TECHNICAL REPORT

Near-Term Feasibility of Alternative Jet Fuels

James I. Hileman, *MIT* • David S. Ortiz, *RAND* • James T. Bartis, *RAND*
Hsin Min Wong, *MIT* • Pearl E. Donohoo, *MIT* • Malcolm A. Weiss, *MIT*
Ian A. Waitz, *MIT*

Sponsored by the Federal Aviation Administration

RAND INFRASTRUCTURE, SAFETY, AND ENVIRONMENT

PARTNER

The research described in this report was sponsored by the Federal Aviation Administration. The research was jointly performed by the Partnership for AiR Transportation Noise and Emission Reduction at the Massachusetts Institute of Technology (Report No. PARTNER-COE-2009-001) and the Environment, Energy, and Economic Development Program within RAND Infrastructure, Safety, and Environment.

Title page photo by Isaiah Shookt

Published 2009 by the RAND Corporation
1776 Main Street, P.O. Box 2138, Santa Monica, CA 90407-2138
1200 South Hayes Street, Arlington, VA 22202-5050
4570 Fifth Avenue, Suite 600, Pittsburgh, PA 15213-2665
RAND URL: http://www.rand.org
To order RAND documents or to obtain additional information, contact
Distribution Services: Telephone: (310) 451-7002;
Fax: (310) 451-6915; Email: order@rand.org

The Partnership for AiR Transportation Noise and Emissions Reduction
Massachusetts Institute of Technology, 77 Massachusetts Avenue, 37-395, Cambridge, MA 02139
PARTNER URL: http://www.partner.aero

Summary

Prior to 2004, the spot price of jet fuel rarely exceeded $1.00 per gallon. The next four years saw spot prices for Jet A climb to a peak in July 2008 of more than $4.00 per gallon. Since then, jet-fuel prices have been highly volatile, swinging to below $1.20 per gallon in March 2009. High spot prices, the corresponding increase in contract prices for jet fuel, and price volatility have wreaked havoc on the commercial aviation industry. Coincident with price increases and volatility has been a growing awareness of the importance of further reducing the adverse environmental impacts of aviation. Important environmental issues include improving air quality in and around airports and addressing aviation's contribution to GHG emissions.

Such concerns prompted FAA's support of a joint MIT/RAND research effort on what alternatives to kerosene-type jet fuel derived from conventional petroleum may be available in the next decade to help reduce price and price volatility as well as the environmental impact of commercial aviation operations. We evaluated five different groups of fuel—those derived (1) from conventional petroleum; (2) from unconventional petroleum; (3) synthetically from natural gas, coal, or combinations of coal and biomass via the FT process; (4) renewable oils; and (5) alcohols—using seven different criteria.

Criteria for Alternative Fuels

For a prospective aviation fuel to have an impact on aviation within the next few decades, the most important criterion to address is *compatibility with current systems*—that is, the existing commercial aviation infrastructure, including fuel delivery and storage and, most importantly, the existing fleet of aircraft. Use of certain fuels that we examined would so significantly degrade safety or adversely affect efficient aircraft operations as to preclude their use in aviation.

The second criterion we examined is the current *maturity of the fuel-production technology*. In a couple of cases, we found that small amounts of the alternative fuel are being commercially produced. But, for most of the alternative fuels we examined, further research and development (including process scale-up) is required before large-scale commercial production of that fuel can occur.

The third criterion we examined is the *production potential* of the fuel in the next decade. In some cases, this is limited by resource constraints; in others, by the maturity of the fuel-production technology, which may limit the number of commercial plants that can be built in the next decade. With regard to this criterion, we also examined the extent to which the prospective fuel could be produced from North American resources.

Whether an alternative aviation fuel will be competitive depends on its *production costs*. Where adequate information was available, we estimated production costs or cost ranges.

To examine the environmental benefits, if any, that would be associated with the use of an alternative aviation fuel, we reviewed potential performance against two criteria: *life-cycle GHG emissions* and *emissions affecting air quality*. Life-cycle GHG emissions covered the GHG emissions associated with land-use change, extraction, processing, delivery, and combustion of a fuel as compared to those of conventional jet fuel. With regard to other emissions, we focused on particulate matter smaller than 2.5 micrometers ($PM_{2.5}$) released during airport operations (especially landing, taxi, and takeoff), since aviation $PM_{2.5}$ emissions have a larger impact on air quality than do other factors, such as ozone.

