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Alternative Unleaded Fuels for General Aviation Piston Airplanes: A Pathway to Sustainability

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This position paper explores the transition from leaded 100 low lead (100LL) aviation gasoline to unleaded alternatives in general aviation (GA) piston-engine aircraft, motivated by environmental and public health risks underscored by the U.S. Environmental Protection Agency's (EPA) 2023 endangerment finding on lead emissions. Drawing on a comprehensive literature review and synthesis of sources, the study identifies and evaluates key unleaded fuel candidates: Auto Gas (Mogas), Swift UL94, GAMI G100UL, Swift 100R, and LyondellBasell/VP Racing UL100E. Each is assessed for regulatory status, engine compatibility, advantages, and challenges. The analysis also examines regulatory frameworks, such as the Federal Aviation Administration's (FAA) Eliminate Aviation Gasoline Lead Emissions (EAGLE) initiative targeting lead-free operations by 2030, alongside technical, economic, liability, and logistical hurdles. Findings highlight GAMI G100UL and Swift 100R as leading drop-in replacement fuel candidates, with LyondellBasell/VP Racing UL100E emerging as a contender under the FAA's Piston Aviation Fuels Initiative (PAFI). However, to make the transition to unleaded fuel feasible, the GA community in the US will need enhanced industry collaboration to overcome barriers, ensuring safe and viable GA operations amid projected piston-engine demand through 2043.

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Introduction

Background and Significance

The Clean Air Act (1970), passed by the United States Congress, required the phased removal of lead from most fuels. Currently, piston-driven general aviation (GA) airplanes operate on high-octane fuel that contains lead, also known as Avgas 100 low lead (100LL). Avgas/100LL is the last remaining fuel under the jurisdiction of the US Department of Transportation that contains lead. Lead has been recognized by the Environmental Protection Agency (EPA) to be detrimental to public health even in small quantities. Under court order in October of 2008, the National Ambient Air Quality Standard (NAAQS) dropped lead quantities by an order of magnitude from 1.5µg/m^3 down to 0.15µg/m^3 (Collin, 2006; EPA, 2010). Within the same year, the Friends of the Earth petitioned the EPA to determine if the lead in aviation fuel is a danger to public health (Friends of the Earth, 2006). In 2023, the EPA issued an "endangerment finding" under the Clean Air Act, determining that lead emissions from aircraft engines using leaded fuel contribute to air pollution that poses a risk to public health and welfare (EPA, 2023). Scientific research has linked lead exposure, even at low levels, to loss of intelligence quotient (IQ) in performance testing and to interference with brain development in children (Balbus, 2008).

Objectives

The objectives of this position paper are to 1) examine the status of the transition process to unleaded aviation fuel for GA piston engine aircraft, including regulatory, economic, liability, and distribution challenges; and 2) identify the most promising fuel candidates suitable to be used as drop-in replacements for 100LL fuel, evaluating their status, compatibility, advantages, and challenges.

Status of Leaded Aviation Gas

EPA Testing

In 2002, the EPA began conducting airport-specific lead emissions estimates and calculating the national inventory for lead emissions from leaded Avgas, utilizing methods to make the estimation of lead emissions like the methods used by the FAA to estimate inventories of other criteria pollutants emitted by aircraft in its Emissions and Dispersion Modeling System (EDMS) (EPA, 2008).

In addition to strengthening the lead NAAQS in 2008, the EPA enhanced the existing lead monitoring network by requiring monitors to be placed in areas with sources such as industrial facilities and airports with estimated lead emissions of 1.0 ton or more per year. According to the EPA (2023), monitored lead concentrations violated the lead NAAQS at two airports in 2012: the McClellan-Palomar Airport and the San Carlos Airport. However, at both airports, lead monitors were in proximity to the run-up areas, where the lead concentrations are expected to be higher and could have affected the results (Aircraft Owners and Pilots Association [AOPA], 2025; Santa Clara County Public Health Department, 2015).

The Role and Cost of Lead in Aviation Gas

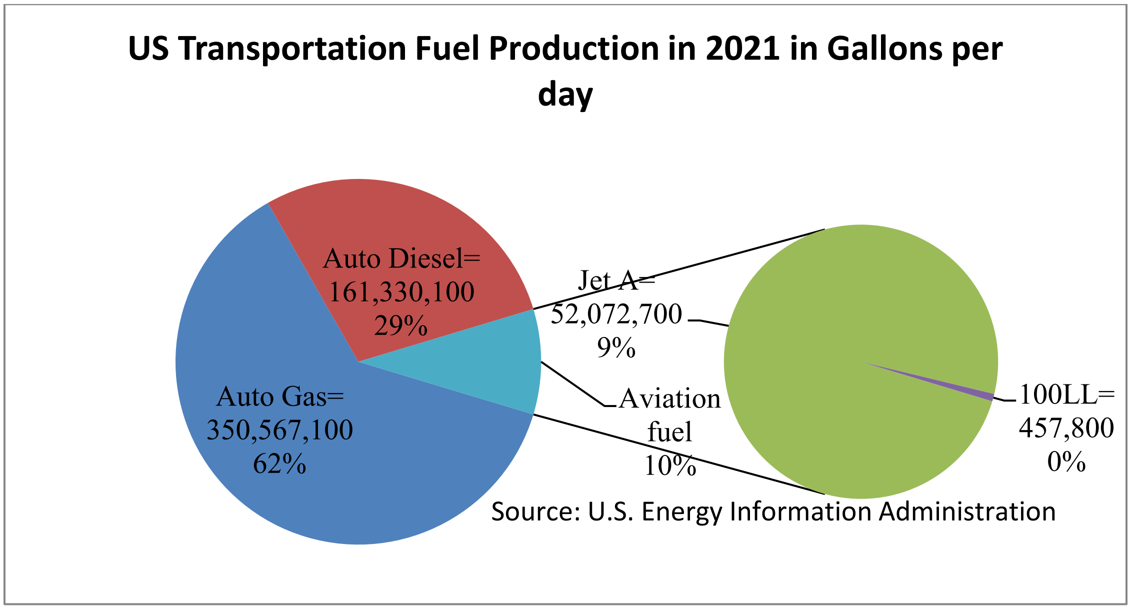
Removing the lead from aviation fuel has been technically challenging. The lead is added to the fuel in the form of tetraethyl lead (TEL) and is used to reduce the fuel's tendency to detonate or spontaneously explode under high loads, high temperatures, and high pressures, especially in high-compression air-cooled aviation engines. Sustained detonation could cause catastrophic engine failure. The lead additive helps boost fuel octane and prevents valve seat recession, which can be a significant concern from a safety standpoint. The maximum lead concentration specified by the American Society for Testing and Materials (ASTM) for 100LL is 0.56 grams per liter or 2.12 grams per gallon (Chevron Corporation, 2006).

