Aviation and Oil Depletion

Posted by Euan Mearns on August 9, 2007 - 10:00am in The Oil Drum: Europe
Topic: Demand/Consumption
Tags: aviation, biofuel, emissions, global warming, hydrogen, transportation [list all tags]

This is a guest post by **Christopher Smith** who is a Captain with the airline BA Connect. It was first published in December 2006, the discussion generated then can be read here. The post is based on a presentation (pdf) made to the oil depletion conference held in London last year.

Aviation is one of the fastest growing industry sectors in the world, growing at 2.4 times the rate of world GDP. The industry consumes over 5 million barrels of oil per day worldwide, almost one tenth of all the oil used for transportation. In the UK, according to the Department for Transport, the UK aviation industry is growing at approximately 5% per year while its fuel consumption is growing at 3% per year.

Carbon dioxide emissions from aviation vary directly with kerosene consumption. The resulting CO_2 from UK aviation accounted for 5% of the national total in 2003. The UK Environmental Audit Committee forecasts the value will be 10 to 12% in 2020 and could rise to 40% by 2050 if not checked. The unconstrained growth of aviation CO_2 emissions is incompatible with the UK government's target to reduce national CO_2 levels to 40% of the 1990 level by 2050.

In this discussion we will look at issues specific to jet aircraft fuel. Jet fuel has several unique requirements that complicate the search for a replacement. Next we will examine the possible alternatives and weigh their pros and cons. Finally we will look at what the airline industry is doing today with the fuel it has available.

Figure 1. The Allison AE3007A Turbofan (Jet) Engine.

Key properties of aviation fuel

Aviation fuel should have several key properties:

High Energy Content

There are two parameters by which we can measure the energy content of fuel. Specific energy is the energy content per unit mass (Joules / Kg) and energy density is the energy per volume (Joules / Litre).

By law, jet aircraft carry at least enough fuel to reach overhead their planned destination, thereafter fly to their planned alternative landing aerodrome, fly an approach to land at that aerodrome and still have enough fuel to hold for 30 minutes. There is always the possibility that some unforeseen difficulty will arise which causes a delay or necessitates a diversion to an alternate aerodrome. Airlines add a bit more to allow for these unexpected delays.

The more fuel an aircraft has on board at takeoff, the heavier it will be. From a design point of view, the more fuel the aircraft needs to carry, in mass or volume, the larger the aircraft and engines would need to be and the more fuel needed to perform the flight. Operationally, the heavier the aircraft is at takeoff, the more fuel that will need to be carried to lift it into the air and carry it to its destination. As fuel is consumed in flight, the aircraft becomes lighter and more efficient.

A fuel with high specific energy would have two benefits. Firstly, the higher the specific energy of the fuel, the lighter the fuel load for a particular range. This in turn means that less fuel would be consumed over the duration of the flight. All fuel on board an aircraft in flight that is not being used at that moment is little more than payload and requires additional fuel to carry it. Secondly, an aircraft designed to achieve its maximum range with a smaller mass of fuel would be built lighter and with smaller engines.

The argument for high energy density is similar. Energy density is the amount of energy per unit volume. For a given flight distance, an aircraft using a fuel with a low energy density would need a larger volume of fuel. Even if the total mass of fuel was the same (or even less), the higher volume would require a larger fuel tank, likely resulting in a larger aircraft. Jenkinson, Simkin and Rhodes, in their book "Civil Jet Aircraft Design", state that for every kilogram of unnecessary structure mass, the maximum takeoff mass will increase by about 3 kilograms. They also state that there is direct relationship between operational empty weight and both purchase price and operating costs. The best jet fuel would be one with a very high specific energy and energy density.

