2016 Outlook – technology and design options for reducing climate impact

J E Green
Greener by Design, Royal Aeronautical Society

2nd ECATS Conference
Making aviation environmentally sustainable
7 - 9 November 2016
Athens, Greece

Headings

- GBD background
- November 2005 conjectured projections to 2050
  - Fuel burn
  - Non-CO_2 emissions (NCE)
  - Status of conjecture 11 years later
- Future outlook
  - NCE
  - Fuel Burn
- Designing for minimum fuel burn per RPK
- Conflict between environmental and commercial goals
- Final messages

Greener by Design

- March 2000, began work as Air Travel – Greener by Design, set up by
  - Royal Aeronautical Society
  - SBAC – UK manufacturers
  - BTA – UK airlines
  - AOA – UK airports
  - DTI – UK Governement
- July 2001, The Technology Challenge published
- April 2004, reconstituted as a Specialist Group of the Royal Aeronautical Society, free from industrial connections
- July 2005, Mitigating the Environmental Impact of Aviation: Opportunities and Priorities published

GBD S&T Sub Group report

July 2005

Republished

The Aeronautical Journal

September 2005

GBD S&T Sub Group Report, July 2005

"Technologies can and will be deployed in combination. The report has identified a number of specific avenues of advance in the reduction of weight, drag and NO_X emission, increase in propulsion efficiency and operational improvement."

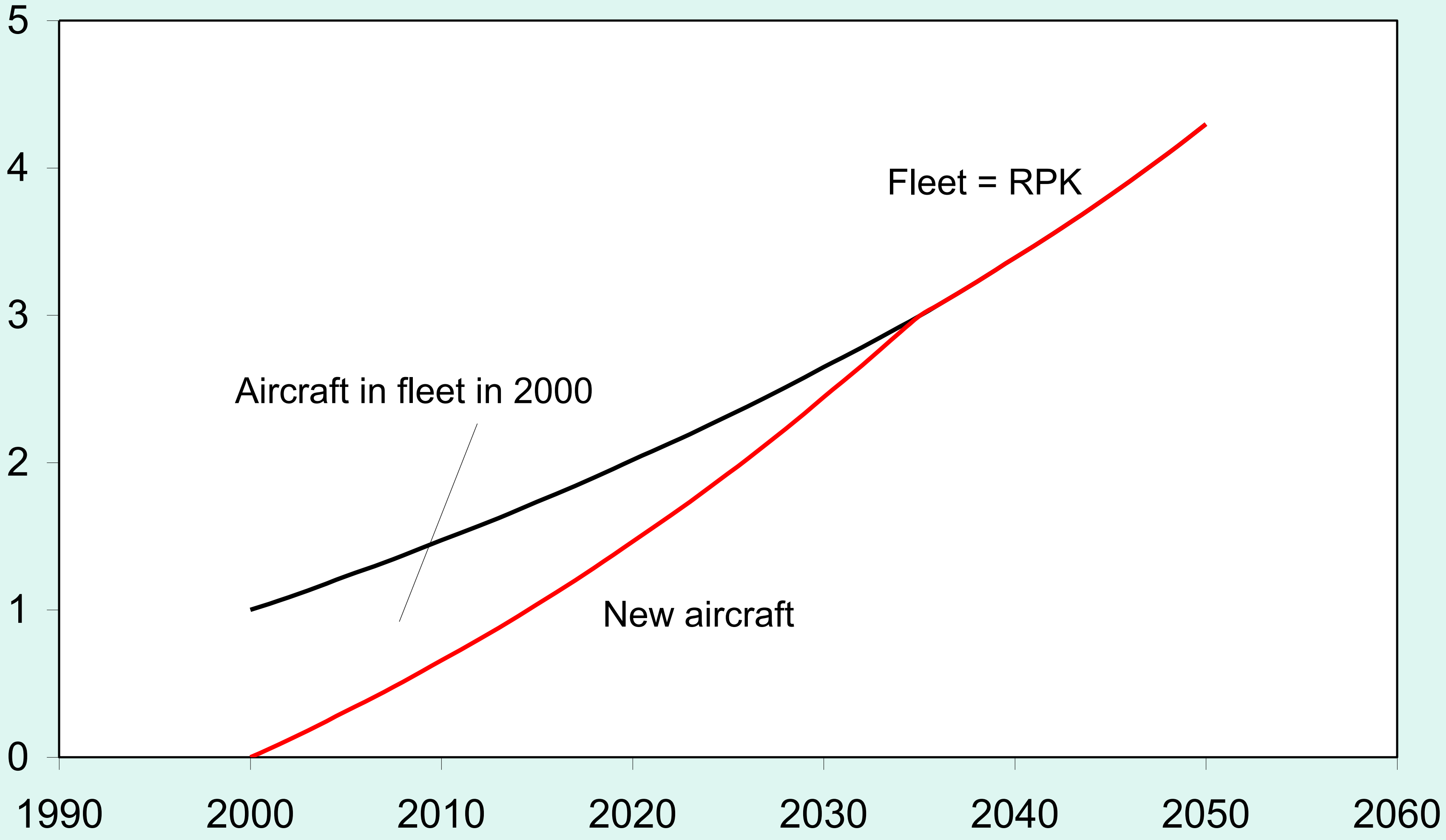
"Taken together, these hold out the prospect that, in the long run, technological, design and operational progress will enable environmental impact per passenger-kilometre to be reduced faster than air traffic increases."

Nature of presentation at GBD conference, November 2005

- Reasoned conjecture in defence of an assertion in GBD S&T Sub Group report
- A personal view, not reviewed by the Sub Group but based on material in the Sub Group report
- Addressed emissions solely in the context of climate change
- Attempted not to be unduly optimistic in timing of new technology
- Two important caveats
  - Still important uncertainties in the atmospheric science
  - There is not a linear relationship between rates of emission and contribution to climate change

Assumptions underlying Nov 2005 paper

- World RPK grows as in FESG scenario “a”
- World fleet grows in proportion to RPK
- Fleet retirement rate is 1.5% per annum
- Fuel efficiency of existing fleet improves at a rate of 1% per annum
- Specific technologies identified in the GBD July 2005 report are introduced at specific dates and are assumed to take 30 years fully to penetrate the relevant sector of the fleet
- Specific operational procedures are assumed to take a shorter but still protracted time to become universally adopted



