation gasoline would negatively affect approximately 30 percent of the GA fleet, generally the newer and higher performance aircraft but also legacy ones which are heavily used by commercial operators (anonymous, personal communication [telephone call], March 1, 2010; *AOPA working*, 2008). These aircraft that are used for business or air taxi operations need the lead to boost octane and protect their engines from malfunctioning (*AOPA working*, 2008). Although the impact is on only 30 percent of aircraft in the GA fleet, it translates into 70 percent of the current 100LL consumption in the U.S. (*AOPA working*, 2008).

It has been established that lead emissions will need to be dramatically reduced by 2017 as declared by EPA mandate in its national ambient air quality standards for lead in October 2008 (*Fact sheet*, 2008). Although not all industry members are convinced compliance with NAAQS for 2017 lead emissions levels and the monitoring of potential sources that it implies will have a great impact on general aviation even with the recent reduction to the allowable tons per year emissions threshold (*Environmental Protection Agency: Revisions to lead ambient air monitoring requirements*, 2009), there is the risk that it could. The aviation industry has been working on solutions for more environmentally friendly avgas fuel options, a.k.a. without lead; for over 25 years via individual and industry research efforts and regulatory authorizations. The following section will discuss a number of existing and forthcoming possible solutions to the leaded avgas conundrum, carry out a SWOT analysis for each, and suggest viable and sustainable solutions for the future.

2.2 Current and Possible Sustainable Alternatives to Leaded Avgas

Dave Hirschman, Senior Editor of AOPA Pilot magazine said it best in a video recorded during the AOPA Aviation Summit in 2009 when he described the leaded avgas dilemma as “one of the most pressing problems in aviation right now … an unleaded avgas replacement that will run across the entire piston-engine fleet.” (*Alternative fuels*, 2009). A number of alternatives to avgas already exist or are in developmental or testing stages. Below is a description of the various options available today and those that are on the agenda for tomorrow to replace lead-containing avgas. A SWOT analysis is carried out for each option with comments on feasibility for production, distribution, storage, accessibility, potential cost to consumer, regulatory requirements for both provider and user, necessary mechanical modifications to aircraft and engines if any, and any operational considerations that must be taken into account where the information is available. The executive summary provides concluding remarks as to the best strategic positions industry might take to resolve the avgas challenge.

2.2.1 Mogas. Autogas, or mogas as it is commonly referred to among pilots, is a viable unleaded solution for airplanes with engines certified for avgas 80 octane fuel as it has proved from its performance record over the last 28 years (*Who we are*, 2010). Research and testing for the use of mogas began in 1964 by the Experimental Aircraft Association (EAA) and became available in 1982 (*Who we are*, 2010). The EAA developed a type certification program to allow aircraft to utilize mogas and later the FAA agreed to issue a supplemental type certificate (STC) for its use starting with a Cessna 150 with a Continental O-200 engine (*Who we are*, 2010). Around the same time, Petersen Aviation which was at first an agriculture spraying business in Nebraska using planes called Grumman G-164 Ag-cats, began their own testing for mogas STCs as they had difficulties getting avgas distributed to them for their business (T. Petersen, personal communication [telephone interview], February 19, 2010). By the time they stopped testing and development in 1993, they had derived over 150 different STCs (T. Petersen, personal communication [telephone interview], February 19, 2010). A STC is authorization from the FAA to be able to “modify the aircraft from its original design” (*Supplemental type certificates*, 2008) and is necessary legal documentation an operator must possess if one wants to make any major alterations to the aircraft that can affect its flying characteristics. It is a system that ensures a certain level of safety for operators as each STC undergoes many hours of ground and flight testing (at least 150) to get approval for its issuance (Petersen, n.d.; *Why are two*, 1996). A number of airplanes and their engines have been added to the STC list since 1982 resulting in more than 70,000 STCs having been issued to date thanks to both EAA and Petersen Aviation, the two major autogas STC providers in the U.S. (*Autofuel STCs*, n.d.; Berry, 2000a; *Intro*, n.d.; *M y airframe/engine*, 2010; *Who we are*, 2010).

In order to use regular unleaded automotive gasoline in aircraft engines, two STCs are required: one for the engine and another for the airframe. They can be purchased before receiving approval from the FAA via an inspection with an Inspection Authority (IA) rated A&P mechanic (*Why are two*, 1996). An aircraft owner may also choose to carry out the STC testing for mogas herself where she would have to develop the necessary data and present it in an acceptable manner to the FAA for approval (Armstrong, 1995). The owner would need to follow the guidelines specified in Advisory Circular (AC) 23.1521-1B where additional AC compliance is described in order to act in accordance with FAA testing procedures and type certificate applications (Armstrong, 1995). It is very important to get an aircraft STC'd before filling it with mogas because there are cases in which the design of the aircraft with its engine model, even if it's rated for 80 octane or lower fuel, may have a number of issues that could impose some modifications in order to ensure safe flight (T. Petersen, personal communication [telephone interview], February 19, 2010; Ruley, 2004). A STC provides the user with the assurance that their particular aircraft and engine have undergone rigorous testing to have their models approved for the modification in question (Ruley, 2004). An aircraft may need adjustments to its fuel delivery system to avoid things like vapor lock which may entail replacing fuel pumps or changing the angle of fuel line fittings from 90 degrees to 45 degrees, or there might be a requirement for the aircraft to only be allowed to use premium 91 AKI fuel and not any lower (T. Petersen, personal communication [telephone interview], February 19, 2010; Ruley, 2004).

According to reports and articles about using unleaded automobile fuel in aircraft engines, autogas has demonstrated to be better for internal engine parts and fuel systems compared to 100LL (Berry, 2000b; *Intro*, n.d.; Ruley, 2004). The aircraft with lower rated octane engines STC'd for mogas have fewer sparkplug fouling issues than when running on avgas 100LL and according to Petersen Aviation, their valves stick less (*Intro*, n.d.; S.

Johnson, personal communication [telephone call], February 2, 2010; Ruley, 2004). EAA asserts that engines running on mogas have better extended life and more "time between overhauls" (*Engine overhaul*, 1996).

To ensure the aircraft is getting enough octane when using mogas, it must have an AKI number at the gas pump of no less than 87 (*Detonation, AKI and octane number*, 1996). This corresponds to an 82 MON octane level (remember MON ratings are similar to lean-mixture ones) giving aircraft engines a 2-octane safety margin (*Detonation, AKI and octane number*, 1996). It is not recommended by the FAA nor other organizations like the EAA to fall below 80 MON or engine efficiency, internal temperatures, and performance cannot be ensured (*Detonation, AKI and octane number*, 1996).

Besides operational benefits and the cost savings mogas can provide thanks to its effect on engine longevity, the number one reason pilots STC their aircraft for mogas is because it's cheaper than avgas 100LL (*Intro*, n.d.; Ruley, 2004; *Savings with autofuel*, 2001). Nine years ago there was a 65 cent difference per gallon between the two fuels in the U.S. (*Savings with autofuel*, 2001). Today there is a $1.30 difference on average nationwide between autogas and avgas (*Fuel price report*, 2010a). If one takes recreational pilot annual flying time to be 50 hours in a plane that burns 10.8 gallons per hour (gph) just like in the case study example EAA did nine years ago on its Autofuel website in the online article entitled *Savings with Autofuel*, pilots will save

$$10\ gph \times 50\ hours = 500\ gallons\ per\ year$$

$$500\ gallons\ per\ year \times \$1.30 = \$650\ per\ year\ at\ today's\ prices.$$

If the time before overhaul (TBO) for the engine takes place at 2,000 hours (a typical TBO time), and the same variables remain constant as discussed above:

$$2{,}000\ hours\ \div 50\ hours\ per\ year = 40\ years$$

$$40\ years\ \times \$650 = \$26{,}000\ savings\ over\ the\ life\ of\ the\ engine.$$

The savings could be more if the pilot chooses to purchase mogas off the airfield at a gas station as most do since mogas is not well distributed in the U.S. (*Fuel price report*, 2010a; *Savings with autofuel*, 2001). For 3,650 FBOs reporting fuel prices nationwide on AirNav.com's website on February, 9, 2010, only 121 tout mogas availability (*Fuel price report*, 2010a). However, the savings in the exercise above are not negligible as they represent the price of a typical low compression overhauled engine (*Aftermarket engine exchange*, 2010).

It might be noted that 40 years to run an aircraft and its engine may appear long in comparison with automobiles which generally consumers exchange after 10 years of use (Kim Kenville, Professor UND Aerospace, personal communication [telephone call], February 9, 2010). As Dr. Kenville, professor at UND Aerospace and specialist in general aviation operations and management and issues in aviation, pointed out in a phone interview February 9, 2010, this is precisely the problem with the avgas issue: "airplanes don't run out." This could make aircraft rather 'green' in some respects as planes that are 80 years old or older continue to be maintained in flying condition. No recycling necessary!

Mogas can save a pilot money over time in fuel costs, and it can also do so from a technical and operational perspective as it is better for engines rated 80 octane or lower than its leaded counterpart (Berry, 2000b; *Engine overhaul*, 1996; *Intro*, n.d.; Ruley, 2004), and although this option has the potential of covering nearly 70 percent of the total piston-powered, spark-ignition reciprocating engine fleet, there is a general stigma for this type of fuel for a number of reasons. Firstly, when approval for the use of mogas began, there were problems with valves sticking particularly in small engine models that had been manufactured during the 1940s (*Engine overhaul,* 1996). This was due to the soft metals used for the valve seats plus their angles needed adjusting (*Engine overhaul,* 1996). EAA on its autofuel portion of its website maintains that this should no longer be a problem today as the issuance of service instructions by the manufacturer for operators to change valve seat angles and add hardened valve seats should have solved the issues (*Engine overhaul*, 1996).

A second reason for the negative perceptions about mogas is that it is said to provoke more vapor lock than its leaded counterpart (Berry, 2000a; *Is vapor lock*, 1996). Given mogas' higher volatility measured by its Reid Vapor Pressure (RVP) compared to avgas, a higher occurrence of vapor lock may occur than with avgas at extreme operating conditions at high altitudes and hot temperatures (Berry, 2000a; *Is vapor lock*, 1996). Vapor lock occurs when leftover gasoline in the fuel lines becomes overheated and evaporates in the lines creating air pockets that disrupt the fuel flow to the engine. It can happen when it is a hot day and the plane is left in the sun heating up the fuel lines, when the plane has a hot engine from flight activity and it is restarted before it has had enough time to cool off allowing the engine to transfer its heat to the fuel lines and cause evaporation, when the boiling point is raised because of a rise in altitude, or a combination of any of these three conditions (Berry, 2000a; *Vapor lock*, 2010). These air bubbles lead to fuel starvation which could make the engine quit and also create difficulties for restarting, a situation that's especially sensitive if it happens just after takeoff. There are special vapor lock tests on the market to verify whether conditions are such vapor lock may be prevalent. However, even with leaded avgas it is not recommended to start a hot engine on a hot day until fuel lines are sure to be cooled down enough to prevent the occurrence of vapor lock. Other ways to avoid vapor lock is via (extra) fuel pumps, 45 degree instead of 90 degree fitting installations, and sometimes redesigning the fuel systems forward of the firewall (*Information: Modifications,* n.d.; T. Petersen, personal communication [telephone call], February 19, 2010). It must be pointed out that not all fuel delivery systems have fuel pumps as the tanks which are located in the wings may be in a high-wing configuration allowing for a gravity-fed system to be used. The aircraft airframe model and engine are the determinants for fuel system modifications under a mogas STC.

