Greener by Design

J E Green
Chief Scientist, Aircraft Research Association Ltd
Chairman, Greener by Design Technology Sub-Group

Aviation, Atmosphere and Climate
Graf-Zeppelin-Haus, Friedrichshafen
30 June – 3 July 2003
The Air Travel - Greener by Design Initiative
(Launched March 2000)
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- Objectives: to assess and progress options for mitigating the environmental impact of aviation
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            Society of British Aerospace Companies
            British Air Transport Association
            Airport Operators Association
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- Sub-Groups: Operations
  Technology
  Market-Based Options
Technology Sub-Group
Technology Sub-Group

Scope
In:

Noise
Local Air Quality (LAQ)
Climate Change
Technology Sub-Group

Scope

In:
- Noise
- Local Air Quality (LAQ)
- Climate Change

Out:
- Supersonic Transports
- ATC & NAV
- Ground Movements
- Manufacture and Disposal
**Technology Sub-Group**

**Scope**

*In:* Noise, Local Air Quality (LAQ), Climate Change

*Out:* Supersonic Transports, ATC & NAV, Ground Movements, Manufacture and Disposal

**Time Horizon:** 2050 (fourfold traffic growth)
Technology Sub-Group

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In:
- Noise
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## Technology Sub-Group

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<td>Manufacture and Disposal</td>
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**Time Horizon:** 2050 (fourfold traffic growth)

**Full Report:** published July 2001 and re-published in The Aeronautical Journal, February 2002

**New paper:** Aeronautical Journal June 2003
Technology perspective 2 years on

- regulation and economic instruments
- conflicts and trade-offs
- focus on climate change

  main contributors
  challenges to technology
    reducing contrails
    reducing $\text{NO}_x$
    reducing $\text{CO}_2$

- design questions
- conclusions and recommendations
Emergence of the dominant configuration
Emergence of the dominant configuration
Emergence of the dominant configuration

- Highly evolved
- Strictly limited scope for improvement
- Commercial forces alone unlikely to break the mould
Regulation and economic instruments
# Regulation and economic instruments

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<td>Local (eg Zurich)</td>
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<tr>
<td>Climate Change</td>
<td>Kyoto (excludes international flights)</td>
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<td>ICAO )</td>
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<td>EU ) considering options</td>
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- Climate proposals tend to be focussed on CO$_2$ emissions (with factor of 2.7 or 3 multiplier): this is likely to prove counter-productive
Annual external costs of UK civil aviation
(from recent HM Treasury/DfT discussion paper)
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- Climate change: £1,400 M
- LAQ: £119 – 236 M
- Noise: £25 M
Annual external costs of UK civil aviation
(from recent HM Treasury/DfT discussion paper)

- Climate change £1,400 M
- LAQ £119 – 236 M
- Noise £25 M

“Aviation’s principal externality, which can be translated into monetary terms, arises from the effect of greenhouse gases and the impact they have on climate change”
Conflicts and trade-offs
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- on modern engines, reducing noise increases fuel burn, CO$_2$ emissions and costs
Conflicts and trade-offs

• on modern engines, reducing noise increases fuel burn, CO₂ emissions and costs

• reducing fuel burn and CO₂ emissions by increasing engine thermal efficiency increases NOₓ
Conflicts and trade-offs

- on modern engines, reducing noise increases fuel burn, CO$_2$ emissions and costs

- reducing fuel burn and CO$_2$ emissions by increasing engine thermal efficiency increases NO$_X$

- operational measures to reduce contrails and cirrus cloud would increase fuel burn and CO$_2$ emissions
Contributions of aviation to climate change

Radiative Forcing from Aircraft in 1992

- CO₂
- O₃
- CH₄
- H₂O
- Contrails
- Cirrus Clouds
- Direct Sulfate
- Direct Soot
- Total (without cirrus clouds)

Radiative Forcing (Wm⁻²)

From NOₓ:

- Good
- Fair
- Poor
- Very Poor
- Fair
### Lifetimes of greenhouse gases and aircraft emissions

<table>
<thead>
<tr>
<th>Gas</th>
<th>Lifetimes</th>
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<tbody>
<tr>
<td>Carbon Dioxide</td>
<td>50 – 100 years</td>
</tr>
<tr>
<td>Methane</td>
<td>8 – 10 years</td>
</tr>
<tr>
<td>Water</td>
<td>days (sea level)</td>
</tr>
<tr>
<td></td>
<td>weeks (tropopause)</td>
</tr>
<tr>
<td>Ozone</td>
<td>week (sea level)</td>
</tr>
<tr>
<td></td>
<td>months (topopause)</td>
</tr>
<tr>
<td>NO$_x$</td>
<td>days (sea level)</td>
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Challenges to technology

- Reducing persistent contrails and cirrus cloud
- Reducing impact of NO$_x$
- Reducing CO$_2$
Challenges to technology: reducing persistent contrails and cirrus cloud
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• Persistent contrails form only in air which is saturated with respect to ice: the conditions for formation and persistence are reasonably well understood
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• There is no prospect of preventing contrail formation in an ice-saturated atmosphere by technological means
Challenges to technology: reducing persistent contrails and cirrus cloud

- Persistent contrails form only in air which is saturated with respect to ice: the conditions for formation and persistence are reasonably well understood.