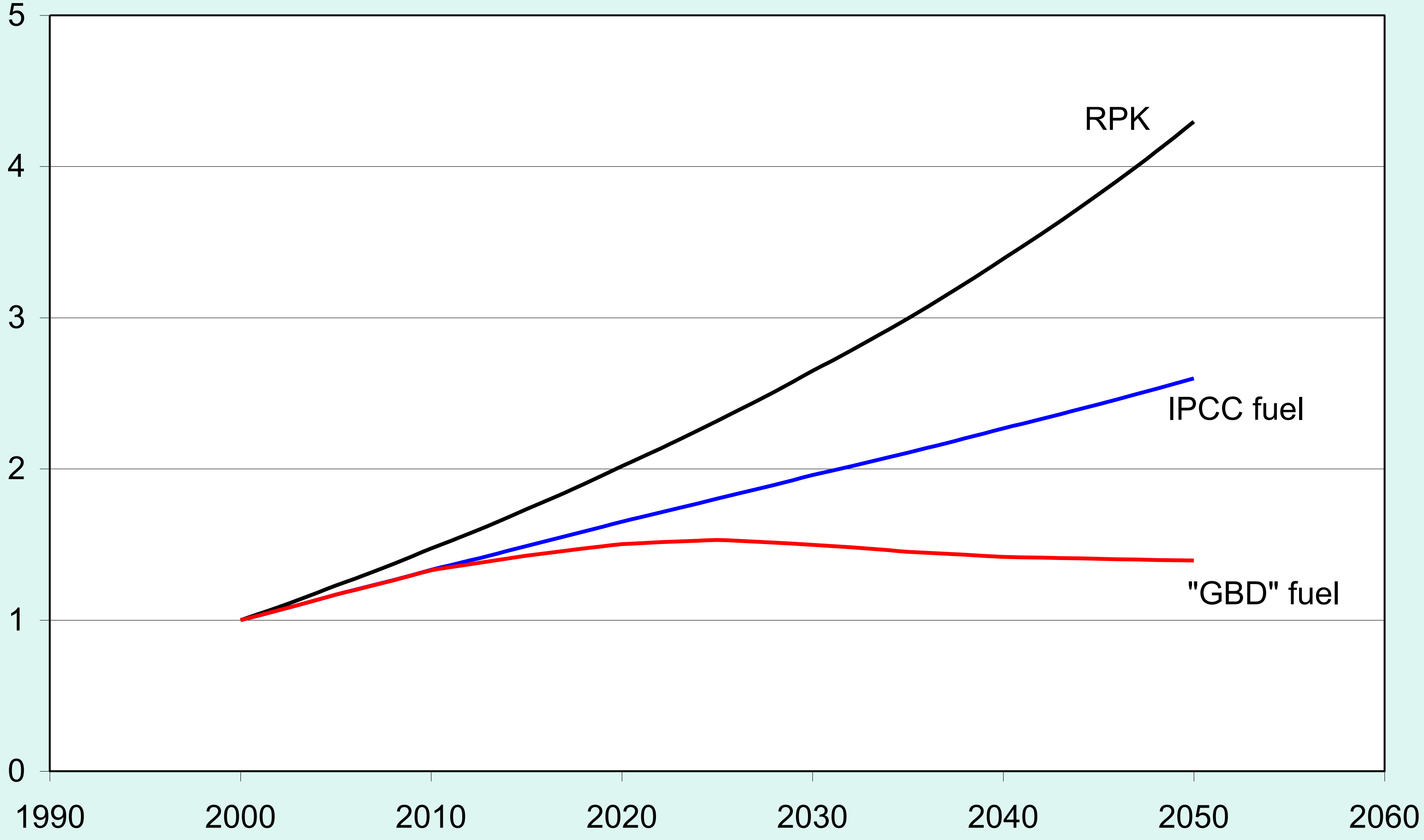
Assumed make up of world fleet, 2000 - 2050

CO_2 emissions
(= fuel burn)

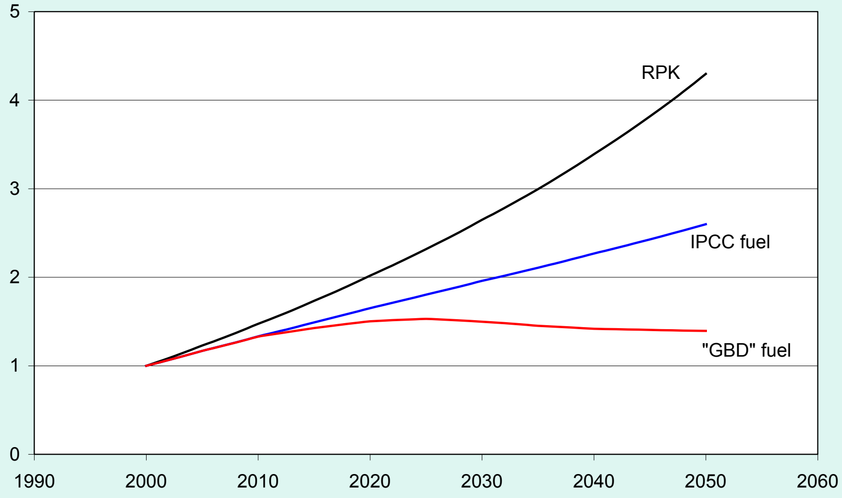
Technology	Fuel burn reduction %	Applicability (fleet fraction)	Overall % reduction	Phase in
Lightweight materials 1	12	all	12	2010 - 2040
Lightweight materials 2	12	all	12	2025 - 2055
Open rotor	12	1/3	4	2018 - 2048
HLFC	15	2/3	10	2020 - 2050
BWB	18	1/3	6	2025 - 2055
LFW	36	1/3	12	2035 - 2065
Cooled cooling air	1	all	1	2015 - 2045
Operations	10	all	10	2010 - 2030
Multi-stage long-distance travel	15	1/3	5	2015 - 2030
Formation flying	10	1/4	2.5	2030 - 2040

Engine thermal efficiency	1% per annum, 2000 – 2015 0.5% per annum, 2015 – 2050 Basis of assumed baseline thermal efficiency of new engines entering the fleet at a given date

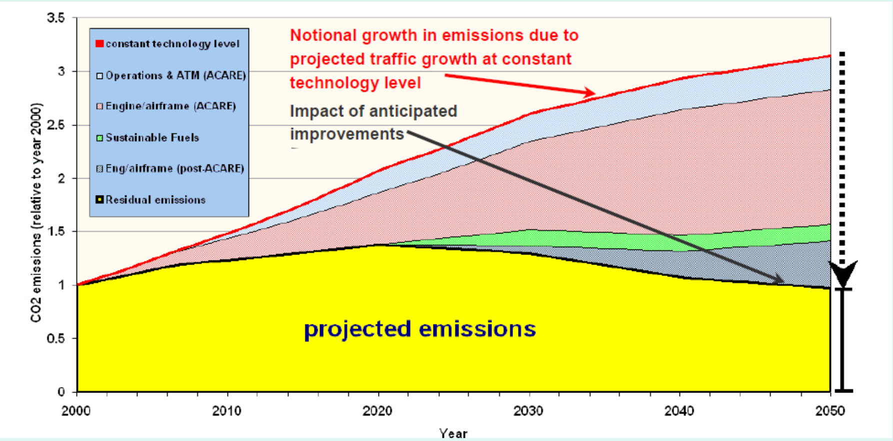
Fuel burn reductions attributed to specific technologies



