

INTERNATIONAL CIVIL
AVIATION ORGANIZATION



REPORT OF THE INDEPENDENT EXPERTS ON THE MEDIUM AND LONG TERM GOALS FOR AVIATION FUEL BURN REDUCTION FROM TECHNOLOGY

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GOALS FOR AVIATION FUEL BURN REDUCTION FROM TECHNOLOGY

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EXECUTIVE SUMMARY

The seventh meeting of the International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection (CAEP/7) held in February 2007 requested advice from Independent Experts (IEs) on the prospects for reduced aviation fuel burn from technology advances over the medium term (MT) and long term (LT), specifically ten and twenty years. The assessment by the IEs of the reduction in aviation fuel burn from technology advances followed a two-step process: an industry led Fuel Burn Reduction Technology Workshop held in London UK in March 2009 and then a formal Fuel Burn Reduction Technology Goals Review, held in Atlanta U.S. in May 2010 led by the IEs. There were seven IEs drawn from France, Sweden, the UK and the U.S.; in addition a representative from Singapore took part up to the initial workshop but then withdrew and representatives from PR China and Italy withdrew around the beginning of the study.

Because the IEs had limited resources they considered only two aircraft types: the single-aisle aircraft (110-210 seats) and a relatively small twin aisle (211-400 seats). Together these aircraft categories are responsible for around 85% of the global fuel burn by commercial aircraft. The goals are expressed as reductions from current levels, which are taken to be those from reference aircraft in service in 2000. The medium term goal therefore represents some 20 years progress whereas the long term goal is only a further ten years on. The single-aisle reference (referred to as SA) is the 737-800 and A320-200 class whilst the so-called small twin aisle (referred to as STA) is the 777-200ER and A330 class. Given that the single aisle aircraft have earlier origins than the twin aisles the potential efficiency gains from new technology for the SA are expected to be larger.

The IEs developed three basic Technology Scenarios (TS). One, referred to as TS1, corresponds to the expectation of a continuation of the current trend where industry continues to introduce new technologies. TS2 represents the effect of increased pressure to reduce fuel burn. TS3 represents even greater pressure for fuel burn reduction and is considered in two parts: the pure technology strand which includes consideration of technology improvements currently deemed likely to be non-viable or unaffordable but might become acceptable under increased pressure; the other strand envisages modest changes to the specification of aircraft and aircraft mission which have the potential to reduce fuel burn. This is in line with the IEs Terms of Reference (ToR), as detailed in CAEP-SG/20082-WP/20 which states “Only operational changes as necessitated by fuel burn reduction technologies need be considered”.

Technology improvements were presented by industry at the workshop and these were augmented and refined on the basis of further discussion and the input from other bodies. These and other future technology improvements were used in the modelling carried out by the IEs and by International Coalition for Sustainable Aviation (ICSA), Georgia Institute of Technology (GaTech), German Aerospace Centre (DLR), and Qinetiq. For incorporation into the models, the numerous technologies were grouped into baskets for aspects of the engine, for the airframe aerodynamics and for the aircraft weight. The judgement of the IEs was required for this, since some technologies are exclusive, some are additive and others are conditional in the sense that more than one must be introduced. Some allowance was made for the probability of achievement as well as for the likely benefit and in some cases likely associated penalties.

In the absence of any standard, it was necessary to define some airplane reference for each airplane category (Regional Jets, Single Aisles, Small Twin Aisles) to benchmark the technology potentials for future milestones (2020 and 2030). Technology potentials were evaluated based upon assumed baseline airplanes in 2020 and 2030. The IEs adopted a fuel burn metric for the purpose of their study, whilst recognising that discussions are ongoing within CAEP to choose a metric for setting a Standard for CO₂ emissions. For this

study the metric used was kilogram of fuel burned per available-tonne-kilometre (kg/ATK) to be calculated at the maximum payload maximum range condition.

It was found that the different calculations of fuel burn for the baseline aircraft agreed reasonably well in terms of absolute kg/ATK but it was also found that if the precise inputs were matched (e.g. lift/drag ratio, empty weight/maximum take-off weight, engine specific fuel consumption, reserve fuel assumptions) then the agreement in absolute values was very close even when different models were used. Even when the absolute values did not agree exactly, the differences predicted for the introduction of the new technologies were sufficiently close that the overall predictions were considered to be sufficiently accurate for the goal-setting exercise. It was considered that the similarity of results despite the differences among assumptions and models tended to support the robustness of the estimates.

The resulting predicted reductions in fuel burn are set out in the report in the form of graphs with lines showing reductions corresponding to the different technology scenarios. The lines are anchored at shorter design ranges (2125 nm) by the single-aisle reference aircraft and at longer design ranges (5750 nm) by the small twin-aisle reference aircraft. The values at the anchor points are detailed below.