Carburetor icing has been found to increase with the use of mogas, again due to its higher RVP (Berry, 2000a, *Information: Octane*, n.d.). This is caused by the latent heat removal from the fuel when it vaporizes in the carburetor, and as autogas' RVP is higher than avgas' (7 to 15 psi compared to 5.5 to 7 psi), it thus removes more heat when it vaporizes (Berry, 2000a). This might be a partial explanation as to why aircraft using autogas are said to be limited to lower altitudes since fuels with higher RVPs will vaporize more quickly at lower pressures found when the aircraft gains altitude. This could contribute to the excessive cooling in the carburetors causing icing which if not remedied via the application of carburetor heat could lead to partial or total loss of power.

A third reason why mogas has been reproached is that oil companies, engine, and airframe manufacturers do not recommend its use as autogas was not used in the original type certification testing and as such not listed on the type certificate, and autogas has less stringent quality standards than aviation fuel which is a perceived liability issue for these players (anonymous, personal communication [telephone call], February 19, 2010; anonymous, personal communication [telephone call], February 25, 2010; Berry, 2000a; Berry, 2000b; T. Petersen, personal communication [telephone call], February 19, 2010). Engine manufacturers have refused to honor warranties if engines have been used with mogas even though the FAA has publically approved of its use (Berry, 2000a; Berry, 2000b; *Fuel for general*, 2008; Gallagher, 1998). In the supply chain, avgas has a dedicated fuel production and distribution network (Hemighaus, et al., 2006, p. 74; *What drives*, n.d.). This type of set-up is expensive for the oil companies to maintain since production facilities must be cleaned thoroughly after each avgas run, and holding tanks and trucks, rail cars, or barges must be assigned exclusively to avgas due to its lead content and the possibility for cross-contamination with other petroleum products (Hemighaus, et al., 2006, p. 74; *What drives*, n.d.). The upside is that this system helps refiners to track avgas' quality throughout the supply chain (Hemighaus, et al., 2006, p. 74). Fuels used in aviation are under stricter regulations than automobile gasoline and must not contain any particulate matter, water, or other contaminants or it must be shipped back to a refinery for reprocessing (Hemighaus, et al., 2006, p. 77). Liability linked to quality controls explains part of why only just over 120 FBOs out of more than 3,650 have mogas tanks on their fields in the U.S. (Visser, 2010; Misegades, 2010). Another reason entirely linked to the first include the fact that since so many services are provided to the FBO through their refiners contract: marketing support, credit card loyalty programs, fuel safety and management training courses, great insurance coverage for the fuel portion of their operations, that risking losing these amenities to put in an autogas fuel tank not recommended by their refiner is incentive enough not to put in the extra tank (anonymous, personal communication [telephone call], February 25, 2010).

Finally, there are a number of external threats that exist for the use of mogas as a leaded avgas alternative. Gasoline producers and vendors have been distributing Reformulated Gasolines (RFG) with ethanol mixed in it at 10 % or more in recent years. Fuel producers were at first required to mix oxygenates in fuel like ethanol or methyl tertiary butyl ether (MTBE) through the 1990 Clean Air Act (*Ethanol-blended fuels*, 2008). The Energy Policy Act of 2005 repealed this wording so that fuel producers were no longer obligated to add oxygenates to fuel (Energy Policy Act of 2005, 2005; *Ethanol-blended fuels*, 2008). The deletion of these conditions was a positive decision for GA. Ethanol in particular is incompatible with aircrafts' fuel delivery system among other engine parts (see section *2.2.11 AGE 85* for more details) and would cause problems to aircraft that are certified to use premium unleaded automobile gasoline under the autogas FAA STC program as it is specifically stipulated that ethanol blended in the fuel is not approved (*Ethanol-blended fuels*, 2008; *Information: Fuel specs*, n.d.). The EAA estimates it would cost a minimum of $10,000 per aircraft to change parts that would be affected by alcohol exposure (fuel lines, any rubber or plastic parts, metal fuel bladders, metal fuel pumps, etc.) and redesign the fuel system (*Ethanol-blended fuel*, 2008). These costs may be acceptable for an operator if they are not much more than $10,000 as evidenced in the results of an informal survey sent to various LinkedIn aviation group sites in the beginning of January 2010 (See Appendix E for survey question and compiled results). However, the Energy Independence and Security Act (EISA) of 2007 in the subtitled section called "Ten-in-Ten Fuel Economy Act" (Energy Independence and Security Act of 2007, 2007), calls for the U.S. to phase in at least 15 billion gallons of renewable fuels like with grain-based ethanol by 2017 (Energy Independence and Security Act of 2007, 2007; *Ethanol-blended fuel*, 2008). Oil refineries and refiners are incentivized to make RFG with ethanol and have created a specific blend stock designed just for the addition of ethanol called RBOB which is not of as high quality as regular or premium unleaded gasoline (anonymous, personal communication [telephone call], February 25, 2010; Petersen, 2008). As the amount of renewable fuels mandated by the EISA 2007 goes up every year, and since flex-fuel vehicles able to consume a petroleum blend with 85 percent ethanol have not massively hit the automobile market as the EISA 2007 oxygenate section was designed to favor, refiners have been obliged to find other places to put the renewable fuels or ethanol (anonymous, personal communication [telephone call], February 25, 2010; *The new reality*, 2008). This will and is causing accessibility problems to GA: the AOPA has estimated that 51 percent of mogas currently available in the U.S. is already blended with ethanol as of March 2008 (*AOPA working*, 2008). Some aircraft engines are able to tolerate a 10 percent blend of ethanol and gasoline, namely low horsepower Rotax 912 and 914 models greatly used in LSA flying (anonymous Rotax employee, personal communication [telephone call], February, 2010). To combat the eventual eradication of regular and premium unleaded autogas, the only solution is to actively lobby against it by putting pressure on State legislature to make exceptions for it to not be blended with ethanol in their State laws. As this issue is not exclusive to mogas aircraft users, EAA recommends gathering forces with boaters, snow mobilers, and lawn equipment users (*Ethanol-blended fuel*, 2008). The EAA also keeps a list of recommended actions and legislative wordings to be put into State law so as to protect the interests of aircraft and other users for regular and premium unleaded autogas.

Overall, mogas is a viable solution for low compression low octane-rated piston-powered, reciprocating engine aircraft. The STCs are inexpensive at only $1.50 to $2.00 per horsepower giving an approximate range from $60.00 for a 37 horsepower engine to $337.50 for one with 225 hp prices quoted from EAA's autofuel site (*Engine modes approved*, 2006; *Order here*, n.d.). An average 160 horsepower engine that can fly a four-seater aircraft would go for $320. Certain aircraft models demand fuel system modifications and can cost up to $3,850 (*Order here*, n.d.). Other costs include decals to placard the airplane appropriately, alcohol and vapor lock testers, and paperwork updating (*Order here*, n.d.; *STC application form*, n.d.). Total cost to the consumer is well under $5,000 for the most expensive models for the whole procedure and in many cases it may be much less as shown in the example pricing exercise based on EAA and Petersen Aviation prices in Table 2.

Table 2. "STC Pricing Exercise for Two Low-horsepower Engine Airframes"

STC Pricing Exercise for Two 160-horsepower Engine Airframes	EAA	Petersen Aviation, Inc.
Example 1: Cessna 172 with Lycoming O-320, 160 hp engine		
STC	240	320
Placards: Airframe	incld in pwk	12,5
Placards: Engine	incld in pwk	10
Paperwork	30	160
Tester: Alcohol	18	15
Tester: Hodges Volatility	Not available	65
Total	**$ 288,00**	**$ 582,50**
Example 2: Piper PA-28-161 with Lycoming O-320, 160 hp engine		
STC (requires modifications)	Not available	2750
Placards: Airframe		12,5
Placards: Engine		10
Paperwork		160
Tester: Alcohol		15
Tester: Hodges Volatility		65
Total	**N/A**	**$ 3 012,50**

Note. Prices from EAA.org's Autofuel website and Petersen Aviation, Inc.'s website.

Add on top of these figures the fact that autogas has been historically less expensive than avgas, and the mogas STCs appear even more financially interesting. Mogas is a fuel with much higher volume production and refiners and refineries are able to use pipelines, the least expensive manner of transporting fuel (Trench, 2001, p. 2). However, due to gasoline's fuel formulation which is much more dependent on crude oil prices than avgas as the latter is comprised more of manufactured synthetic components rather than straight-run distillates, autogas is much more susceptible to crude oil market fluctuations (*What drives*, n.d.). So long as this solution remains available despite threats from the application of EISA 2007 for ethanol blending built to support flex-fuel cars consuming E85, and given a better acceptance among oil companies, engine, and airframe manufacturers, including the FBOs that would have to be willing to provide an additional fuel tank (an expense which represents around $80,000 to $100,000 to purchase an average-sized 12,000 gallon tank and install it not including extra insurance coverage) (two separate aviation fuel tank contributors from Fuel Tech Inc. & Garsite, personal communication [telephone calls], February, 2010), at the risk of losing much needed marketing support and other bells and whistles, all of which may not be entirely likely due to liability risks linked to reduced quality control measures for automotive fuels, mogas could be an effective replacement for 70 to 80 percent of the GA fleet burning roughly 30 percent of today's total avgas consumption (*AOPA working*, 2008).

2.2.2 82UL. Another solution exists for low-compression piston-powered aircraft that doesn't involve all the associated liability risks as found with automotive gasoline: 82UL. The FAA approved of its use for all mogas-using 87 AKI STC'd aircraft in March 1999 (*FAA approves*, 1999). GA industry members initiated the creation of this unleaded low octane rated fuel with the intentions of eventually getting it approved to replace the leaded 80/87 that beginning in the mid-1980s began progressively disappearing (*FAA approves*, 1999; *New unleaded*, 1998). The process took ten years to get the ASTM D6227 specification, and to this day has yet to be produced (Billing, 2010; *FAA approves*, 1999; Hemighaus, et al., 2006, p. 56; *New unleaded*, 1998). As existing low compression engines do not have this fuel listed on their type certificates, 82UL would need to be STC'd for each engine and airframe model unless given a blanket approval by the FAA (anonymous, personal communication [telephone call], February 26, 2010). It appears that this type of approval was never sought perhaps because industry members had become convinced that a two-fuel system was no longer economically viable (Billing, 2010; Visser, 2010). If engines were designed for the use of 82UL, and if these engines had 82UL listed on their type certificates at the time of certification, there would be a potential demand for this product (Billing, 2010; Hemighaus, et al., 2006, p. 56). As it stands, the lack of interest in pursuing the use of this fuel, although potentially capable of solving the liability complaints from oil companies, engine, and airframe manufacturers for mogas users and it could cover 70 percent of the GA fleet representing 30 percent of current avgas consumption (*AOPA working*, 2008), indicates that 82UL will probably never be produced.