Early in our study, we recognized that certain fuels may be more appropriate for automotive applications than for aviation. Moreover, supplies are limited for nearly all the alternative fuels we examined. To address the potentially adverse economic or societal impacts of diverting limited supplies of fuels from automotive or other uses to aviation applications, we added the criterion *relative merit for aviation use*.

Prospective Jet Fuels

Conventional Petroleum Fuels

Jet A, the standard commercial jet fuel in North America, is the benchmark fuel against which we compared alternatives.

An ultralow-sulfur (ULS) version of Jet A fuel is an alternative fuel that may be produced from conventional and unconventional petroleum sources. In the past few years, sulfur levels in Jet A sold in the United States have been about 700 parts per million (ppm) on average. Lowering jet-fuel sulfur content would reduce $PM_{2.5}$ emissions, yielding improved air quality at airports. To understand the implications of a lower-sulfur standard for jet fuel, we examined a ULS case—namely, 15 ppm, which is comparable to the U.S. standard for road diesel.

The process of hydrodesulfurization may lead to a slight loss of 1 percent in energy per unit volume of fuel. A small reduction of fuel lubricity may also result, but this can be overcome with appropriate additives. Because of hydrotreating, we anticipated that a ULS Jet A would have greater thermal stability and reduced aromatic content, which may lead to a reduction in certain maintenance costs. ULS fuel may improve multiuse pipeline operations, which currently are complicated by the transport of fuels with varied fuel sulfur standards.

The technology for hydrodesulfurization is in widespread commercial use today, and full introduction of a ULS Jet A could easily occur by 2017. The cost of sulfur reduction is approximately $0.05 per gallon. The net impact of a shift to a ULS Jet A on aviation economics, air quality, and global climate change is uncertain and remains a subject of investigation.

Unconventional Petroleum Fuels

Three unconventional sources of petroleum—Canadian oil sands, Venezuelan VHOs, and oil shale—may offer alternative jet fuels.

Oil sands and VHOs already yield a fuel meeting all current specifications for Jet A. Processing oil sands and VHOs for fuel is likely to be profitable as long as world oil prices exceed $50 per barrel. Once capacity is in place, production is likely to be profitable even if crude-oil prices decrease.

Due to the additional energy required to extract and process oil sands and VHO, the use of Jet A derived from these resources would have life-cycle GHG emissions ranging from 10 to 25 percent greater than those of conventional Jet A. Once the fuel reaches the tank, there are no differences in emissions or effect on air quality.

Oil shale is a solid sedimentary rock containing an organic material called kerogen. When the kerogen is heated sufficiently, it decomposes to form an oil that can be distilled like conventional petroleum. Because of work performed by the U.S. Department of Defense (DoD) in the 1980s, shale oil is included in the specification for Jet A as a conventional source of jet fuel that would be fully compatible with current aviation systems.

The prospects for oil-shale production in the United States remain uncertain. The conventional approach, consisting of mining and heating the recovered material in large retorts, is both expensive and environmentally intrusive. Promising approaches are under development, but their technical and economic viability have not yet been established. Oil-shale production requires significant energy inputs. If this energy is supplied from fossil fuels, life-cycle GHG emissions associated with oil-shale use could be 50 percent higher than those from Jet A. But life-cycle GHG emissions could be slightly below those of Jet A if oil-shale production includes methods to manage or prevent CO_2 emissions.

Considering the technical maturity of oil-shale production methods, oil shale is unlikely to support appreciable production of jet fuel prior to 2020. But the U.S. oil-shale resource base is very large, and success in ongoing technology-development efforts could lead to a commercial oil-shale industry that could eventually provide appreciable amounts of jet fuel.