	2020		2030	
	SA	STA	SA	STA
TS1	23	19	29	26
TS2	29	25	34	35
TS3			41	41
TS3 Open rotor			48	

Estimated percent reduction in fuel burn metric at the single aisle (SA) and small twin-aisle (STA) anchor points relative to 2000 baseline at maximum payload maximum range

Whilst TS1 represents what would happen with continued and consistent funding and dedicated programs, and without additional pressure other than market forces, TS2 does represent a clear challenge. Therefore the goal has been set as a band in kg/ATK below TS2 for 2020 and for 2030 as a band between TS2 and TS3. Achieving the goal has been defined by the IEs as having a value of kg/ATK below the TS2 line, but additional progress would be indicated by moving down towards the TS3 line and the band has been included to indicate what level of further progress might be possible. The IEs felt that reaching the level corresponding to TS2 by technology alone was possible though by no means certain, but, when coupled with the potential arising from the changes in aircraft mission specification and aircraft configuration, the probability of achievement is substantially higher. Therefore the goal will be said to have been achieved in 2020 if the fuel burn reduction relative to the 2000 baseline exceeds 29% for the single aisle reference aircraft and exceeds 25% for the small twin-aisle aircraft with suitable interpolation and extrapolation for other aircraft categories. In 2030 the goal will be achieved with similar interpolation across the range of aircraft from single- to twin-aisle aircraft if the reduction exceeds 34% to 35% relative to the 2000 baseline. A 35% reduction by 2030 corresponds to an annual compound reduction of about 1.4%, which may be compared with the ICAO aspirational goal of 2% per annum fuel efficiency improvement out to 2050. The ICAO aspirational goal relates to the entire commercial aircraft/air-traffic system as a whole, whereas the IEs have only considered individual aircraft design and only its technology aspect. The modelling by the IEs and other organisations confirms the view that technology on its own is not able to deliver the reductions which are judged to be required by the ICAO goals.

Further reductions are possible and the ultimate goal for 2030 with TS3 could be as large as 41% with a turbofan engine or 48% if open rotors were used. In addition, it has been found that quite modest changes in design Mach number, design range and wing span (the latter having an effect on airport layout) can lead to additional savings which are comparable to a change in TS level from 1 to 2 or from 2 to 3.

The IEs believe that these goals must be regarded as interim. The topic should be revisited with full participation and engagement with industry when the CO₂ certification parameter has been resolved. The IEs also believed that it is important to conduct system analyses to evaluate the contributions of various strategies toward meeting these goals, particularly the overall system effects of changes in Mach number and design ranges, including the potential effect on the number of operations, which could affect safety, operating costs, noise exposure and air quality impacts.

ACKNOWLEDGEMENTS

In carrying out this review the Independent Experts (IEs) have been helped by people in a number of organisations, including the Georgia Institute of Technology, the German Aerospace Centre – DLR, the International Coordinating Council of Aerospace Industries Associations, the International Council on Clean Transportation (part of the International Coalition for Sustainable Aviation) and QinetiQ. The IEs wish to express their gratitude to all of them, but especially to Dr. Michelle Kirby for also hosting the review meeting in Georgia Tech in May 2010.

An essential part of the review has been carrying out calculations specifically for the IEs under the direction of Professor Juan J. Alonso. The IEs particularly wish to thank Sean R. Copeland and Thomas D. Economon, both graduate students in Stanford University, for their excellent work.

It is possible that the review would not have taken place without the work of Peter Newton who, until his retirement early in the review, was employed by the UK Department for Business, Innovation and Skills. In addition Peter Newton played a key part in setting up the workshop in March 2009. It is also true that the review would have foundered without the excellent work of Dr. Samantha Baker, also of the UK Department for Business, Innovation and Skills. Her contribution in facilitating and supporting the meetings and telephone conferences, and in preparing the report is gratefully acknowledged.

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1 INTRODUCTION

1.1 The seventh meeting of the International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection (CAEP/7) held in February 2007 requested advice from Independent Experts (IEs) on the prospects for reduced aviation fuel burn from technology advances over the medium term (MT) and long term (LT), specifically ten and twenty years from 2010. The CAEP Steering Group provided guidance on the remit for this task: the Review should consider the effects of “major technologies” on fuel burn/efficiency, as well as combinations of improvements from aircraft and engine, including best possible integration. The panel of experts were to focus their analyses only on technologies and not on operations or new types of fuels. Only operational changes required to implement and derive the benefits of fuel burn reduction technologies needed to be considered and interdependencies were to be qualified where quantification was not possible.

1.2 The assessment of the reduction in aviation fuel burn from technology advancements over ten and twenty years was to follow a two-step process:

- a) An industry-led Fuel Burn Reduction Technology Workshop to be held in early 2009;
- b) A formal Fuel Burn Reduction Technology Goals Review, to be held early in the ninth CAEP cycle (CAEP/9) led by the IEs.