TEL is only produced by one plant in the world, so there is no price competition. To make 100LL, the refinery takes alkylate and re-distills it, where it is then pumped into tanks, and two grams of lead are added to each gallon of fuel (Price, 2013). Batches of 100LL aviation gasoline are tested, and if the octane rating falls below the 100/130 specification, a toluene concentrate is added to raise the octane level in compliance with ASTM D910 standards, which define the required properties of AvGas (ASTM, 2011). Because 100LL is a specialty product containing lead, U.S. pipelines will not allow it to soil their pipes. Therefore, 100LL must travel by truck or rail, costing about $2,000 to ship 8,000 gallons 500 miles (Price, 2013).

Demand for Leaded Aviation Gas

The production of 100LL accounts for less than 1% of the total fuel production in the US, with approximately 457 thousand gallons per day as compared to 350 million for auto-gas in the U.S; therefore, aviation fuel is considered a "boutique fuel" (see Figure 1). North America is the primary market for both production and consumption of Avgas, producing 16 million gallons of fuel per year and consuming 17.5 million gallons per year. This type of fuel is already unavailable in some parts of Europe and Africa. It is estimated that by 2043, more than 50% of general aviation will be piston-powered aircraft, which means that aviation fuel will need to be produced to operate aircraft for at least the next 20 years (Ershov et al., 2023).

Figure 1
Fuel Production per Day in the U.S in 2024 in Gallons per Day (US Energy Information Administration, 2024).



Transition to Unleaded Aviation Gas

Efforts in Transitioning to Unleaded Aviation Gas

The transition from leaded aviation gas (Avgas), also known as 100LL, to unleaded fuel alternatives is essential, as the continued reliance on 100LL threatens environmental health, regulatory compliance, and future operational viability. In addition to the increasing global environmental issues, the dwindling global market demand for gasoline containing TEL has raised concerns regarding the continued use of 100LL by GA aircraft (AOPA, 2006).

In 2011, the FAA appointed the creation of the Unleaded Avgas Transition Aviation Rulemaking Committee (UAT ARC). The Piston Engine Aviation Fuels Initiative (PAFI) in 2014was established as a result of the recommendations from the UAT ARC and in collaboration with the FAA and industry groups. This initiative was created to support the evaluation of candidate unleaded fuels to replace approved leaded gasoline, with the objective of ultimately qualifying a fleet-wide solution. In 2022, the PAFI program evolved into the Eliminate Aviation Gasoline Lead Emissions (EAGLE) initiative, under the FAA and critical government and industry partners. The main purpose of the EAGLE program is to safely eliminate leaded aviation fuel by the end of 2030 without impacting the safe and efficient operation of the piston-engine fleet (FAA, n.d.).

The FAA (2024) has two pathways available to obtain FAA authorization for the use of new unleaded fuel:

1) FAA fleet authorization process that was established by Congress, in conjunction with PAFI; and

2) Traditional FAA aircraft type certification, Supplemental Type Certificate (STC) process.

While the ASTM D7960 specification is not required, and fuels used in certified engines and aircraft are ultimately approved by the certifying authority (the FAA in the case of the US) (ASTM International, 2021). The advantage of obtaining an ASTM specification is that it would have gone through the industry consensus standards process of approvals, and therefore, it would have the "blessing" of the industry and the engine manufacturers as to their warranties. An ASTM specification, in the eyes of the aircraft and component manufacturers, has a liability protection that an STC does not (Schnitzler, 2024).

As part of its efforts to test and implement the fleet authorization process and assist in the transition to unleaded fuels, the FAA (2024) granted fleet authorization for Swift's UL94/UL91 unleaded fuels in 2024. However, higher compression engines cannot use the lower-octane UL94 fuel because it may not prevent detonation (Baker, 2023). In 2022, General Aviation Modifications Inc. (GAMI) received FAA STC approval for its G100UL fuel, authorizing its use in all spark-ignition piston engines and airframes. This designation made G100UL the first unleaded 100-octane fuel to achieve fleetwide approval (GAMI, n.d.; *General Aviation News*, 2025, January 22). In 2024, Swift's 100R received an FAA STC for Cessna 172R and 172S Skyhawk aircraft with Lycoming IO-360-L2A engines, with additional STCs under evaluation. In September of 2025, Swift 100R received the ASTM D7719 specification (Swift Fuels, n.d.). LyondellBasell/VP Racing UL100E is currently the only fuel undergoing full-scale engine testing under the PAFI program. Two other fuels passed the initial screening to be PAFI program candidates: a fuel produced by Shell and another fuel produced by Phillips. Both fuels suspended testing, leaving UL100E as the only candidate remaining under PAFI testing (Niles, 2024).

