Professor John Green

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Jock Lowe

Welcome to the afternoon's proceedings. I'm Jock Lowe, a stand in for Keith Mans, I hope you like the disguise. I'm the Chairman of the Royal Aeronautical Society Environmental Group and was previously Chairman of Greener By Design – these are my credentials for sitting here.

This morning I thought there were very interesting debates, slightly different perspectives but all were coming together in a number of different ways, both in terms of the priorities, the routes to achieving some of the objectives.

So we'll continue with those themes this afternoon. The first speaker who was almost speaking this morning – John Green, he doesn't like me calling him Professor but he is. An aerodynamicist trained at Cambridge and RAE. Primary field of research was turbulent boundary layers as on golf balls with dimples.

His research at RAE was cut short by his appointment as Head of the Subsonic-Supersonic Wind Tunnel Division and then Propulsion Division and then Noise Division before becoming Head of Aerodynamics Department. Subsequent appointments were Director Project Time and Cost Analysis in MOD, Deputy Head of British Defence Staff in Washington, Deputy Director Aircraft RAE and Chief Executive of the Aircraft Research Association.

He retired in 1995 but continues to do some work for ARA and, in the meantime, has been President of the Royal Aeronautical Society and the International Council for Aeronautical Sciences.

I've very grateful to him for being Chairman of the Greener By Design Technology Sub-Group which produced an excellent report and I'm sure we'll find some of the things that John has to say to us fascinating.

John Green

Just let me revert back to that Technology Sub-Group report, Fig 2. We covered the three things at the top of the slide: noise, local air quality, climate change. We didn't cover the items in the second block. We took a 50 year time horizon at 2050 and we finished our work just about 2 years ago and published it first in a report in the conference here in July of 2001 and re-published it in the Aeronautical Journal in February 2002.

What I want to do today is take a perspective two years on from then, and this will be a personal perspective rather than that of the Technology Sub-Group collectively.

Looking at the items in the next slide, Fig 3, I will just touch on regulation and economic instruments, the conflicts and trade-offs that exist here. Primarily, I want to focus on climate change, the main contributors to it and what challenges to technology are presented by seeking to reduce the impact of these, ie contrails, NO_X, CO_2. Finally I will touch on some questions about design philosophy, draw some conclusions and make some recommendations.

Let me start by reminding us all that we now have a dominant configuration for jet aircraft. A very interesting paper by Murman, published in the Aeronautical Journal in October 2000, addressed the question of whether civil aviation is a mature science and in its - what analysts in business would call - specific phase. The characteristic of a specific phase is that a dominant configuration emerges.

The first picture in Fig 4, taken 99 years and 4 months ago, shows Orville Wright taking off with Wilbur watching him on the first flight of the Wright Flyer. 44 years later to the day the Boeing B47 Stratojet, shown in the second picture, had its maiden flight. 55 years on from then, the A380 in the third picture has not yet flown. It looks rather like the B47 and has about the same cruise altitude and cruise Mach number.

The swept wing aeroplane is now a highly evolved design with strictly limited scope for improvement and commercial forces alone are unlikely now to break the mould. On the other hand, regulation and economic instruments might break the mould – might, I should stress.

As Fig 5 shows, for noise and LAQ we have international regulations through ICAO and we also have local constraints like the night time noise rules at Heathrow. I fully endorse what was said about ICAO this morning but we do have to recognise that it has been practising the art of the possible. It has followed technology rather than particularly driven technology. It has influenced technology to some extent but it has not been the prime driver. Local rules now usually have the stronger influence on new designs.

When we come to climate change we're still at the discussion stage. Kyoto covers flights within a country's borders but not international flights and its ratification is still uncertain. ICAO, the European Union and the British Government are discussing the impact of aviation on climate and are considering options.

My concern is that climate proposals tend to be focussed on CO_2 emissions, usually with a factor of 2.7 or 3 multiplier, as we heard this morning. My contention is that this is likely to prove counter-productive.

There's been a recent Treasury and the Department for Transport discussion paper on the external costs of UK civil aviation. As Fig 6 shows, climate change is put at £1.4 billion, local air control quality at between £119-236 million, noise at £25 million although, as was pointed out this morning, Parliamentarians get more complaints about noise, in fact the ratio of noise to air quality complaints is about 200:1.

The last sentence in the figure was the conclusion of the Treasury and the Department of Transport discussion paper. In simple terms, "the priority is climate change". And that was the view of the Technology Sub-Group too, and that's what I'm going to focus on now.

Fig 7 shows some conflicts and trade-offs, and these are not just conflicts between commercial objectives and environmental objectives, some are between conflicting aspects of environmental objectives. For some years, meeting noise targets has resulted in increased fuel burn, CO_2 emissions and costs. On the other hand, reducing fuel burn and CO_2 emissions by pushing up engine thermal efficiency increases NO_X. And, if we could indulge in operational measures to reduce contrails and cirrus cloud by avoiding critical regions of the atmosphere, that would increase fuel burn and CO_2 emissions. So we are in an area where there are conflicts between various environmental and commercial objectives and we have to get the balance right.

