Fuel effects on range versus payload for modern jet aircraft

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ABSTRACT

With changes in the availability and quality of existing aviation fuels anticipated in the next 30 years it is timely to assess how changes in fuel properties would affect the range payload performance of aircraft. The effects on range and payload of a wide range of candidate fuels for aviation are investigated, including changes to the blends of conventional hydrocarbon fuels. Lighter fuels tend to be more desirable for commercial flights, where the flight is as close to the maximum payload as possible. Flights favouring range over payload are better suited by a more dense fuel. The hydrocarbon blends suggest for each aircraft, an optimum fuel may exist for the maximum payload and allowing the maximum range. Specific flight plans below the maximum range of the aircraft may be met with a lower specific energy fuel.

NOMENCLATURE

FAME	fatty acid methyl ester
FT	Fischer Tropsch
g	Gravitational constant (m/s^2)
IFR	Instrument Flight Rules
LCV	Lower calorific value (specific energy) (MJ/kg)
L/D	Lift/Drag ratio
R	Range (km)
SPK	synthetic paraffinic kerosene
sfc	Specific fuel consumption (mg/Ns)
V	flight speed (ms^{-1})
W	Weight (N)
ρ	Density (kg/m^3)

Subscripts

0	Initial condition at start of flight cycle
e	empty
f	fuel
i	Section of flight cycle
p	payload

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1.0 INTRODUCTION

The operating weight of an aircraft W_0 at the start of the flight cycle is usually as close to the maximum structural load of the aircraft as possible. How that weight is made up is dependent of a combination of the payload expected and the fuel required for the flight range. The operating empty weight of the aircraft W_e, including crew, is the only other component making up W_0 as defined by Equation (1), and is assumed constant in this analysis:

$$W_e + W_p + W_f + W_0 \leq W_{max} \quad \ldots (1)$$

Clearly if the maximum structural load of the aircraft is exceeded the aircraft will have difficulty in take off, and in the worst case will not be safe to land.

If the maximum structural load of the aircraft is not met by W_0 the use of that particular aircraft for that particular flight should be justified by some other operational criteria, as the airframe and power plant are oversized for the flight and will result in a greater consumption of energy than necessary.

There are further limitations to Equation (1) however, as for aircraft, the volume available for the payload and fuel are restricted by the airframe. Whereas the former is not usually significant, as the payload weight limit is often met before the payload volume limit, the fuel volume restriction on range will become significant as the desired operating range increases.

As such the ranges achievable for a set of payloads, spanning from no payload to that matching the maximum structural load of a particular aircraft can be plotted in a range versus payload diagram. This indicates the limitations of that particular design of aircraft, and identifies the trade off between payload and fuel carried.

In the comparison of range and payload the key characteristics of the fuel are the calorific value of the fuel (*LCV*) and the density (ρ) as shown in Fig. 1, which are both associated with the chemical composition of the fuel.

A high *LCV* and high density would be most desirable for flight, offering the maximum energy release per unit volume and per unit mass. A line has been added to the hydrocarbon group in Fig. 1 showing the clear trade-off between high energy densities (having the units MJ/m^3) and low 'mass' densities and showing the upper limit to the desirability of high *LCV* and high density using hydrocarbons. Higher energy content fuels are in existence, notably Pentaborane, however the toxicity of such chemicals mean that they are only considered as emergency fuels[3] and fall outside the scope of this study. In general, heavy fuels have high energy content per unit volume and light fuels have high energy content per unit mass.

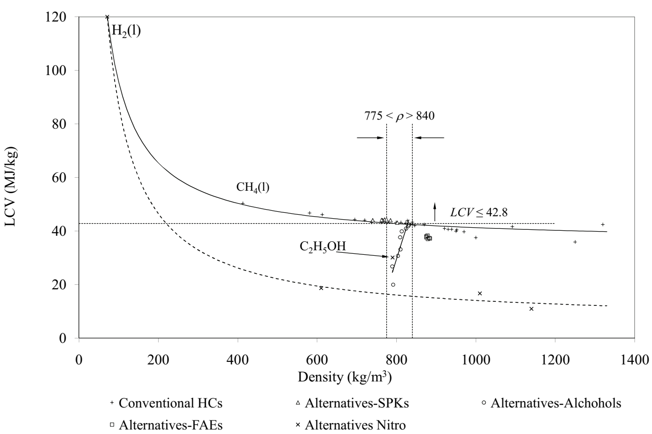

Figure 1. Relationship between *LCV* and density for range of liquid fuels showing limits of Jet A-1 specification[2,7,8,9].

The most common specifications for jet fuel are the Defence Standard 91-91 and the ASTM D1655 specifications, which control the quality and suitability of fuel in jet aircraft. The limits on density and calorific value of these specifications have been added to Fig. 1 as dotted lines.