Aviation Fuel Characteristics

Energy content in aviation fuels is a key characteristic. Other important performance properties are knock-resistance, volatility, fluidity, stability, non-corrosivity, and purity (Chevron Corporation, 2006). Previous research indicates the most effective way to produce a 100LL equivalent is by combining traditional high-octane aliphatic components - mainly alkylate and isooctane with aromatic hydrocarbons, a small amount of oxygenates, and aromatic amines (Ershov et al., 2021).

Energy Content. Chemical energy stored in the fuel is converted into mechanical energy in aircraft piston engines. The energy content of the fuel can be measured by the heat released (also called heat of combustion) when a known quantity of fuel is burned under specific conditions (Chevron Corporation, 2006). The amount of power generated by a specific engine depends more on its design than on the fuel used.

Knock Resistance. Knocking or detonation occurs when an air-fuel mixture ignites spontaneously and burns too quickly, causing a rise in cylinder pressure and producing a knocking sound. This negatively impacts engine performance. The octane number indicates Avgas's resistance to detonation, with numbers above 100 typically achieved by mixing isooctane and tetraethyl lead. Each engine is designed for a specific fuel with anti-knock properties, and using a lower-octane fuel can lead to detonation and potential engine damage. Higher octane fuels are especially important for turbocharged and high-compression engines (Chevron Corporation, 2006).

Volatility. Volatility is the fuel's tendency to vaporize. Volatility is an important consideration because of carburetor icing and vapor lock.

Non-Corrosivity. It is essential that the fuel does not corrode any of the materials it comes in contact with, especially those in aircraft engines and fuel systems. Engine and airframe manufacturers conduct extensive fuel compatibility testing before approving material for fuel system use (Chevron Corporation, 2006). One of the problems with leaded fuels is that lead requires the addition of a bromine compound to scavenge lead residue from the engine. The burning of lead with the bromine compound is carried out with exhaust gases; however, a small amount remains in the engine. When it is mixed with water, metals, and oil, it can initiate corrosion processes that damage the engine or its components.

Fuel Purity. A fuel is considered "clean" when it is free of water, contaminants, and solid particles like rust or dirt, which could clog filters and other components. These solid particles could plug fuel filters or other components. Water will freeze at low temperatures encountered at high altitudes and will not burn in an engine; the resulting ice may also plug fuel filters as well as facilitate the corrosion of some metals and the growth of microorganisms in the fuel (Chevron Corporation, 2006). Due to the critical nature of aviation, the industry has developed strict quality control guidelines that are designed to ensure the quality of the fuel by recommending practices for transportation, storage, and delivery of the fuel (ASTM International & Gammon, 2009).

Methodology for Identifying Prospective Unleaded Fuels

This position paper is grounded in a synthesis of existing literature and a conceptual integration of findings across disciplines relevant to leaded aviation fuel and general aviation operations. Sources were identified through targeted searches conducted between 2000 and 2025, focusing on peer-reviewed journal articles, government reports, and authoritative publications from federal agencies, including the EPA, FAA, and the U.S. Energy Information Administration (EIA), as well as materials from recognized aviation advocacy organizations. A thematic analysis approach guided the synthesis, allowing recurrent concepts such as regulatory readiness, drop-in compatibility, scalability, environmental risk, and economic feasibility to be identified, organized, and integrated across sources. The goal of this approach was to develop an evidence-informed perspective that integrates technical, policy, and safety considerations, providing a coherent understanding of the issues surrounding leaded aviation fuel. This manuscript provides a structured integration of existing knowledge intended to clarify the readiness levels, limitations, and practical implications of leading unleaded Avgas candidates. Consistent with the purpose of a position paper, no new sampling, experimental testing, or quantitative analyses were performed; instead, the paper synthesizes credible evidence to support an informed, forward-looking perspective on the transition to unleaded fuels in general aviation.

Key Factors and Challenges in the Transition to Unleaded Fuels

A thematic analysis of the literature revealed several interrelated dimensions shaping the transition to unleaded fuels in general aviation, ranging from environmental and regulatory drivers to technical, economic, infrastructural, operational, and liability considerations. These key factors and the challenges associated with each are summarized in Table 1.

Table 1
Key Factors and Challenges in the Transition to Unleaded Fuels for GA

Key Factor	Challenge
Environmental and health benefits	The primary driver for replacement is eliminating lead emissions, which pose health risks, especially to communities near airports.
Regulations and policies	The FAA's Eliminate Aviation Gasoline Lead Emissions (EAGLE) initiative targets a lead-free aviation system by 2030.
Technical specifications and possible candidates	Replacements must match or exceed 100LL's 100-octane rating to prevent detonation in high-performance engines.
Compatibility and fleet impact	About 30% of the fleet can use lower-octane unleaded fuels like UL94, but the majority requires 100-octane options to avoid engine damage.
Economic implications	Unleaded fuels may cost more initially due to production scaling, refinement, and distribution investments, and infrastructure updates.
Infrastructure and distribution challenges	Building supply chains for unleaded fuels involves refiners, distributors, and airports.
Stakeholders and outlook	Key players include aviation advocacy groups like AOPA, EAA, GAMA; Government entities like the FAA and EPA; Oil companies, alternative fuel companies, airports, distribution suppliers, flight schools, and many more.
Liability	One of the main issues that concerns aircraft and component manufacturers, as well as fuel distributors, is liability and warranty.

