CO_2: the ICAO Metric, the ICAO Standard and the future outlook

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Greener by Design

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Headings

- The ICAO CO_2 metric system agreed at CAEP/9 in February 2013
- The ICAO CO_2 Standard for new aircraft agreed at CAEP/10 in February 2016
- The ICAO proposed global market-based measures (GMBM) scheme
- The future outlook for aviation climate impact, particularly CO_2 emissions, gross and net, and the challenges to the manufacturers, operators and regulators

ICAO Cir 337

- CAEP/9-agreed certification requirement for the Aeroplane CO_2 Emissions Standard, ICAO Cir 337, AT/192, 2013
  - Applies only to fuel efficiency of basic aircraft
  - Operational issues – seating layout and operating range, both of which have an important effect on aircraft fuel efficiency – are not included

- CAEP/9-agreed certification requirement for the Aeroplane CO_2 Emissions Standard: a comment on ICAO Cir 337,

  J E Green and J A Jupp

  The Aeronautical Journal, April 2016, pp693-723

ICAO ambitions: resolution at 37th Assembly, October 2010

That States and relevant organisations will work through ICAO to achieve a global annual average fuel efficiency improvement of 2 per cent until 2020 and an aspirational global fuel efficiency improvement rate of 2 per cent per annum from 2021 to 2050, ***calculated on the basis of volume of fuel used per revenue tonne kilometre performed***

The CAEP/9 metric does not measure this

The CAEP/10 Standard does not limit this

After 6 years of work, a disappointing result

ICAO metric - the argument

- The ICAO metric value MV for fuel burn in mid-cruise is given by a formula for which no explanation or justification is offered in Cir 337 and for which no scientific rationale is apparent. It does not measure "rate of fuel burn per revenue tonne kilometre performed" as called for by ICAO.
- We argue that the metric should be the trip fuel used per revenue tonne kilometre, as given by the Breguet range equation

- The ICAO CO_2 standard is defined by lines of MV plotted against MTOM
- We argue that MTOM is not an appropriate parameter. The most appropriate quantity against which to correlate trip fuel per revenue tonne kilometre is design range.

- Cir 337 specifies the measurement of only two quantities to determine the ICAO MV, specific air range SAR and reference geometric factor, RGF. These two quantities, together with the certificated values of MTOM and MZFM, are sufficient define trip fuel economy and design range

Basis of the Breguet range equation

Rate of work production by engine

= fuel mass flow rate x calorific value x prop efficiency

= $m_f \times (LCV/g) \times \eta$

=rate of doing work against drag

= engine thrust x flight velocity

= aircraft drag x flight velocity (in steady flight)

= aircraft weight/(L/D) x flight velocity

whence

Fuel flow rate/flight velocity = 1/specific air range

= aircraft weight/$((LCV/g)\eta L/D)$ kg/km

Key parameter and key identity

Range parameter

$$X = \frac{LCV}{g} \eta \frac{L}{D} \quad \text{km}$$

Key identity

$$\frac{1}{SAR} = \frac{GM}{X} \quad \text{kg/km}$$

Cir 337 requires SAR to be measured at a specific gross mass, enabling the range parameter X and, thereby, the product $\eta L/D$ to be determined

The basic Breguet range equation

Aircraft gross mass is the sum of the operating empty mass, the payload mass and fuel mass, i.e.

$$GM = OEM + PM + FM = GM_1 \quad \text{at start of cruise}$$

Now $$\frac{1}{SAR} = -\frac{dFM}{dS} = \frac{GM}{X} = \frac{OEM + PM + FM}{X} \quad , \quad \text{whence}$$

$$\frac{dS}{X} = -\frac{dFM}{OEM + PM + FM} \quad \text{which, for } X \text{ constant, integrates}$$

over a range R to give a logarithmic expression from which we obtain

$$\Delta FM_{cruise} = -GM_1\left(1 - \exp\left(-\frac{R}{X}\right)\right) \; ,$$