1.3 The first step, the Fuel Burn Reduction Technology Workshop was led by ICCAIA and held in London, UK between 25 and 26 March 2009. The workshop was an opportunity for industry and research organizations to share information on the status of the technologies for fuel burn reduction explored by airframe and engine manufacturers and government researchers. The IEs attended the Workshop for familiarisation with the materials presented. A list of presentations from the Workshop can be found in Appendix A-1. The IEs provided CAEP with a formal report reflecting on the Workshop and information received subsequent to it at the meeting of the CAEP Steering Group in 2009 (SG2009), CAEP-SG/20093-WP/21.

1.4 The CAEP/8 Steering Group in 2008 required a final report from the IEs to be delivered to the first meeting of the CAEP/9 Steering Group in 2010 and specified that the review should address the following:

- a) the status of technology developments for fuel burn reduction that will be brought to market within ten years from the date of review, and the twenty year prospects for fuel burn reduction technologies suggested by research progress.
- b) assessments for fuel burn reductions in the future, stated as improvements against an identified performance metric.
- c) recommending mid- and long- term fuel burn/efficiency technology goals at the overall aircraft level, taking into account the information presented and using their judgment as appropriate.
- d) assessment of the possibility of success in achieving the recommended mid and long term technology goals, based on experience from past research and development programs
- e) comment on the importance of fuel burn as the primary technology focus, based on current scientific understanding of environmental impact of aircraft engine emissions.

- f) report on the status of understanding of environmental impacts of aircraft engine emissions and identify areas where further research is needed to help focus ongoing and future technology development efforts.

1.5 The policy importance of this IE review is clear. Many governments now advocate that to avoid the most dangerous climate change it will be necessary to hold temperature rise to less than about 2°C above pre-industrial values, and this is reflected in the UNFCCC Copenhagen Accord. To date, over half of the amount of CO₂ which corresponds to this temperature rise has been released. In 2009, ICAO agreed to a global goal for an annual improvement of 2% in fuel efficiency of the international civil aviation in-service fleet for the medium-term (up to 2020) and an aspirational global goal for an annual improvement of 2% in fuel efficiency of the international civil aviation in-service fleet for the long-term (up to 2050) as part of the contribution of the sector to stabilize and subsequently reduce aviation's absolute emissions contribution to climate change. (It is noteworthy that the metric for efficiency was not defined.) This will require significant resources and investments to improve all aspects of the aviation sector. ICAO has committed to undertake further work on medium and long-term goals, including exploring the feasibility of goals of more ambition including carbon-neutral growth and emissions reductions. It is therefore important to understand what reductions in fuel burn and hence CO₂ emissions technology can be expected to deliver.

1.6 The title of the review refers only to Fuel Burn Reduction Technology, whereas the underlying concern of the review is climate change impacts. Items e) and f) of the remit, in section 1.4 above, support this wider understanding. As is well known, several emissions contribute to climate change; only in the case of CO₂ is the impact known with a high level of confidence and for other emissions considerable uncertainty remains. Moreover the persistence of the pollutants varies, with CO₂ being most long lived, so the impacts differ depending on the time over which they are assessed. There are several metrics available to represent the impacts of emissions, including Radiative Forcing (RF), Global Warming Potential (GWP), and Global Temperature change Potential (GTP). The importance of different species and operations varies depending on the metric adopted and on assumptions adopted (e.g., time horizon).

1.7 The complexity involved in looking at climate change and the difficulties inherent in considering only the creation of CO₂ convinced the IEs that the narrower remit of fuel burn, referred to in the title of this Review, is more appropriate. Their wish to consider only fuel burn was endorsed by SG/2009.

1.8 A second progress report was provided to CAEP in February 2010 via CAEP/8-WP/11. The IEs identified that progress had not been as significant as they would have liked, largely due to a conflict in resources for ICCAIA with work to develop CO₂ Standards (CAEP/8 WG3 Remit E.08). The meeting noted the perceived lack of coordination between the industry and the IEs, and urged that the preparatory work for the review be accelerated by the industry in order to deliver the review within the timescale requested by CAEP. The formal Review was held in Atlanta, U.S. between 25 and 27 May 2010. A list of attendees and presentations from the Review can be found in Appendix A-3.

1.9 Throughout the process, engagement with stakeholders was critical. Attendees at the Workshop and the Review included representatives from government, industry, academia, research establishments and NGOs. They have also been kept informed of progress at a working group level, predominantly through WG3 which has responsibility for the delivery of the review to CAEP. In addition, regular teleconferences between the IEs and ICCAIA were instrumental in preparing for the Review.

1.10 The Fuel Burn Reduction Technology Independent Experts (IEs) nominated by various CAEP Members and Observers are:

- Nick Cumpsty, UK (Elected by the IEs as Chair)
- Juan J. Alonso, U.S.