2.2.3 91/96 Hjelmco Oil. A 91-octane unleaded aviation gasoline that is a fully transparent drop-in solution for lower octane-rated aircraft (a.k.a. one that does not require any engine modifications in order to use the fuel) exists, is in full production, and is distributed on the general aviation market today (Dolph, 2008; Malone, 2006; Moscrop, 2007). News flash? Actually this fuel has 19 years of experience, 29 years total time if its first generation version the 80/87 unleaded is counted, and has accumulated millions of flying hours, but it is virtually unknown except for in ASTM and IAOPA circles (L. Hjelmberg, CEO of Hjelmco Oil, Inc., personal communication [telephone call], January 29, 2010; *Hjelmco Oil*, 2010). Indeed, major engine manufacturers such as Lycoming, Teledyne Continental, and Rotax have approved the use of this fuel in their engine service instructions, some as early as 1995 (L. Hjelmberg, CEO of Hjelmco Oil, Inc., personal communication [telephone call], January 29, 2010; *Hjelmco Oil*, 2010; Malone, 2006). What's more, the 91/96 Hjelmco Oil unleaded fuel meets all of ASTM D910 standards for the 91/96 and 91/98 specifications except for the color and the lead (L. Hjelmberg, CEO of Hjelmco Oil, personal communication [telephone call], January 29, 2010). The 91/96 UL sells for cheaper than its leaded counterpart by 10 percent (Bertorelli, 2010d) thanks in part to the fact its transportation costs are lower because it doesn't contain any lead, it is centrally distributed on the Swedish market (L. Hjelmberg, CEO of Hjelmco Oil, personal communication [telephone call], January 29, 2010; Malone, 2006), and up until recently, this unleaded avgas was able to take advantage of taxation legislation that allowed it to be exempt from either state or value-added taxes (Bertorelli, 2010d; Malone, 2006; *An unleaded future?*, 2009). Its fuels are sold through a franchise-type retail structure and they are also shipped to Japan where buyers take care of their own retail (Bertorelli, 2010d). Further advantages for the use of unleaded avgas under

Swedish civil aviation authority regulations, is that it allows engines using this fuel to increase their TBOs by an additional 50 percent which significantly reduces maintenance projections in operating costs (L. Hjelmberg, CEO of Hjelmco Oil, Inc., personal communication [telephone call], January 29, 2010; Malone, 2006).

Hjelmco Oil, Inc., is a family-owned company based in Sweden started in 1981 by Lars Hjelmberg, former President of AOPA Sweden (L. Hjelmberg, CEO of Hjelmco Oil, Inc., personal communication [telephone call], January 29, 2010; Malone, 2006; *An unleaded future?*, 2009). Prior to founding his company, Mr. Hjelmberg used to fly around Europe selling pharmaceuticals, mostly in Soviet-controlled Eastern Europe (Malone, 2006). He found that the price of avgas was much lower in these countries, and he began researching the market to find out why as "'The communists weren't known for giving the capitalists a break.'" (Malone, 2006). What he discovered is that "'The Russians were simply able to supply avgas more cheaply,'" (Malone, 2006), and they didn't use the lead (Malone, 2006). He decided to look into avgas formulations further for, as he explained in an article called "Avgas – time to panic yet? Part II" in *General Aviation* by Pat Malone: "'our original driver was cost rather than environmental concerns,'" (2006) and he soon after came up with his first fuel formula, the 80/87 UL, which received approval in Sweden in 1981 (L. Hjelmberg, CEO of Hjelmco Oil, Inc., personal communication [telephone call], January 29, 2010; Malone, 2006). Hjelmco Oil was able to gain ample market share for the introduction of his product for two main reasons: the major oil companies had already begun focusing on a one-fuel aviation gasoline strategy as lower octane avgas sales volumes had been experiencing a steady decline for several years and didn't mind exiting the market, and the timing for the introduction of his product was early enough in avgas history to be able to take over existing infrastructure (delivery tankers, tanks, and nozzles on the fields) (Malone, 2006). In addition, Hjelmco Oil unleaded products have been able to benefit from forward-thinking and environmentally-focused Swedish legislation that allows products of superior environmental quality to take precedence on the market over other less eco-friendly equivalents (L. Hjelmberg, CEO of Hjelmco Oil, personal communication [telephone call], January 29, 2010). This last fact also partially explains why 80/87 UL was superseded by 91/96 UL. Another reason is that the latter fuel version could cover more of the GA market using its higher octane rating (Malone, 2006).

With all the positive attributes this fuel purports, it is difficult to understand why it hasn’t been more widely accepted in Europe, the U.S., or other parts of the world. The answer may be threefold: Mr. Hjelmberg never patented his formulas so as to better, paradoxically, protect them; his fuels were presented to the consensus-driven ASTM board to begin standardization but his proposal did not gain support to begin the process (L. Hjelmberg, personal communication [e-mail], February 24, 2010); and, as the U.S. avgas market has never been required to use an unleaded fuel, there has not been any demand for 91/96 unleaded Hjelmco Oil. The last reason is quite the industry’s argument as to why none of the other lower octane unleaded fuel formulations like 82UL or 91 under ASTM D6227, have ever been launched on the market (Orr, 2009). Many members agree that the political landscape has changed and whether or not the U.S. GA market is ready for an unleaded fuel, its use will likely be imposed (several anonymous contributors, personal communication [telephone calls], February – March, 2010). Had this fuel been accepted a few years back, right around the time the Clean Air Act of 1990 banned lead in autogas, newer engines in their newer planes would have been able to be designed to run on it already. In its current form, 91/96 UL cannot cover the 30 percent of the GA fleet that consume most of the avgas and need all of the octane boost (*AOPA working*, 2008). Articles have been hinting at, and Mr. Hjelmberg in interviews too, that his company is working on new fuel formulations to address the need for a 100-octane unleaded aviation gasoline via the use of environmentally-friendly octane-boosting additives (Gallagher, 2009; L. Hjelmberg, CEO of Hjelmco Oil, personal communication [telephone call], January 29, 2010; Moscrop, 2007;). Given Hjelmco Oil's proven experience using unleaded fuel variations, and given any future higher octane unleaded fuel formulation follows regulatory procedures and finds refineries willing to produce it, the political environment may be primed to finally create demand for his product.

2.2.4 94UL. Sometime this year a 94UL ASTM specification is expected to be approved and many industry members have concluded that it is the fuel of the future, even though these same members agree that it will neither cover the entire GA fleet as desired, nor will it be implemented seamlessly (Misegades, 2010; multiple anonymous contributors, personal communication [telephone calls], February 8 to March 1, 2010). The fuel formulation is essentially 100LL without the lead that meets the existing ASTM D910 standard except for the lead criteria (Bertorelli, 2009b; Hirschman, 2008; Visser, 2010). Once approved, engine manufacturers will be able to design to this fuel spec and it appears one major one has already begun to do so (Bertorelli, 2009b; Bertorelli, 2009c). Teledyne Continental has developed a turbocharged high horsepower engine, the TSIO-550-G, which once consumers of its turbo-normalized version reach their TBO as some of them are expected to do in the near future (Bertorelli, 2009c), owners will have the choice of installing a new factory engine able to create as much power as their previous one while ensuring safe operations on an unleaded, lower octane fuel (see *Glossary of Terms and Abbreviations* for turbocharge and turbo-normalize definitions) (Bertorelli, 2009c). Industry believes this fuel will cover around 80 to possibly 95 percent of the fleet and that the remaining five to 20 percent may be able to use hardware adaptations such as FADEC or spark-ignition management systems (see description of this hardware in section *2.2.8 Hardware Solutions: FADEC & Spark-ignition Management Systems*) to safely use 94UL without detonating (anonymous, personal communication [telephone call], February 23, 2010; Hjelmberg, 2009).

These hardware applications would cost upwards of $10,000 in order to prevent detonation (Ells, 2006), although some smaller independent companies that create spark-ignition management systems could sell their products for a third of the price though they are currently only available to the experimental and homebuilt market, but using mainstream engines (*Light Speed Engineering's*, 2000). Keeping the price around $10,000 or lower appears to be an acceptable cost to the consumer according to the results of a tiny sampling of interested parties in an informal survey designed to prompt discussion in aviation-related groups on LinkedIn (See Appendix E for breakdown of these results from the one-question survey entitled "Avgas Alternative Retrofit Kit"). Current FADEC systems have not been designed with the intention of preventing detonation while using 94UL in the place of 100LL, but it is expected that this type of application would work (multiple anonymous contributors, personal communication [telephone calls], January 29 to March 4, 2010). Other considerations include fuel flows as these may be modified from performance data derived when these engines were originally certificated and changes in fuel flow may affect its detonation margin and how the engine is cooled. When engines are certified they must be calibrated to have a 12 percent margin in fuel flow above that which causes knocking in order to pass testing and obtain type certification (anonymous, personal communication [telephone call], February 23, 2010). For engines that were designed at higher compression ratios to really get the best performance from 100LL, using a fuel below this octane would remove the engine's fuel flow detonation margin and if 100LL were discontinued, these engines would either need to become de-rated or obsolete (anonymous, personal communication [telephone call], February 23, 2010). De-rating an engine brings complications to those who might wish to do so as it ultimately requires more money to carry out additional testing to see how the de-rating affects all the performance parameters, namely fuel flows, useful load, takeoff data, power settings, engine cylinder head and exhaust temperatures, etc. (multiple anonymous contributors, personal communication [February 24 to March 1, 2010; C. Gonzalez, personal communication [telephone call], March 4, 2010). However, Teledyne Continental believes most of their engines will be able to operate safely on 94ULwithout any hardware applications (Bertorelli, 2009c, multiple anonymous contributors, personal communication [telephone calls], February 8 to March 1, 2010). Not all members are convinced nor agree with this approach, and contend that it is better to continue testing and perhaps wait for newly released fuel formulations to prove they can provide a full drop-in solution (anonymous, personal communication [telephone call], February 25, 2010). If however, the 94UL approach is taken, designing engines able to produce necessary power on a lower octane unleaded fuel, since logically the 30 percent of the engines consuming the majority of the avgas can be expected to reach TBO in a faster timeframe somewhere in the order of four to 10 years (anonymous, personal communication [telephone call], March, 1, 2010), and granted the engine manufacturers receive certification for each engine and airframe using the new fuel, these engines could potentially replace the higher octane rated engines at TBO. The 94UL fuel may be an alternative given oil companies agree to produce it and industry members create the demand for it.

2.2.5 Ultra Low Lead100 LL. Ultra low lead 100LL is an idea among industry members to create an intermediary fuel containing a portion of the lead found in the regular 100LL and blending in an octane-boosting additive that would help to bridge the gap between 100LL and a future fully unleaded fuel (two anonymous contributors, personal communication [telephone calls], February 26 & March 1, 2010: C. Gonzalez, personal communication [telephone call], March 4, 2010). It is not an idea that is highly publicized to date but it is discussed in industry stakeholder circles. Ultra low lead 100LL fuel would remove approximately 20 to 50 percent of its current lead content and then blend in a particular oxygenate to make up for the octane difference (C. Gonzalez, personal communication [telephone call], March 4, 2010). This oxygenate would not be ethanol, but it would be derived from the same bio feed stocks: ethyl tertiary butyl ether (ETBE) (*Fuel ethers supply*, n.d.; C. Gonzalez, personal communication [telephone call], March 4, 2010). An ASTM specification for ETBE should be approved by this summer and work can be begun on creating a fuel spec using the existing D910 standard and combining it with the future ETBE standard (anonymous, personal communication [telephone call], February 26, 2010; C. Gonzalez, personal communication [telephone call], March 4, 2010). Those who support this step-down approach find that in this way existing infrastructure for leaded fuel will continue to be kept in place while a completely unleaded or bio derivative seeks standardization. It allows industry to gain experience with new additives and fuel formulations to eventually develop other fully unleaded versions once the altered formulas have been validated and deemed safe (C. Gonzalez, personal communication [telephone call], March 4, 2010). Should the removal of half the lead from new fuel formulations prove to be inadequate, unreliable, or unsafe, the possibility of reverting back to the fully leaded 100LL fuel could be done, worst-case scenario, more easily than if the infrastructure for producing this fuel were entirely removed (C. Gonzalez, personal communication [telephone call], March 4, 2010). Those who do not support this approach believe that investing in this intermediate fuel would distract the industry from achieving its ultimate goal: introducing an unleaded avgas so that equipment manufacturers can begin producing engines and airframes adapted to it thus creating demand for it (anonymous, personal communication [telephone call], March 1, 2010). The GAMA-led FAST group must consider these arguments and direct industry accordingly, keeping in the forefront the experience gained from the changeover from 100/130 to 100LL in the 1970s (C. Gonzalez, personal communication [telephone call], March 4, 2010). Ultra low lead 100LL appears to be a logical course to follow, moreover since the FOE petition and the EPA have not obligated that lead emissions produced from the use of aviation gasoline be completely zero, only that the possibility of reducing lead be pursued (*Friends of the Earth*, 2006; *Petition requesting*, 2007; C. Gonzalez, personal communication [telephone call], March 4, 2010). If stakeholders bought into the safety cushion the ultra low lead 100LL approach could provide, and the potential extra expense it may incur for the additional time and money that would be spent on the ASTM specification process and the FAA certificating testing that would ensue, this appears to be a safe and viable alternative. Furthermore, if enough test data is collected early in the ultra low lead 100LL's development that proves to the FAA it is a drop-in solution, intermediary or not, it could result in the much sought after blanket approval.