Safety over a wide temperature range

Fuel used in commercial aircraft must meet stringent safety requirements. Aircraft operate for long periods in the heat of the desert and in the freezing cold of the stratosphere, and from the high atmospheric pressure at sea level to the extremely low pressure at high altitudes. Aircraft are subjected to turbulence and, occasionally, lightning. The Jet A-1 kerosene used in Europe has a flash point of not lower than 40° Celsius. This high flash point minimizes the flammability and explosion hazard within the fuel tank and in aircraft accidents. The air temperature at jet aircraft operating altitudes is extremely cold. It is critical that the fuel does not freeze or thicken at temperatures as low as -47°C. It is equally important that the fuel does not contain or absorb water. In these cold temperatures ice crystals will form which will block fuel filters and lead to fuel starvation.

Environmentally clean and energy efficient

The consumption of kerosene in jet aircraft generates 3.2 tonnes of CO_2 for every 1 tonne of kerosene consumed. While there is currently no restriction on the production of CO_2 from aviation sources it is only a matter of time. Domestic aviation sources of CO_2 are included in national greenhouse gas emissions inventories and are likely to be subject to emissions limits in the next couple of years. International aviation emissions are more problematic but there is increasing pressure on the International Civil Aviation Organization (ICAO) and national governments to develop a workable solution. There is increasing likelihood that aviation will be included in the EU Emissions Trading Scheme as early as 2011.

In 1999, the Intergovernmental Panel on Climate Change (IPCC) produced a report titled "Aviation and the Global Atmosphere". The report was the first comprehensive assessment of the climate change effects of air transport. One of the most significant results of the study was the determination that the current focus on CO_2 and Global Warming Potential was unsuitable for aviation. The report states that Radiative Forcing is a better indicator because it takes into account CO_2, water vapour, soot, particulates and ozone. Due to the high altitudes at which jet aircraft operate, these other products of combustion play an increased role. The contrails formed by jet aircraft in some environmental conditions may also have a significant radiative forcing value. The IPCC determined that the overall climate change effects of aviation are approximately 2.7 times greater than the effect of the CO_2 alone.

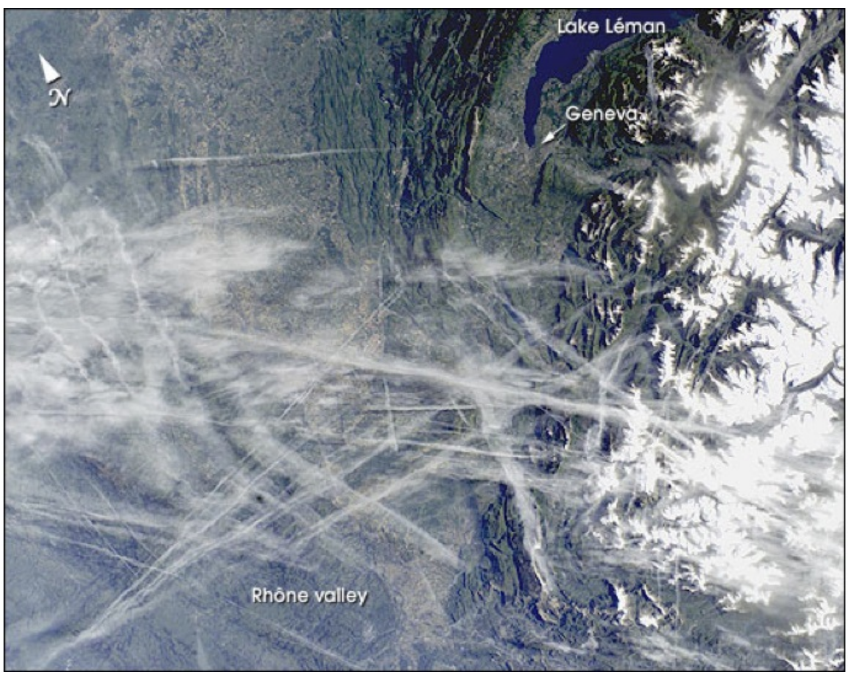


Figure 2. Contrails over France & Switzerland. Do they contribute to global warming? Photo: veimages.gsfc.nasa.gov/3450/ISS004-E-11807.jpg

The aircraft and engine manufacturers have made great strides in improving the energy efficiency of their products. The problem for the aviation industry is that its growth is outstripping the efficiency improvements in technology. As other industries strive to reduce their overall CO_2 emissions, the aviation industry percentage of the total will increase. This is bringing the industry under increasing scrutiny from all quarters. The aviation industry needs a fuel with less environmental impact if it is to continue to grow.