- Serge Eury, France
- Lourdes Maurice, U.S.
- Bengt-Olov Nas, IATA
- Malcolm Ralph, UK
- Robert Sawyer, ICSA

1.11 IEs were also nominated by Peoples Republic of China, Singapore and Italy, and useful inputs were made in the early stages but unfortunately they were not able to take part in the Review or in the preparation of this report.

1.12 The IEs are aware that the task given them, assessing prospects for fuel burn reduction technologies and setting fuel burn goals, is one of great complexity. Earlier IE Reviews to establish medium and long term technology goals have looked at oxides of nitrogen (NO_x) or noise, but this Review looks at an issue which is central to the competitive position of all stakeholders: engine makers, airframe makers and airlines. Furthermore, fuel burn does not lend itself to convenient demarcation between engines, airframes, aircraft mission specification and the way the aircraft is operated; all these impact fuel burn and therefore need to be considered.

1.13 The IEs were conscious that this goal-setting review differs from earlier ones in another way: the lack of an existing regulatory standard to provide a baseline. The IEs concluded that the baseline should be in-production technology of 2010, while recognising that the technologies embodied were matured and design decisions were made long before. In practice the IEs judged the reference aircraft to embody, on average, 2000 technology.

1.14 The IEs are aware of the discussions going on within CAEP on the most appropriate metric for CO₂ Standard. In order to proceed and to be able to report in 2010 the IEs urgently needed a fuel efficiency metric applicable to technology goals within the review process. The IEs had extensive discussion on the metric to be used for fuel burn and elected to use kg-fuel/Available-Tonne-Kilometre (kg/ATK). This is simple and the use of available-tonne focuses on the aircraft, and its technology, rather than the operation of the airline. The metric used for this review does not pre-empt discussions elsewhere in CAEP and the IEs have co-ordinated with WG3 to keep abreast of relevant developments. The fuel burn metric was evaluated at the maximum-payload maximum-range point, denoted by A at range R1 in Figure 1.1. This is a simple and hypothetical version of a plot widely used in the industry to show range and payload variation for a given aircraft. The line shown corresponds to the aircraft taking off with the maximum allowable payload for the range. In the horizontal portion the payload is unaltered as more fuel is added to allow the range to be flown, but when point A is reached, at range R1, the aircraft has reached its maximum take-off weight. For greater range than R1, when increased fuel must be carried, there must be a compensating reduction in payload to limit the take-off weight to its maximum value. As the mission requires additional range beyond B, where the maximum fuel capacity has been reached, further decreases in payload become necessary. The payload used here is based on the manufacturer's empty weight (MWE), making the payload larger than the frequently used operating empty weight (OWE) and which includes operational items determined by the airline customer.

1.15 Aircraft operations are outside the scope of this review, but issues related to operations impinge on any assessment of fuel burn. For short flights the way in which take-off, climb and descent are managed influences the mission fuel burn strongly. For all flights the reserve fuel which is carried, fuel which would not normally be burned during the mission, has been considered. However, none of these factors was varied for this review as they were felt to be too close to purely operational issues. On the other hand, the effects of

varying cruise Mach number and of varying the maximum range achievable at maximum payload were investigated (referred to later as R1).

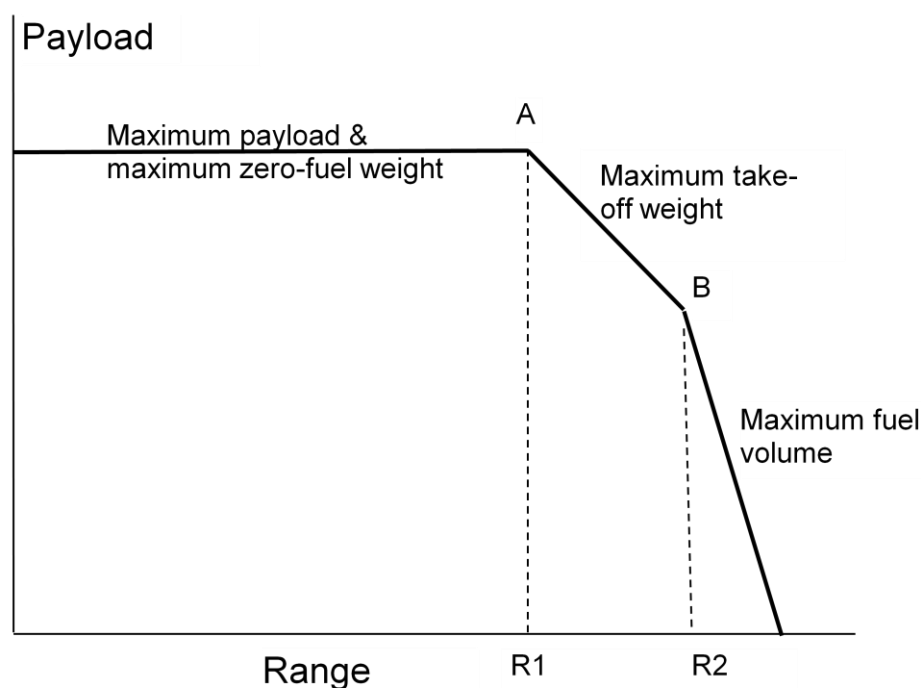


Figure 1.1: Diagrammatic payload-range diagram for a commercial airliner. (Maximum structural payload also corresponds to maximum zero-fuel weight. For a given mission, take-off weight is zero fuel weight plus the weight of fuel, which is fuel to be consumed in the mission plus reserve fuel.)