2.2.6 Swift fuels: *100SF*. In April 2008, Swift Enterprises introduced a new bio-derived synthetic fuel formulation that had a higher than 100 octane performance number and proclaimed it would be a drop-in fuel replacement for 100LL (*Swift Enterprises introduces*, 2008). The name of the fuel is 100SF and it is called a binary fuel as it is composed of only two chemical components (anonymous, personal communication [telephone call], February 23, 2010). To produce this fuel, first a high carbohydrate source is needed like sorghum, switch grass, sugar beets, or even plant waste (*Alternative fuels*, 2009; Bertorelli, 2009a; Sargent, 2009). Second, it is converted it into an oxygenate or an alcohol followed by a reaction that further transforms the elements into one or more hydrocarbons in two steps (*Alternative fuels*, 2009). The result is what co-founder John Rusek calls "a selective component." (*Alternative fuels*, 2009). Rusek further describes this component and major element in Swift fuel of having a motor octane number of 136 (*Alternative fuels*, 2009). A second component is then derived during the refining process which contains a motor octane number of 92 (*Alternative fuels*, 2009). The blend gives a resulting 102 motor octane number (*Alternative fuels*, 2009), a bit better than 100LL. According to Rusek, bacteria or yeast contamination like that which can be a problem in biodiesel is not an issue with Swift fuel as the last two steps in the refining process expose the components to "high temperature reactors," (*Alternative fuels,* 2009) thus eliminating contaminants (*Alternative fuels*, 2009).

This fuel touts a number of desired attributes that sometimes surpass 100LL's capabilities but moreover it is said to meet ASTM D910 except for the lead content (*Swiftfuel benefits*, 2008). During full detonation testing carried out at the FAA's William J. Hughes Technical Center in January 2009, 100SF demonstrated better antiknock properties than 100LL in the highest octane rated engines in the GA fleet it was tested on (Atwood, 2009). This testing also found that 100SF was slightly heavier than 100LL by approximately one pound per gallon due to its higher mass, but it showed a higher energy content of around 13 percent per gallon over 100LL (Atwood, 2009). The fuel volumetric flow of 100SF compared to 100LL was reduced by eight percent meaning it gets better range than 100LL despite its heavier weight and thanks to its higher energy content (Atwood, 2009). It was found that a slight change in ignition timing would help 100SF get better power output if it were advanced three degrees so that the fuel would have enough time to burn properly in the combustion chamber (Atwood, 2009). This appears to be the only, very minor engine modification necessary in order to most effectively use 100SF that has been mentioned so far in its testing phase. The 100SF was found to have consistently higher exhaust gas temperatures at around 50°F compared to use with 100LL (Atwood, 2009). This explains the recommendation to discover how these raised temperatures affect engine components over longer endurance and flight testing (Atwood, 2009).

Consumer testing of the 100SF corroborates the laboratory tests: cylinder head temperatures run lower and exhaust gas temperatures run higher as experienced by AOPA's Senior Editor Dave Hirschman (*Alternative fuels*, 2009). He found no other apparent difference in aircraft performance (*Alternative fuels*, 2009). According to Swift Enterprises' co-founder John Rusek in AOPA's video interview during the AOPA's last summit in

November 2009, the higher octane is providing the engine with more power but it isn't completely burning the fuel and afterburning (*Alternative fuels*, 2009). This can be resolved as described above through advancing the ignition timing (*Alternative fuels,* 2009; Atwood, 2009).

Swift Enterprise's 100SF has been moving forward quite rapidly in the standardization and certification process. Full detonation testing was completed in January 2009 and test fuel status was granted by the ASTM board in December 2009 (Wood, 2009). Achieving the latter signifies that 100SF has officially begun the certification process which should take around two years before it can get an ASTM specification (*Alternative fuels*, 2009; P. J. Catania, personal communication [telephone call], February, 2010). Swift Enterprises is equally enjoying finding key industry partners to assist it in this fuel's advancement including GAMI who provided the original testing data for the 100SF but who has also entered the 100 octane drop-in fuel race (Bertorelli, 2009e; Bertorelli, 2010a; *Synthetic avgas?*, 2008), Teledyne Continental who test flew the fuel in April 2009 (*Teledyne Continental Motors flies*, 2009), and most recently Embry-Riddle who has agreed to carry out the certification testing necessary to use 100SF on half of its Cessna 172 fleet (*Embry-Riddle*, 2010).

The issue with Swift fuel seems not to be whether it will succeed as a replacement but whether it will be a cost-effective solution for pilots (multiple anonymous contributors, personal communication [telephone calls], January 29 to March 4, 2010; Bertorelli, 2009a). Rusek argues that as there are only three major steps in the refining process of Swift fuel, and as oil refining requires many more processes, Swift fuel should be much less expensive to produce (*Alternative fuels*, 2009). He further contends that while petroleum-based fuels depend on the market and availability of one commodity, Swift fuels can be made from a variety of biomass sources like sugar cane, sorghum, sugar beets, plant waste, etc., but not dependent on food sources (*Alternative fuels*, 2009; Bertorelli, 2009a; Sargent, 2009). This would allow Swift fuel producers to play the markets to get the best priced commodity from a variety of sources, thus theoretically keeping the price low to the consumer (*Alternative fuels*, 2009). Rusek does not promise a cheaper price for Swift fuel, but he does maintain that it should be "comparable." (*Alternative fuels*, 2009).

Industry appears quite skeptical about the pricing structure of this fuel citing $60-65 per gallon laboratory scale prices (Bertorelli, 2009a; Sargent, 2008). However, Swift Enterprises maintains that once production is ramped up in several small refineries strategically located around the country, prices out of the refinery should be around $1.80 to $2.00 (Bertorelli, 2009a; Sargent, 2008). What's not discussed is how expensive it might be to set up production facilities as using bio-components depends on a completely different manufacturing process unrelated to crude oil refining thus not benefiting from the current network in this portion of the supply chain, nor how those costs will be transmitted to the customer. In addition, since 100SF does not contain any hazardous components, it hopes to use existing transportation infrastructure utilized by other unleaded fuels so as to further reduce costs (Hirschman, 2009). Once taxes and overhead are added to that price, 100SF could reach $4 to $5 per gallon which falls in line with current 100LL prices (Bertorelli, 2009a). It seems promising, indeed, as many industry members have agreed and time will tell if the economics for producing this fuel transpires (multiple anonymous contributors, personal communication [telephone calls], February 8 to March 1, 2010; Sargent, 2008).

2.2.7 G100UL. General Aviation Modifications, Inc. (GAMI), has recently entered the 100 octane unleaded fuels picture. GAMI is a highly advanced research center that does independent certification and testing for the general aviation sector (*Synthetic avgas?*, 2008). They have numerous hardware solutions for augmenting the efficiency of normally air-aspirated piston engines from fuel injectors to certified additional alternators to equipping engines with turbo-normalizing systems (*General Aviation Modifications, Inc.*, n.d.). In

December 2009, they decided to compile their knowledge gained from years of experience testing fuels (a procedure that must be done to ascertain whether the testing fuels are appropriately rated during equipment certification processes) and apply it to fuel formulation (G. Braly, personal communication [telephone call], February 23, 2010). After only one month of testing, they derived what they believe will be the future replacement fuel for 100LL as their formula meets the minimum 100 octane levels (Bertorelli, 2010b; G. Braly, personal communication [telephone call], February 23, 2010). Not much information is available on this fuel's formulation yet, but preliminary testing data confirms that it meets both octane levels and proper detonation performance (Bertorelli, 2010b; G. Braly, personal communication [telephone call], February 23, 2010). George Braly, co-founder of GAMI, declares that G100UL does not contain any toxic elements; however it does contain a component that is not currently produced in refineries (personal communication [telephone call], February 23, 2010; Bertorelli, 2009e). Mr. Braly says that GAMI is now working with a major refinery, and that the G100UL should have no infrastructure hiccoughs, it will be able to be mixed with today's 100LL, and it will be a transparent drop-in (personal communication [telephone call], February 23, 2010). The G100UL is slightly heavier than 100LL, but it gets 3.5 percent better range as it has this much more BTUs (Bertorelli, 2010b). In the online video on AvWeb on February 7, 2010, entitled *AvWeb Flies G100UL*, both Editorial Director Paul Bertorelli and GAMI co-founder George Braly explain that the G100UL will pursue an STC program for the turbocharged Cirrus SR22 as they find the ASTM-FAA procedure slow and cumbersome. As much information remains to be released on this fuel, it is too early to know exactly what the economics of this fuel formula will amount to in order to properly assess whether or not it will be a viable solution to the 100LL dilemma. Normally the G100UL should have to jump through the same standardization and certification loops as any of its other unleaded counterparts in order to get industry-wide acceptance and approval. The

G100UL is definitely a fuel to keep on the radar screen, particularly if it is able to prove performance that is both safe and reliable.

2.2.8 Hardware solutions: FADEC & spark-ignition management systems. Full Authority Digital Electronic Engine Control is a system that controls various engine parameters to improve the efficiency and performance of an engine while reducing pilot workload by using just one control lever (*FADEC*, 2010; *Full authority*, n.d.). It controls fuel injection and mixture control, ignition timing, cylinder head and exhaust gas temperatures, and provides fuel diagnostics and monitoring (*Full authority*, n.d.). FADECs require two separate sources of ignition system power to comply with FAA regulations, such as two buses or two batteries (anonymous, personal communication [telephone call], February 23, 2010). Although these types of systems were not necessarily originally manufactured with the intentions of allowing a higher octane rated engine accept a lower octane unleaded fuel and to keep it from detonating, major engine manufacturers purport that these FADEC systems will help in transferring into that type of environment (anonymous, personal communication [telephone call], February 23, 2010). There are different methods to control the engine from detonating either using FADEC or a spark-ignition management system: via knock sensors, cylinder pressure sensors, or other more automotive-based systems that have proven technology (anonymous, personal communication [telephone call], February 23, 2010). The major engine manufactures have begun certifying FADEC on their engines (Bertorelli, 2008; *Full authority*, n.d.). Smaller independent firms have developed versions of spark-ignition control that can be applied to the majors' engines: GAMI Prism system and Light Speed Engineering's ignition systems for instance (*Light Speed Engineering*, 2000; *Pressure Reactive Intelligent Spark Management*, n.d.). All of these types of systems should help existing engines to transfer to an unleaded environment that may contain less octane than previously has been experienced (anonymous, personal communication [telephone call], February 23, 2010). If a 100-octane replacement fuel is found, engines could still use these engine or spark-ignition management systems to increase their power output and performance (G. Braly, personal communication [telephone call], February 23, 2010). The downside is that these systems are costly starting at $10,000 or more (Ells, 2006) and not many piston-powered engines have been certified to use FADEC yet. GAMI Prism is not FAA certified on any system (*Pressure Reactive Intelligent Spark Management*, n.d.). The Light Speed Engineering version is for experimental or homebuilt aircraft only, but it is much less expensive than others at around $2,000 to $3,000 dollars per system depending on the engine model (*Light Speed Engineering*, 2000). FADEC and spark-ignition management systems are viable, albeit slightly onerous methods of keeping the engine from detonating that could help in the transition period from a leaded to an unleaded environment and thereafter be used in engines designed for whichever appropriate fuel will exist, to increase its efficiency.