Possible Unleaded Fuel Alternatives

As the GA community prepares a transition away from 100LL, several unleaded fuel candidates have emerged, each offering different levels of readiness, certification progress, and fleet applicability. These options range from low-octane fuels suitable for limited segments of the fleet to 100-octane formulations intended as universal drop-in replacements. The fuels outlined in this section represent the most current and promising alternatives, and their comparison highlights the technical, operational, and regulatory challenges that continue to shape the pathway toward a viable unleaded future. See below the most current fuel candidates to replace 100LL.

Auto Gas (Mogas)

Description. Auto Gas, also known as Mogas, is an ethanol-free automotive gasoline, typically 91-94 octane, adapted for aviation use under STCs, meeting ASTM D4814 (automotive) rather than aviation-specific standards (Experimental Aircraft Association [EAA], n.d.).

Status. This fuel is available at approximately 75 U.S. airports and widely at automotive fuel stations, but aviation-specific supply is limited and requires STC compliance. FAA STCs are available through the Experimental Aircraft Association (EAA) and Petersen Aviation for specific low-compression aircraft (e.g., Cessna 150, Piper J-3 Cub). This fuel was not a primary focus of the EAGLE program as it is not aviation-specific, but it is used by some pilots mainly for cost savings and availability in remote areas (EAA, n.d.).

Compatibility. This fuel is compatible with low-compression engines (e.g., Continental O-200, Lycoming O-320, Rotax 912) in aircraft with STCs or experimental approvals. This fuel is not suitable for high-compression or turbocharged engines (e.g., Continental TSIO-520, Lycoming TIO-540) due to insufficient octane, risking detonation. Auto gas may cause vapor lock, seal degradation, or fuel system issues without modifications (e.g., fuel pumps, hoses) (EAA, n.d.).

Advantages. This fuel offers a cost-effective solution, typically priced at approximately $2.5 to $6 per gallon at fuel stations, making it significantly more economical than Avgas. It is also environmentally friendly as it does not contain lead. While ethanol-free mogas may be somewhat harder to find, they remain widely available at most automotive stations. Approved since 1982, this fuel has been successfully used in low-compression engines, such as the Continental 200 and Rotax 912, for decades, particularly in regions like Canada and Europe (EAA, n.d.).

Challenges. There is not an aviation-specific ASTM standard for this fuel, only an ASTM for automotive use, which raises safety, quality, and consistency concerns. There is limited compatibility, covering only approximately 30% of the GA fuel consumption in low-compression aircraft. Non-aviation sources of Mogas typically contain Ethanol, which can damage aircraft fuel systems and components. An STC is required for the use of Mogas in certified aircraft (EAA, n.d.).

94 UL (Swift UL94)

Description. A 94-octane unleaded aviation gasoline developed by Swift Fuels is specifically formulated to meet ASTM D7547 standards for aviation use. This fuel serves as a direct replacement for the 80/87 Avgas, and it is designed to cater to lower-compression engines (Swift Fuels, n.d.).

Status. Currently, this aviation fuel is **c**ommercially available at approximately 100 U.S. airports, predominantly used by flight schools and light aircraft, as of May 2025. An FAA Supplemental Type Certificate (STC) has been approved for around 1,600 aircraft models, which constitutes approximately 60-75% of the U.S. General Aviation (GA) piston fleet. Swift Fuels has announced plans to gradually phase out the UL94 as the Swift 100R becomes more widely available, projected around 2026 (Swift Fuels, n.d.).

Compatibility. The compatibility of this aviation fuel is limited to low- to mid-compression engines typically found in aircraft such as the Cessna 172 and Piper Cherokee. It is unsuitable for high-compression or turbocharged engines that necessitate 100-octane fuel, like those in the Cirrus SR22 or Beechcraft Bonanza. Certified aircraft require a Supplemental Type Certificate (STC) to use this fuel, which can be obtained through Swift's "Forever STC" program for a one-time fee of $100 (Swift Fuels, n.d.). Moreover, this fuel can be intermixed with 100LL, provided that the aircraft's engine and airframe, or rotorcraft, are approved for the use of Swift Fuels UL94 (Swift Fuels, n.d.).

Advantages. 94 UL (Swift UL94) is ASTM-compliant for aviation use. This aviation fuel is widely tested and reliable for compatible aircraft, with a strong track record in flight schools. Utilizing this fuel reduces maintenance costs as it reduces the chances of spark plug fouling compared to 100LL. This fuel is available at a growing number of airports, especially on the West Coast of the US, and can be intermixed with 100LL at any ratio (Swift Fuels, n.d.).

Challenges. The use of UL94 fuel presents several challenges within the general aviation (GA) sector. Notably, this fuel is incompatible with approximately 25-40% of GA fleet high compression engines that require 100-octane fuel, thereby limiting its applicability. Additionally, there have been reports of valve seat recession during its use at the University of North Dakota (UND) with Lycoming engines, which raises concerns about its long-term suitability for certain engine models (Bertorelli, 2023). Furthermore, as Swift advances its approval process for Swift 100R, there are plans to phase out UL94. This impending transition could potentially disrupt users who currently rely on UL94 (Swift Fuels, n.d.).

G100UL

Description. A 100-octane unleaded aviation gasoline engineered by General Aviation Modifications, Inc. (GAMI), this fuel was designed as a drop-in replacement for 100LL. This proprietary fuel blend incorporates aromatic amines, including chemical constituents such as xylene and m-toluidine, to achieve a high-octane rating without the use of lead.