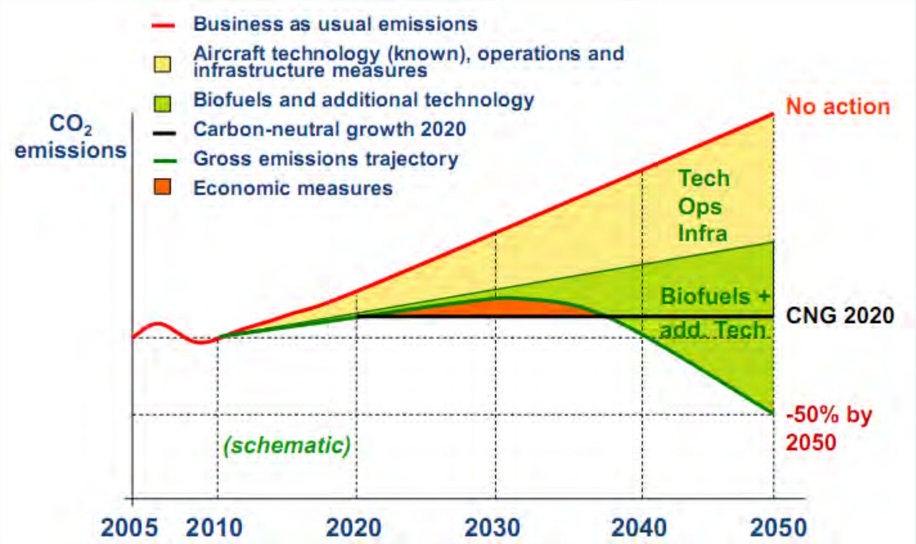
World fleet fuel burn projections, 2000 - 2050



“GBD” projected world fuel burn, November 2005



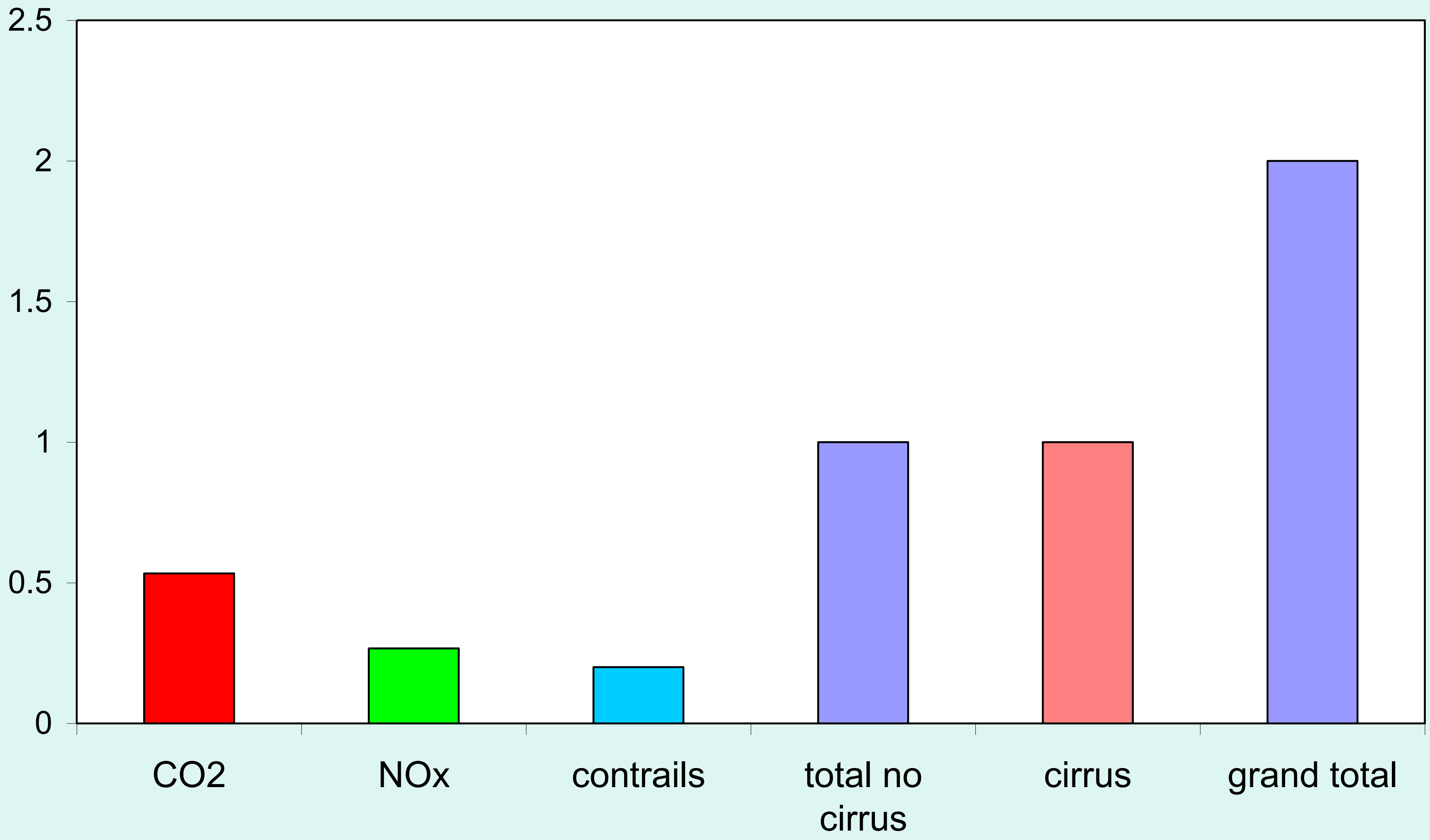
Sustainable Aviation UK CO_2 roadmap, December 2008



ATAG CO_2 emissions reduction roadmap, presented to ICAO, March 2010

CNG 2020 proposed by IATA, June 2009: target 2050 emissions half 2005 level

Non–CO_2 emissions (NCE)



Estimated breakdown of RF due to aviation in 2000
(after EC TRADEOFF study, 2003)