2.2.9 Jet-A/Diesel piston or turbine engines. In recent years, diesel or Jet A technology has appeared on the piston-powered small aircraft market. There are many industry members who are staunch critics of diesel and turbine technology for this market for several reasons while others find it to be promising once it becomes more mature within the next five to ten years as more development and a better operations history has been accumulated (multiple anonymous contributors, personal communication [telephone calls], February 8, 26, & March 1, 2010). A diesel or a turbine engine, both of which can consume Jet A, could become sustainable alternatives to their avgas-consuming equivalents for airframes requiring engines with horse powers ranging from 135 to 500. These engines have lower fuel consumption and CO_2 emissions than avgas ones and depending on the model can have longer time between overhauls. Jet-A consuming engines also do not suffer from future fuel availability nor distribution problems in the U.S or around the world. Petroleum refineries produce jet fuel in much higher volumes: 21.4 billion gallons in the U.S. in 2009 equating to roughly 16 percent of total finished motor gasoline production supplied in the U.S. in the same year (*U.S. product supplied*, 2010a; *U.S. product supplied*, 2010b). Aviation gasoline is much lower at a mere 219 million gallons supplied for 2009 equaling 0.2 percent of motor gasoline figures (*Supply and disposition*, 2009). Moreover, many companies have been conducting research on bio-synthetic jet fuels which would eventually decrease dependence on crude oil, contributing to this fuel's sustainability (Grady, 2009). The downside to using a higher volume petroleum-based product is that it is more price sensitive to crude oil market fluctuations. However, at the time of this writing, jet fuel is cheaper at around $4.31 per gallon compared to avgas at $4.61 per gallon, nationwide average fuel prices taken from AirNav.com's website on February 28, 2010 (*Fuel price report*, 2010b).

Looking at turbine technology for its use in smaller aircraft, it is still quite new to this market and slow to gain acceptance even though many light turboprop engines have been in existence for fixed-wing aircraft from as early as the 1960s (*Forecast International*, 2009). There are only about three manufacturers who have very light small turboprop technology that produce shaft horsepowers in the 300 to 500 range which is a power output that would be competitive with both higher horsepower spark-ignition or compression-ignition engines (*Forecast International*, 2009). Some models are even lighter than their piston equivalents at only 215 pounds compared to 400 or more pounds in either types of pistons (*540 series*, 2004; *Forecast International*, 2009; *Product program,* 2008; *Products*, 2007; *Type certificate,* 2007). There are three negative points for using this technology: turbines burn the same amount of fuel regardless of the power setting, small turboprops still need to be certified in the airframe models desired by customers, and the acquisition costs for these engines is quite high starting at $140,000 or more per engine (*Forecast International*, 2009).

Focusing now on diesel piston-driven technology, there is a factor that should be taken into consideration while burning jet fuel: its ASTM specifications do not regulate the fuel's cetane number (C. Gonzalez, personal communication [telephone call], March 4, 2010). Whereas octane defines an aviation gasoline's quality, diesel fuel's quality is linked to its cetane number. The cetane number is a "measure of the fuel's tendency to ignite" (C. Gonzalez, personal communication [telephone call], March 4, 2010), and Jet A, a fuel which is designed to burn in turbine engines, does not contain stringent specifications on its cetane number for its use in diesel engines (C. Gonzalez, personal communication [telephone call], March 4, 2010). One can hypothesize that this factor might affect the engine's overall efficiency even if the engines are equipped with FADEC systems, however, there was not much mention of this problem in non-scientific literature review.

There are other downsides that affect diesel technology in small aircraft. First of all they tend to have a higher power to weight ratio than air-cooled spark-ignition types due to the use of stronger metals designed to support higher compression and internal temperatures, the additional weight incurred through liquid cooling, and often a reduction gear box to reduce the RPMs going to the propeller for engines originally designed for automobiles (Bertorelli, 2009d: two anonymous contributors, personal communication [telephone calls], February 26 & March 1, 2010). This last reason is one related to what's called an engine's duty cycle (C. Gonzalez, personal communication [telephone call], March 4, 2010; Mac McClellan, 2009). A duty cycle is "the engine's typical expected operating range of rpm, power output and so on." (Mac McClellan, 2009). Automobile engines are designed to operate on a wider range of RPMs, they must be able to accelerate quickly, to idle smoothly, to cruise efficiently all while using only a small proportion of their maximum power (Mac McClellan, 2009). Airplane engines, on the other hand, act like stationary generators which must produce full "rated power continuously for long periods." (Mac McClellan, 2009). Automotive engines cannot typically sustain continuous operations at 75 percent of its maximum power output for very long which could ultimately affect this type of engine's longevity. This also explains why these engine designs require a reduction gear box: an automotive engine's RPMs are higher than that which a metal propeller can support (Bertorelli, 2009d). One such model adapted from a Mercedes Benz sedan engine requires a reduction from 4,000 to the 2,400 RPMs the propeller can withstand (Bertorelli, 2009d). Using automotive technology is not all negative, and Paul Bertorelli, Editorial Director of *The Aviation Consumer* magazine points this out quite succinctly in an article re-assessing diesel engines: "the automotive world brings one large advantage: the benefit of millions of Euros in research into cutting-edge diesel technology, specifically FADEC-controlled high-pressure common rail injection." (Bertorelli, 2010c).

Secondly, diesel technology loses efficiency as it is scaled down to small piston airplanes and can have problems with vibrations and other problems (anonymous, personal communication [telephone call], February 24, 2010: Bertorelli, 2009d). Thirdly, some models have difficulties operating at cold temperatures which in turn limits their service ceilings (Bertorelli, 2010c). Fourthly, pilots will need to exercise more precise speed control while landing (Bertorelli, 2010c). Fifthly, as this type of product is still in the early stages of its lifecycle curve, diesel technology has not yet hit major growth and very few airframe models have designed, tested, and been approved for these engines in either an original airframe or for retrofit kits. Sixthly, but linked to the last point, there are so few diesel engines in small piston airplanes that they haven't got much of a performance record and thus lack credibility in the eyes of the potential consumer. Seventhly, acquisition costs for these engines are high (they can range from $50,000 to $80,000) which can increase an operator's projected maintenance costs compared to a spark-ignition engine if TBOs are 1,000 hours or less (Bertorelli, 2009d, Bertorelli, 2010c; *Meanwhile*, 2010). These are factors that seem to be high up on the list of value drivers for purchasing an engine in a particular airframe as shown in an informal survey sent to piloting friends to measure their purchase criteria for a turboprop, canard-configured, composite aircraft (see Appendix F on *Value Drivers Survey*). TBOs are expected, and usually do increase with experience and necessary inspections which greatly decreases the projected maintenance costs factored into an operations hour, sometimes even having an engine pay for itself when fuel savings are added up (Bertorelli, 2010c).

As using diesel and turbine technology is still relatively new for the light small aircraft market of about ten years or so, these engines will probably have to wait a little longer before they start experiencing growth. It is a bit of a catch-22 for engine OEMs: it is difficult to prove to the discerning customer that these engines will have safe, reliable, and cost-effective operations without a verifiable track record. This can only be obtained over time and use which will also help improve these engines TBOs, effectively reducing operations expenses to the consumer. Moreover, the engine's acquisition costs will remain high until the volume of production is increased. However, if avgas reaches a certain price point, for example one anonymous contributor suggested $9 a gallon (personal communication [telephone call], February 8, 2010), diesel and turbine technology could look much more affordable. With 100LL under threat of extinction, diesel and turbine technology may find their big break to replace the high-octane rated, high horsepower piston-powered spark-ignition engines amounting to 68,000 aircraft making up 30 percent of the current GA fleet in the U.S.

2.2.10 Octane Enhancers from Crop Oils. A low-key yet active project to create a replacement additive for 100LL's tetraethyl lead is being accomplished through one of the FAA's centers for excellence called the Center for Excellence for General Aviation Research (CGAR) (*What is CGAR?*, 2005). CGAR is a consortium of GA members from industry, government, and aviation-related universities tasked with technology and research projects that address the safety and efficiency needs of GA air transportation (*What is CGAR?*, 2005). Dr Wayne Seames, Professor of Chemical Engineering at the University of North Dakota (UND) in Grand Forks, is leading a team studying crop oils to create an "aromatic-rich organic liquid product (OLP)" (*CGAR*, n.d.) that should replace the lead in the avgas formula, reach 100 octane, and do so without creating any additional undue impact on Mother Nature or public health (*CGAR*, n.d.). The project is called Octane Enhancers from Crop Oils and has been ongoing since 2008 (*Welcome to CGAR.org*, 2005). The feed stock currently being studied is soybean oil, but Dr. Seames affirms that any oilseed such as sunflower, corn, cotton, etc., would work (personal communication [telephone call], February 25, 2010). These feed stocks would ultimately produce heavy aromatics and cycloparaffins which are similar to hydrocarbons found in avgas as the base for the OLP (W. Seames, personal communication [telephone call], February 25, 2010). The team is now working on further enhancing its aromatic production process to achieve a higher octane blend stock (*CGAR*, n.d.). They are also preparing a Rotax 912 ULS engine (80 hp) for proof of concept testing in the lab (*CGAR*, n.d.). The project must produce results by August 2010, and if it does, which Dr. Seames feels confident it will (personal communication [telephone call], February 25, 2010), industry may discover yet another high octane unleaded fuel formulation to join the standardization and certification line-up with all the production and distribution efforts that entails.

2.2.11 AGE 85. Aviation Grade Ethanol (AGE) 85 is a fuel made up of 85 to 88 percent ethanol, biodiesel, gasoline, and other additives (*Commercialization*, 2000; Ells, 2006). Its study was initiated in order to replace 100LL since ethanol by nature has high octane levels (Johnson, 2006), but for various reasons this fuel never wrought popularity. It was developed by the Energy and Environmental Research Center's (EERC) National Alternative Fuels Laboratory® (NAFL®) in collaboration with American Society of Testing and Materials (ASTM) Ethanol Aviation Fuel Development Task Force and the University of North Dakota Odegard School of Aerospace Sciences, Baylor Institute of Air Science at Baylor University, South Dakota State University, oil companies, ethanol producers, airplane manufacturers, and other industry partners (*Centers of excellence*, 2009). By June 2005, AGE

85 had applied for ASTM specification status which is still under development today (Orr, 2009).