an exact statement of the physics for flight at constant X over a range R

Fuel Burn per unit payload-range

Trip fuel $TFM = FM_{cruise} + \varepsilon TOM$ ("lost" fuel for climb, etc) and

$$GM_1 = (1-\varepsilon)TOM$$

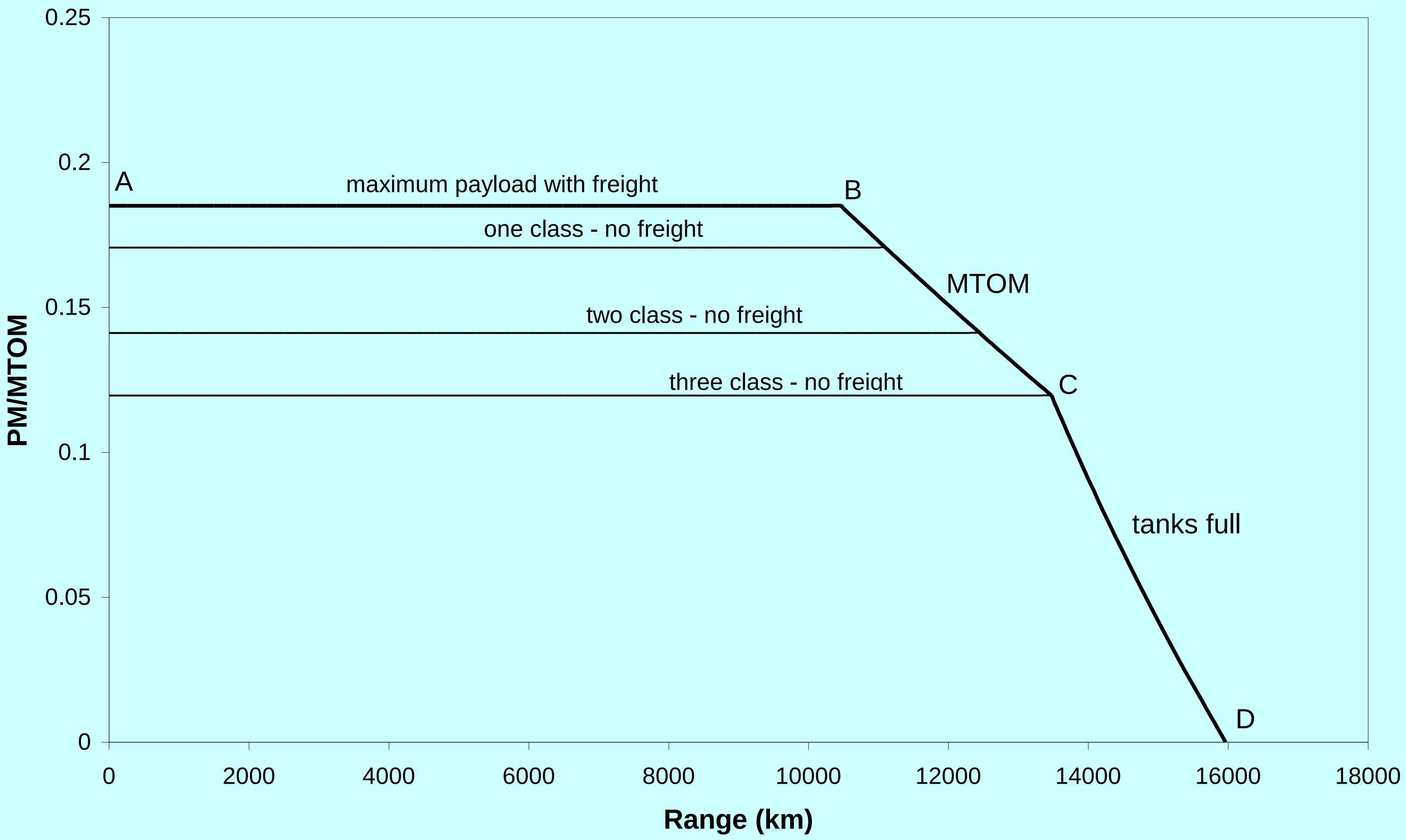
At take off, total fuel = trip fuel + reserve fuel $= TFM + \beta TOM$