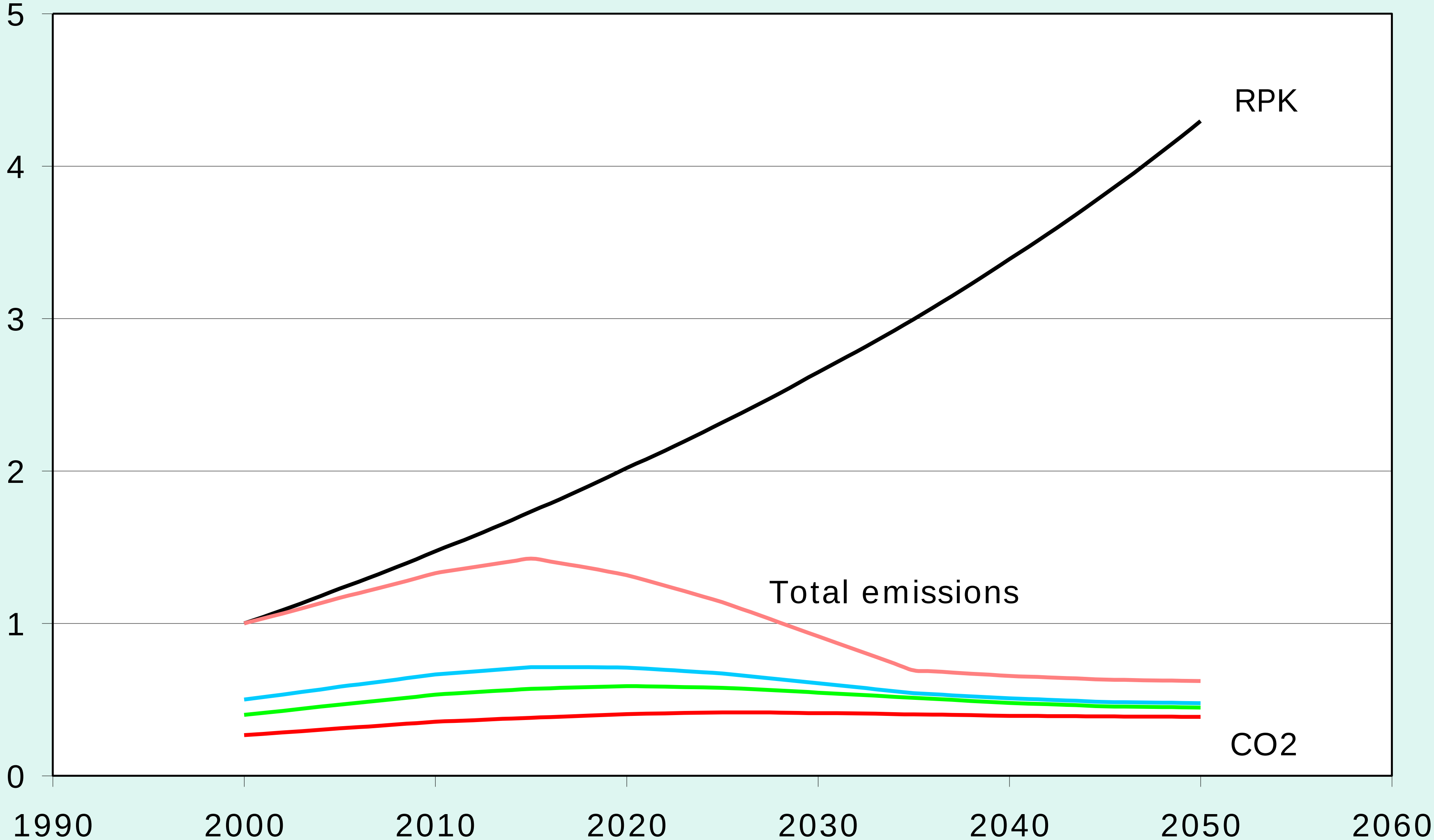
Technology	Cruise EI_{NOx} reduction %	Phase in
Lean-burn combustion	50	2015 - 2045
Cooled cooling air	10	2015 - 2045
Inter-cooling	30	2020 - 2050

Reductions in EI_{NOx} in cruise
attributed to specific technologies

Persistent contrails and cirrus cloud

Conjectured reduction in contrail formation

- Persistent contrail formation can be reduced by ATM action to deny flight at critical cruise altitudes
- Studies at Imperial College suggest achievable reductions in the European ATM area in the range 65%-90% for fuel burn penalties in the range 2%-7%
- For this paper, a reduction of 80% is assumed at a fuel burn penalty of 4%
- It is conjectured that ATM avoidance measures will first appear in ten years' time, ie 2015, and will become universal by 2035
- It is assumed that cirrus will be reduced in proportion to contrails
- There is still considerable scientific uncertainty about aviation-induced cirrus and its radiative impact



Projected emissions of CO_2 and NO_X and formation of contrails and cirrus cloud (scaled in proportion to estimated contributions to RF)

My proposition, November 2005

- The technologies, design concepts and operational measures identified in the GBD S&T report of July 2005, if phased in over the timescales envisaged here, offer the following reductions in emissions per RPK by the year 2050
  - Fuel burn and CO_2 emission down by a factor of 3
  - NO_X emission at altitude down by a factor of 10
  - Contrail and contrail-induced cirrus down by a factor of 5 – 15
- To assess the consequent impact on climate change requires atmospheric modelling
- A more robust understanding of the relative impact of the main contributors, particularly contrail-induced cirrus, is needed
- A critical assessment of the credibility of my assumptions with respect to technology capability and timing from the viewpoint of the manufacturers and operators would be of value

Status of Nov 2005 conjecture after 11 years

- Most of the identified technologies are under development within Clean Sky
- Dates of introduction into service are later, sometimes much later, that envisaged.
- Progressive increases in engine efficiency and fleet fuel efficiency are lower than assumed
- Slow evolution of fleet suggests that CO_2 reduction by 2050 probably overestimated

Where do we go from here?

Where do we go from here?

- Facts of life

Where do we go from here?

- Facts of life
  - Laws of physics – no escape from:
    - The Breguet Range Equation
    - The Second Law of Thermodynamics
    - The stoichiometric limit
    - Lanchester-Prandtl formula for induced drag
    - Laminar boundary layer stability equations

Where do we go from here?

- Facts of life
  - Laws of physics – no escape from:
    - The Breguet Range Equation
    - The Second Law of Thermodynamics
    - The stoichiometric limit
    - Lanchester-Prandtl formula for induced drag
    - Laminar boundary layer stability equations
  - Requirements of commerce
    - Manufacturers produce the aircraft the airlines want
    - Airlines compete to satisfy their shareholders and the travelling public

Where do we go from here?