AGE 85 is a possible replacement fuel for avgas 100LL. It meets octane levels and thus detonation resistance, and enough testing has been carried out to show that an aircraft can fly while using it to the point of receiving four approved STCs for appropriately modified Cessna 152, 180, and 182 engines and airframes including a Piper Pawnee (J. Behnken, personal communication [e-mail], March 16, 2010; *Centers of excellence*, 2009; *Commercialization*, 2000; Helder, 2005; Johnson, 2006). There are, however, several issues with the use of this fuel that could potentially cost the industry billions in testing and certification since an aircraft needs to be specifically designed to use it (Visser, 2006). First of all, ethanol can be corrosive particularly when it has any water in it (J. Behnken, personal communication [e-mail], March 16, 2010; Johnson, 2006) on materials not compatible with it like those used in the legacy fleet’s fuel storage and delivery system made from aluminum, magnesium, copper, and pot metal (C. Gonzalez, personal communication [telephone call], March 4, 2010; Johnson, 2006). It dissolves plastics such as Lexan and Plexiglass used in certain fuel indicators, lacquers that can coat cork floats used in carburetors, and composites used for airframe structures after only one or two days if submitted to submerged soak tests (Johnson, 2006). Ethanol attacks elastomeric seals, hoses, and gaskets (C. Gonzalez, personal communication [telephone call], March 4, 2010). It can also damage adhesives used to join structural and wing tank parts together that are exposed to the fuel although the testing carried out to show this involved complete submersion of the parts whereas they may only experience “open-air splashing” (Helder, 2005). Secondly, ethanol will absorb water to a certain extent but if enough water is present to over-saturate the solution, it will separate from the gasoline and create a layer of ethanol and water at the bottom of the tank (Johnson, 2006). This can cause damaging power surges when the fuel mixture goes from the water and ethanol layer to a rich gasoline layer resembling a high power setting and suddenly speeding up the engine (Johnson, 2006).

Ethanol requires a couple of hardware modifications that do not appear to be overly strenuous if an engine and fuel system only want to be able to use AGE 85. Things like drilling larger jet holes in the carburetor or “backing out the idle mixture needle valve” (Johnson, 2006) are required to accommodate the extra fuel flow necessary in order to get the same power avgas provides (Johnson, 2006). The fuel flow issue is one of the more discouraging characteristics about AGE 85 as a higher fuel flow rate is required at around 30% to 48% more than its 100LL counterpart translating into reductions in range for a given quantity of fuel (Helder, 2005). However, if one wants to be able to better exploit ethanol’s properties, major changes that would augment the engines compression ratio, for example creating longer pistons, would be necessary requiring engineering (T. Aulich, personal communication [telephone call], February 23, 2010; Ells, 2006). Other modifications include adding fuel pumps even to gravity-fed systems, pump pressure regulators, and fuel return lines to help avoid vapor lock, and hardened valve and valve stems in cylinders (Johnson, 2006).

Operational differences apply too including changing how the fuel is sampled to be certain there is not phase separation in the tank and mixture settings and handling must be adjusted, particularly in reduced power operations where testing showed a tendency for the engine to quit (Helder, 2005) This is an undesirable trait during the landing phase especially if it should need to be aborted. The fuel shouldn’t sit in the tanks for extended periods like six months or more, but this is not a procedure any different than for a plane using automotive gasoline (Visser, 2005) as it will cause gumming of the fuel metering devices (Johnson, 2006). Lastly, ethanol has a lower Reid Vapor Pressure than 100LL avgas, so it has difficulties starting especially when temperatures are 20° F or lower (Helder, 2005; Johnson, 2006). To counter this, the engine either needs preheating (Helder, 2005) or a start canister linked to the start primer system using “plain gasoline” (Johnson, 2006).

Another reason and probably the main one why AGE 85 has not taken off is the fact that industry has simply not shown much interest in investing in this option, including the oil companies and corn grower associations who would produce this fuel (T. Aulich, personal communication [telephone call], February 23, 2010). Ted Aulich, Senior Research Manager at the Energy and Environmental Research Center attached to the University of North Dakota in Grand Forks who worked on the AGE 85 project, explained in a telephone interview on February 23, 2010, that although the FAA had encouraged the development of an ASTM standard, the ethanol and oil producers de-prioritized the program partly because aviation gasoline represents only 200 million gallons of production a year (T. Aulich, personal communication [telephone call], February 23, 2010). As the EISA 2007 mandates oil companies to blend relatively high levels of renewable fuels such as ethanol in automotive gasoline, and as the ethanol producers are limited in the amount of ethanol they can produce (T. Aulich, personal communication [telephone call], February 23, 2010), high percentage ethanol as a fuel for the aviation sector has fallen by the wayside.

The multiple hardware, operational, and performance issues related to the use of AGE 85 make it less interesting as an alternative to avgas 100LL. A specification for this fuel is still waiting for approval (Orr, p. 25, 2009), and certification to use this fuel in additional aircraft engines and airframe model combinations is not currently underway (T. Aulich, personal communication [telephone call], February 23, 2010). It is not clear as well whether this type of fuel would need a whole new and adapted infrastructure or if it would be partially able to take 100LL’s place in designated distribution facilities (Visser, 2006). Had it been invested in, it would have been cost effective at the pump at just $1.30 per gallon in the year 2000 South Dakota prices versus the average avgas price plus taxes of $2.39 in the same period according to AGE 85's commercialization outline (AOPA, 2001; *Commercialization*, 2000).

2.2.12 Car racing fuels. Although car racing fuels share similar octane needs to avgas and even though they have developed some high octane rated unleaded fuels, this is not a sustainable solution for GA's legacy fleet. As Mike Miller, Head of racing fuels at Sunoco explained in a telephone interview in January 2010, Sunoco used to sell avgas yet they stopped since they got "lousy margins" and because they wanted to focus more on serving the racing community especially after winning their NASCAR contract. If avgas starts at $4.61 per gallon which is today's nationwide average as shown on AirNav's Fuel Price Report based on reported prices of 3,639 FBOs, a historically already expensive price for the pilot or operator, car racing fuels sell for $2.40 to $22.40 more per gallon than aviation gasoline (Fuel price report, 2010b; M. Miller, Head of racing fuels at Sunoco, personal communication [telephone call], January 2010). In comparison, jet fuel and mogas average $4.31 and $3.34 a gallon respectively nationwide February 28, 2010 prices (*Fuel price report*, 2010b).

If however, general aviation needed to resort to the option of purchasing highly priced unleaded high octane fuels from a dedicated car racing fuel provider, the fuel provider would first need to be convinced of any incentives for producing and distributing to the aviation community in order for them to want to ramp up production. Once the supply was secured, the aircraft owner or operator would need to proceed with a testing program to get the unleaded fuel approved for use with their engine and airframe probably via an accepted FAA STC type of approach. It doesn't seem likely that aircraft owners and operators would approach car racing fuel providers to begin with, as the price of the fuel would be too discouraging. It seems the reverse is true as well since margins to the fuel provider would not be quite as promising as those made from car racing fuel prices.

2.2.13 Solar planes & electric hybrids. Other solutions to the leaded avgas conundrum that merit reflection yet are still in developmental phases and do not actually solve the legacy fleet's energy source problem, include solar powered aircraft or electric-solar-petroleum hybrids. These aircraft are designed using carbon composite airframes and typically seat no more than two people. There are green-sponsored competitions that exist to encourage participants in solar, electric, or bio-fuel design development such as the CAFE Foundation contests (*CAFE: Comparative aircraft*, 2009). Otherwise private investors make up the remainder of funded research. One such company is called Solar Impulse who is designing a solar-panel battery charging aircraft with a wingspan the size of an Airbus 340 or a Boeing 747 and it will seat two (Smith, 2009). The project is lead by a team in Switzerland with the French adventurist Bertrand Piccard and CEO André Borschberg at its head (*Founders*, n.d.). Their goal is to fly around the world after 2012 using only solar energy (*The main stages*, n.d.; Smith, 2009). Solar Impulse is currently working on a prototype called the HB-SIA to validate computer generated design and solar energy storage in an intermediate step to achieving its 2012 flight (*The HB-SIA's mission*, n.d.). Although the aircraft does not incorporate a practical design for ownership, the project should result in much needed advances in better electrical storage capabilities via the transformation of solar energy to enhanced batteries for powering engines.

As renewable energy and less dependence on fossil fuels ideas continue to retain center stage, more and more alternative energy technological projects and companies appear. One such example is with Bye Energy's George Bye who is in initial stages of creating an electric-petroleum hybrid engine under the banner "The Green Flight Project" (Bye Energy's, 2010). Mr. Bye hopes to find partners interested in using his lightweight 168 hp engine in an airplane equipped with photovoltaic solar panels with the goal of reducing exhaust emissions, noise, and maintenance costs (Bye Energy's, 2010). Another example is with LISA Airplanes based in France. It has an aircraft called the Hy-Bird that combines hydrogen and oxygen to power the fuel cells of an electric engine and also uses solar panels to recharge its batteries (*Hy-bird*, n.d.). Many of the concepts and projects mentioned in this section will not likely help power the legacy fleet of aircraft once leaded fuel is taken off the market, yet these innovations and the entrepreneurs behind them will soon capture the attention of the next generation of flyers.

Conclusion

General aviation provides a service to society whether it is flying in the furtherance of business, medical flights, humanitarian missions, training, or for recreation. The impact this industry has on the rest of society is largely positive including contribution to a strong trade balance in the U.S. with $4.6 billion in exports representing more than 50 percent of U.S. GA airplane manufacturers sales in 2009 (GAMA, 2009). This figure is included in the $150 billion total economic output in direct, indirect, and induced benefits the GA sector produces (NEXA Advisors, LLC, 2009). Moreover, it employs more than one million people in high-tech, high-paying jobs (*GA: A vital tool in our economy*, n.d.). GA connects communities by giving convenient access to ten times more public-use airports than commercial aviation; moves 166 million passengers a year; and enables businesses to deliver products and services, gives them a competitive edge for making deals, and raises productivity and the quality of life of its users of which two thirds are staff or middle managers (*GA: A vital tool in business and industry*, n.d.; *GA: A vital tool in transportation*, n.d.). The statistics above focus on the U.S. market since it happens to be the largest GA market in the world; however, many of these same benefits apply to international GA markets. Steps have been taken to create more sustainable bio and synthetic jet fuels to decrease exhaust emissions, the negative impact its use has on the environment, and participate in energy security. The same actions need to safely take place for all the general aviation piston-powered, aviation gasoline-consuming, 200,000-plus active aircraft in the U.S. and around the world today.