Fischer-Tropsch Synthetic Fuels

The FT process produces liquid fuels from carbonaceous feedstocks, such as natural gas, coal, and biomass. The FT process begins with gasifying the feedstock and ends with a mix of hydrocarbon products that can be used to produce gasoline, diesel, and jet fuel. All jet fuels produced by FT synthesis have similar characteristics. In particular, they contain neither sulfur (less than 1 ppm) nor the aromatic compounds that tend to increase soot formation. Choice of feedstock does not affect fuel quality but does affect production costs and life-cycle GHG emissions.

Since 1999, blends that are up to 50 percent FT liquids have been used by commercial airlines leaving O. R. Tambo International Airport in South Africa. Standards and approval for this use is limited to FT fuels produced by Sasol production facilities. Efforts are under way to extend this standards-and-approval process to blends based on any FT fuel. In comparison to conventional jet fuels, pure FT fuels have reduced lubricity and do not contain aromatic compounds; the absence of aromatic compounds can cause leaks in certain types of fuel systems. Both of these issues may be resolved by blending the fuel with conventional jet fuel and may be addressed with the appropriate use of fuel additives.

The availability of FT jet fuels within the next decade depends on feedstock, the world price of oil, resolving uncertainties in production costs, and regulatory and technical issues associated with capturing and sequestering large quantities of CO_2. Existing and planned plants in Malaysia, Qatar, and South Africa can be configured to produce 75,000 barrels of jet fuel daily from natural gas within the next decade at a cost of $1.40 to $2.50 per gallon (in 2005 dollars). Assuming near-term construction of pioneer coal-to-liquids facilities in the United States, we estimate that approximately 75,000 barrels of jet fuel could be produced daily from coal within the next decade at a cost of $1.60 to $1.90 per gallon. Under similar assumptions, plants accepting a combination of coal and biomass may be able to produce approximately 12,000 barrels of jet fuel daily at a cost of $2.00–2.40 per gallon.

The life-cycle GHG emissions of FT jet fuel depend on the feedstock and whether options for permanently sequestering plant-site CO_2 emissions are available and utilized. For FT fuels produced from natural gas, life-cycle GHG emissions are comparable to those of conventional Jet A from oil sands. Jet fuel produced at a coal-to-liquids facility employing CCS could have life-cycle GHG emissions that are comparable to those of conventional Jet A, but, if the facility is less efficient, the emissions could exceed those of conventional Jet A from oil sands; without CCS, the life-cycle GHG emissions would be more than twice those of conventional Jet A. Depending on the amount of biomass that is used and whether CCS is employed, fuel produced from a combination of coal and biomass at a production facility employing CCS could have life-cycle GHG emissions that are less than 50 percent of those of conventional Jet A; however, achieving large reductions in GHG emissions requires considerable biomass use and would result in increased production costs.

Fuels from Renewable Oils

Biodiesel and *biokerosene* are fuels produced from fatty acids and triglycerides obtained from plants or animal processing. Biodiesel is typically produced by chemically processing the feedstock oil with methanol. Biodiesel inherits the properties of its feedstock oil, so biodiesels created from plant oils with carbon chain lengths in the kerosene range have been termed *biokerosenes*.

Biodiesel and biokerosene have been suggested as appropriate for blending with conventional jet fuel. Our research indicated that neither fuel is appropriate for use in aviation, even when used in light (i.e., low-concentration) blends. These fuels may break down during storage or during use in aircraft fuel systems, leaving deposits that could compromise performance and safety. Pure biodiesel would freeze at temperatures typical of high-altitude flight, and some tests of light blends have indicated freezing at typical operating temperatures as well. These issues are not present in most ground-based applications of biodiesel.

Hydroprocessed renewable jet (HRJ) fuel is produced by methods common in petroleum refining. In the first step, the fatty acids and triglycerides are hydrotreated to remove oxygen. The resulting paraffinic hydrocarbons are next processed to yield a mixture of straight-chain, branched-chain, and cyclic paraffinic hydrocarbons with collective properties that are similar to those of conventional jet fuel.

The properties of HRJ are similar to those of FT jet fuel: near-zero sulfur, high thermal stability, reduced lubricity, and near-zero aromatic content. As in the case of FT jet fuels, issues posed by the reduced lubricity and aromatic content may be addressed through the use of blending with conventional jet fuel or the appropriate use of additives. Several aircraft and airline companies have tested HRJ fuels, and DoD is in the process of procuring a large quantity of HRJ for testing and certifying for use in its aircraft.