Availability and Cost

The greatest advantage of kerosene over other fuels today is that it is available everywhere. Aircraft are expensive and highly mobile assets but they are of no value if they cannot be refuelled. Wherever they go on the planet there will usually be a supply of aviation kerosene. Kerosene is portable, storable and available. For many years it has also been relatively inexpensive. Even so, for most airlines, fuel is their single greatest expense at somewhere between 10% and 35% of total operating costs. The price of fuel is frequently cited in airline profit and loss statements.

Other useful characteristics

Jet aircraft fuel performs other useful functions which have a bearing on the suitability of alternatives:

- Aircraft in flight operate within a narrow centre of gravity range. The consumption of fuel during the flight alters the aircraft's centre of gravity and, on larger aircraft, fuel may be pumped forward or aft to maintain trim. This may not be possible with solid or gaseous fuels.
- The heat absorption qualities of the fuel are used to cool engine oil and sometimes cool the airframe. These qualities also allow it to be pre-heated before use to improve combustion efficiency without compromising safety.
- Kerosene provides lubrication to fuel pump and fuel metering components.

Current aircraft technology is optimised around the use of kerosene. Changes in aircraft fuel will require changes in both aircraft and engine design. Aircraft being manufactured today are expected to be in service for 30 years or more. Airlines will be unwilling to turn their backs on these major financial investments mid way through their amortized life. We can expect these assets will still be flying and will still be using kerosene at that time. In the long term there will have to be an alternate to petroleum aviation fuels. One major uncertainty is whether technology will change to accommodate the future fuel or whether the fuel will be selected to match the available technology. The ideal jet aircraft fuel will have a high energy content, wide operating temperature range, safe, clean, inexpensive and widely available.
Lets take a look at some of the alternatives.

Alternative fuels

Hydrogen

The most commonly discussed alternative aviation fuel is hydrogen. At first glance, hydrogen is a good choice. It has a specific energy 2.5 times greater than kerosene and generates no CO_2. Hydrogen does have some disadvantages however. Hydrogen requires a cryogenic storage system. The pressures involved will require cylindrical or spherical tanks and even with this high pressure storage system, hydrogen's energy density would be only 40% of kerosene. That means that for the same design range, the fuel tanks will need to be 2.5 times larger and significantly heavier. Hydrogen power will therefore require a radical change in aircraft and engine design. The combustion of hydrogen generates 2.6 times as much water vapour as the equivalent quantity of kerosene. At high altitudes, water vapour is a potent greenhouse gas. Notwithstanding this, the IPCC forecast that a hydrogen powered aircraft would be more environmentally friendly than the kerosene version at all altitudes.

Figure 3. This NASA Blended Wing Body airliner would give a 30% improvement in fuel efficiency over conventional tube and wing designs regardless of the fuel used. Photo: www.nasa.gov/centers/langley/images/content/70059main_2003-81-01.jpg

The greatest single problem with hydrogen will be its availability and possibly cost. Before manufacturers will invest in the design of a hydrogen aircraft for commercial service and before airlines would consider adding them to their fleets, there would have to be universal availability of hydrogen at every airport the aircraft is intended to serve, as well as every conceivable alternate aerodrome that might be selected due to weather or technical difficulty. There is currently no worldwide infrastructure and hydrogen will not be a practical jet aircraft fuel until there is.