Status. G100UL fuel received FAA Supplemental Type Certificate (STC) approval in September 2022, authorizing its use in all spark-ignition piston engines and airframes. This milestone marks G100UL as the first unleaded 100-octane fuel to receive fleetwide approval (GAMI, n.d.; General Aviation News, January 2022). Currently, the fuel is commercially available at a select number of U.S. airports, with a notable presence in California, including Reid-Hillview, Watsonville, and Santa Maria. As of early 2025, production by Vitol Aviation has reached approximately 1.2 million gallons (General Aviation News, January 22, 2025). Despite its approval, GAMI has decided not to pursue the ASTM D7719 specification due to timeline constraints, which have limited broader industry acceptance by fuel distributors, Fixed-Base Operators (FBOs), and Original Equipment Manufacturers (OEMs) (Aviation Consumer, January 29, 2025). This decision has led to ongoing scrutiny from OEMs such as Cirrus Aircraft, which has not approved G100UL for their aircraft, citing unresolved material compatibility and airworthiness concerns (Aviation Consumer, January 29, 2025). G100UL is supported by the FAA's EAGLE initiative as a transitional fuel. However, its long-term adoption remains uncertain due to competition from ASTM-compliant fuels like Swift 100R and UL100E (FAA, n.d.).

Compatibility. G100UL is compatible with all piston aircraft, including high-compression and turbocharged engines (e.g., Continental TSIO-550, Lycoming TIO-540), without modifications other than placards and a POH addendum. This fuel is intermixable with 100LL in any ratio, simplifying transitions. Some concerns have been raised by Cirrus Aircraft and other manufacturers about material compatibility (e.g., paint degradation, seal swelling, fuel bladder leaks), although GAMI disputes these claims.

Advantages. Fleetwide compatibility is G100UL's major advantage, covering all GA piston aircraft, making it the most versatile unleaded option. This remarkable compatibility ensures that it can seamlessly replace 100LL without compromising performance. In fact, G100UL not only matches but potentially exceeds the performance of 100LL, offering a slight increase in range, approximately 1% higher, thanks to its higher energy density. Additionally, the introduction of G100UL is expected to lead to reduced maintenance costs, such as those associated with spark plugs and oil changes, due to the absence of lead fouling. Another noteworthy advantage is its early market availability, as this fuel is already accessible at select airports, particularly in California.

Challenges. The introduction of G100UL fuel presents several significant challenges. One of the primary issues is the absence of an ASTM specification, which hampers its acceptance among fuel distributors, Fixed Base Operators (FBOs), and original equipment manufacturers (OEMs) such as Cirrus, Continental, and Lycoming. These entities have expressed concerns regarding liability and warranty, which are exacerbated by G100UL's lack of standardized specifications (Schnitzler, 2024). Furthermore, reports have indicated material compatibility problems associated with G100UL. Instances of paint staining, seal degradation, and yellowing of fuel caps have been noted. However, General Aviation Modifications, Inc. (GAMI) attributes these issues to improper handling or pre-existing conditions rather than the fuel itself (Schnitzler, 2024). Another critical challenge is the cost. G100UL is priced approximately $0.70 to $1.05 per gallon higher than 100LL, which could deter widespread adoption (General Aviation News Staff, 2025). Additionally, the distribution network for G100UL is currently limited, with availability confined to about three airports as of May 2025. Resistance from OEMs remains a significant hurdle. For instance, Cirrus has explicitly disapproved of using G100UL in their aircraft, citing concerns about airworthiness. The co-founder of GAMI has emphasized that GAMI has successfully submitted the requisite information to secure an ASTM specification. It was discovered that a major oil company, which had a representative on the ASTM committee, had used GAMI's confidential information to file a competitive patent (General Aviation News Staff, 2025). Braly further stated that the FAA recognized this issue and established an FAA-approved specification equivalent to an ASTM specification (General Aviation News Staff, 2025). These multifaceted challenges underscore the complexities involved in the adoption and acceptance of G100UL as a viable aviation fuel alternative.

Swift 100R

Description. Swift 100R is a 100-octane unleaded aviation gasoline developed by Swift Fuels, designed as a drop-in replacement for 100LL. It uses a chemical called ethyl tert-butyl ether (ETBE) to raise the octane (Swift Fuels, n.d.).

Status. In September 2024, the FAA granted an STC approval for the Cessna 172R and 172S Skyhawks, both equipped with Lycoming IO-360-L2A engines. Additional STCs are currently under evaluation. Furthermore, in September 2025, Swift 100R fuel met the ASTM D7719 specification (Swift Fuels, n.d.). This fuel is available on a restricted-use basis at select U.S. airfields, primarily in California, for approved aircraft. By November 2024, approximately 22,000 gallons had been ordered.

Compatibility. The Swift 100R fuel is currently certified exclusively for use in Cessna 172R/S aircraft equipped with Lycoming IO-360-L2A engines. However, there are future plans to extend its applicability to all piston aircraft, including those with high-compression and turbocharged engines. Notably, Swift 100R can be intermixed with 100LL fuel without necessitating any modifications to the fuel system, apart from the addition of placards and STC documentation. Comprehensive testing has not indicated any material compatibility issues, with thorough evaluations conducted on paint, seals, and fuel bladders (Swift Fuels, n.d.).

Advantages. The Swift 100R fuel is engineered for comprehensive fleet utilization, delivering performance that matches or exceeds 100LL, making it suitable for all piston engines. Having an ASTM specification also increases industry acceptance. Notably, Swift 100R is lead-free, having undergone extensive toxicology and environmental testing, and aligns with EAGLE objectives. Additionally, Swift's "Forever STC," available for $100, covers both UL94 and 100R, facilitating a smoother transition for airplane owners and operators (Swift Fuels, n.d.).