then, adopting as engineering approximations values of 0.015 for *ε* and 0.046 for *β*, we can obtain:

$$\frac{1}{R}\frac{TFM}{PM} = \frac{1}{X}\left(1+\frac{OEM}{PM}\right)\frac{1.015-\exp\left(-R/X\right)}{\left(\exp\left(-R/X\right)-0.046\right)\left(R/X\right)}$$

not an exact statement, but an accurate expression for aircraft flown in cruise-climb mode in still air on a great circle route. This is what the 37th ICAO Assembly called for.

Payload-range diagram



Payload-range diagram for typical wide-body airliner

Design range

The ICAO Independent Experts proposed point B on the payload range diagram, with the aircraft flown at its optimum value of X, as its design range.

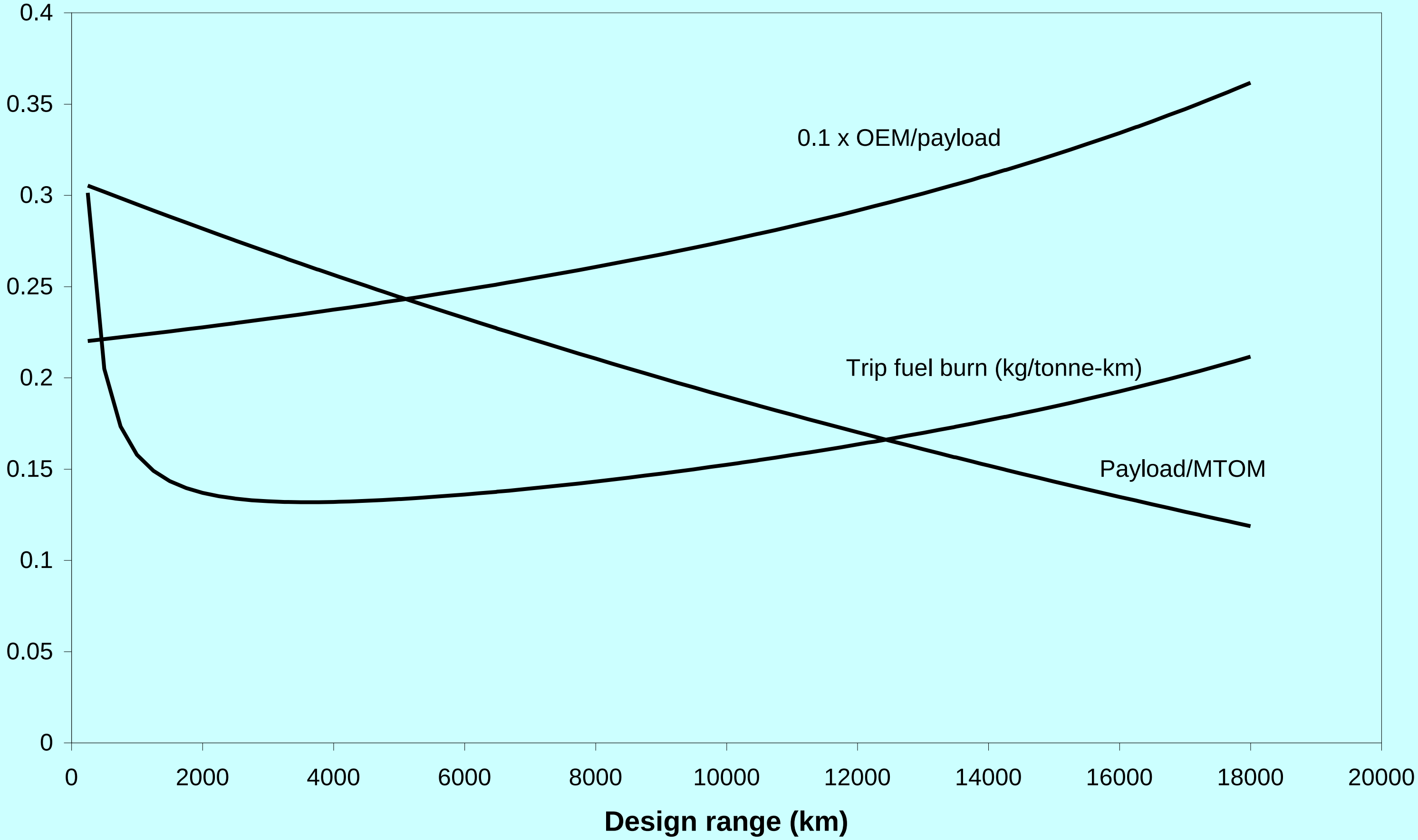
This can be derived from the Breguet range equation as