Ethanol / Methanol

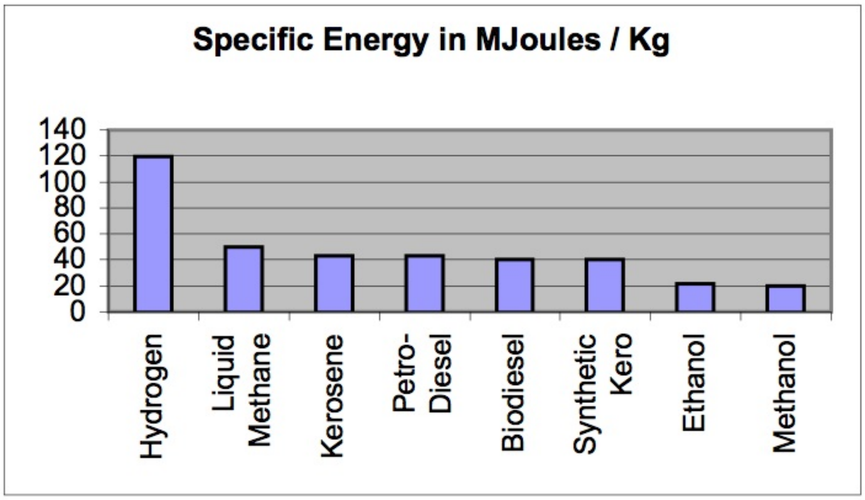
Alcohols are another potential fuel but they too have their complications. Alcohol fuels have between 50% and 75% of the specific energy of kerosene. An alcohol fuelled aircraft might be 25% larger than an equivalent kerosene powered aircraft due to the increased volume of fuel. The engines may be 50% larger due to the combined increase in fuel and aircraft weight. Another significant argument against alcohol is its affinity for water. Alcohol readily absorbs water vapour which, in the extreme cold of the stratosphere, would turn to ice crystals and block fuel filters. Alcohol evaporates at significantly lower temperatures than kerosene and it has a flash point of at most 18°C. Alcohols are worse for Volatile Organic Compounds which are bad for the ozone layer and when operating at low power settings alcohol fuelled engines generate some hazardous by-products, including formaldehyde.

Biodiesel

Biodiesel is another potential aircraft fuel. On its own, biodiesel is unsuitable for jet aircraft due to its very high flash point, very low volatility and because it thickens and crystallizes at the temperatures found at jet cruising levels. Biofuels generate less than half the greenhouse gas emissions of kerosene. For this reason, the International Airline Transportation Association (IATA) has committed to using 10% biofuel across the industry within ten years. Biodiesel is currently approved as a "Kerosene Extender" at concentrations up to 10%. It may eventually be approved for use at concentrations up to 20%.

Synthetic Fuels

The fuel that holds the greatest promise in the immediate future is synthetic kerosene (synfuel). Synthetic kerosene can be made from coal, natural gas or biomass. It is currently approved for use in commercial aircraft in a 50/50 mix with petroleum kerosene and aerospace manufacturers plan to have a fully synthetic fuel approved in 2006. The biggest advantages of synfuel are that it frees the aviation industry from dependence on petroleum resources and that it can be used in existing aircraft. Synthetic kerosene is slightly cleaner than petroleum kerosene but this does not take into account the large amount of CO_2 generated during production. The relative merits of synfuel will depend on the raw material used to produce it and the CO_2 mitigation strategy employed.