Challenges. The Swift 100R fuel has limited STC approvals (only Cessna 172R/S as of May 2025), delaying fleetwide adoption. This aviation fuel encounters significant competition from G100UL, which has received broader approvals, and UL100E, which is likely to obtain fleet authorization soon (Swift Fuels, n.d.).

LyondellBasell/VP Racing UL100E

Description. The UL100E fuel, which was developed collaboratively by LyondellBasell Industries and VP Racing Fuels, represents a significant advancement in aviation fuel technology. This 100-octane unleaded aviation gasoline is specifically designed to serve as a direct replacement for the widely used 100LL fuel. Currently, UL100E is undergoing rigorous testing under the FAA's PAFI, as reported by AOPA (2023). Notably, similar to Swift 100R, this fuel utilizes ETBE to enhance its octane rating, ensuring optimal performance and reliability for aviation applications.

Status. This fuel has undergone extensive full-scale testing under the Piston Aviation Fuels Initiative (PAFI). It successfully passed a rigorous 150-hour engine durability test in 2023 and has completed approximately 25% of the necessary materials compatibility, detonation, and performance testing by May 2025. The UL100E fuel is anticipated to receive fleet-wide authorization from the FAA by the end of 2025. This approval will necessitate only the addition of a placard and a Pilot's Operating Handbook (POH) addendum. An ASTM specification for this fuel is currently being developed, with the balloting process ongoing. This process is addressing feedback and criticisms from the initial rounds of evaluation (AOPA, 2023).

Compatibility. UL100E is designed to achieve fleetwide compatibility, covering all piston aircraft, including those with high-compression and turbocharged engines. Comprehensive testing has been conducted on ten engine models and eight distinct airframes. Notably, UL100E can be intermixed with 100LL without requiring any modifications beyond placards, pending final approval. However, LyondellBasell has highlighted potential performance limitations for certain engines, indicating that it may not serve as an ideal drop-in replacement for all high-performance models (AOPA, 2023).

Advantages. The UL100E fuel produces no lead emissions, aligning with EAGLE's 2030 lead-free goal. PAFI testing ensures rigorous evaluation of this fuel, enhancing safety and industry acceptance. ASTM specification pursuit supports distributor and OEM confidence, potentially easing supply chain integration. The authorization of this fuel for fleet use will streamline its adoption process by necessitating minimal modifications to existing aircraft (Aircraft Owners and Pilots Association, 2023).

Challenges. This fuel is not yet commercially available, with full-scale testing projected to commence in April 2024 and expected to conclude within 12 to 18 months. This suggests a tentative approval date around late 2025. However, there are concerns about performance limitations for some high-performance engines, potentially requiring operational adjustments. Current ASTM specification delays due to balloting criticisms could further postpone commercialization. UL100E faces significant competition from G100UL, which has already received approval, and Swift 100R, which is close to securing broader approvals (AOPA, 2023).

Both of these alternatives exhibit their own advantages and disadvantages and are strong contenders to replace 100LL. Meanwhile, LyondellBasell/VP Racing UL100E is currently undergoing full-scale testing under PAFI, positioning it as a potential third option. Table 2 provides a comparative analysis of these three fuels.

Table 2

Comparison Summary of Top Three Fuel Contenders to Replace 100LL

Fuel	Status	Compatibility	Advantages	Challenges
GAMI G100UL	• Has FAA fleetwide STC • Commercially available at a limited number of U.S. airports • No ASTM spec	• Compatible with all piston aircraft, including high & low compression & turbocharged engines • Intermixable with 100LL in any ratio	• Fleetwide compatibility • Intermixable with 100LL in any ratio	• No ASTM spec • Reduced acceptance due to liability and warranty concerns • Possible material compatibility issues • higher cost, approximately $0.70-$1.05/gal more than 100LL • limited distribution network
Swift 100R	• FAA STC for Cessna 172R and 172S Skyhawks with Lycoming IO-360-L2A engines only • ASTM D7719 specification • Available at limited airfields, mainly in California	• Approved for Cessna 172R/S only, with plans to expand to all piston aircraft, including high-compression and turbocharged models.	• Intermixable with 100LL	• limited STC approvals (only Cessna 172R/S) • Unknown materials compatibility
LyondellBasell/VP Racing UL100E	• This fuel has been in full-scale testing under PAFI • ASTM D7719 specification is in development for this fuel, with balloting ongoing and addressing criticisms from initial rounds	• Aimed at fleetwide compatibility, potential performance limitations for some engines, may not be a drop-in replacement	• Going through PAFI certification instead of STC	• Not commercially available • Concerns about performance limitations for some high-performance engines

Considerations for the Transition to Unleaded Fuel

Technical. Ensuring safety in aviation remains paramount, necessitating that an unleaded aviation fuel solution be compatible with 100LL, possess appropriate materials compatibility, and ideally serve as a drop-in replacement for the entire GA piston engine fleet (Fly Eagle, 2024). Both 100R and UL100E utilize ETBE, whereas G100L employs aromatic amines to boost octane. However, there are toxicity concerns regarding ETBE as it has been classified as possibly carcinogenic to humans (Group 2B) based on sufficient evidence of cancer in experimental animals (Turner et al, 2025). Aromatic amines, on the other hand, could potentially pose component compatibility issues.

Liability. By the mid-1980s, the GA industry in the US was nearing a state of collapse. This period marked significant challenges, with Cessna Aircraft halting the production of its piston aircraft and Piper Aircraft facing imminent bankruptcy. The primary factor contributing to this downturn was the escalating issue of product liability. Congress passed the General Aviation Revitalization Act (GARA) to shield most manufacturers of small GA aircraft from liability involving their products that are older than 18 years. The GA industry overall is very sensitive to liability (Wilson, 2024).