- There is no prospect of preventing contrail formation in an ice-saturated atmosphere by technological means.

- Increasing propulsive efficiency reduces the mean exhaust temperature and increases the altitude range over which contrails will form.
Challenges to technology: reducing persistent contrails and cirrus cloud

• Persistent contrails can be avoided by flying above, below or around ice-saturated regions: this will increase fuel burn and CO₂ emissions
Challenges to technology: reducing persistent contrails and cirrus cloud

- Persistent contrails can be avoided by flying above, below or around ice-saturated regions: this will increase fuel burn and CO\textsubscript{2} emissions

- To minimise the economic penalty of such a strategy, future aircraft design should aim for flexibility in economic cruise altitude
Challenges to technology: reducing persistent contrails and cirrus cloud

- Persistent contrails can be avoided by flying above, below or around ice-saturated regions: this will increase fuel burn and CO₂ emissions.

- To minimise the economic penalty of such a strategy, future aircraft design should aim for flexibility in economic cruise altitude.

- Further advances in atmospheric science, air traffic management and meteorology are needed before such a strategy can be justified or adopted.
Challenges to technology: reducing persistent contrails and cirrus cloud

- Persistent contrails can be avoided by flying above, below or around ice-saturated regions: this will increase fuel burn and CO₂ emissions

- To minimise the economic penalty of such a strategy, future aircraft design should aim for flexibility in economic cruise altitude

- Further advances in atmospheric science, air traffic management and meteorology are needed before such a strategy can be justified or adopted

- Nevertheless, reducing persistent contrails might prove to be the single most powerful means of reducing the impact of aviation on climate, even though it would increase CO₂ emissions
Challenges to technology: reducing NOX
Challenges to technology: reducing NO\textsubscript{X}

(a) General Electric
(b) Snecma
(c) Pratt and Whitney

Staged Combustors
Challenges to technology: reducing NOX

Aero-engine NOX emissions

Engine Pressure Ratio vs. NOX emissions (Dp/Foo g/KN)

Legend:
- Engine data
- ICAO 86
- CAEP 2
- CAEP 4
- NASA 50% target
- NASA 30% target
- Karlsruhe based line
Challenges to technology: reducing NOX

Trade off between reduced Global Warming Potential and increased SFC relative to minimum SFC datum (Whellens and Singh)
Challenges to technology: reducing CO$_2$ = reducing fuel burn per passenger km
**Challenges to technology: reducing CO₂**

Fuel burn per passenger kilometre: -

\[
\frac{W_f}{RW_p} = \left( 1 + \frac{W_e}{W_p} \right) \left( \frac{\exp \left( \frac{R}{X} \right) - 1}{R} \right)
\]

**Breguet range equation**

<table>
<thead>
<tr>
<th>where</th>
<th>X</th>
<th>=</th>
<th>H(\eta)L/D</th>
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<tbody>
<tr>
<td>H</td>
<td>calorific value of fuel</td>
<td></td>
<td></td>
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<tr>
<td>(\eta)</td>
<td>overall propulsive efficiency</td>
<td></td>
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<tr>
<td>L/D</td>
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Challenges to technology:
reducing CO$_2$ by reducing empty weight
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- Increased use of CFRP and other light structural materials: cost is a significant inhibitor (1983 forecasts for use of composites by 1995 ranged from 25% to 65% by weight – actual composite weight in A330 and B777 is around 15%)
Challenges to technology: reducing CO$_2$ by reducing empty weight

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- Design parameters – design range, cruise Mach number
Challenges to technology: reducing CO$_2$ by increasing propulsive efficiency

Overall propulsive efficiency

$$\eta = \eta_E \eta_P$$

where $\eta_E = \text{thermal efficiency}$

and $\eta_P = \text{jet propulsive efficiency}$
Challenges to technology: reducing fuel burn by increasing propulsive efficiency - Joule cycle turbofan

- Increasing thermal efficiency requires increases in both overall pressure ratio and turbine entry temperature: these increase NO\textsubscript{X} production.
Challenges to technology: reducing fuel burn by increasing propulsive efficiency - Joule cycle turbofan