Currently, several pathways are being explored for the production of synthetic paraffinic kerosenes (SPKs) such as Fischer Tropsch (FT) and the hydrotreating of oils, allowing the production of jet fuels from feedstocks other than crude oil, tar sands and old shale. These processes produce a fuel of mainly *n*- and iso paraffins and do not have the spread of hydrocarbons seen in conventional fuels. As such, without the addition of heavier compounds, SPKs tend to fall on the lower density limit of the aviation fuel specification as can be seen in Fig. 1. SPKs can offer advantages such as an absence of sulphur or other trace compounds dependent on processing technology. They also typically have narrower boiling ranges than conventional jet and freeze points beyond the requirements of the certification specifications[4].

Many alternative fuels fall away from the hydrocarbon line, such as alcohols and fatty acid methyl ester (FAME) fuels. The calorific value of the Alcohol group rises steeply with increasing molecular size. However, the freeze point of these fuels also rises to the point where the fuel's cold flow properties would become a concern for aviation use. Octanol has a freeze point around –20°C (the conventional Jet fuel specification freeze point limit is –47°C). Unlike the other fuel groups it is not possible to create a line plot through the FAME data. This is mainly due to the properties of the fuel being dependent on the feedstock and triglyceride groups from which it is created, such as Rape seed methyl ester (RME) which is derived from Rape seed oils.

With changes in the availability and quality of existing aviation fuels anticipated in the next 30 years[5] it is timely to assess how changes in fuel properties would effect the range payload analysis of aircraft.

This paper aims to investigate the effects of fuel characteristics on the payload range diagram for a specific aircraft design; particularly for small changes in the 'cut' of the petroleum fuel. This will be compared to some alternative fuels currently proposed in the literature.

In addition, simple analysis of the tank to wake portion of the CO_2 impact of particular fuels will be made relative to conventional Jet A-1. In order to make a complete assessment of the environmental impact of the fuels investigated it would be necessary to compare the CO_2 emissions during the growing/extracting of any feedstock, their associated processing into fuel and supply to the aircraft .

More radical studies have already been completed; particularly on the potential for hydrogen fuelled aircraft in the late 1970s[10] and again in the 1990s as part of the European CRYOPLANE project[11]. These studies are more complex and include changes in the airframe structure to increase the available fuel volume.

Other fuels have been investigated such as Ethanol blends[12], which will also require complex changes to airframe structure. In the Ethanol blend study, a 20% energy consumption reduction for the lighter fuel weights on long range aircraft was demonstrated. However for medium to short range aircraft, an energy consumption increase of 17-38% was reported. Similar results were indicated for liquid methane.

Although properties of methanol, higher alcohols and FAME fuels have been studied at length for the ground market, no studies have been found which model the range performance of aircraft carrying such fuels. Due to their higher densities, the use of these fuels may require much less drastic changes to the airframe for flight. A more complete analysis may reject such fuel types due to changes in freeze point; a study of Soya ME suggests only a blend of 2% in regular kerosene is possible before the freeze point of the fuel is higher than allowed by the specifications[5].

Some flights involving changes to the specification of conventional fuels have been carried out, in 1989 a direct flight from

Heathrow, UK to Sydney, Australia (approximately 18,000km) was undertaken using a stripped out (to lower the W_e weight), empty (zero W_p) Quantas 747-400 running on a fuel as dense as the Jet A-1 specification would allow[13].

The development of alternative fuels for aviation is currently a rapidly progressing field. Since February 2008 there have been at least five demonstration flights of alternative fuel blends by commercial aviation companies as well as numerous ground based research activities. An approval process for jet fuels from unconventional sources has been created[14], and generic approval has been granted to 50% blends of SPKs from FT processes with conventional jet fuel[15]. In addition to this a specific approval has been granted to 100% coal derived synthetic fuel as the heavier hydrocarbons needed for a FT SPK based product to match the specification can also be created from coal.

2.0 AVAILABLE FLIGHT MODELS

The simplest calculation of aircraft range can be made by use of the Breguet range equation[16]. This assumes that the aircraft is already in straight and level flight (i.e. at cruise) in still air with full fuel tanks before the calculation of range is made.

In straight and level flight, the thrust and drag balance just as the aircraft weight and lift also balance, and the range can be estimated thus:

$$R = \frac{V \cdot L/D}{g \cdot sfc} ln\left(\frac{W_{i-1}}{W_i}\right) \qquad \ldots (2)$$

where W_{i-1} is the aircraft weight at the start, and W_i is the weight at the end of cruise.

However, the range of an aircraft is also limited by the fuel consumption in other sections of the flight cycle: such as lift off, landing and reserves (for example, the FAA requires 45mins of fuel for cruise after the alternative leg of the mission under Instrument Flight Rules, IFR[17]).

Marginally more detailed approaches for calculating range exist which allow for these additional demands on fuel reserves by a series of ratios defining the weight difference at start and end of each flight cycle[18]. This allows a calculation of the range of an aircraft including Breguet equations of the form of Equation (2) for cruise and reserve and weight ratios for take off, landing and manoeuvres. Values for these flight section ratios using historical values from one source are shown in Table 1. In this simplified analysis the decent is ignored, assuming that cruise ends with decent and that the distance of the decent is part of the cruise range.