An STC approval grants legal permission to sell a product without risking the certification of the aircraft. This certificate will not provide any liability support in case of a problem. Many believe that while a product qualified against an ASTM specification does not directly provide legal liability protection, it may carry the support of an industry agreement in a court of law. This implies that the product should meet the requirements of all general aviation aircraft, rather than just those of the STC holder (Schnitzler, 2024).

Cost. One of the most significant challenges in transitioning to unleaded fuel is meeting the substantial demand that Avgas currently fulfills, which amounts to approximately half a million gallons per day (Wolfe, 2023). Recently, the Los Angeles city council decided that the city would cover the $2-$4 per gallon price difference between Swift Fuels and 100LL, in addition to covering the cost for the STC required for aircraft to legally use the fuel (Niles, 2024). In contrast, the co-founder of GAMI explained that scaling up from small-scale production to millions of gallons would be a gradual process due to supply chain limitations. Consequently, prices are not expected to align with 100LL until production increases significantly. GAMI has also introduced incentives, including a complete refund of the STC for pilots who purchased it and a voucher equivalent to their previous fuel purchase (Britton, 2024). Transition costs encompass various factors such as fuel storage, distribution, STCs, and maintenance. The pricing of UL Avgas will ultimately depend on fuel volume, airport location, and market conditions.

Distribution and Logistics. Airports and FBOs must ensure UL Avgas availability to support aircraft refueling across the country. As of June 2025, there are three airports in California, two in Texas, and one in Mississippi that offer G100UL (General Aviation News, 2025). In addition, approximately 99 airports across the United States provide 94UL. There is one airport in California that offers Swift fuel 100R, and this fuel is also available at other airports on a restricted (non-resale basis. Swift expects to have 100R broadly commercially available by mid- to late 2025, pending approval of its ASTM production specification. Once certified, Swift Fuels expects to have its 94UL clients and airports transition to 100R (Fly Unleaded, n.d.; Swift Fuels, 2024).

AvFuel is one of the main aviation fuel distributors in the US and has expressed a commitment to supporting any viable UL avgas solution. The company plays a key role in managing the logistics associated with product distribution and in helping to establish a scalable supply chain capable of delivering G100UL Avgas to the market. AvFuel currently distributes both Swift and GAMI fuels at selected airports (Avfuel Corporation, 2022).

In June 2025, a California court denied a motion from the Center of Environmental Health (CEH) asking the court to require leaded Avgas to be banned once unleaded fuel alternatives were "commercially available". The ruling upheld the terms of the 2014 settlement agreement between FBOs and fuel distributors, thereby maintaining the existing regulatory framework governing Avgas sales in the state (General Aviation News Staff, 2025).

CEH asserted that GAMI's G100UL is FAA-approved and already being sold at FBOs in California and therefore contended that the court should enforce the terms of the prior settlement. However, the court noted that since G100UL has not received an ASTM specification, it cannot be considered "commercially available". In the ruling, the court cites declarations received from aviation OEMs and trade organizations, including GAMA, Piper, Cirrus, Aviat, Diamond, Schweizer RSG, Robinson Helicopters, and Textron Aviation, which include Lycoming engines, Cessna, and Beechcraft. These organizations submitted information to the Court that stated the new unleaded Avgas variant was not approved or supported by manufacturers for use in their models, as they lacked sufficient data and information to verify its safety and material compatibility (General Aviation News, 2025).

Current Efforts to Adopt Unleaded Fuels

Several organizations have conducted testing and begun transitioning to unleaded fuels. Some of these organizations include:

Embry-Riddle Aeronautical University (ERAU). The Eagle Flight Research Center at ERAU has conducted testing on multiple unleaded fuels, including participation in PAFI fuel testing efforts. At GAMI's request, ERAU, acting as an independent third party, completed a 150-hour engine durability test conducted on an engine that already accumulated more than 1400 hours of operation on 100LL. According to GAMI, the post-test engine teardown showed that the engine and combustion chambers were noticeably cleaner after operating for 150 hours on G100UL than they had been prior to the test. That testing at ERAU was closely monitored by the FAA with personnel from the Atlanta Aircraft Certification Office (GAMI, n.d.).

AOPA. In 2023, AOPA conducted a series of test flights using a twin-engine Beech Baron operating one engine on G100UL and the other on 100LL for comparison. The results indicated that the performance of both engines was nearly identical across fuel types. The evaluation included several full-power takeoffs and an extended high-power cruise at over 75% power (AOPA, 2023).

Utah Valley University (UVU). In 2023, UVU transitioned its flight training program to unleaded fuel using Swift UL94 for its 25 airplanes that include Diamond DA-40 and Piper Seminole (Kurtz, 2023; Bubel & Wedekind, 2021).

Purdue University. In 2020, the School of Aviation and Transportation Technology professional flight program purchased a new fleet of Piper aircraft certified to run in Swift UL94 (Pereira, 2019).

San Carlos Flight Center. As of November 2024, Swift Fuels 100R had been formally adopted, although the company had been operating exclusively on Swift Fuels UL94 since 2021 (Thurber, 2024).

University of North Dakota (UND). UND elected to transition to unleaded Avgas UL94 to **reduce** aircraft maintenance costs and to **adopt** a cleaner, more environmentally sustainable fuel alternative (Kurtz, 2022). However, after just four months of use of unleaded fuel, UND **elected** to transition back to 100LL, citing evidence of noticeable exhaust value recession (Bertorelli, 2023).