$$R_{des} = X \ln\left(\frac{(1-\varepsilon)MTOM}{MZFM + \beta_{\min} MTOM} \right) = X \ln\left(\frac{0.985MTOM}{MZFM + 0.046MTOM} \right)$$

where $MTOM$ and $MZFM$ are the certificated maximum values of take-off mass and zero-fuel mass.

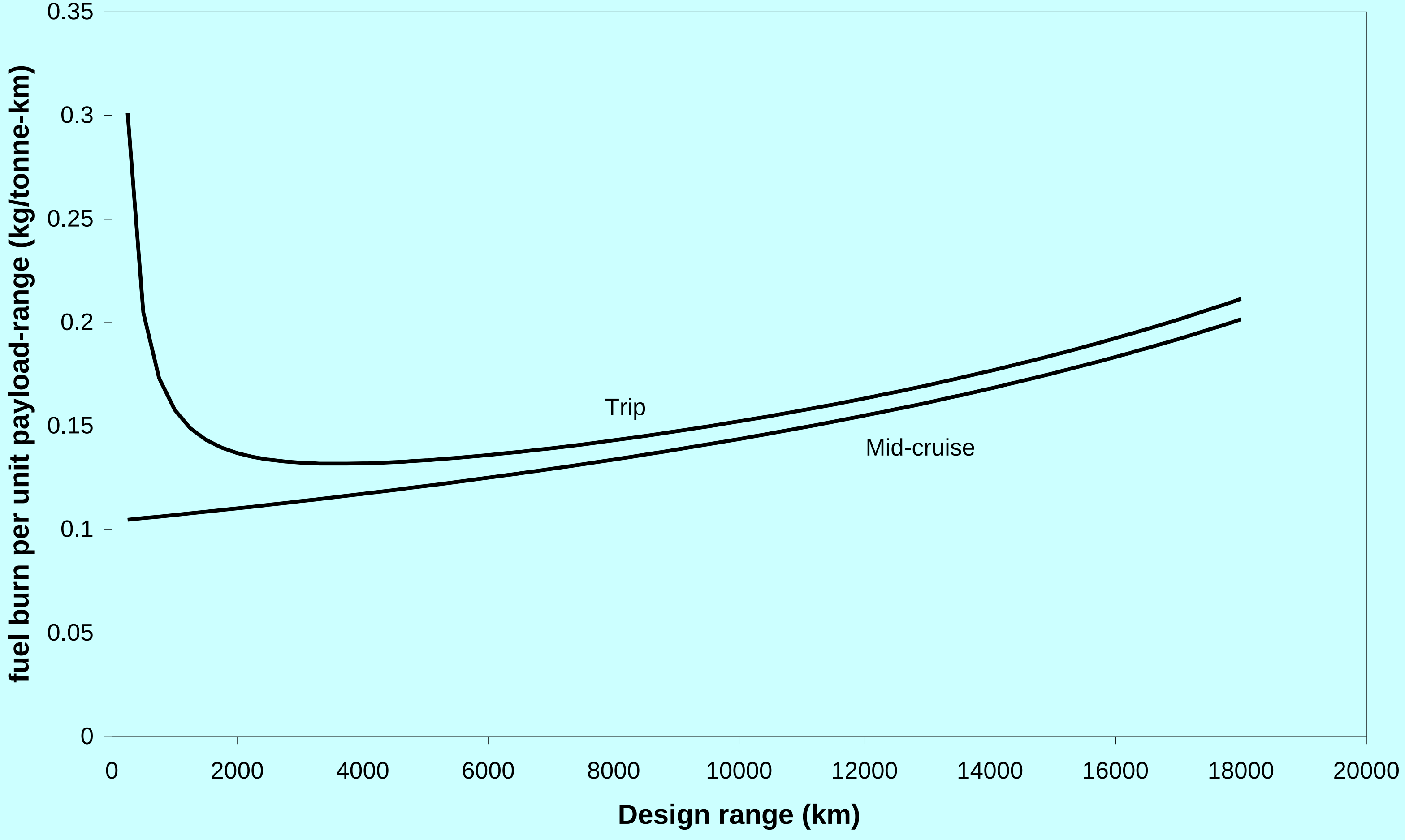
With X obtained from SAR measured at a specified GM as specified in Cir 337, design range – point B – can be determined unambiguously