- Facts of life
  - Laws of physics – no escape from:
    - The Breguet Range Equation
    - The Second Law of Thermodynamics
    - The stoichiometric limit
    - Lanchester-Prandtl formula for induced drag
    - Laminar boundary layer stability equations
  - Requirements of commerce
    - Manufacturers produce the aircraft the airlines want
    - Airlines compete to satisfy their shareholders and the travelling public
  - Conflicts between different environmental objectives

Where do we go from here?

- Facts of life
  - Laws of physics – no escape from:
    - The Breguet Range Equation
    - The Second Law of Thermodynamics
    - The stoichiometric limit
    - Lanchester-Prandtl formula for induced drag
    - Laminar boundary layer stability equations
  - Requirements of commerce
    - Manufacturers produce the aircraft the airlines want
    - Airlines compete to satisfy their shareholders and the travelling public
  - Conflicts between different environmental objectives
  - Conflicts between environmental and commercial objectives

Where do we go from here?

- Facts of life
  - Laws of physics – no escape from:
    - The Breguet Range Equation
    - The Second Law of Thermodynamics
    - The stoichiometric limit
    - Lanchester-Prandtl formula for induced drag
    - Laminar boundary layer stability equations
  - Requirements of commerce
    - Manufacturers produce the aircraft the airlines want
    - Airlines compete to satisfy their shareholders and the travelling public
  - Conflicts between different environmental objectives
  - Conflicts between environmental and commercial objectives
  - Long production and service lives of modern aircraft

Where do we go from here?

- Facts of life
  - Laws of physics – no escape from:
    - The Breguet Range Equation
    - The Second Law of Thermodynamics
    - The stoichiometric limit
    - Lanchester-Prandtl formula for induced drag
    - Laminar boundary layer stability equations
  - Requirements of commerce
    - Manufacturers produce the aircraft the airlines want
    - Airlines compete to satisfy their shareholders and the travelling public
  - Conflicts between different environmental objectives
  - Conflicts between environmental and commercial objectives
  - Long production and service lives of modern aircraft
  - High level of investment needed for new projects

The Good News

- With low NOx combustors at an advanced state of development and other technologies in the pipeline, we can expect a substantial reduction in NO_X emissions at cruise by 2050
- Similarly, current research suggests that a substantial reduction in contrails and contrail-cirrus can be achieved economically by tactical flying to avoid critical regions
- Together with some reduction in fuel burn per RPK and some help from biofuels, these should reduce aviation RF per RPK by a factor of between 3 and 4
- This should be regarded as an expectation rather than an aspiration
- It is important to recognise the magnitude of the NCE contribution and the real potential for reducing it
- Agreement on a metric for climate impact is needed
- Regulation is required, both for NO_X emissions in cruise and for contrail avoidance practices

The Not So Good News

- Because CO_2 is so long-lived, it is the most important emission from aircraft
- At today's fuel and carbon prices, the minimum CO_2 and minimum DOC aircraft are very different
- The minimum CO_2 aircraft will fly appreciably slower and lower than today's aircraft. At today's fuel and carbon prices, this is commercially unacceptable

Designing for minimum fuel burn per RPK

The Breguet range equation

Fuel burn per tonne-kilometre

$$\frac{W_F}{RW_P} = \frac{1}{X}\left(1 + \frac{W_E}{W_P}\right)\left(\frac{1.022\exp\left(\frac{R}{X}\right) - 1}{\left(\frac{R}{X}\right)}\right)$$