1.16 Technology Readiness Level (TRL), described in Appendix E, was extensively discussed. It was recognized that anticipating the TRL for a new and immature technology in ten or twenty years time is a matter of expert judgment as discussed more fully in section 3.7. The IEs decided for the setting of both the 10 year (MT) and 20 year (LT) goals they should consider the levels of fuel burn performance thought likely to have been achieved by the due dates and matured to TRL 8 – ready for service which is in line with the approach adopted for the NO_x IE review. In making this judgment it is necessary to combine the present TRL with some assessment of likelihood of the advances being made. Some greater confidence was achieved in the validity of judgment by independent assessments being made by government, non-governmental organisations, university and industry experts as well as the IEs.

1.17 The IEs concluded that four classes of aircraft should be considered: regional jets, single-aisle aircraft, small twin-aisle (211-400) seats and large twin-aisle (more than 400 seats). This division is in line with the CAEP Forecasting and Economic Support Group (FESG) categories. Because of limitations of resources, the IEs have focussed the majority of their work on the single-aisle (SA) and the smaller twin-aisle categories (STA), since these together account for 85% of the total fuel burn by commercial aircraft. Supplementary analysis on the regional jets was provided by some participants.

1.18 The IEs adopted three Technology Scenarios (TS) for 2020 and 2030, which are intended to reflect a range of possible future scenarios and represent technology responses to increasing pressure for improvement dependent on, for example, a variety of future environmental pressures and fuel prices. The formulation of these scenarios has adapted somewhat as the study has progressed and they are described in more detail in sections 3.4 and 3.5:

- TS1 – ‘Continuation’ - a continuation of the current trend of improvement, resulting from current market forces and environmental pressures.
- TS2 – ‘Increased pressure’ - increased pressure to incorporate more technologies to reduce fuel burn though still with ‘tube and wing’ architecture.
- TS3 – ‘Further increased pressure’ justifying more radical technology innovations and allowing ‘doing things differently’ - including modest alterations to aircraft configuration and/or modest alterations to aircraft mission specifications. The open rotor applied to the single-aisle aircraft is included in this category.

1.19 The IEs have discussed issues which relate to the specification of the aircraft, a feature of consideration under TS3. Whilst the remit of the task is to develop goals that can be delivered through technology progress, there are significant inter-relationships with other variables: changing the specification of the mission or the aircraft can change the technologies available and the magnitude of the benefits produced. The IEs have come to realise that a considerable part of the benefit of improved technology introduced in the past has been used to improve the performance of the new aircraft, mainly range, rather than to reduce fuel burn per ATK. They therefore believe it is essential to look at alterations in terms of aircraft mission specification, particularly for the longer term, which is in line with their ToR and is discussed further in Section 3.5.3. Consideration of operational issues consequent upon changes of specification should, it was felt, be postponed until the potential benefits are quantitatively estimated.

1.20 Aircraft design is frequently a trade-off among conflicting requirements and in the present context concern has been raised that noise or NO_x emissions might be increased by the alterations to reduce fuel burn. For the purposes of this review, the IEs have assumed that aircraft would continue to be specified and designed so as to meet existing regulatory standards and goals for NO_x and noise.

2.1 It is possible to get insight into some of the controlling features of commercial aircraft fuel burn by simple analytic methods based on some idealisations. The approach adopted is set out in a paper by Poll¹. The aircraft is assumed to operate in an idealised manner during cruise, which is the majority of the flight, at constant lift-drag ratio, L/D . Likewise the engines are assumed to operate at a constant overall efficiency, which corresponds to operating with constant specific fuel consumption, sfc . To achieve this there is a continual climb during cruise to maintain optimum L/D and sfc as the weight of the aircraft decreases – an idealised procedure referred to as cruise-climb. Most aircraft on long flights change altitude in steps as their weight decreases.