Current and planned production capacity of HRJ is nearly 60,000 barrels per day (bpd), but reaching that production assumes the availability of appropriate feedstocks at competitive prices.

Current feedstocks for both biodiesel and HRJ include soybeans, rapeseed (canola), and palm-kernel oils. Additional feedstock options include camelina, a plant similar to rapeseed; babassu, a type of palm tree; and jatropha, a shrub, which all produce seeds with high oil content. Future feedstocks could include salicornia and algae. Significantly increased production of plant oils from current feedstocks would displace food production or require the conversion of tropical lands to farming, both of which would require changes in land uses and result in emissions of soil-based carbon. These so-called land-use–change emissions dominate the life-cycle GHG emissions of fuels derived from renewable oils, which can be two to eight times those of conventional jet fuel. If emissions due to land-use change are ignored, life-cycle GHG emissions of HRJ are roughly half those of conventional jet fuel.

Alcohols

Ethanol is not suitable for aviation operations. It has a low flash point, making it dangerous to handle and posing a risk to crew and passengers. Its high volatility could lead to problems during high-altitude flight. Moreover, its energy content per unit mass and per unit volume is approximately 40 percent less than that of jet fuel. Ignoring incompatibilities, if ethanol were used as an aviation fuel, range would be reduced and the amount of energy used to fly a given distance would increase relative to Jet A. These issues are not present when ethanol is used in ground-transportation applications.

Butanol is a simple, four-carbon, straight-chain alcohol that can also be made by fermentation of sugars. Research and technology-development activities are under way that are aimed at automotive use of blends of butanol and conventional gasoline. While butanol may be an attractive automotive fuel (especially in comparison to ethanol), butanol is not suitable for aircraft operations. While not as incompatible as ethanol, it still poses unacceptable safety risks due to its low flash point and high volatility.

Key Findings

In the Next Decade, Up to Three Alternative Jet Fuels May Be Available in Commercial Quantities

The alternative aviation fuels that are not derived from conventional petroleum that have the greatest production potential over the next decade are as follows: (1) Jet A derived from Canadian oil sands and Venezuela's VHOs; (2) FT jet fuel produced from coal, a combination of coal and biomass, or natural gas; and (3) HRJ produced by hydroprocessing renewable oils. All three are or can easily and inexpensively be made fully compatible with current aircraft and fuel-delivery systems. Canadian oil sands and Venezuelan VHOs have the largest potential of several hundred thousand barrels per day of jet fuel, but their use would result in increased GHG emissions. The prospects for FT jet fuels depend crucially on construction of a few pioneer commercial plants in the next few years. Production of commercial quantities of HRJ depends on the availability of appropriate feedstocks at competitive prices.

In the Next Decade, Alternative Fuels Will Be Available to Reduce Aviation's Impact on Climate, Although Supplies Are Limited

Certain HRJ and FT fuels are able to reduce the GHG emissions from aviation. For HRJ to be effective in reducing GHG emissions, it must be produced from oils that do not incur land-use changes, either directly or indirectly, that cause a large release of other GHGs. This constraint places a severe limit on the amount of climate-friendly HRJ that can be produced within the next decade. For FT jet fuels to be effective agents for GHG reduction, they must be produced from biomass or a combination of coal and biomass. In the former case, the fuels will be expensive and demand extensive cultivation of biomass for inputs. In the latter case, capture and sequestration of plant-site carbon emissions would be required, but overall costs would be much less, as would biomass consumption. As with HRJ, the provision of biomass must not incur land-use changes, either directly or indirectly, that cause a large release of GHGs.