where $X = H\eta L/D$

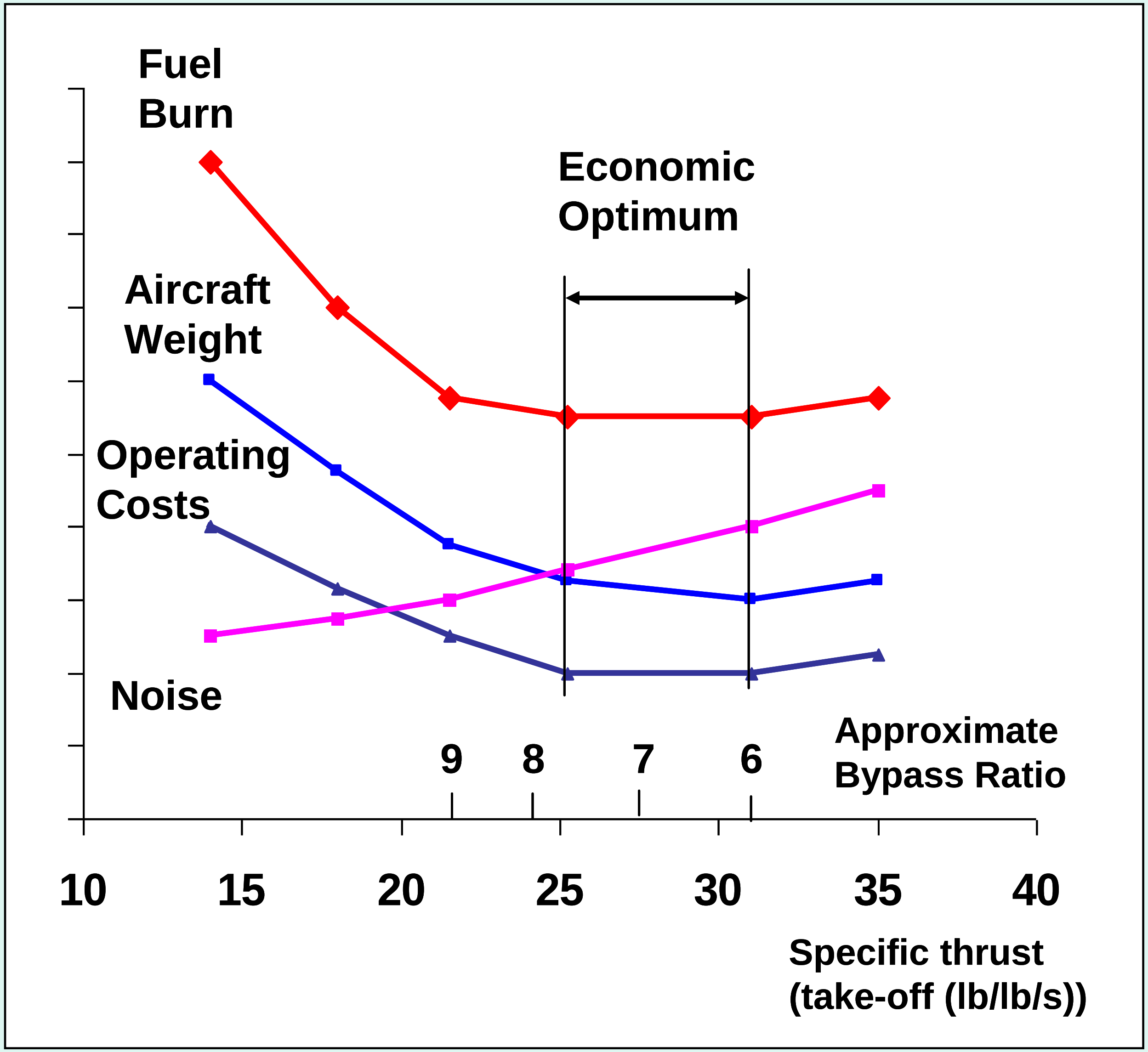
H = calorific value of fuel

η = overall propulsion efficiency

L/D = lift/drag ratio

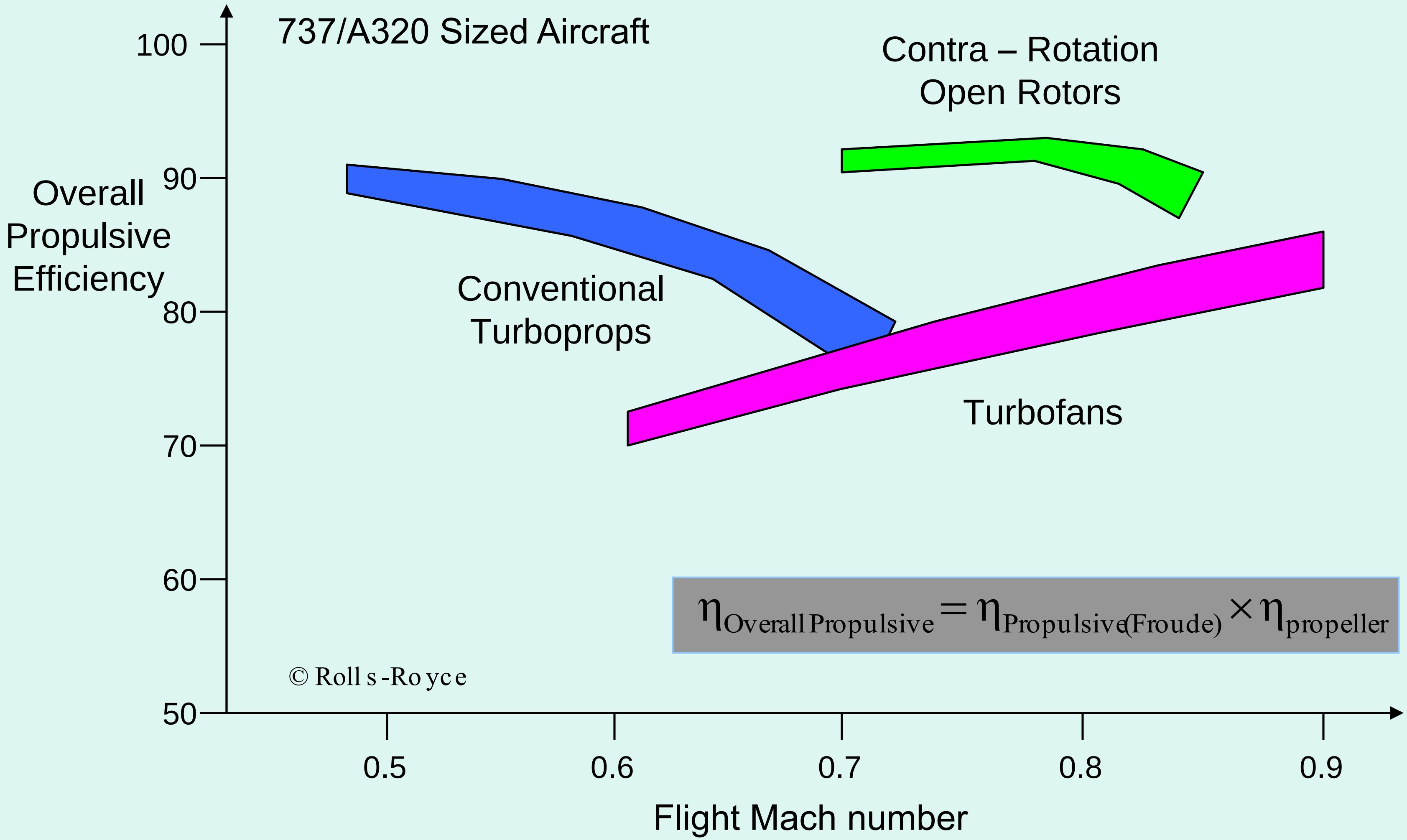
Propulsive Efficiency

Variation of turbofan-powered aircraft characteristics with engine specific thrust



Source Rolls-Royce

Propulsive efficiency of alternative forms of propulsor



Source Rolls-Royce

Aerodynamic Efficiency L/D

Designing for maximum lift to drag ratio

$$\left(\frac{L}{D}\right)_{MAX} = b\sqrt{\frac{\pi}{4kS_{DO}}}$$

Designing for maximum lift to drag ratio

$$\left(\frac{L}{D}\right)_{MAX} = b\sqrt{\frac{\pi}{4kS_{DO}}}$$

Maximum L/D is directly proportional to wing span *b* and inversely proportional to the square root of the zero-lift drag area S_{DO}.

Designing for maximum lift to drag ratio

$$\left(\frac{L}{D}\right)_{MAX} = b\sqrt{\frac{\pi}{4kS_{DO}}}$$

Maximum L/D is directly proportional to wing span *b* and inversely proportional to the square root of the zero-lift drag area S_{DO}.

Maximising wing span without a weight penalty requires minimising sweep, possibly increasing wing thickness *b* and, to avoid increasing S_{DO}, reducing chord. Aerodynamics at high subsonic speeds mean that all these reduce optimum cruise Mach number

Designing for maximum lift to drag ratio

$$\left(\frac{L}{D}\right)_{MAX} = b\sqrt{\frac{\pi}{4kS_{DO}}}$$

Maximum L/D is directly proportional to wing span *b* and inversely proportional to the square root of the zero-lift drag area S_{DO}.