If $(M_F)_{\text{cruise}}$ is the weight of fuel burned during cruise and M_1 is the aircraft weight at start of cruise, then the long-established Breguet² equation gives for optimum cruise-climb

$$(M_F)_{\text{cruise}}/M_1 = 1 - \exp\{-R/H\},$$

where R is the range and H is the range factor which is given, for flight speed V , by

$$H = (V \cdot L/D) / sfc$$

If plausible assumptions are made for lift/drag ratio and engine specific fuel consumption, numerical values may be created: it is assumed in this section that $L/D=20$ and $sfc= 0.525 \text{ kg h}^{-1}\text{kg}^{-1}$, which are values representative for cruise of the latest twin-aisle aircraft. In addition cruise speed is taken to be 252 m/s, corresponding to a Mach number of 0.85 at 35000 ft in a standard atmosphere. It then follows that

$$H = 34.6 \times 10^3 \text{ if } R \text{ is in kilometres and } 18.65 \times 10^3 \text{ if } R \text{ is in nautical miles.}$$

2.2 Fuel is also burned during taxi, take-off, climb and landing and here it will be assumed that fuel equal to 2% of take-off weight is used in a way which exceeds that needed for optimum cruise between take-off and landing points. It is also necessary to carry reserve fuel, with the amount dependent on rules and the region of operation. The weight of reserve fuel can have a significant impact on the fuel burn and here this weight is taken to be 5% of the take-off weight, a value which corresponds quite closely with the assumed reserve used in section 5 of this Report. It is assumed that take-off occurs with the minimum weight of fuel consistent with range and reserves; increasing range invariably requires an increase in the weight of fuel at take-off.

2.3 The Breguet equation allows the weight of fuel consumed on a mission to be found subject to the stated assumptions. Three key weights determine the performance of the aircraft: maximum take-off weight (MTOW), empty weight (M_E) and maximum payload (M_{PL})_{max}. At maximum take-off weight, as an idealisation, the wing lift, engine thrust and structure should be approaching their acceptable limits. Empty weight is taken here as the manufacturer's empty weight before items like seats are added and maximum payload, (M_{PL})_{max} therefore includes cabin fittings as well as passengers, baggage, and freight. The ratio of empty weight to maximum take-off weight M_E/MTOW is a measure of the level of technology; improving the material properties, joining technology and structural design all lead to a reduction in M_E/MTOW . For the results presented in this section the ratio is taken to be 0.45, which is typical of a recent twin-aisle aircraft.

¹ Poll, D.I.A. The optimum aeroplane and beyond. Lanchester Lecture of the Royal Aeronautical Society. 2009 *Aeronautical Journal* 113.

² Breguet, L. Calcul du poids de combustible consommé par un avion en vol ascendant. 1923 *Comptes Rendus de l'Académie des sciences*, 177, pp. 870-872

The ratio tends to be a bit higher for single-aisle aircraft than twins and the ratio tends to fall as aircraft are stretched to make better use of the structure.

2.4 For the present it will be assumed that the aircraft is operating at the highest payload allowable for the range chosen. Operation is therefore along the line shown in Figure 1.1. Along the horizontal part of the line, from the axis to point A, the payload is constant and as range is increased the fuel weight is increased until at point A the maximum take-off weight is reached. Point A is the maximum-payload maximum-range point and the range here is denoted by R1. For the present report point A is taken to be the design point. The weight of fuel for range R1 is denoted by $(M_F)_{R1}$ so the maximum take-off weight is given by

$$MTOW = M_E + (M_{PL})_{max} + (M_F)_{R1}$$

2.5 For operation between points A and B the maximum take-off weight is assumed constant so that any increase in range beyond R1 implies a reduction in payload coupled with a corresponding increase in fuel load.

2.6 In considering a new aircraft design the selection of design range, here taken as R1, is a decision about how the difference between maximum take-off weight and empty weight is used, that is how payload and weight of fuel are split at point A. Design range is therefore a decision on the ratio of the weight of fuel for range R1 to the maximum payload $(M_F)_{R1}/(M_{PL})_{max}$ at point A in Figure 1.1. Long range designs have larger values of this ratio than short range designs. The ratio of fuel weight for R1 to maximum payload, $(M_F)_{R1}/(M_{PL})_{max}$, and the ratio of empty weight to maximum take-off weight, $M_E/MTOW$, therefore determines maximum payload as a fraction of maximum take-off weight.

2.7 Figure 2.1 shows the fuel burn parameter kg-fuel/ATK plotted against range derived by the approach outlined above. There are two sets of curves. The solid line corresponds to region AB in Figure 1 where maximum take-off weight is constant (in this case such that the empty weight is equal $0.45M_{TO}$). Each broken line corresponds to operation where the payload is held constant at its maximum value; the three lines shown correspond to different ratios of fuel weight for range R1 to maximum payload, $(M_F)_{R1}/(M_{PL})_{max}$: a value for this ratio of 0.75 corresponds to a single aisle aircraft like the Boeing 737 or A320 whilst 2.25 corresponds to a long-range version of a twin aisle, like the Boeing 777-200LR. As stated earlier, the curves shown are for hypothetical aircraft flown in an idealised manner. In practice, and particularly for very long ranges, many engineering design constraints need to be considered and these may limit the achievement of some theoretical performance improvements.