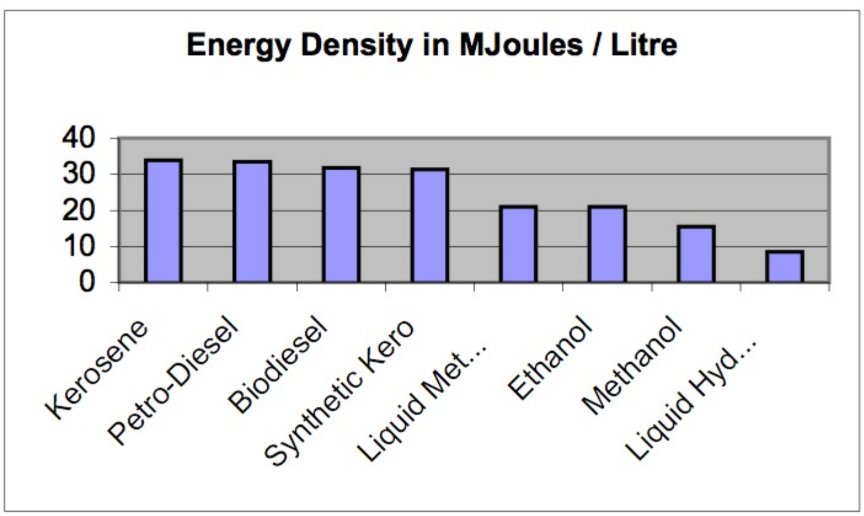


Figure 4. A comparison of the energy content of potential jet fuels.

Fuel saving strategies

Aircraft engines have been using kerosene for decades and engine technology has been fine tuned around this fuel. Every year, incremental improvements increase the overall efficiency of aircraft but no large technical advances are forecast. Operational efficiency improvements are now offering the greatest rewards. Technical improvements generally apply to new aircraft but operational improvements apply to all aircraft, new and old. In fact, the less efficient the aircraft, the greater the benefit. Aircraft consume large amounts of fuel during their lifetime and even small reductions can have a large cumulative effect. As emissions are directly related to fuel consumption, any reduction in consumption will also mean a reduction in environmental impact. Manufacturers and airlines are putting significant effort into fuel efficiency.

There are several strategies being pursued by the aviation industry to reduce fuel consumption:

Minimum fuel

In the past, determining the required fuel load for a flight was an inexact science and included a healthy contingency factor. There are significant savings to be had by reducing the total amount of fuel on board the aircraft at departure to the minimum safe amount. The key is being able to accurately determine the fuel required based on aircraft weight, expected routing and accurate forecasts of winds and temperatures aloft. Modern sophisticated flight planning computer programs allow an accurate determination of the minimum fuel needed to carry out the flight. The calculations will even vary with individual aircraft. For large aircraft on long flights the savings can be measured in tonnes. Further improvements will be realized when air traffic control forecasts of traffic density can be factored in at the flight planning stage, rerouting flights to minimize delays and therefore fuel consumption. Modern onboard navigation systems and satellite positioning systems allow aircraft to navigate the forecast routing to a high degree of accuracy. Computer generated flight plans can be accurate to within one minute and several kilograms of total fuel requirements.

Air Traffic Control efficiency improvements

The longer the routing from departure to destination, the greater the fuel consumption. Many new routes take advantage of the improved navigational accuracy of modern aircraft allowing more routes and greater use of shortcuts between enroute waypoints. The new Y1 and Y2 air routes over central China are a good example. IATA forecasts that these new air routes will save 30 minutes on flights between China and Europe, resulting in a combined saving of 27,000 tonnes of fuel per year. Similar improvements are realized by new air routes across the North Pole. The IPCC predicts a 6 to 12% improvement in aircraft fuel efficiency by 2020 through more efficient air routes.

Figure 5. The new Y1 & Y2 air routes over central China will save 30 minutes flight time. Photo: www.iata.org/NR/rdonlyres/15FDF950-F4F8-4B69-8192-5FC4E61F6AF2/0/IATA1RouteMap.pdf

These savings are modest compared to the predicted savings from the next generation of air traffic control. The Future Air Navigation System (FANS) or Free Flight allows aircraft to fly the most efficient direct routing between airports and eventually from gate to gate. FANS relies on accurate flight navigation computers on board the aircraft, sophisticated air traffic control computers on the ground and satellite positioning and communications systems. FANS is currently being tested on selected aircraft and routes.

Other potential fuel saving:

- The move towards larger, integrated air traffic control centres which provide a seamless service across a larger area.
- Continuous Descent Approaches which minimize the time aircraft spend at lower, less fuel efficient altitudes.