Maximising wing span without a weight penalty requires minimising sweep, possibly increasing wing thickness and, to avoid increasing S_{DO}, reducing chord. Aerodynamics at high subsonic speeds mean that all these reduce optimum cruise Mach number

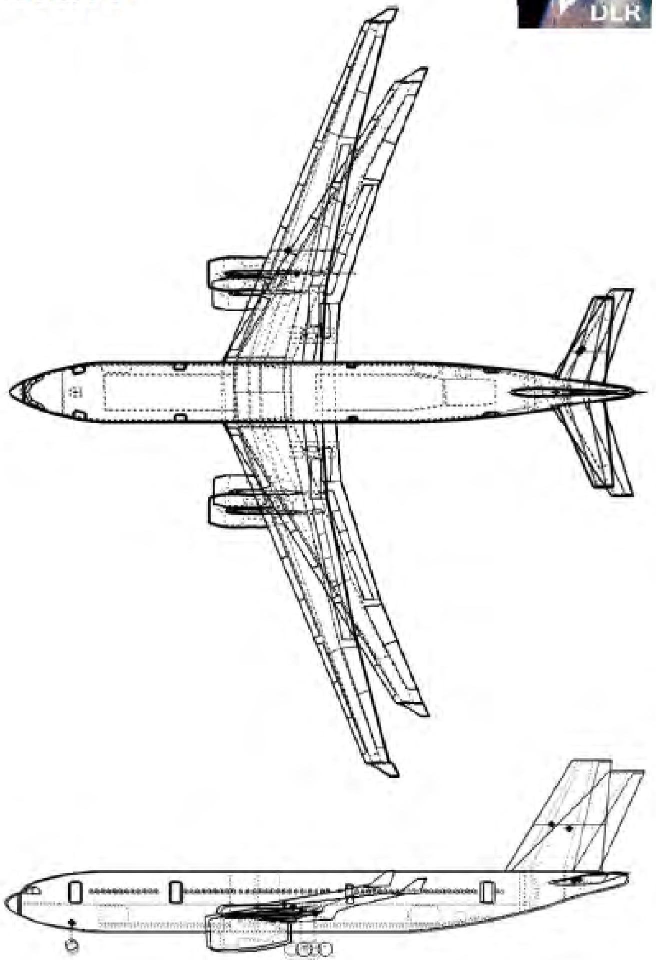
The optimum cruise condition is given by the equation below. The reduction in cruise Mach number is the most powerful effect and means that the aircraft cruises at higher static pressure, ie lower cruise altitude

$$0.7\,pM^2 = W\sqrt{\frac{k}{\pi b^2 S_{DO}}}$$

Comparison of reference vs. redesigned aircraft

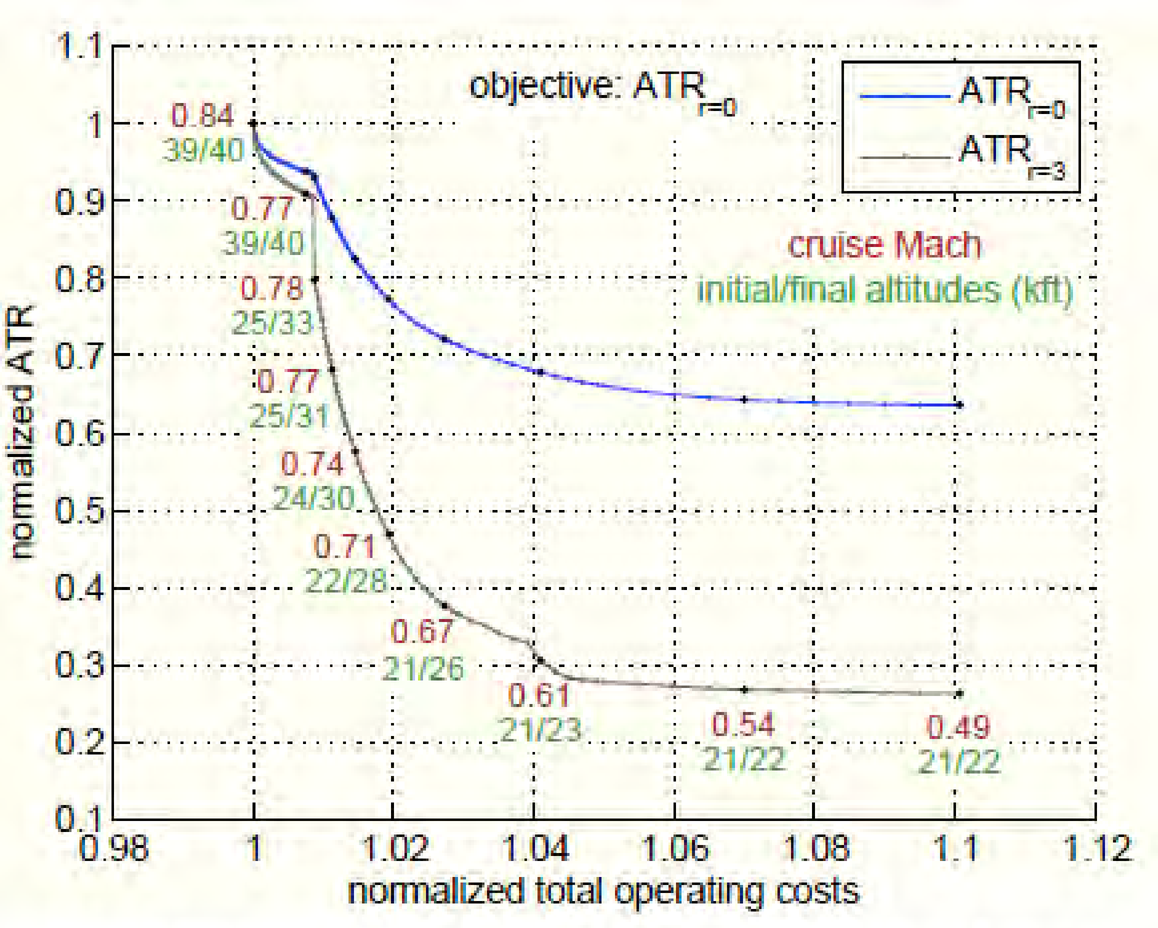
Geometry changes		Opt.	Ref.	Rel. Change
Wing area	[m²]	360	362	<< 1 %
Span	**[m]**	**68.5**	**58**	**+ 18 %**
Wing aspect ratio		13	9.3	+ 39 %
Wing LE sweep	**[deg]**	**22**	**33**	**- 31 %**
HTP area	[m²]	59	71	- 17 %
HTP LE sweep	[deg]	24	33	- 27 %
VTP area	[m²]	64	53	+ 20 %
VTP LE sweep	[deg]	31	44	- 29 %

Performance at ICA 8000 m and Mach 0.72				
L/D @ ICA		**22.9**	**19.9**	**+ 15 %**
SFC @ ICA	[kg/kN/h]	58.3	58.2	<< 1 %
Mission fuel	**[t]**	**54.3**	**61.2**	**- 11 %**
OWE	[t]	120.2	115.6	+ 4 %
MTOW	[t]	223.6	221.6	<< 1 %



Koch (2012)

Illustration of aircraft re-design to reduce fleet ATR



(a) Optimized $ATR_{r=0}$; evaluated $ATR_{r=3}$ also shown.