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Appendix A

Number of Airports in EU

Table A1*: Number of airports in 13 and 27 EU countries*

Number of Airports in 13 & 27 EU Countries			
	2005 Comparative study	2009 CIA World book	EUROCONTROL's 2007
	2000 pax annually min.	Total recognizable by air, used/unused	Data: Airports with at least
Austria	6	55	One IFR Departure in 2006
Denmark	12	92	(Note: covers more than 13
Finland	21	148	countries listed here: 27 in EU)
France	68	475	
Germany	33	550	
Greece	38	81	
Iceland	13	99	
Ireland	13	39	
Italy	36	132	
Norway	51	98	
Spain	36	153	
Sweden	44	249	
UK	58	506	
TOTAL	**429**	**2677**	**2087**

Sources: Williams, G. (2005, January). Comparative study of European airport provision.
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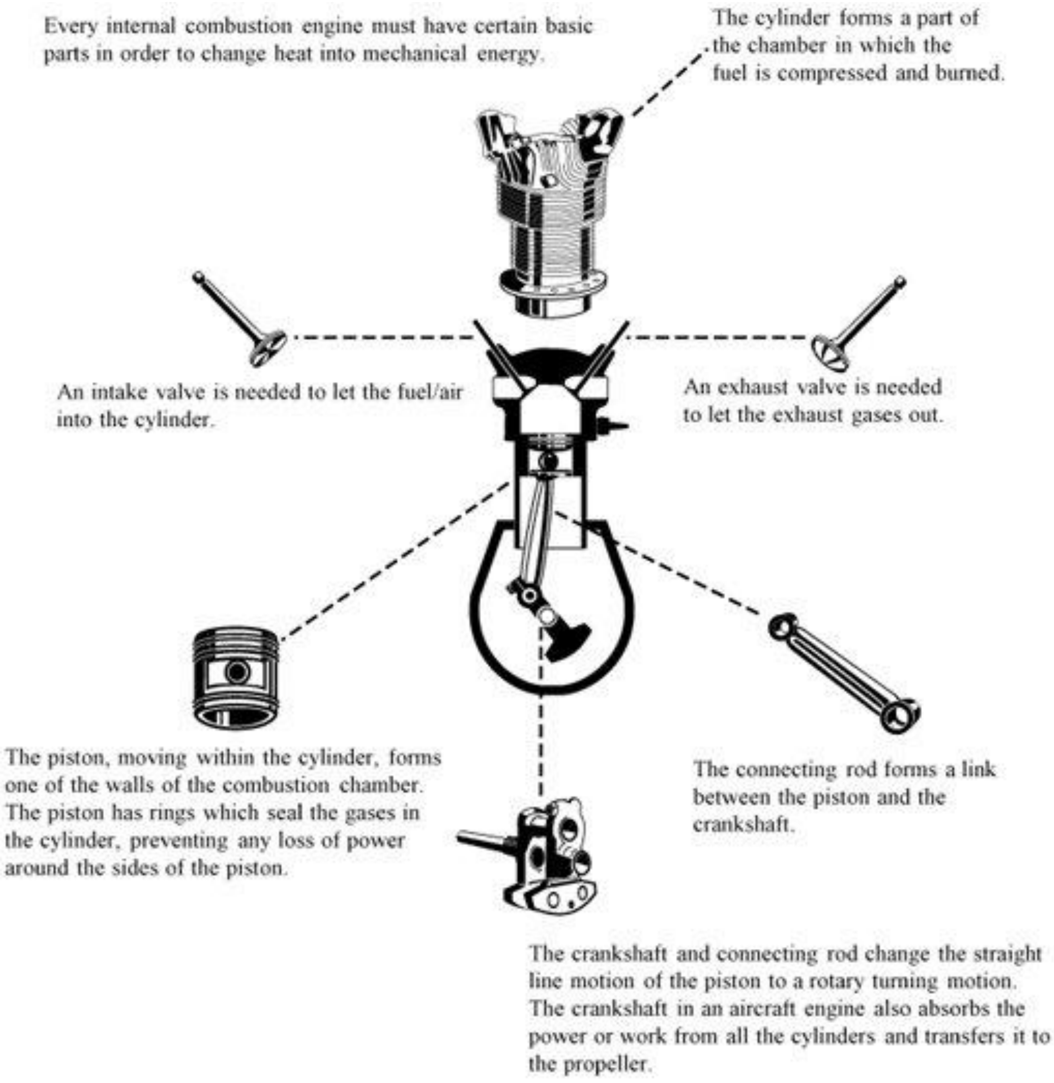
Appendix B

Basic parts of a reciprocating engine

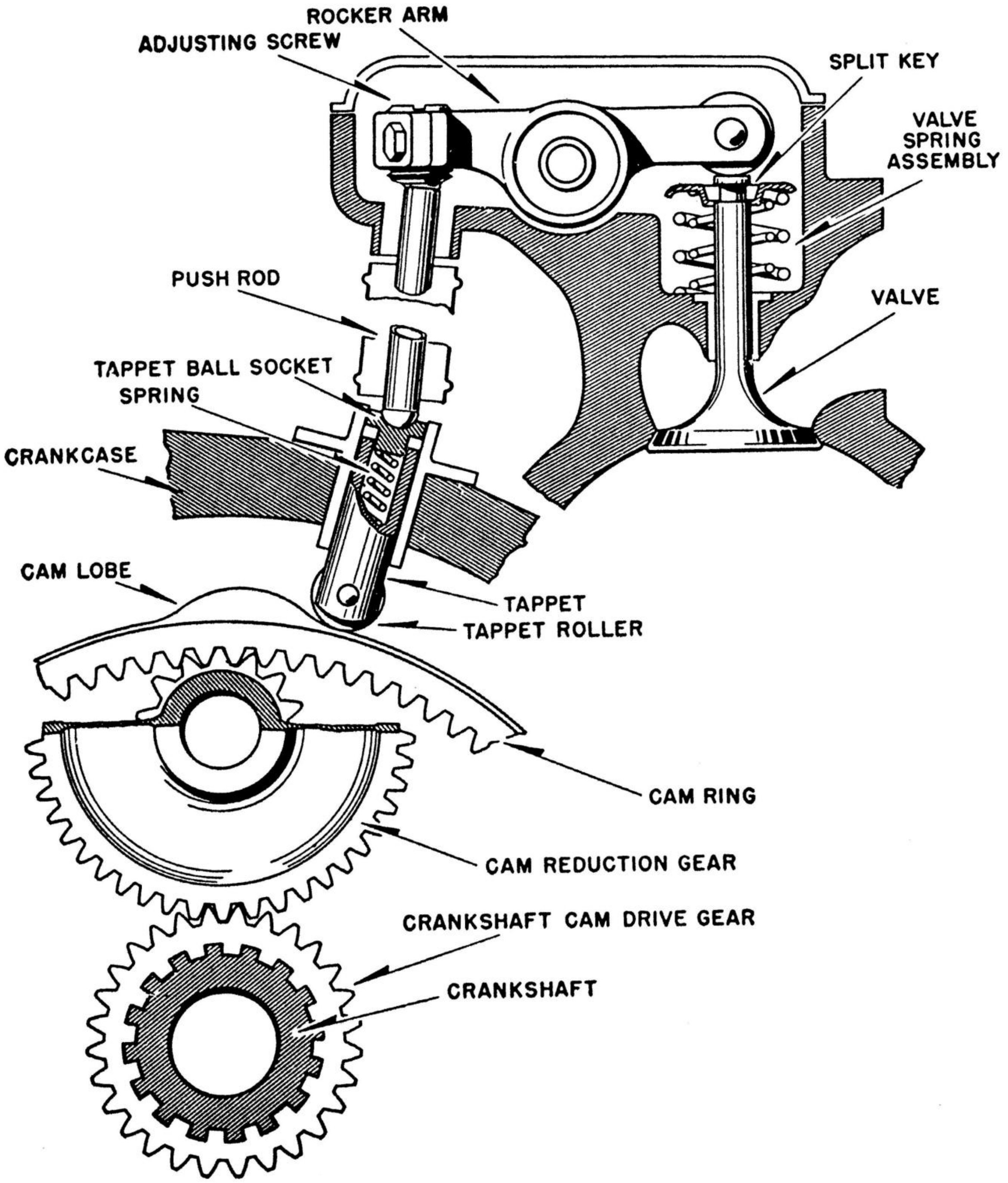


Note. Title of appendix quoted directly and figure from *Pilot's Handbook of Aeronautical Knowledge* (p.2-6), by U.S. Department of Transportation Federal Aviation Administration Flight Standards Service, 1997, Newcastle, WA: reprinted by Aviation Supplies & Academics.

Appendix C

Valve and Valve Seat

Figure C1. Example schematic of valve, rocker arm, and tappet assembly.

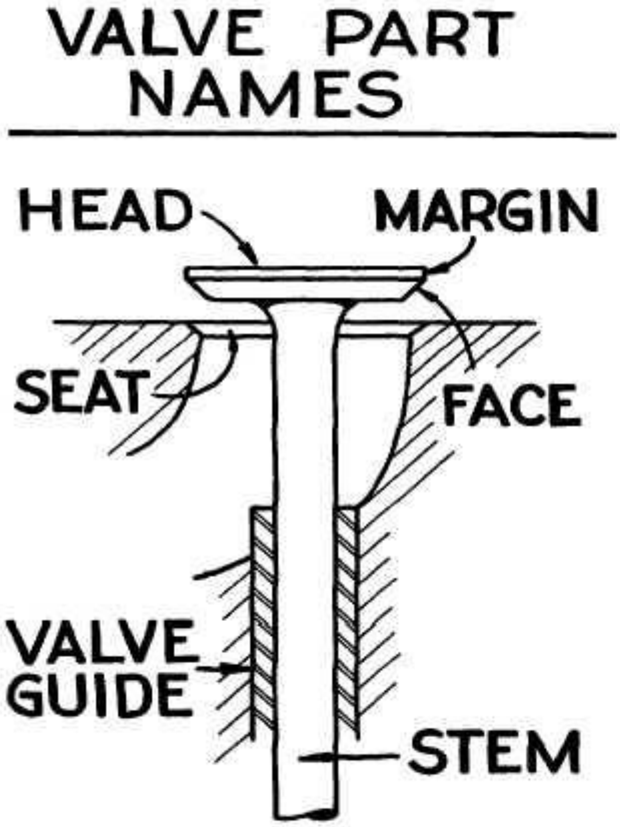


Note: From “Part 3 - materials and processes, small air-cooled engines” by G. Genevro, 2010, in *Air-cooled cylinders 3: An evolutionary odyssey*.

Appendix C

Valve and Valve Seat

Figure C2. Valve part names.



Note. From "Recovery Vehicles and Equipment," by Integrated Publishing: The most informative site on the internet, 2007, Port Richey, FL. Figure on public domain via Google search. Permission not requested.

Appendix D

List of Notes & Titles to Tables & Figures from GAMA's 2009 General Aviation Statistical Databook and Industry Outlook found at the end of this composition

Table D1. "Table 2.1. Active General Aviation and On-Demand FAR 135 Number of Aircraft by Primary Use by Aircraft Type (2008)." From GAMA's "2009 General Aviation Statistical Databook and Industry Outlook," p. 30. Reprinted with permission.

Figure D1. "Figure 2.1. Active General Aviation and On-Demand FAR 135 Aircraft by Type (2008)." From GAMA's "2009 General Aviation Statistical Databook and Industry Outlook," p. 30. Reprinted with permission.

Table D2. "Table 2.2. Active General Aviation and On-Demand FAR 135 Total Hours Flown (in Thousands) by Actual Use and Aircraft Type (2008)." From GAMA's "2009 General Aviation Statistical Databook and Industry Outlook," p. 31. Reprinted with permission.

Figure D2. "Figure 2.2. Active General Aviation and On-Demand FAR 135 Total Hours Flown (in Thousands) by Aircraft Type 2008." From GAMA's "2009 General Aviation Statistical Databook and Industry Outlook," p. 31. Reprinted with permission.

Table D3. "Table 2.3. Active General Aviation and On-Demand FAR 135 Aircraft by Type (1980-2008)." From GAMA's "2009 General Aviation Statistical Databook and Industry Outlook," p. 32. Reprinted with permission.

Table D4. "Table 2.4. Active General Aviation and On-Demand FAR 135 Estimated Hours Flown (in Thousands) by Type (1980-2008)." From GAMA's "2009 General Aviation Statistical Databook and Industry Outlook," p. 32. Reprinted with permission.