Aircraft and Engine Improvements

Aircraft technologies are continually improving. Aircraft coming off the assembly line are significantly more efficient than earlier models. They are also more efficient than the same model of last year. This continual improvement results in a year on year improvement in efficiency of at least 1%. Aircraft currently in service will become less efficient over time as they accumulate minor surface damage, coats of paint and dirt. In this respect, the general improvement in safety is reducing even minor incidents that result in repairs and the resulting increased weight and reduced efficiency. The company "Gas Turbine Efficiency" claims that their engine turbine cleaning service can win back a 1% improvement in fuel efficiency. While these individual strategies each produce only small improvements, together they add up to major savings. The International Airline Transport Association (IATA) claims that member airlines have improved their fuel efficiency by nearly 20% over the last ten years and 5% in the last two years.

Competition

Load factor is a measure of airline efficiency. It is the percentage of the total number of seats that are occupied by passengers on a particular flight. The load factor of a flight will vary from day to day but will follow a normal distribution around a mean. There is a limit to the mean load factor an airline can expect to achieve without losing customer goodwill and losing passengers, perhaps to the competition. A situation known as spill. Improved revenue management and direct sales channels allow airlines to increase average load factor while minimizing spill. Sometimes this improved revenue and capacity management allows an airline to operate fewer services on routes on which load factors were too low. Across airlines and the industry this trend has led to a reduction in overcapacity and is one of the reasons that airline fuel consumption has been growing at a slower rate than total passenger growth.

Coming up

Large fuel savings will be realized when passenger perception of airline quality is de-linked from energy wasting activities. Many airlines will start engines and join the queue at the runway knowing that there will be significant delays on departure. This improves the airline's on time departure and arrival statistics but is extremely wasteful. Similarly, aircraft will aim to get airborne on time knowing that favourable winds will bring them to their destination well ahead of schedule, sometimes before the airport even opens.
For years, the aviation industry has been playing on passenger perception that jets are better than propeller aircraft. After a period of time in which the turboprop aircraft was almost completely wiped out of the market they are starting to make a comeback. The turboprop engine is simply a jet engine driving a propeller. Modern turboprop aircraft are able to match the speed and comfort of regional jets on flights up to 500 miles. These aircraft use the same fuel and have the same reliability as jets while delivering outstanding reductions in fuel consumption, greenhouse gas emissions and noise.
If airlines fail to achieve emissions reduction targets on their own we could see a return to increased government intervention in which restrictions are placed on aircraft size and frequencies on each route. This is effectively the system in place at the moment on most international routes. While the current move is towards a more liberal system called Open Skies, government climate change objectives may force a reversal of the trend.

Figure 6. The DeHavilland Q400 turboprop aircraft: fast, efficient and quiet. Photo: www.flybe.com/images/gallery/flybe400.jpg

The Aviation Energy Trend

There is currently no alternative to the use of kerosene in aircraft engines. The hydrogen economy is still decades away and it will be decades after that before the majority of long haul transport aircraft are hydrogen powered. By that time there is likely to be serious supply problems with petroleum kerosene and fuel efficiency and fuel conservation strategies will continue to dominate airline fuel policy. These efficiency strategies are currently driven by high fuel costs but in the very near future these costs will be compounded by the cost of the fuel's associated greenhouse gas emissions. The switch from petroleum to synthetic kerosene will be driven by availability and price. The lower switching costs in other industries may help aviation avoid a kerosene supply crisis but is unlikely to mitigate the rising cost. The increasing cost of fuel and associated emissions may mean some of today's flying will no longer be viable. A lot of short haul point to point flying could be pushed onto alternative transport systems that are better able to switch to cleaner fuels

Hydrogen powered aircraft in particular offer little hope until there is a world wide supply in a mature hydrogen economy. Global warming emissions will continue to be a problem whichever fuel is being used. Even ultra clean hydrogen has global warming issues and we can expect that aviation will eventually be called upon to account for all its climate change effects, not just carbon dioxide. The cost of switching to non kerosene fuels is extremely high. The aviation industry is likely to accept very high fuel costs before any wholesale switch to an alternative.

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