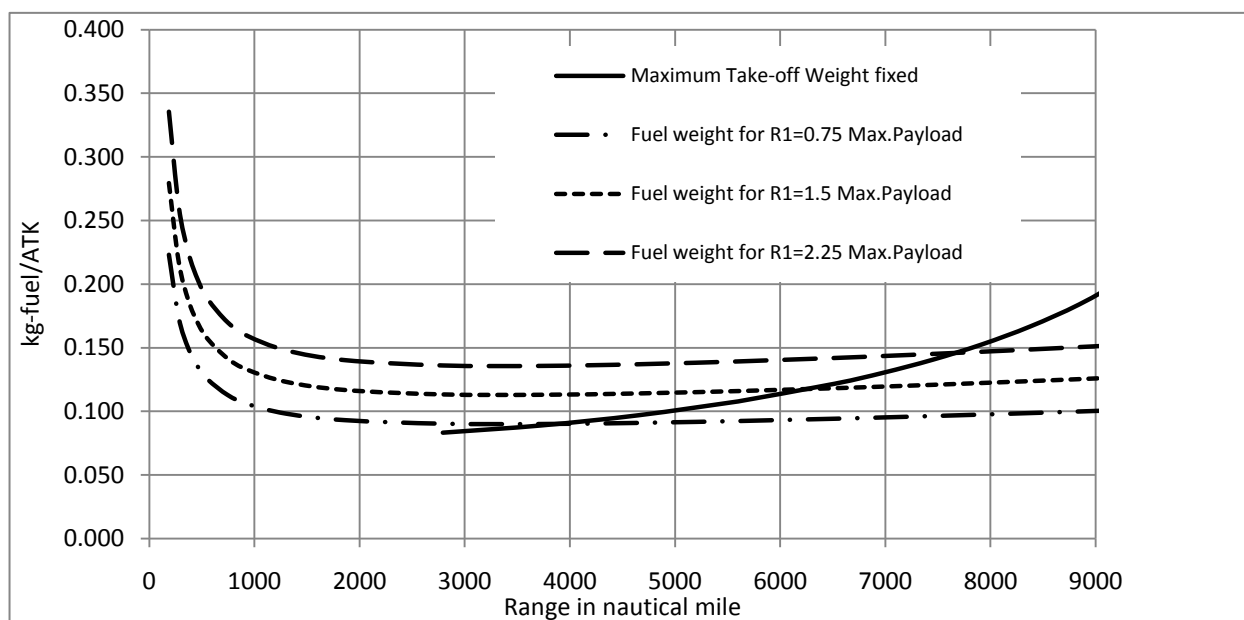


Figure 2.1: Fuel burn (kg-fuel/ATK) versus range for a hypothetical aircraft. Take-off and climb fuel $0.02M_{\text{TO}}$; reserve fuel $0.05M_{\text{TO}}$; aircraft empty weight $=0.45(M_{\text{TO}})_{\text{max}}$.

2.8 The broken and solid lines in Figure 2.1 intersect at range R_1 and, as the fraction of fuel at point A increases, so too does R_1 . The fuel burn parameter rises steeply for range in excess of R_1 , primarily because the payload is being reduced in the denominator in the fuel burn parameter. For ranges below R_1 there is a minimum in the fuel burn parameter, which is slightly below the value at R_1 , and the small rise in fuel burn prior to reaching R_1 is a consequence of the cost inherent in carrying fuel which is burned late in the flight. What is more striking is that the minimum level of fuel burn increases with the increase in design range, i.e. with increase in $(M_F)_{R1}/(M_{PL})_{\text{max}}$, even though the technology assumed in all cases is the same.

2.9 The steep rise in fuel burn parameter for ranges below about 1500 nm is a consequence of the fuel required for take-off, climb and descent. This increase is very dependent on the assumptions made for the excess, which in turn depends strongly on the way the aircraft is flown and the air traffic management constraints imposed. The pilot has some control over the engine thrust, speed and climb (or descent) rate, and these should be optimised, but additional requirements of air traffic management may also constrain the flight to be far from that for lowest fuel burn. If these phases of the flight can be optimised there is potential to reduce the excess fuel with significant impact on fuel burn for short flights, for example, flights under 1000 nm.

2.10 As already noted, in Figure 2.1 all parameters related to the technology level of the aircraft (lift/drag ratio, engine specific fuel consumption, empty weight/maximum take-off weight) are held constant for this comparison. The differences in fuel burn parameter for the three curves are an ineluctable consequence of the specification of design range in terms of $(M_F)_{R1}/(M_{PL})_{\text{max}}$. The absolute levels in Figures 2.1 depend, of course, on the parameter values assumed and these could be easily varied to agree with measured data. The values of input parameters correspond to a modern twin-aisle aircraft and for single-aisle, shorter range aircraft L/D is typically lower than 20 and η is typically higher than 0.525. As a result, data from in-service aircraft, such as Fig.3.1, tend to obscure the consequence on the fuel burn parameter directly attributable to range.