We saw the next chart, Fig 8, this morning and you had a useful tutorial on it so I don't need to go into great detail. What I do want to say is that the important thing from a climate change point of view is this total, on the right of the diagram, rather than the CO_2 emissions alone. My strong message here is that we should be focussing both our regulatory thinking and our design thinking on what we do to reduce that total. The commercial interests of the operators will drive us in the direction of reducing fuel burn and therefore CO_2; the real challenge is how to reduce the total.

I'm going to go on to suggest that there are things that we can do about the contrails and cirrus cloud budget and also things that can be done about NO_X. In both cases, there will be an increase in CO_2 emissions and I'm going to be arguing that we should be prepared to pay the price of increased CO_2 in order to reduce impact on climate.

But, having said that, I have to take into account Fig 9, which shows the lifetimes of the greenhouse gases in the atmosphere. NO_X and the ozone that it produces are relatively short-lived. Carbon dioxide on the other hand is long-lived. Almost all the carbon dioxide that has been emitted by aviation since the Wright Brothers' first flight is still in the atmosphere. Therefore, although I'm going to suggest that the intermediate term targets are to do something about NO_X and about contrails, in the long run we really have to do something substantial about CO_2 emissions and that is going to require something other than the standard swept winged aeroplane.

So, Fig 10, the challenge facing technology is to reduce those three primary contributors to climate change. Let me start with contrails and cirrus cloud, Fig 11.

Persistent contrails, which in time degenerate into cirrus cloud, only form in air which is saturated with respect to ice and the conditions for their formation and persistence are reasonably well understood. There's no prospect of a technological fix for that. If you fly through an ice-saturated region in the atmosphere, you'll produce a persistent contrail.

Increase in propulsive efficiency actually has a slightly adverse effect because it reduces the main exhaust temperature of the engine and therefore increases the altitude range over which contrails will form.

In principle, Fig 12, formation of persistent contrails can be avoided by flying above, below or around the ice saturated regions. That will increase fuel burn and hence CO_2. To minimise the economic penalty of such a strategy, we might seek to design future aircraft to have maximum flexibility with respect to economic cruise altitude.

We cannot justify such a strategy until we have a better understanding of the atmosphere. Advances in atmospheric science are needed to lead the way. But, if the atmospheric science established the case beyond doubt, we would also need advances in air traffic management and in meteorology before it would be practical to adopt such a strategy.

Having said all that, reducing persistent contrails might prove to be the single most powerful means of reducing the impact of aviation on climate, even through it would increase CO_2 emissions.

Let us turn now to reducing NO_X, Fig 13. There are active programmes aimed at reducing $NO_{X,}$ particularly in the landing and take-off cycle, and this slide shows three advanced combustors which have been developed with that aim. Only one of them has entered service, and the technology has so far proved successful only on small engines. The problem for the engine designer is that increasing overall pressure ratio in order to increase thermal efficiency also increases NO_X. The lines in Fig 14 are past, present and future ICAO regulatory limits, together with NASA longer term goals. The points are engine data. The difference between an engine with a pressure ratio of 25 and one of 35 is about 7% in thermal efficiency while there is a factor of 2 difference in NO_X output. So you're trading a doubling of NO_X emission for a reduction of 7% in CO_2 emission.

The Technology Sub-Group raised the question of whether the drive towards higher engine pressure ratio for the sake of higher thermal efficiency was really the right way to go in an environmental context.

One of the things we recommended in the Sub-Group report was that there should be a study of designing engines to minimise impact on climate rather than to minimise fuel burn. A research student at Cranfield took this up, as part of a wider study of engine optimisation, and Fig 15 is just one figure from his thesis. The baseline here is a large, modern engine optimised with respect to specific fuel consumption. By reducing engine pressure ratio and turbine inlet temperature and re-optimising the engine he produced a reduction of the order of 40% in global warming potential for about a 5% increase in fuel burn.

That cannot be regarded as definitive because the atmospheric science underlying his estimate of impact on climate is still very uncertain. But, nevertheless, the general trend is that if you back off on pressure ratio you reduce impact on climate. As the graph shows, you start to hit diminishing returns, so designing for minimum impact on climate isn't the thing to do, but designing to reduce impact on climate by a significant amount appears to have a tolerable price.

He also included in his study an engine with a modelled advanced combustor. This showed greater reductions in climate impact for a much smaller fuel burn penalty, suggesting that the development of low NO_X combustors might with benefit from focussing on the cruise condition rather than the LTO cycle.