Some Fuel Feedstocks May Provide Greater Benefits If Used for Purposes Other Than Alternative Jet Fuels

All of the alternative fuels considered in this study, regardless of feedstock, could be used to generate electricity, heat, fuels for ground transportation, or fuels for aviation. FT fuels and HRJ are attractive aviation fuels because they have specific energies that are slightly greater than current petroleum-derived jet fuel; however, high-performance diesel fuels can also be made via either FT synthesis or hydroprocessing of renewable oils. Both ground and aviation users of these fuels would benefit from the low sulfur and low aromatic content of these fuels, but, because of current U.S. and European regulations, ground-transportation uses of these fuels pay a premium for these qualities. Since the potential supplies of all of the alternative fuels, other than ULS Jet A, examined in this study will be limited in the next decade, if not longer, forcing certain feedstocks and fuels into one or another application (e.g., aviation versus automotive) may result in diseconomies and reduce progress toward reducing overall GHG emissions and increasing energy security.

Alcohols Do Not Offer Direct Benefits to Aviation

Alcohol fuels, due to their incompatibilities with aircraft fuel systems and their low energy content, are more appropriate for ground-transportation applications than for use in gas-turbine applications.

Biodiesel and Biokerosene Are Not Appropriate for Use in Aviation

Biodiesel and biokerosene have poor thermal stability and high freezing points, leading to problems in transportation, storage, and use of these fuels. HRJ may be produced from the same feedstocks and poses none of these issues.

The Economic Benefits of Producing Alternative Fuels Extend to All Petroleum Users

The major societal economic benefit of producing alternative fuels is a reduction in the demand for conventional petroleum, which would cause world oil prices to be lower than they would otherwise be. This effect of reduced world oil prices is independent of whether the alternative-fuel production and use occur in the United States or in some other country. This effect is also independent of whether the alternative fuel is used in aircraft or in some other application in which conventional petroleum is currently used, such as ground transportation, building heating, and industrial-process heating. Further, it is independent of whether the reduction in demand is due to additional supply or to conservation. The world oil price reduction stemming from each additional 1 million barrels of alternative-fuel supply is estimated to be 0.6 to 1.6 percent of the oil price that would otherwise prevail.[1]

[1] The wide range in the estimate is due to uncertainties in the behavior of OPEC and the price elasticities of petroleum.

Alternative-Fuel Production Yields Large Benefits to Commercial Aviation, Whether or Not Those Fuels Are Used in Aviation

In the next decade, large amounts of alcohol-based fuels and fuels derived from oil sands and VHOs will likely enter the world oil market: The Energy Information Administration's (EIA's) 2009 projection of future supplies of liquid fuels shows unconventional sources yielding about 7.5 million bpd in 2017. Based on prior RAND analyses, it is estimated that this level of production would cause long-term world oil prices to be between 5 and 12 percent lower than what they would be in the absence of such production. For world crude oil prices in the range of $100 per barrel, this amounts to a price impact of roughly $5 to $13 per barrel. In 2017, jet-fuel consumption in the United States (commercial aviation plus military) is projected to be about 1.9 million bpd. Applying the per-barrel savings to this consumption yields net annual jet-fuel cost savings of between $3.2 billion and $8.3 billion.

An Ultralow-Sulfur Specification for Jet A Would Reduce Aviation's Impact on Air Quality

ULS jet fuel would virtually eliminate secondary particulate matter due to sulfur-oxide emissions while also reducing primary particulate emissions due to sulfur. The introduction of a ULS jet-fuel specification would act to ease the introduction of FT synthetic fuels and HRJ into commercial aviation, as they pose similar concerns in terms of infrastructure compatibility of lubricity and effect on seals due to their low sulfur and reduced aromatic content. Finally, unlike new aircraft and engine technologies, which take some time to diffuse into the fleet, the air-quality benefits of sulfur elimination could be realized as soon as a ULS jet fuel were introduced. Adverse consequences of a ULS jet fuel would be higher fuel prices (by about $0.05 per gallon), an increase (about 1 percent) in the fuel volume purchased and consumed, a reduction (about 1 percent) in the aircraft range with full fuel tanks, an increase (by about 2 percent) in life-cycle GHG emissions, and the elimination of sulfur aerosols, which have a short-term cooling effect. This study did not attempt to assess the balance among these effects to determine whether introduction of a ULS jet-fuel standard is cost beneficial.

Recommendations

From the findings, the research team makes the following recommendations.