While operating on UL94, UND's fleet accumulated approximately 46,600 flight hours, consuming 386,778 gallons of UL94, averaging 464 hours per aircraft (Wilson et al, 2025). Wilson (2025) notes that one potential cause of the excessive valve seat wear observed during this period is microwelding, a phenomenon in which the mating surfaces of valve and valve seat bond at high-temperature conditions. When lead was removed from US automotive fuel in the 1970s, heavy wear of engine exhaust valve seats was observed. Further research found that lead oxides present in leaded fuel had provided a protective layer between the valve and the seat. In the automotive sector, micro welding was ultimately addressed through the widespread adoption of hardened valve seat inserts (Forsberg et al., 2011; Khan et al., 2018). According to Swift, 5 US flight schools utilize 100R as well as 5 flight schools in the EU (Germany, Belgium, Austria, and the Netherlands) (Swift Fuels, n.d.).

Conclusions

It is the authors' position that the GA community in the US is not ready to completely transition to unleaded fuel yet. Before such a transition occurs, it is critical that the industry identifies a viable unleaded fuel alternative that can be safely and effectively adopted across the GA piston fleet. An acceptable solution must be fully interoperable with 100LL, exhibit comprehensive materials compatibility, and be suitable for use in all GA piston aircraft—ideally functioning as a true drop-in replacement.

Based on the alternative fuels discussed, the two candidates that appear closest to providing a viable unleaded replacement are GAMI G100L and Swift 100R. GAMI G100L holds a fleetwide FAA STC and is approved for both low-compression and high-compression piston engines. However, the absence of an ASTM specification has limited its acceptance among fuel distributors, FBOs, and OEMs, who cite concerns related to liability, warranty coverage, and long-term operational support. Material compatibility concerns have also been raised regarding the use of aromatic amines such as xylene and m-toluidine, which are employed in some formulations to increase octane rating. Swift 100R possesses both an ASTM specification and an FAA STC, but it is currently approved only for use in the Cessna 172 R/S model, and its suitability with high compression engines has not yet been demonstrated. A third candidate, LyondellBasell UL100E, is emerging and undergoing fleet authorization through the FAA's PAFI program. Two other fuels that had initiated testing under PAFI, Phillips and Shell, ultimately suspended their efforts due to technical challenges and adverse findings, leaving UL100E as the sole remaining candidate under PAFI testing.

Theoretically, PAFI testing is designed to provide a pathway to fleet-wide approval; however, no PAFI fuel candidate has achieved success to date. UL100E remains considerably behind GAMI and Swift fuels as UL100E as it is not yet commercially available, and concerns persist regarding its performance in high-performance engines. It is also possible that a major oil company could ultimately license one of the existing unleaded formulations and leverage its established supply chain and distribution infrastructure to support broader market adoption. Both 100R and UL100E rely on ETBE as an octane enhancer, whereas G100L uses aromatic amines to achieve the required octane rating. Toxicological concerns have been raised regarding ETBE, which has been classified as possibly carcinogenic to humans (Group 2B) on sufficient evidence of carcinogenicity in experimental animals. Aromatic amines, on the other hand, may introduce risks related to component materials compatibility within aircraft fuel systems and engines. Thus, although the detrimental environmental effects of lead are well established, the octane boosting additives employed in unleaded alternatives also present potential safety and health risks that must be carefully considered.

Fuel additives and certain operational or hardware modifications, including mixture leaning procedures and hardened seat valve inserts, might be necessary when transitioning to unleaded fuels. A major concern among aircraft and component manufacturers, as well as fuel distributors, involves the potential transfer of liability from the fuel's patent holder to the operator and manufacturers of aircraft and associated components. Many industry stakeholders contend that while qualification to an ASTM specification does not directly confer legal protection, it may, in practice, provide stronger support in a court of law by signaling broad industry consensus that the fuel should be suitable for all GA aircraft rather than only for those covered under a specific STC. Additional challenges include cost, distribution logistics, infrastructure readiness, and long-term fuel availability, all of which require collaboration between the aviation industry, government agencies, and fuel manufacturers. This regulatory and technical uncertainty contributes to apprehension across the sector, potentially hindering investment and innovation. Projections indicate that through 2043, more than 50% of the general aviation fleet will continue to be powered by piston engines, meaning that Avgas, leaded or unleaded, must remain available for at least the next two decades. Ultimately, the widespread adoption of unleaded fuel is not solely a technical undertaking, but a long-term commitment to protecting public health and the environment.

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Appendix A – Acronyms

AOPA – Aircraft Owners & Pilots Association
ASTM – American Society for Testing & Materials
CEH – Center for Environmental Health
EAA- Experimental Aircraft Association
EAGLE – Eliminate Aviation Gasoline Lead Emissions
EDMS – Emissions & Dispersion Modeling System
EPA – U.S. Department of Environmental Protection
ETBE- ethyl tert-butyl ether
ERAU – Embry-Riddle Aeronautical University
FAA – Federal Aviation Administration
FBO – Fixed Base Operator
GA – General Aviation
GAMI – General Aviation Modifications Inc.
GARA – General Aviation Revitalization Act
IQ – Intelligence Quotient
LL – Low Lead
LTO – Landing & Takeoff
NAAQS – National Ambient Air Quality Standards
OEM – Original Equipment Manufacturer
PAFI – Piston Aviation Fuels Initiative
STC – Supplemental Type Certificate
TEL – Tetraethyl Lead
UAT ARC – Unleaded AvGas Transition Aviation Rulemaking Committee
UL - Unleaded
UND – University of North Dakota
UVU – Utah Valley University