2.11 In Figure 2.1 it is assumed that the maximum permissible payload is being used; for the shorter ranges this is the maximum payload for the aircraft and for ranges above R_1 it is the payload which with the

fuel load leads to maximum take-off weight. Aircraft often operate with the payload below the maximum allowed (load factor less than unity) either because the airline has chosen to configure the aircraft in such a way that the maximum payload cannot be achieved or because the requisite number of passengers and weight of cargo has not been loaded. In either case the value for the metric for this case, fuel burn per revenue ton kilometre, will be higher. Put another way, the lowest fuel consumption will occur when the ratio of payload to empty weight is as high as possible.

2.12 The results presented here do not remove the need for more complete modelling of aircraft. They are presented to show how many features of aircraft performance are determined by quite fundamental features of the system at cruise: lift-drag ratio, engine specific fuel consumption, the ratio of empty weight to maximum weight and the specification of design range R1. They also demonstrate that design decisions regarding range determine the minimum level of fuel burn which can be achieved for a given level of technology: long range designs inevitably have increased kg-fuel/ATK compared to medium range aircraft at the same technology level.

2.13 The most efficient operation in terms of fuel burn always occurs when the aircraft is operating at its maximum payload, although airlines can in many cases increase profitability by operating at different conditions. For long range aircraft minimum kg-fuel/ATK is only slightly smaller than the value of kg-fuel/ATK at R1 and occurs at a range which is approaching R1. For shorter range designs minimum fuel burn is at R1. Increasing range beyond R1, where payload is reduced to allow the necessary extra fuel to be carried, inevitably leads to rapidly increasing values of kg-fuel/ATK.

3.1 FUEL EFFICIENCY METRIC

3.1.1 There is currently no existing ICAO Standard for fuel burn and therefore there is no prescribed ICAO metric by which it should be measured for an individual product. Work on fuel/CO₂ efficiency metrics for specific application to CAEP work has been ongoing since CAEP/8, and is covered by an ad-hoc group under WG3. Progress on fuel efficiency metrics was reported to CAEP/8 in CAEP/8-IP/20. The additional task in CAEP/9 to develop a CO₂ Standard means that there is now additional urgency to agree on the metric. The choice of a metric continues to be studied and, it is understood, there is a long list of possibilities still under consideration. It was apparent to the IEs early on that in order to be able to set fuel burn goals in the required timescale they would need to make an early choice of metric which, if necessary, might require later amendment to fall in to line with an ICAO CO₂ certification parameter, if and when, one is eventually agreed.

3.2 FUEL BURN PER ATK

3.2.1 The IE report to CAEP SG2009 (CAEP-SG/20093-WP/21) proposed that the fuel burn technology goals should be based on fuel quantity burned (kg) per Available Tonne Kilometre (ATK) flown, as the IEs believe this best reflects the efficiency of the aircraft at its technology level. This metric excludes effects of airlines' business models such as load factors, seating configurations, and freight policies. Available Seat Kilometre (ASK) was also considered but was not selected as it would be influenced by, and require information on, the variability of seat counts between airlines.

3.2.2 In many ways it was felt that the choice of this metric was straightforward; how it should be computed and applied were felt to be the more difficult questions. It was necessary to standardise on a point on the characteristic payload /range diagram from which to compute ATK. It was decided to use the maximum payload maximum range R1, point A in Figure 1.1. It was well understood that in airline operations many flights are not at MTOW, and arguments could be made for a point below this weight. Using MTOW has the crucial advantages of it being a certification data point, and the fuel burn parameter at R1 will be a good indicator of minimum fuel burn at ranges below R1.

3.2.3 A definition of payload was needed with there being two leading contenders: MZFW-OWE (where MZFW is maximum zero fuel weight and OWE is operating empty weight) which is commonly used, or alternatively MZFW-MWE (where MWE is manufacturer's empty weight). It was noted there is a significant disadvantage in using OWE as, for any given aircraft, this figure varies for each airline as it is dependent on the individual cabin layout and buyer furnished equipment. It was for this reason that it was decided to use MZFW-MWE – which the IEs have termed the 'Ultimate Payload'.

ATK is therefore defined as $[(MZFW - MWE) \times R1 \text{ range}]$ with weight in tonnes and range in kilometres.

Estimates for MWE were used recognising the variability of MWE across airplanes.

3.3 FUEL EFFICIENCY VERSUS RANGE

3.3.1 Fuel efficiency initially increases with mission distance, as progressively the climb and take-off portions of the flight have less impact. At longer distances the fuel burn parameter rises slowly until maximum payload maximum range R1, point A in Figure 1.1, is reached. Beyond R1, where the available tonne payload is limited and traded for more fuel to increase range, the fuel burn parameter increases more rapidly. In practice, many flights will be operated below the maximum take-off weight (MTOW) though airlines do not generally plan operations with significant payload limitations as these are often not economically viable. Figure 3.1 illustrates some typical fuel burn versus distance profiles for generic aircraft