Influence of design range on key parameters



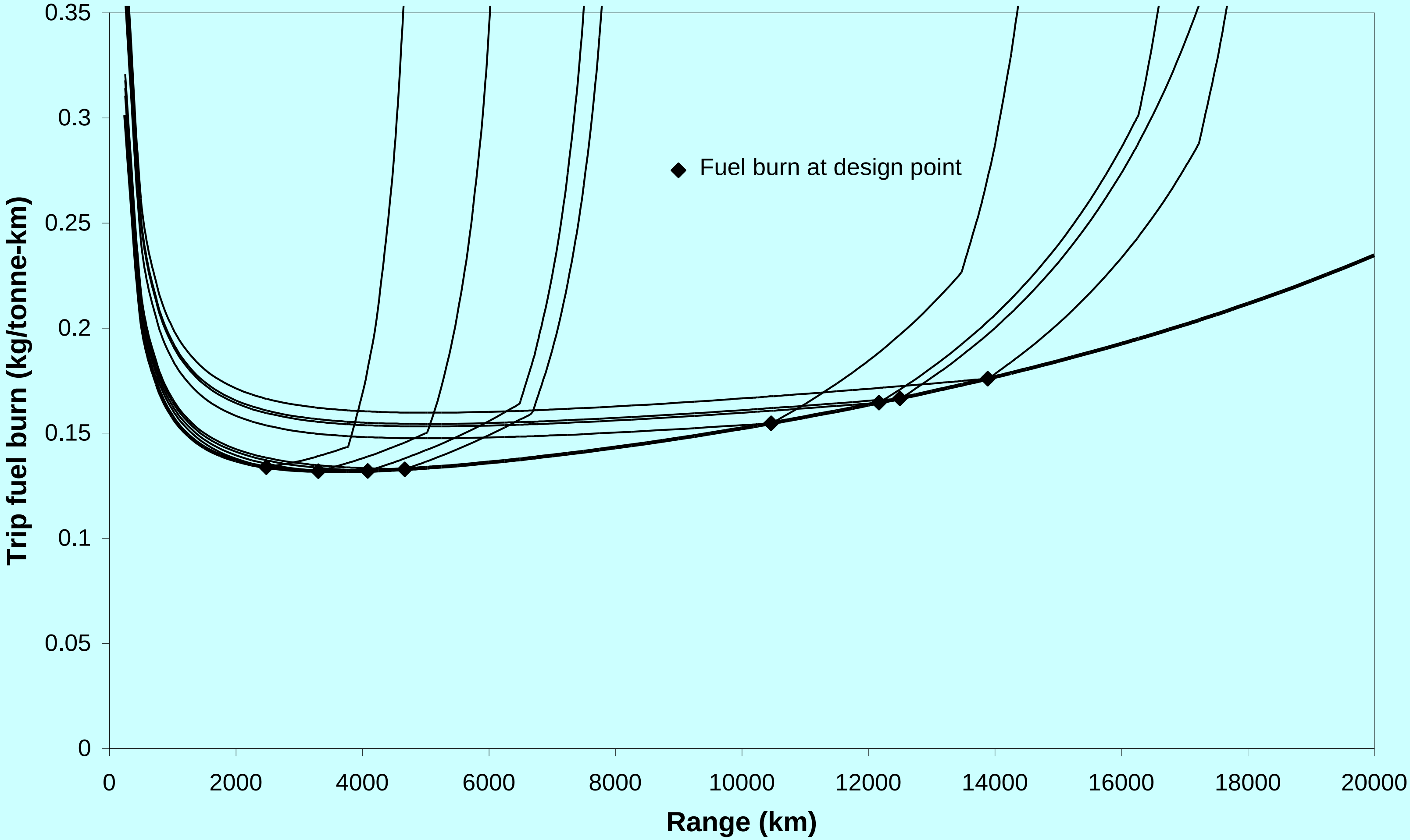
Variation of key parameters with design range when X is constant