Table D5. "Table 2.5. Active General Aviation and On-Demand FAR 135 Aircraft and Average Hours Flown (in Thousands) per Aircraft by Type (2004-2008)." From GAMA's "2009 General Aviation Statistical Databook and Industry Outlook," p. 33. Reprinted with permission.

Table D6. "Table 2.8. Total Fuel Consumed and Average Fuel Consumption Rate by Aircraft Type Based on FAA's Survey (2008)." From GAMA's "2009 General Aviation Statistical Databook and Industry Outlook," p. 36. Reprinted with permission.

Table D7. "Table 2.9. Average Age of Registered General Aviation Fleet (2005-2009)." From GAMA's "2009 General Aviation Statistical Databook and Industry Outlook," p. 36. Reprinted with permission.

Appendix E

Avgas Alternative Retrofit Kit Questionnaire & Results

Survey Monkey one-question survey to stimulate discussion on the topic and results posted on multiple aviation-related LinkedIn sites (about 12) in January 2010.

Title of questionnaire: *Avgas Alternative Retrofit Kit*

Question: *If aviation gasoline 100LL was no longer available and alternate fuels required engine and fuel system modifications, how much would you be willing to spend on a retrofit kit in order to continue flying your airplane?*

Appendix E

Avgas Alternative Retrofit Kit Questionnaire & Results

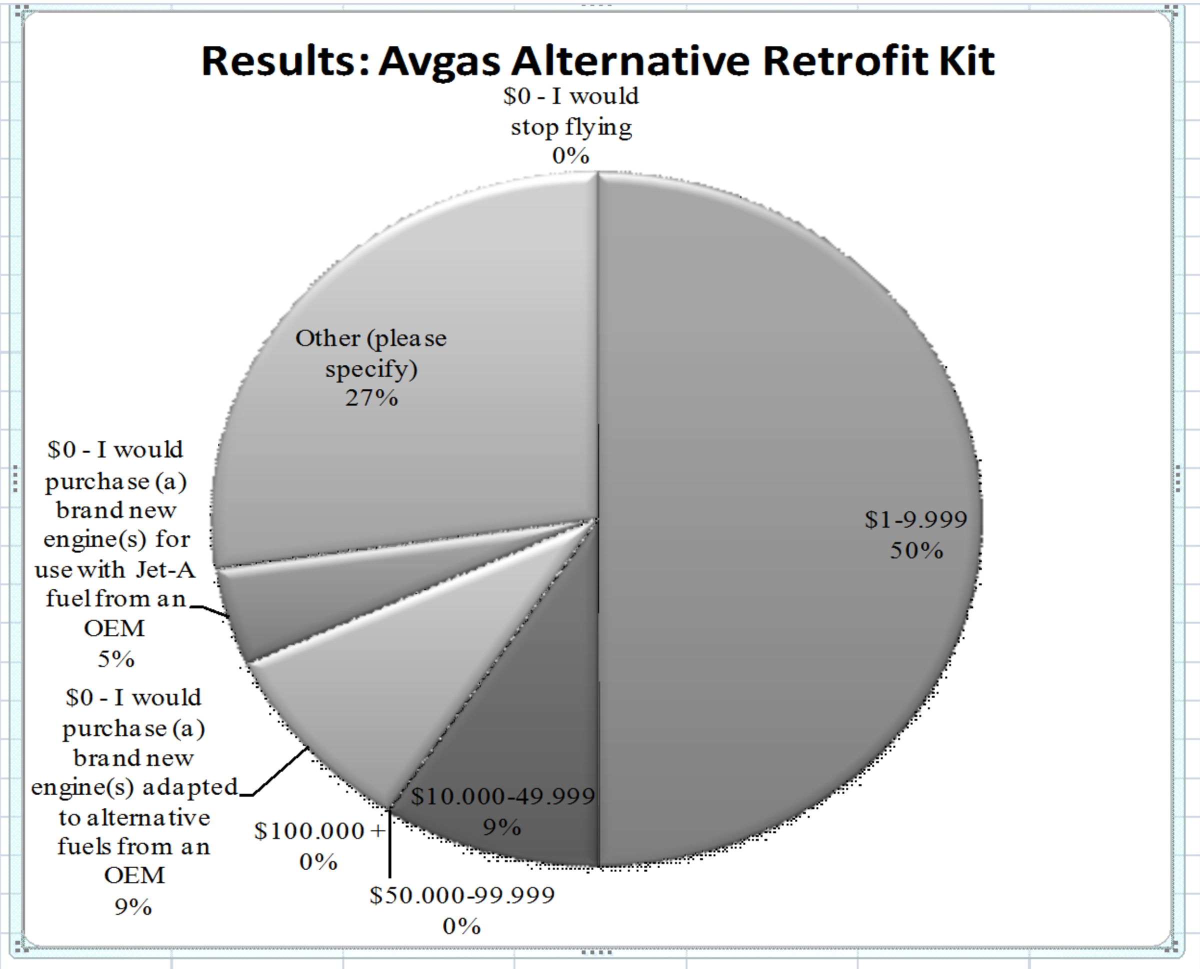
Table E1: Multiple choice responses and results to *Avgas Alternative Retrofit Kit* questionnaire

Response Choices	Response Percen	Response Count
$0 - I would stop flying	0,0%	0
$1-9.999	50,0%	11
$10.000-49.999	9,1%	2
$50.000-99.999	0,0%	0
$100.000 +	0,0%	0
$0 - I would purchase (a) brand new engine(s) adapted to alternative fuels from an OEM	9,1%	2
$0 - I would purchase (a) brand new engine(s) for use with Jet-A fuel from an OEM	4,5%	1
Other (please specify)	27,3%	6
"Your choices above are way too broad. I would be willing to spend up to $2500 on a fuel conversion. Anything more would be considered adverse to GA." Sat, Jan 9, 2010 12:16 AM		
"Over the life of the aircraft--the savings I would incur from making the retrofit to a new fuel source." Fri, Jan 8, 2010 12:47 AM		
"This depends heavily on the actual cost of the conversion. If it got to be 50% of the cost of a new engine I would simply buy a new one." Fri, Jan 8, 2010 12:19 AM		
"There will not be a "retrofit" kit for engines. They will require complete redesign with new parts to change compression ratios. It costs over $30k to overhaul a typical lycoming 6 cylinder engine. Peter Bunce of GAMA talked to us about this issue at the recent ICAS convention because this has severe impact to those us who fly with high performance engines although we are a small group. This is a made up problem with PPM's of lead in the air around airports. The question NO ONE can answer is what is an unacceptable amoount of lead to be considered dangerous." Thu, Jan 7, 2010 10:29 PM		
"I do not believe that the question can be evaluated as simply as you state it. Any purchase will depend on the economics of the retrofit/new engine alternatives. Price for performance/maintenance/fuel availability/regulatory operational requirements must all be factored in." Thu, Jan 7, 2010 7:29 PM		
"Up to 50% nof the aircraft value. If greater than that I would sell or scrap the aircraft and replace it with an aircraft capable of running on the available fuel." Thu, Jan 7, 2010 3:54 PM		
Total responses		22

Appendix E

Avgas Alternative Retrofit Kit Questionnaire & Results

Figure E1: Pie chart for *Avgas Alternative Retrofit Kit* results



Appendix F

Value Drivers Survey

Excerpt from Entrepreneurship paper entitled "Contradicting Dominant Design: The Canard Configured Civilian Co50" about Value Drivers Survey Results

> "Not knowing really what people looked for in this type of aircraft, I sent out my own little survey to a few pilot friends of mine to see what they thought. I had hoped to get ten value driver responses per respondent, but I also wanted to be sure to get enough surveys back to be able to use the results. So I asked people to only spend five to ten minutes completing the survey. Only two out of the ten surveys were completed to ten responses so a proper weighting for the statistics could not be done. Instead I reversed the ten-point scale so that the highest value that was 1 in the survey became 10 in the tallying." (Cloche, 2009)
>
> "The results came back with an average of 6.6 value drivers per person, so I decided to take into account the top six results. There was also one major mistake in the survey, in that I asked people to pretend they wanted to buy a turboprop and not a turbo-charged version of the plane. Regardless, I feel the results I received (since this was an imaginary test group) would be good for any type of private use single engine aircraft, but not necessarily for the niche business market [name of company] is pursuing. Speed and performance was the most important value driver, followed by initial cost, then useful load, maintenance projections and availability, interior options and number of seats and the last value was a tie between operational costs and range." (Cloche, 2009).

Appendix F

Questionnaire

Value Drivers Survey Questionnaire from Entrepreneurship paper entitled "Contradicting Dominant Design: The Canard Configured Civilian Co50"

In your opinion, what do you/your customers look for in a new single-engine, turbo-propeller, civil airplane?

Directions: Please list in the order of importance 1-10 (10 being the LEAST important), the features/specifications/services, etc., you or your customers look for in this type of aircraft purchase in the table below. Then put a 'weight' on the value (for example 10% for interior, 25% for after sales services, etc.). The purpose of this survey is to attempt to discover a customer's purchase criteria in this niche market by first sampling a small population (5-10) of people from various related backgrounds (meaning are currently pilots or training to become one but business sectors vary) and pool the results to come up with a list of 10 value drivers for single-engine, turbo-propeller, civil airplanes. You are essentially acting as my imaginary focus group (you are interested in purchasing this product) that in practice would be the first step in defining a customer's purchasing criteria before sending out massive surveys. This is an *informal* survey to help me write my papers, but the results may be interesting for you! (although some of you who work in aircraft sales have probably got similar types of information available to you in your marketing departments – willing to share?).

An incomplete sample has been done below to help put you in the right direction. This survey shouldn't take up too much of your time (5-10 minutes maximum!) and I would be very happy to send you the results once they are all in. If possible, could you send me your results by *Wednesday 11 February, 2009*?

Thank you very much in advance for your time and happy flying to all you out there who are lucky enough to be up in the sky!

Example list of values:

Value	**Rank**	**Weight**
Speed	2	35%
Resale value	1	40%
Range	3	25%
	Total	**100%**

YOUR OPINION: (double click on table to fill in form – then click outside to close)

Value	Rank	Weight
	Total	0%

Comments:

If you were purchasing a plane would you consider one of this type?

Does it matter to you whether your plane is made from fabric, aluminum (or any other metal alloy), or composite?

Do you feel having a lifting surface on the nose to prevent wing stalling is an interesting added safety feature or it doesn't really matter?

Appendix F

Value Drivers Survey Tabulated Results

Table F1*: Value Drivers Survey Results from Entrepreneurship paper entitled "Contradicting Dominant Design: The Canard Configured Civilian Co50"*

	RESULTS		
70	Speed/Performance	1	
45	Useful Load/Payload	3	
12	Resale Value	12	TIE
19	Fuel Burn/Economy	8	
30	Range	6	TIE
14	Avionics/Technology	11	
4	Insurance Coverage	16	
12	Stability/Maneuverability/How it flies	12	TIE
42	Maintenance Projections/Costs & Accessibility/Support	4	
33	Interior Options/Comfort/number of seats/size	5	
29	Safety	7	
47	Initial Cost	2	
30	Operational Cost/Hourly Costs	6	TIE
17	Reliability/Robustness	9	
9	Ergonomics	14	TIE
9	Class Qualification	14	TIE
10	Esthetics/aesthetics	13	
8	Financial Health of Manufacturer (staying power)	15	
16	Match between pilot's ability & airplane handling (non-c	10	
Average	6,6		