Reducing M and cruise altitude reduces ATR

Discounting future impact emphasises impact of NO_X and AIC

Schwartz Dallara and Kroo, AIAA 2011 265

Cranfield study of truss braced wing

Cranfield study of truss braced wing

NASA WT study of transonic truss braced wing (ttbw)

The conflict between environmental and commercial goals

- Flying slower
  - Increases block time
  - Reduces aircraft utilisation
  - Reduces return on investment
  - Requires increase in fleet for given route structure
  - Requires increase in aircrew numbers for given route structure
  - Requires increase in investment for given route structure.
  - Increases Direct Operating Cost

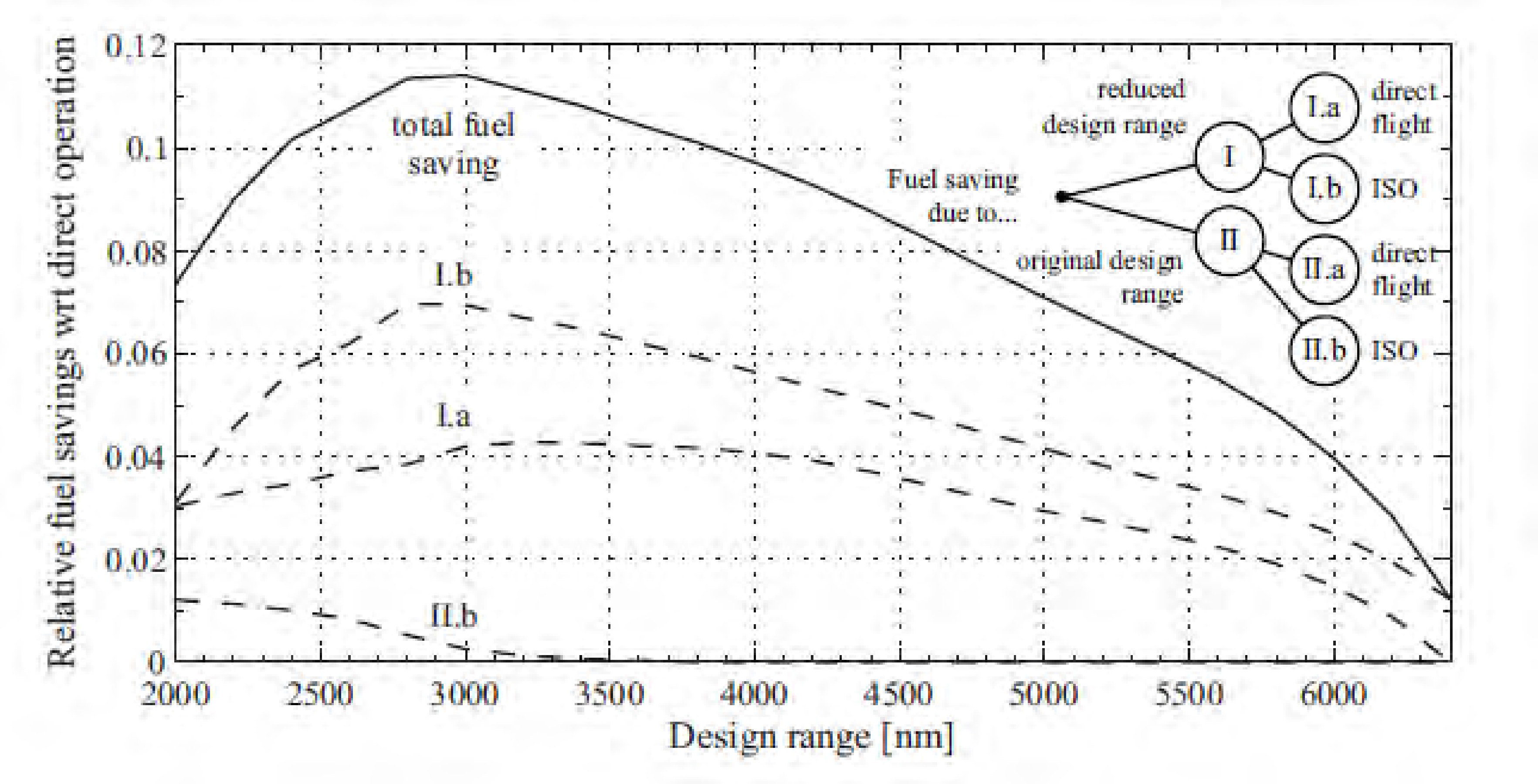
- Only a large increase in fuel and carbon prices will reduce the cruise Mach number of the minimum DOC design to bring it closer to that of the design with minimum fuel burn per RPK

- Regulation is the other mechanism by which cruise Mach numbers might be reduced. On recent evidence, the chance of that happening in the foreseeable future appears to be approximately zero

Importance of design range

- Most fuel efficient design range with today's technology and kerosine fuel is around 5,000km
- GBD report of 2001 proposed long-distance travel using medium-range aircraft with one or more intermediate stops (ISO)
- Several engineering studies of ISO using existing long-range aircraft redesigned for medium range support this
- GBD reports of 2001 and 2004 recommended full system study of ISO

Effect of design range on fuel burn per tonne-km



Substitution of new aircraft flying direct or intermediate stop operations (ISO) on all A330 and B777 routes flown in 2010

From Linke et al, AIAA-ATIO, 2011

Obstacles to ISO

- Despite fuel savings and improved bottom line, airlines do not want ISO – primarily because of expected passenger resistance, particularly from first and business class passengers who provide much of the airlines’ profit.
- There has been no medium range aircraft suitable for ISO
- A321LR, entering service in 2019, has a range of 4,000 nm, ideal for ISO
- Perhaps a low cost operator with start ISO with the A321LR?

Final messages

- The technologies highlighted in the July 2005 Greener by Design report are all still being pursued and all hold promise.
- Their entry into service will be later than envisaged in the November 2005 paper and therefore the projected reductions in climate impact will be less than suggested in 2005
- The long term prospects for substantially reducing the climate impact of NO_X and contrail-cirrus are good; they require the introduction of low NO_X combustor technology, the development of contrail avoidance by ATM, agreement on a climate impact metric for NCE and the introduction of appropriate regulation
- Reduction in NCE, together with reduced fuel burn and significant use of biofuel, is likely to reduce aviation climate impact per RPK in 2050 by a factor of 3 or 4 relative to 2000
- HOWEVER, design is as important as technology. Shifting aircraft design towards minimum fuel burn rather than minimum DOC appears a formidable challenge at today's fuel and carbon prices. Given the long production and service lives of current aircraft, and with little prospect of any radically new design entering service in the next decade, the outlook for reducing gross CO_2 emissions per RPK by a factor of three between 2000 and 2050 is not so bright

Thank you for your attention