Table 1
Historical flight section weight ratios[18]

	W_i/W_{i-1}
Warm up and take off	0.970
Climb	0.985
Landing	0.995

Many other increasingly complex models of the aircraft flight and mission profile are available ranging from PIANO[19] to full design codes for specific aircraft. These generally apply more realistic flight conditions and pay closer attention to the lift and drag generated by the aircraft over the complete flight cycle; they allow the estimation of additional data such as total emissions for the flight cycle. Such complex models also incorporate the prevailing conditions in the atmosphere which will affect the possible range of the aircraft.

However for the purposes of a comparison of changes in range caused by changes in fuel, it was assumed that the flight was in still air, and thus the simplified models of Ramyer were used as they could be manipulated fairly simply. The flight mission was simplified to five stages: Warm up and take off, climb, cruise, decent and landing and a reserve of 45mins at cruise. In addition, much of the required data for more complete models is not readily available. Instead, validation of this technique was made against published range payload data for the aircraft modelled.

It is felt that under cruise conditions changes in the atomisation characteristics of the fuel will not be significant, and as such the combustion efficiency will be constant. Therefore in order to allow a comparison of a range of fuels, a correction is made to the *sfc* from the engine performance data running on standard jet fuel, so that the thrust and heat release of the combustion will remain the same.

Although this analysis takes no account of other important restrictions on the use of fuel for aircraft (freeze point, volatility, re-light capabilities, fuel pumps and ground handling for example), as a first order assessment on the effects of changes in fuel characteristics it provides a framework for discussion to develop.

3.0 COMPARISON OF MODELING TECHNIQUES

In order to assess which modelling technique would be best used for this study a comparison was made of the simple Breguet equations, the Raymer approach and the output of a more complex model, PIANO. Using each of these three techniques, a range/payload chart was created for the flight of a Gulfstream 550 business jet as the data for this aircraft was readily available (see Table 2) in the literature, the results of which can be seen in Fig. 2.

In Fig. 2 the three regions of the range payload diagram can be clearly seen. Starting with maximum payload on the left of the chart, fuel is added increasing the possible range of the aircraft. This continues until the maximum structural weight of the airframe is reached at around 11,000km, at which point further increases in range are achieved by trading payload for fuel. There are two effects operating at this condition: clearly more fuel equates to more range, but less payload equates to more weight lost during flight as the fuel is burnt, which also extends range. Once the trade off between payload and fuel is limited by the volume of the fuel tanks available, increases in range are only possible by moving away from the maximum structural weight of the airframe by reducing the payload further, as seen in the bottom section of Fig. 2.

There is little difference between the calculated range from the PIANO model and the Raymer model. The advantage being that the Raymer calculation can be made easily in a spreadsheet. The over-estimation of the Breguet equation can clearly be seen in the context of its simplicity.

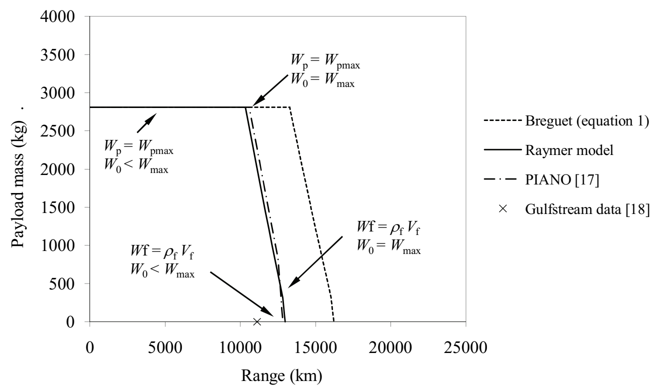

Figure 2. Comparison of range/payload calculation techniques for Gulfstream G550, cruise at 39,000ft, Mach 0·85, (45min extra cruise).

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4.0 MODELLING

In order to carry out a representative analysis of the effects of changes in fuel, three aircraft were modelled: The Gulfstream G550, a business jet, the 737, a short haul commercial aircraft and the 747 a long haul commercial jet. The three aircraft were modelled for a range of fuels. These aircraft were chosen as representative of different types of commercial aircraft currently in service.

The important characteristics of the aircraft are listed in Table 2;

Table 2
Characteristics of aircraft modelled

	G550	737-300-CFM563B1	747-200B-RB211-S24D4
W_{max} (N)	404788	553804	3660886
W_c (N)	214849	322452	1725955
$W_{p\ max}$ (N)	27801	151284	616034
V_f max (m3)	23	20	206
L/*D* at cruise	18.4	17.9	17.5
Cruise Thrust (N)	19335	48041	51733
sfc (mg/Ns) (kerosene)	18.15	17.88	17.46

In order to model the effects of changes in fuel type several assumptions have been made which impact on all the calculations which take place in this study. Firstly, it has been assumed that the heat liberated in the combustion chamber of the engine and the cruise thrust is the same as the kerosene case listed in Table 2. This can be achieved by adjusting the *sfc* of the alternative fuel such that:

$$sfc_{alt} = sfc_{kero} \frac{LCV_{kero}}{LCV_{alt}} \qquad \ldots (3)$$

Practically, for this study it is assumed that the engines are capable of efficiently combusting the modelled fuels. Existing engines have been optimised for operation using kerosene and significant movement away from the density and heating value of conventional fuels will affect the validity of any modelling. The impact of such changes has been estimated by gas turbine simulation codes to be between 0·5 and 2% difference between the ratios of sfc to *LCV* for a JT15D-4 engine[22].