- Increasing thermal efficiency requires increases in both overall pressure ratio and turbine entry temperature: these increase NO\textsubscript{X} production

- Most large turbofans have specific thrust around the optimum for fuel burn: reducing specific thrust below this optimum in order to meet noise targets increases fuel burn and CO\textsubscript{2}
Challenges to technology: reducing CO₂ by increasing propulsive efficiency

Intercooled recuperative engine cycle
- reduced fuel burn & CO₂
- reduced NOₓ
- capable of podded installation
- increased weight and complexity
Challenges to technology: reducing CO₂ by increasing propulsive efficiency

Intercooled recuperative engine cycle
- reduced fuel burn & CO₂
- reduced NOₓ
- capable of podded installation
- increased weight and complexity

Unducted fan
- reduced fuel burn & CO₂
- reduced cruise Mach number
- complexity and flight safety issues
Challenges to technology: reducing CO$_2$ by reducing drag

- Dominant configuration with hybrid laminar flow control
- Blended wing body
- All laminar flying wing
Challenges to technology: reducing CO$_2$ by reducing drag

Payload fuel efficiency versus design range for kerosene fuelled aircraft
Challenges to technology: reducing fuel burn – effect of range

Payload Fuel Efficiency versus Range and Design Range

- Range = Design Range
- Design Range = 15,000 km
- Design Range = 5,000 km
- Design Range = 7,500 km
Reducing fuel burn: effect of design range

<table>
<thead>
<tr>
<th>Design range km</th>
<th>Payload tonne</th>
<th>Fuel tonne</th>
<th>Max TOW tonne</th>
<th>Empty Weight tonne</th>
<th>Fuel for 15,000 km tonne</th>
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<tr>
<td>15,000</td>
<td>44.8</td>
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<tr>
<td>5,000</td>
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<td>28.6</td>
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<td>95.6</td>
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Multi-Sector Long Distance Travel?
### Reducing fuel burn: effect of design range

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**Multi-Sector Long Distance Travel?**
Significance of range

Distribution of Fuel Burn over Range
1998 Scheduled Flights

% of total fuel burn

Range (nautical miles)
Design questions
Design questions

- Design range
  - multi-segment long distance travel?
Design questions

• Design range
  • multi-segment long distance travel?

• Cruise altitude
  • contrail avoidance, reducing NO\(_X\) impact?
Design questions

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• Engine pressure ratio
  • trade-off increased CO\textsubscript{2} for reduced NO\textsubscript{X}?
Design questions

- Design range
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  - contrail avoidance, reducing NO$_x$ impact?
- Engine pressure ratio
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- Cruise Mach number
  - reduce fuel burn & CO$_2$, enable unducted fans?
Design questions

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  • contrail avoidance, reducing NO_X impact?

• Engine pressure ratio
  • trade-off increased CO_2 for reduced NO_X?

• Cruise Mach number
  • reduce fuel burn & CO_2, enable unducted fans?

• Design for minimum impact on climate
  • trade off between operating and environmental costs?
Conclusions

- In the long term, impact on climate change is the most important environmental effect of aviation.
CONCLUSIONS

• In the long term, impact on climate change is the most important environmental effect of aviation.

• Reducing NO\textsubscript{X} and persistent contrails are probably the two most potent means of reducing this impact: in each case, the best environmental result is likely to entail some increase in CO\textsubscript{2} emissions.
CONCLUSIONS

• In the long term, impact on climate change 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: 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. Aircraft design parameters – design range, cruise Mach number and altitude – are also significant factors.
CONCLUSIONS II

• To achieve large reductions in CO$_2$ requires radical changes - a departure from the dominant configuration and the use of laminar flow control as a minimum.
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- To achieve large reductions in CO₂ requires radical changes - a departure from the dominant configuration 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 CO₂ emission will probably do more harm than good.
CONCLUSIONS II

• To achieve large reductions in CO₂ requires radical changes - a departure from the dominant configuration 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 CO₂ emission will probably do more harm than good.

• The challenge to technology is severe: the atmospheric science is not yet robust: the timescales for introducing new technology and new design concepts are long: the need for research and demonstration is urgent.
RECOMMENDATIONS – The Next Steps
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Research priorities
• Atmospheric science
• Ultra low NO\textsubscript{X} combustion
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• Atmospheric science
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Technology demonstration
• Hybrid laminar flow control in airline service
• Low NO$_X$ combustors
• Intercooled recuperative engine cycle
• Blended wing-body concept
RECOMMENDATIONS – The Next Steps

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Design studies
• Design to minimise impact on climate
• Design to increase cruise altitude flexibility
• Multi segment long-range travel