Fuel burn per unit payload range



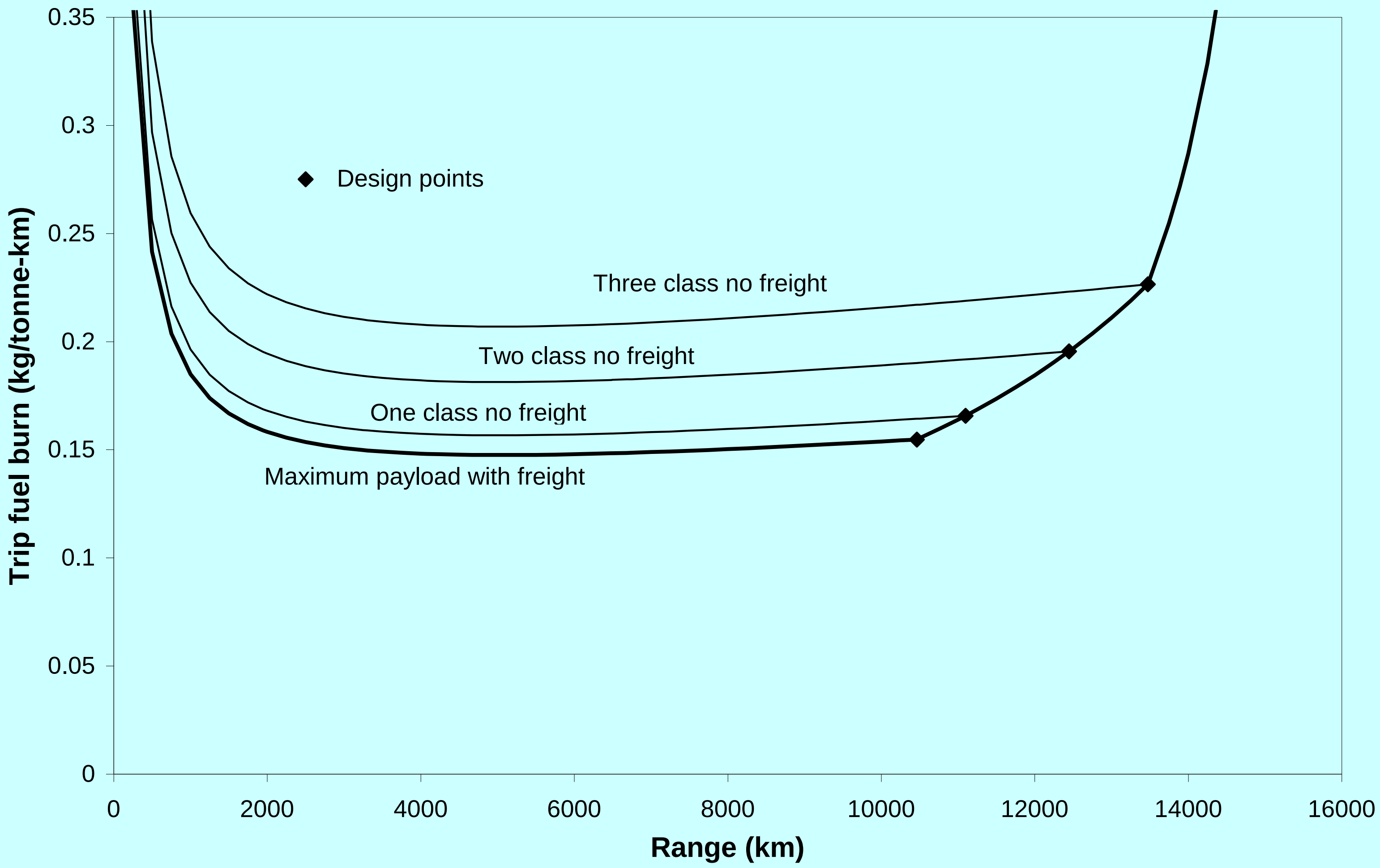
Variation of trip and mid-cruise fuel burn with design range (X constant)