Several studies have also used these approaches, and more sophisticated models to compare the impact of FT and biodiesel fuels on the range payload performance of single aircraft[22,23,24] . All find that the less dense, higher calorific FT fuel offers benefits in range at full payload ($W_p = W_{pmax}$). Conversely they suggest, more dense, lower calorific fuels offer benefits in range at the opposite end of the range payload diagram, when the fuel tanks are full ($W_f = \rho_f V_f$)[22,24].

It has also been assumed that no changes have been made to the airframe. For cryogenic fuels this is perhaps less likely than for normally liquid fuels, as in order to protect the cryogenic fuel from high heat transfer it is not suitable to store it in the wings of the aircraft[5]. Such changes could only be taken into account using more detailed modelling.

All subsequent calculations assume a payload mass to be given and the range to be calculated using an adaptation of Equation (2) including the weight ratios shown in Table 1. As the payload increases, the available range is eventually limited by the aircraft fuel tank volume, and then the maximum takeoff weight of the aircraft, which bound the calculation of available range.

The mission profile is assumed to be greatly simplified as discussed above.

5.0 CONVENTIONAL HYDROCARBON FUELS

Although Fig. 1 shows discrete points on the hydrocarbon curve, most hydrocarbon fuels above 700kg/m^3 are multi component, not simple fuels. This means that any point along the curve beyond this point represents a possible fuel, assuming the components are miscible.

The traditional range versus payload diagram is shown for the Gulfstream G550 in Fig. 3 for a range of hydrocarbon fuels, some real, and some possible fuels chosen to show the trend of the curve in Fig. 1. For comparison purposes, the 20 year average in annual volume weighted average properties of Jet fuel within the UK was used. These are reported in the Energy Institute annual survey . The changes in payload/range diagram for the Boeing 747 (Fig. 4) and 737 (Fig. 5) are also modelled.

The Raymer calculation predicts quite well the shape of the Range/Payload diagram for the 737 and 747. The discrepancy at the fuel volume limited end of the diagram may be caused by differences in the quoted and actual fuel tank volumes for the aircraft in[26], or in differences in the version of the aircraft modelled for which engine data is available and the one for which range payload information is available.

The non linear decline for 737-300 data from the volume limited point onwards is due to natural log relationship of the Breguet model and the relatively small fuel tank in the 737. This gives a

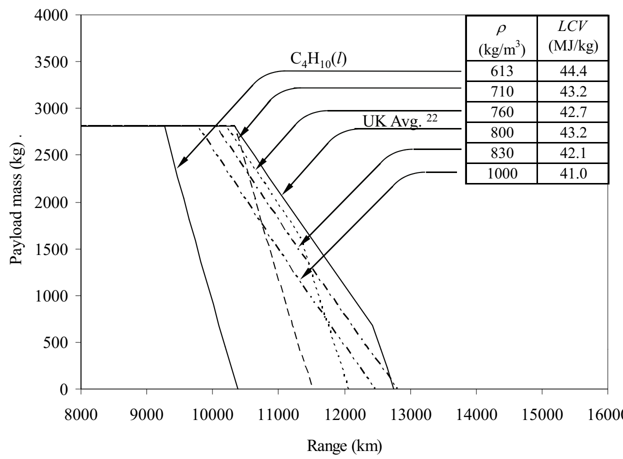

Figure 3. Changes to the range performance of Gulfstream G550 due to alterations to the Hydrocarbon fuel used for flight (UK Avg. is the 20 year average Jet A-1 in the UK[25]).

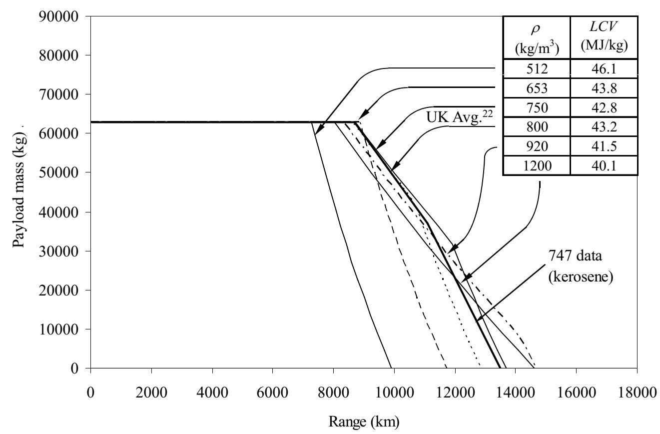

Figure 4. Changes to the range performance of Boeing 747-200B-RB211-S24D4 due to alterations to the Hydrocarbon fuel used for flight (747 data shown as bold line from Ref. 26).

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weight ratio during cruise of between 0·86 and 0·64 which is much closer to unity than for the other aircraft.