From NO_X to CO_2, with apologies for the tutorial in Fig 16. Reducing CO_2 emission simply requires reducing fuel burn, with fuel burn per passenger kilometre as the appropriate metric. Fig 16 shows the Breguet range equation, from which you can see that, if the range R and the weight of the payload W_P are fixed, then the only variables remaining are the empty weight and the range performance parameter X. This is the product of the calorific value of the fuel – which is fixed if the fuel is kerosene – the overall propulsion efficiency eta and the lift to drag ratio. So we have three things we can do to reduce fuel burn; reduce empty weight, increase propulsion efficiency, increase lift drag ratio.

Reduce empty weight first, Fig 17. We can make more use of carbon fibre reinforced plastic and other light-weight structural materials, but cost has been an inhibitor – it was forecast in the mid '80s that we would see somewhere between 25-65% by weight of civil aircraft structures made out of composites by the mid '90s. In fact, the actual take-up by then was about 15%. So there is potentially some way to go, but the weight savings ultimately achieved from greater use of composites is unlikely to be more than about 15% relative to today's standards.

We can talk about more efficient structural design but, for the swept wing aeroplane, after 50 years development, further significant improvements are unlikely. We may be able to make savings by going to a flying wing for a larger aircraft because that can be made inherently more structurally efficient.

We can reduce system weight, as in the More Electric Aircraft, but we're now talking small percentages; there's not a lot to come here.

Design parameters also affect weight. Design range is a very strong variable, cruise Mach number less so, but we could reduce wing weight slightly by designing for a lower cruise Mach number. In the case of design range, the ratio of empty weight to payload weight is approximately 3 for a long range aeroplane, 2 for a medium range aeroplane. So changing our design paradigm from long range to medium range would have more impact on the ratio of empty weight to payload than anything we could do technologically.

Let's turn now to propulsive efficiency, Fig 18. As the slide shows, overall propulsive efficiency can be written as the product of the thermal efficiency of the gas turbine and the propulsive (Froude) efficiency of the jet.

In Fig 19, the upper graph shows the variation of thermal efficiency with pressure ratio, the individual curves being lines of constant turbine inlet temperature. The ellipses show the evolution of pressure ratio, turbine inlet temperature and thermal efficiency from the 1960s to the 1990s and the circle is a target suggested by Rolls Royce for the next generation of engines. To achieve this target will require an increase in both overall pressure ratio and turbine entry temperature, the combined effect of which will be to increase NO_X emissions substantially.

The lower graph shows the variation of fuel burn, weight, operating costs and noise with specific thrust. The propulsive (Froude) efficiency of the jet, not shown on the graph, increases continuously as specific thrust is reduced and bypass ratio increased. However, reducing specific thrust means increasing fan diameter and hence increasing nacelle diameter, nacelle weight and nacelle drag, and at low specific thrusts these effects more than offset the gain in Froude efficiency. As a result, fuel burn, aircraft weight and operating costs all have minima at values of specific thrust round about those on today's long-range aircraft. With current technology, a bypass ratio in the range 6 to 8 is around the economic optimum.

The graph shows that only noise continues to reduce as specific thrust is reduced below the economic optimum. It is worth noting that the airline customers for the Airbus A380 have accepted an engine which, in order to meet Heathrow night time noise regulations, has a specific thrust lower than the economic optimum and, as a result, entails a small fuel burn penalty.

Fig 20 shows two more radical options for increasing propulsive efficiency. The upper figure is the temperature-entropy diagram for an intercooled-recuperative (ICR) engine cycle, which is a more complex alternative to the simple Joule cycle used in today's engines. It offers increased thermal efficiency and, by being capable of optimisation at lower engine pressure ratios, may be operable with advanced combustors which reduce NO_X substantially. Like current turbofans, it would be capable of podded underwing installation. However, the heat exchangers and additional air ducting necessary to the concept will increase engine weight substantially and offset some of the gains in efficiency. Some key elements of an ICR engine are currently being studied under EU funding.

The lower picture shows an advanced, contra-rotating propeller, the so-called unducted fan. This achieves the increase in Froude efficiency that comes from reduced specific thrust without the weight and drag penalties of a nacelle. It was studied in depth more than a decade ago but was not taken up by the industry. Increased pressure to reduce CO_2 emissions may bring it back into consideration.

The third way of reducing fuel burn is to increase lift-drag ratio, primarily by reducing drag. The laws of physics give the aircraft designer more opportunity here than in either the weight or propulsion arenas, but it will require rather heroic steps in aeroplane design to grasp the opportunity.