Measures Designed to Lower Greenhouse-Gas Emissions Should Not Treat Commercial Aviation Separately from Other Sectors

Our findings on alternative fuels in the near term show that the opportunities that are available to reduce the life-cycle well-to-wake (WTW) GHG emissions from aviation operations are costly and could potentially be counterproductive. Over at least the next decade, the feedstocks (and associated land requirements) used to produce low-GHG alternatives to Jet A, such as FT jet fuel from coal and biomass or HRJ, are limited in supply. These same feedstocks can also be used to make low-GHG automotive fuels or for other energy needs. Rather than legislating or regulating the sector to which these feedstocks should be directed, we suggest broader-based mechanisms that place a price on GHG emissions and allow economically efficient choices to be made across multiple sectors. Examples of these approaches include cap-and-trade systems and carbon-tax-and-rebate systems.

Any Measures Designed to Promote Alternative-Fuel Use in Aviation Should Consider the Potentially Large Greenhouse-Gas Releases Associated with Land-Use Changes Required for Cultivating Crops for Producing Biomass or Renewable Oils

Although understanding the magnitude of the GHG releases associated with land-use changes remains a topic of research, sufficient information is available to warrant a precautionary approach. This is a special concern for any fuel produced from energy crops grown in carbon-rich soils, such as palm oils. The potential magnitude of GHG release is sufficiently large that we recommend that no GHG credit be given to any biofuel production from deforested areas until the U.S. Environmental Protection Agency establishes criteria for accounting for direct and indirect land-use changes.

Establish a Standard Methodology for Assessing Life-Cycle Greenhouse-Gas–Emission Inventories and Impacts

At present, uncertainties associated with the treatment of fuel production and in-flight GHG emissions allow for a broad range of emission estimates and impacts for alternative jet fuels. To better prepare commercial aviation for potential regulation of GHG emissions, a standard methodology for estimating life-cycle GHG-emission inventories and impacts is required. Such a methodology would include standards for accounting for key inputs, setting system boundaries, allocating emissions among alternative fuel products and co-products, all combustion emissions, and the effects of land-use change. Additionally, such a methodology should include explicit means for accounting for key uncertainties.

For Improved Air Quality, Consider the Adoption of a Reduced-Sulfur Standard or an Ultralow-Sulfur Jet Fuel

Given the human-health impact of aviation emissions of particulate matter (PM) and gaseous PM precursors during takeoff, landing, and ground operations, the aviation community should consider the adoption of a ULS jet fuel.

A ULS specification for jet fuel could have the effect of bringing aviation to a similar specification to that for highway diesel fuel, potentially improving refinery scheduling and operations and multiuse pipeline operations. The introduction of a ULS jet-fuel specification would act to ease the introduction of FT synthetic fuels and HRJ into commercial aviation, as they pose similar concerns in terms of infrastructure compatibility of lubricity and effect on seals due to their low sulfur and reduced aromatic content. Finally, unlike new aircraft and engine technologies, which take some time to diffuse into the fleet, the air-quality benefits of sulfur elimination could be realized as soon as ULS jet fuel were introduced.

The benefits of ULS jet-fuel use in reducing air-quality impact need to be balanced against the potential positive and negative impacts on global climate change and economic considerations.

Utilize Emission Measurements from Alternative Jet Fuels to Understand the Influence of Fuel Composition on Emissions

As part of the certification process for general FT aviation fuels, the FAA, U.S. Air Force (USAF), NASA, and some international organizations are currently funding research to measure the emissions from burning alternative jet fuels. Continuing emission measurements are essential to assess accurately the impact of alternative-fuel combustion on both air quality and climate change.

Support Long-Term Fundamental Research on the Creation of Middle-Distillate Fuels for Use in Ground Transportation and Aviation

Middle distillates represent about 30 percent of the petroleum products used in the United States. They are essential not only to commercial aviation but also to the movement of freight by land and water. Moreover, middle distillates power the aircraft, ships, and fighting vehicles of the armed forces. At present, the technical options to provide these applications with low–GHG emission fuels are severely limited. The extensive use of first-generation feedstocks, such as soy and palm, will incur land-use changes that will cause a large increase in GHG emissions. Next-generation biomass feedstocks are needed that do not compete with food production and that consume little fresh water.