For low density/high calorific value fuels, the range limit for all possible payloads is entirely limited by the volume of the fuel tanks. As mentioned above, situations where the maximum structural load is not met by the weight of the various elements in Equation (1) leads to inefficiencies and clearly would not be the optimum flight cycle in terms of fuel consumption alone. The optimisation of aircraft design based on fuel type is further illustrated by the fact that based on the above calculations none of the aircraft modelled would be able to fly on liquid hydrogen or liquid methane. Volume limitations preclude the aircraft having enough fuel for take off, landing and meeting the required reserves of fuel for manoeuvres.

As the density of the hydrocarbon fuel increases, the range can be extended to a certain degree by balancing the payload and fuel weights to reach the maximum structural load of the aircraft. As can be seen from the average UK jet fuel case, the G550 is fuel volume limited for very low payloads. The 737 and 747 are fuel volume limited at a payloads below 60% and 70% of their maximum payloads respectively.

At higher densities (> 830kg/m^3 for the G550, > 1,200kg/m^3 for the 737 and >920kg/m^3 for the 747) the fuel is dense enough for the range not to be limited by the volume of the fuel tank. However, as the calorific value of the fuel is dropping, the range possible also decreases. As can be seen in Fig. 3, using these dense hydrocarbon fuels are of little benefit for the 747 and G550, except in the region discussed in the last paragraph, where the payload is very low. The 737 has relatively small fuel tanks, and therefore is fuel limited for much of payload variance, some increased benefits in range could be realised by the use of higher density fuels.

By comparing conventional hydrocarbon fuels, it can be seen that some fuels would out perform the range possible from kerosene at maximum payload, particularly fuels in the range $560 < \rho < 775$kg/m^3. These fuels offer a small increase in range at the maximum payload, although the limitations of the tank volume result in a reduced range in the range/payload pay-off region.

The beneficial increases in range for small changes in the hydrocarbon fuel are correspondingly small however, with the greatest increase seen in for the 747 of around an additional 1·2% range at maximum payload.

6.0 ALTERNATIVE FUELS

Unlike the hydrocarbon fuel density and *LCV* used for Fig. 3, data available in the literature for alternative fuels tends to be quoted at discrete values rather than a curve of possible fuels. This makes the creation of a set of curves for alternative fuels more difficult.

Instead, some discrete points have been used to create Fig. 6, showing the range payload diagram for several possible fuels. The fuels were chosen to represent the classes of alternatives suggested in the literature and used in the recent test flights, primarily alcohols, Fatty Acid Methyl Esters (FAMEs) and SPKs. For comparison, data for 1,1-Dimethylhydrazine (UDMH) are also shown to illustrate the performance of a specialist chemical propellant.

As mentioned previously, SPKs consist of a narrower band of straight chain hydrocarbons than conventional kerosene and the SPK range payload data presented represents the limit of paraffinic hydrocarbons. As the SPK product is blended either with other synthetic hydrocarbons or with conventional kerosene to produce a fuel which meets the specification, the actual performance of an approved SPK fuel is likely to fall between the SPK limit data and the average jet fuel data. This is in line with the results of the previous section which suggest that the range at maximum payload can be extended using a lighter hydrocarbon.

This analysis does not reflect the limits of possibility for alternative fuels as they may be blended with conventional hydrocarbons to provide a range of specific energies and energy densities.

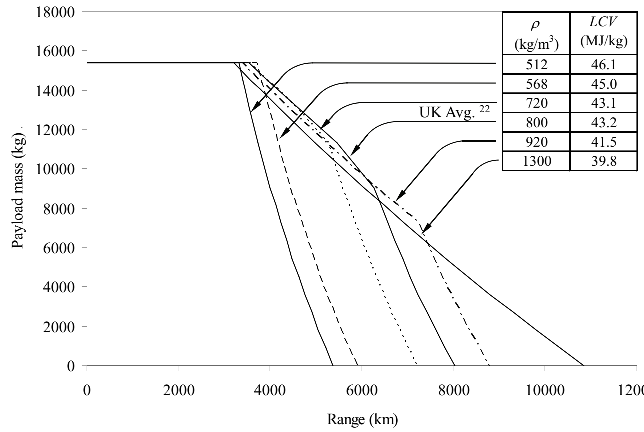

Figure 5. Changes to the range performance of Boeing 737-300 due to alterations to the Hydrocarbon fuel used for flight.

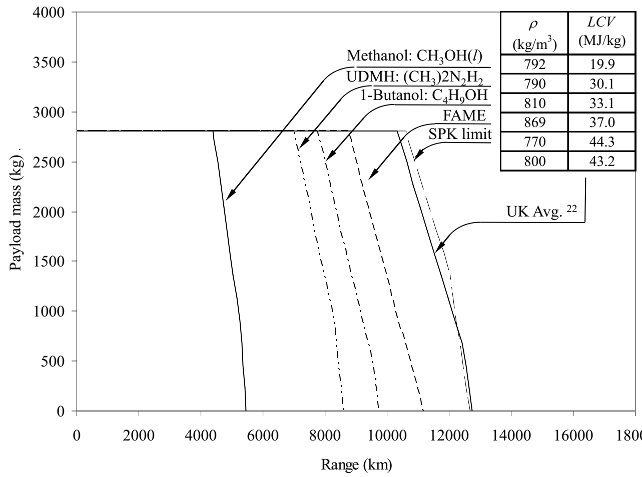

Figure 6. Changes to the range performance of Gulfstream G550 due to alternative fuels used for flight.