In the Technology Sub Group we explored the potential drag reduction that might be achieved on the three configurations shown in Fig 21. We looked first at applying hybrid laminar flow control to the swept wing aircraft – the dominant configuration. We then looked at the more aerodynamically efficient blended wing body configuration without laminar flow control. The third aircraft studied was the all laminar flying wing. The slide shows a drawing of a project that Handley-Page proposed more than 40 years ago. It was a 300-seat aircraft with a cruise Mach number of 0.8. The laminar flow was to be achieved by all-over suction through a porous outer skin. There was a great deal of work done on laminar flow aircraft in the late 50s and 60s, including detailed engineering studies, and the Handley Page project was put forward as a serious contender with studies undertaken of military as well as civil applications.

The Technology Sub Group report includes performance and environmental estimates for 13 aircraft configurations derived from the three shown in Fig 21. With alternative propulsion options and two assumed technology standards (2000 and 2050), a total of 42 variants were studied. The report sets out the characteristics of these variants in detail but today I will simply consider the fuel burn characteristics of five of the main variants, all kerosene fuelled and with current technology standards.

Fig 22 shows the variation of payload fuel efficiency, ie payload times range divided by fuel burn, against design range for these five variants. The lowest curve is for the classical swept wing aircraft with turbofan propulsion. Its most efficient range is around 4,000km and it is reasonably efficient between, say, 2,000km and 7,500km. Fuel efficiency begins to fall off increasingly steeply below 2,000km, as was noted this morning, but it also falls off with increasing range above 4,000km and, by the time we reach the 15,000km of today's long range aircraft, we are again well below the optimum.

Applying hybrid laminar flow control technology to the turbofan powered swept wing aeroplane produces the next curve up in Fig 22, and the successive curves are for the blended wing body, the laminar flying wing and, finally, the laminar flying wing with unducted fan propulsion. This last gives a factor of two improvement in the optimum performance and interestingly enough it increases the optimum range from about 4,000km to about 8,000km.

Relative to the baseline swept wing aircraft at its optimum range, the respective reductions in fuel burn per unit payload-range are 14%, 17%, 44% and 50% for each configuration at its optimum design range. For a design range of 15,000km for all configurations, the reductions are 21%, 24%, 56% and 62%.

Fig 23 lists the key design questions that have come out of the study. First, since a medium range aircraft is considerably more fuel efficient than a long range one, we ask whether long journeys should be broken down into two or more segments of around 5,000km. This is discussed more fully in the Sub Group report and a recommendation is made for a full system assessment of multi-segment long distance travel as a means of reducing total CO_2 emissions.

Second is the question of cruise altitude. A reduction in average cruise altitudes may reduce the climate impact of NO_X and the formation of persistent contrails, though it will slightly increase CO_2 emissions. Future aircraft design thinking should take this into account.

In the case of engine pressure ratio, should we accept a reduction in fuel efficiency in order to reduce NO_X and hence total impact on climate?

A reduction in design cruise Mach number could reduce fuel burn and CO_2 emissions. A reduction to below Mach 0.8 could open the way to the use of unducted fans and could achieve appreciably greater fuel and CO_2 savings.

The overriding question we face is how to go about the process of designing to minimise impact on climate rather than minimise fuel burn, and how to achieve an appropriate balance between operating and the environmental costs.

So let me come to some conclusions, Fig 24.

In the long term we think, and the Treasury and DfT think, that impact on climate is the most important environmental effect of aviation.

Reducing NO_X and persistent contrails are probably the two most potent means of reducing this impact and in each case the best environmental result is likely to entail some increase in CO_2 emissions.

Because CO_2 is such a long lived greenhouse gas, reducing its emission is a key long-term goal, drag and weight reduction are the two most potent technologies, particularly drag reduction. Aircraft design parameters have a significant impact, particularly design range, but the effect of cruise Mach number and altitude needs also to be assessed.

Further conclusions, Fig 25.

To achieve large reductions in CO_2 we require radical changes, a departure from the swept wing aeroplane and the use of laminar flow control as a minimum.

Regulatory and economic measures should be framed so as to promote the greatest possible reduction in impact on climate. Measures based solely on CO_2 emission will probably do more harm than good.

The challenge to technology is a very severe one. The atmospheric science is not yet robust, the timescales for introducing new technology and new design concepts are long and so the need for research and technology demonstration is urgent.

Finally, Fig 26, recommendations for the next steps.

Proposed research priorities are atmospheric science and ultra low NO_X combustion.

For technology demonstration, high priority should be given to demonstrating the viability of hybrid laminar flow control in airline service. We need also to demonstrate that very low NO_X combustors are really practical, and work on the intercooled recuperative engine cycle and the blended wing body concept should be taken to the point where the potential and limitations of each is well understood.

Finally, design studies. Developing an approach to designing the aircraft and engine so as to minimise impact on climate is a key objective. Designing to increase cruise altitude flexibility is not so important but nevertheless, if we see the contrails as a big target, and perhaps one that we might hit within a 20-year timeframe, it could be of competitive value to new designs. And finally I return to the controversial proposal that we made in the Sub Group report, to do a full system, operational and economic study of multi-sector long-range travel.