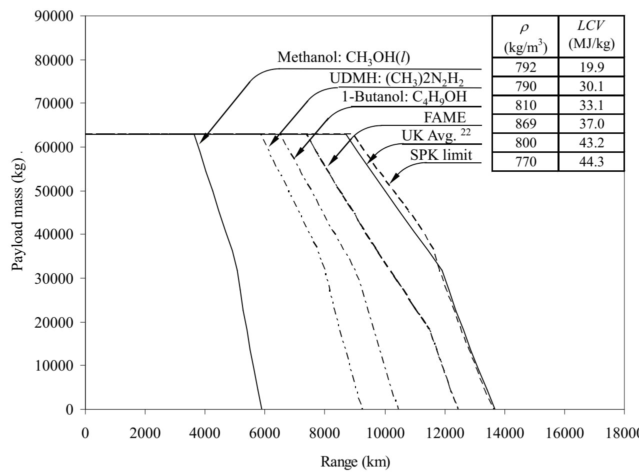

Figure 7. Changes to the range performance of Boeing 747-200B due to alternative fuels used for flight.

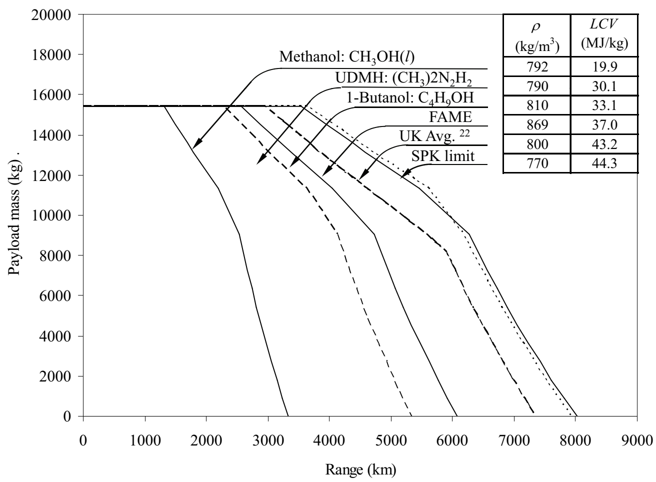

Figure 8. Changes to the range performance of Boeing 737-300 due to alternative fuels used for flight.

7.0 SPECIFIC FLIGHT PLAN COMPARISON

The previous analysis has shown the effect of changing fuel on the limits to the range payload performance of a range of aircraft. Of more interest to users of aircraft are the changes in fuel volume and weight requirements for a specific flight plan. Obviously, there is very large but finite set of possible ranges and required payloads; in order to provide some figures for the basis of a comparison, it was chosen to calculate fuel weight change requirements for a specific range of 8,000km for the Gulfstream G550 and Boeing 747 using identical boundary conditions to the previous model.

This data for the Gulfstream is shown in Table 3 and for the 747 is shown in Table 4. The variation in mass of fuel required to fly these distances between the two aircraft for identical fuels is a function of the airframe design, engine design and the proportion of the flight spent at optimum cruise conditions.

The fuel data for which the fuel weight has been calculated comes from a range of sources, some calculated fuels (limits of the specification and those from the range payload analysis) and some real fuels from the UK fuel survey and specific alternative fuels. This explains why there is a negative change in fuel weight for the Gulfstream G550 at the maximum payload range as the comparison is made with the average fuel from the UK survey and not the calculated variation in hydrocarbon fuels shown in Fig. 1.

The CO_2 emission change during the mission is presented in the tables below, assuming the carbon content of particular fuels and comparing it against the UK average fuel's emission.

8.0 DISCUSSION

In the range payload section of this paper it has been assumed that in every case, the plane is filled with as much fuel as possible, and the range calculated. This of course may not be true for commercially operated aircraft, were the destination is known and only sufficient fuel will be loaded to achieve the desired range, such as in the previous section. Without specific flight plans only the maximum range of the aircraft can be used to compare the performance of the aircraft and fuels. It is worth mentioning however, that although some of the lighter hydrocarbon and alternative fuels appear to perform less well than conventional jet fuel, if the range allows, they may offer an alternative without any sacrifice of payload.

As the results from this paper show, for a specific flight plan the average conventional fuel may not offer the best performance. Purely on the basis of range and payload, a variety of fuels for a range of flight plans may be more appropriate. Although this is impractical for most operations, it is reflected in the choice of standard fuels for opposite extremes of aircraft use: commercial and military aviation. Commercial aircraft tend to be flown close to, or at the maximum payload; therefore the prime interest would be to have as light a fuel as possible to achieve the range required. For military applications, the prime interest is the range achievable for the given full tanks and hence denser fuels are more appropriate. The latter statement may also be true for private jets such as the G550.

Until recently this possibility has not presented itself, as one standard commercial aviation fuel has been widely in use since the Second World War. However current concerns about the stability and sustainability of supply have raised the opportunity to alter the standards. This is demonstrated through the increasing number of alternative fuel demonstration flights.

Clearly, the effects of changes in density and calorific value of fuels for aviation cannot be looked at in isolation of the other characteristics of the fuel significant for aviation. Several authors have suggested general requirements for the aviation industry (not necessarily in order of significance)[27,28,29]:

Table 3
Change in fuel consumption for Gulfstream G550 flying a 8,000km flight with maximum payload (comparisons made against UK 20 year average fuel[25])

	LCV (MJ/kg)	ρ (kg/m³)	W_f for 8000km (kg)	*sfc* mg/Ns	Fuel tank usage (m³/m³)	Fuel tank usage (kg/kg)	Fuel reduction (kg/kg)	Energy reduction (MJ/MJ)	CO_2 reduction (kg/kg)
Spec limits min*	42.8	775.0	12701	18.35	70%	70%	-0.1%	0.92%	0.35%
Spec limit max	42.8	840.0	12829	18.35	65%	71%	-1.1%	-0.08%	-1.91%
Conventional									
Uk avg	43.3	800.0	12685	18.16	68%	70%	N/A	N/A	N/A
Range payload analysis									
Peak range (Wpmax)	44.4	613.0	12719	17.69	89%	70%	-0.3%	-2.94%	3.32%
Peak range (Wp=0)	43.2	710.0	13061	18.18	79%	72%	-3.0%	-2.84%	-1.19%
Alternatives									
SPK at spec limit	44.3	775.0	12362	17.73	68%	68%	2.5%	0.18%	3.01%
FAME	37.4	868.6	14890	21.00	73%	82%	-17.4%	-1.51%	-12.61%
Hexanol	39.9	813.0	13871	19.71	73%	77%	-9.4%	-0.75%	2.03%

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Table 4
Change in fuel consumption for 747 flying a 8,000km flight with maximum payload (comparisons made against UK 20 year average fuel[25])

	LCV (MJ/kg)	density (kg/m^3)	Fuel required for 8000km (kg)	Cruise sfc (mg/Ns)	Fuel tank usage (m^3/m^3)	Fuel tank usage (kg/kg)	Fuel reduction (kg/kg)	Energy reduction (MJ/MJ)	CO_2 reduction (kg/kg)
Spec limits min*	42.8	775.0	125021	17.675	78%	78%	-0.9%	-0.20%	-0.65%
Spec limit max	42.8	840.0	125021	17.675	72%	78%	-0.9%	-0.20%	-1.91%
Conventional									
Uk avg	43.2	800.0	123614	17.511	75%	77%	N/A	N/A	N/A
Range payload analysis									
Peak range (Wpmax)	43.3	797.6	121942	17.471	74%	76%	0.2%	1.12%	1.40%
Peak range (Wp=0)	41.3	956.1	129979	18.317	66%	81%	-4.6%	-0.52%	-8.29%
Alternatives									
SPK at spec limit	44.3	775.0	120464	17.076	75%	75%	2.5%	0.07%	3.01%
FAME	37.4	868.6	145168	20.227	81%	91%	-15.5%	-1.67%	-12.66%
Hexanol	39.9	813.0	135204	18.983	81%	85%	-8.4%	-0.89%	2.01%

1. high heat content for maximum range or payload. This can mean a high specific energy or High energy density.
2. good atomisation (low viscosity)
3. rapid evaporation (high volatility)
4. good burning characteristics, including re-light capability at altitude.
5. low explosion risk – low vapour pressure, low volatility, high flash point and high conductivity.
6. high specific heat
7. free from contaminants
8. minimum carbon formation
9. low viscosity and high lubricity – good storage and pumping characteristics, including low freezing point to facilitate altitude operation
10. good thermal stability/chemical stability
11. wide availability and acceptable cost
12. products of combustion acceptable environmentally
13. good ground storage and handling characteristics

In addition to the list above, fuel used for military purposes would be restricted by several additional logistical requirements .

Clearly some of these requirements (such as numbers 3 and 5) are contradictory, this reflects the complexity of the situation. The core of this paper has focused on the first of these requirements, and offers the starting point for some discussion on the effects of changes in fuel characteristics. The characteristics of hydrocarbon fuels are well understood: those denser than jet fuel tend to be more viscous, have lower thermal stability, increasing aromatic contents and atomise and evaporate less well. Those less dense behave for the most part in the opposite fashion. In addition, lower combustion temperatures associated with higher carbon content fuels will result in less NO_x production; although this should be balanced against the increased fuel bound nitrogen of such fuels.

Alternative fuels are less well understood, although they follow similar trends to the hydrocarbons. The larger chemical structures in the fuels tends to result in lower hydrogen contents for hydrocarbon fuels of a similar density, this clearly results in lower energy densities (as evident from Fig. 1), although the energy content rises steeply with molecular size. Large molecules are likely to result in increased clouding and waxing of the fuel at low temperatures, which makes such fuels less suitable for flight purposes as indicated in the introduction. This is certainly the case for FAMEs and the higher alcohols. The reduction in heating value of the non-conventional fuel will also affect the mixing characteristics of the combustor and impact on the combustion related properties of the fuel.

The hydrocarbon blends suggest for each aircraft, an optimum fuel may exist for the maximum payload and allowing the maximum range. For such a case, there is never any trade-off between fuel and payload at the maximum structural weight of the aircraft as increases in range are fuel volume limited. Similarly, if blends of alternative fuels were to be investigated, optimum alternative fuels for specific aircraft should be achievable. Such a study would also allow the investigation of alternative fuels which would meet existing specification standards.

The variation permissible in the fuel specifications of Jet A density is 775kg/m^3 to 840kg/m^3 at 288·15K, effectively 807·5 ± 32·5kg/m^3. The variation in density due to temperature for 289 ± 15K will be 807·5 ± 5·5kg/m^3. This simple calculation would tend to suggest that the variation in density of kerosene due to the specification is larger than any changes resulting from reasonable temperature variations. The calorific value of the fuel is currently restricted to values ≥ 42·8MJ/kg.

For a 747-200B, the difference between a denser kerosene and a lighter kerosene within the specification limits is about 48km further at full payload. As shown in earlier graphs, the denser kerosenes increase the range of aircraft flying below the maximum payload. The lighter kerosenes offer a total CO_2 emission saving of around 1·7% for identical ranges based on fuel carbon content. This variation coupled with uncertainties in fuel tank volume measurement mean that accurately assessing the specific energy content of the fuel, the energy delivered to the aircraft and hence the associated range is complex.

The best fuel group from the point of view of range/payload performance were the SPKs. Although as stated, without blending synthetic paraffins do not meet the current specification for jet fuel. Recently published results from the demonstration flights of New Zealand airways suggest an improved fuel burn through the use of a Hydrotreated plant oil (producing an SPK) blended with kerosene . The results of this paper would support this, as SPKs tend to have a greater calorific value per unit weight in comparison to a conventional kerosene blend of a similar density.

As the fuel proposed for use in the engine deviates further from the traditional jet fuel, and cannot be classed as a 'drop in' fuel, more changes to the existing engine will be required. In addition to the approvals process, many technological constraints exist from the size and complexity of the atomizers and combustion chamber volume to the fuel pumps and trace heating. Such changes will effect the performance of the aircraft as a whole, and for more dense fuels, are likely to result additional weight penalties. Such effects have been ignored in this study as the models become increasingly complex and inflexible.

All of this should be considered in the wider climate surrounding aircraft design and operation. The operating empty weight of aircraft is reducing as new materials are introduced, which will further extend the range and emissions performance of new aircraft. The likelihood of airports operating on a dual, or even multi fuel basis seem implausible currently, however this may change in the future.

Changes in fuel will also change the fuel consumption and energy consumption of any flight. Some data for this is reported for Ethanol blends of fuel in Ref. 12 with changes in aircraft aerodynamics and fuel tank size. Calculations have been made for relatively small changes in fuel properties and shown in Table 3 and Table 4. These calculations show that changes in fuel properties will also have an effect on the energy consumed during a flight, and the mass of fuel required. This will have an effect of the environmental impact of a flight.

If the carbon content of the fuel is know, an estimation of the change in CO_2 emission from the flight can be made. The best performing fuels under the conditions in Tables 3 and 4 seem to be the lighter, higher calorific value SPKs. However, as noted, it is important to assess the full life cycle CO_2 emissions for any particular fuel type, encompassing production and distribution, to obtain a complete understanding of environmental benefit.

9.0 CONCLUSIONS

Although far from a complete analysis of the possible use of alternative fuels in aviation, this paper aims to provide data for the discussion of changes in fuel characteristics and their effect on aircraft performance.

If SPKs were to be produced and used in service as allowed by ASTM D7566, up to 50% blends of SPK with conventional Jet A-1 would be in use. This will result in a general reduction in average densities and increase in calorific values. The operational implications of this will only become clear over the longer term use of these fuels.

Lighter fuels such as SPKs offer greater range for maximum payload, denser fuels offer greater range at low payloads. Depending on the mission payload, maximum range might be achievable with a specific fuel somewhere between these limits, which will be aircraft specific. If one considers actual flight plans, it may not be necessary to reach the maximum range at full payload to complete the mission. In such cases, alternative fuels of a lower specific energy might be acceptable.

Lighter, higher calorific value hydrocarbon fuels result in a reduction in CO_2 emissions due to the lower fuel carbon content, however full life cycle calculations are necessary to determine the true impact from their use. This suggests that examination of higher calorific value fuels which are currently beyond the low density limit of the specification may be environmentally advantageous. Importantly, the value of the CO_2 saving is dependent on the aircraft type.

More work needs to be completed investigating the effects of blends of fuels on the range and performance of aircraft. Without changes to the specification limits, a purely synthetic paraffinic fuel will not meet the current specification for aviation fuel, blends may offer a way of reducing the environmental impact of aviation, and increasing the security of supply.

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