Effect of range on trip fuel efficiency



Variation of trip fuel with range for eight characteristic aircraft (X constant)

Effect of cabin layout on trip fuel efficiency



Typical variation with seating layout of trip fuel per unit payload-range

The ICAO Cir 337 CO_2 metric – reference masses

Cir 337 specifies three reference masses at which SAR is to be measured:

(a) high gross mass = 92% $MTOM$

(b) mid gross mass = average of high and low gross mass

(c) low gross mass = $\left(0.45 \times MTOM\right) + \left(0.63 \times MTOM^{0.924}\right)$

The equation for the metric the average involves $(1/SAR)_{AVG}$ of the values of $1/SAR$ at these three masses.

Since SAR is to be measured at the optimal flight condition, which will be at the same, optimal value of X at all three masses, it follows from the identity relating GM and X to SAR that

$$\frac{1}{SAR_{AVG}} = \frac{1}{X}\left(0.685MTOM + 0.315MTOM^{0.924}\right)$$

Cir 337 reference geometric factor

Cir 337 introduces a Reference Geometric Factor (RGF) which is the cabin floor area, in square metres, determined by rules set out in the circular.

In fact, as Poll has shown, cabin floor area is proportional to the maximum single-class passenger payload across the full range of civil aircraft. For current aircraft, maximum payload is fairly well approximated by

Maximum payload = $0.2RGF$ tonnes

Cir 337 makes no reference to payload and the justification for the introduction of RGF obscures the important fact that it is a surrogate for payload. For a given MTOM, the metric as it stands does nothing to promote more efficient structural design

The Cir 337 metric formula

“The metric shall be defined in terms of $(1/SAR)_{AVG}/RGF^{0.24}$ where $(1/SAR)_{AVG}$ is the average of the 1/SAR values established at each of the three reference masses defined in 2.3”. This has been termed the metric value MV.

Cir 337 offers no derivation or explanation of this formula. It has the units kg/km/m$^{0.48}$ and it is difficult to see any scientific justification for it.

If the exponent 0.24 was removed from RGF, the resulting expression divided by 0.2 (typical floor loading in tonne/metre^2) would give

$$MV = (1/SAR)_{AVG}/(0.2RGF) \text{ kg/tonne-km,}$$

the measure of fuel efficiency called for at the 37th ICAO Assembly in 2010.

Key aircraft design parameters

Only three parameters determine fuel burn per unit payload range:

(a) Range parameter X, the product of the fuel calorific value, which is fixed, and the combined aerodynamic-propulsive efficiency $\eta L/D$

(b) The ratio OEM/PM

(c) Operating range R

The ratio OEM/PM is strongly dependent on design range. The range parameter is also, but less strongly, dependent on design range.

The overall aircraft design is then determined by the combination of design range, maximum payload and the aerodynamic, propulsion and structural efficiencies. These together determine the maximum take-off mass $MTOM$. This is a dependent quantity. Design range and payload are the determining parameters.

$MTOM$ as design parameter

From ICAO Cir 337, "The overall design of the aircraft is represented in the CO_2 metric system by the certified $MTOM$. This accounts for the majority of aircraft design features which allow an aircraft to meet its market demand."

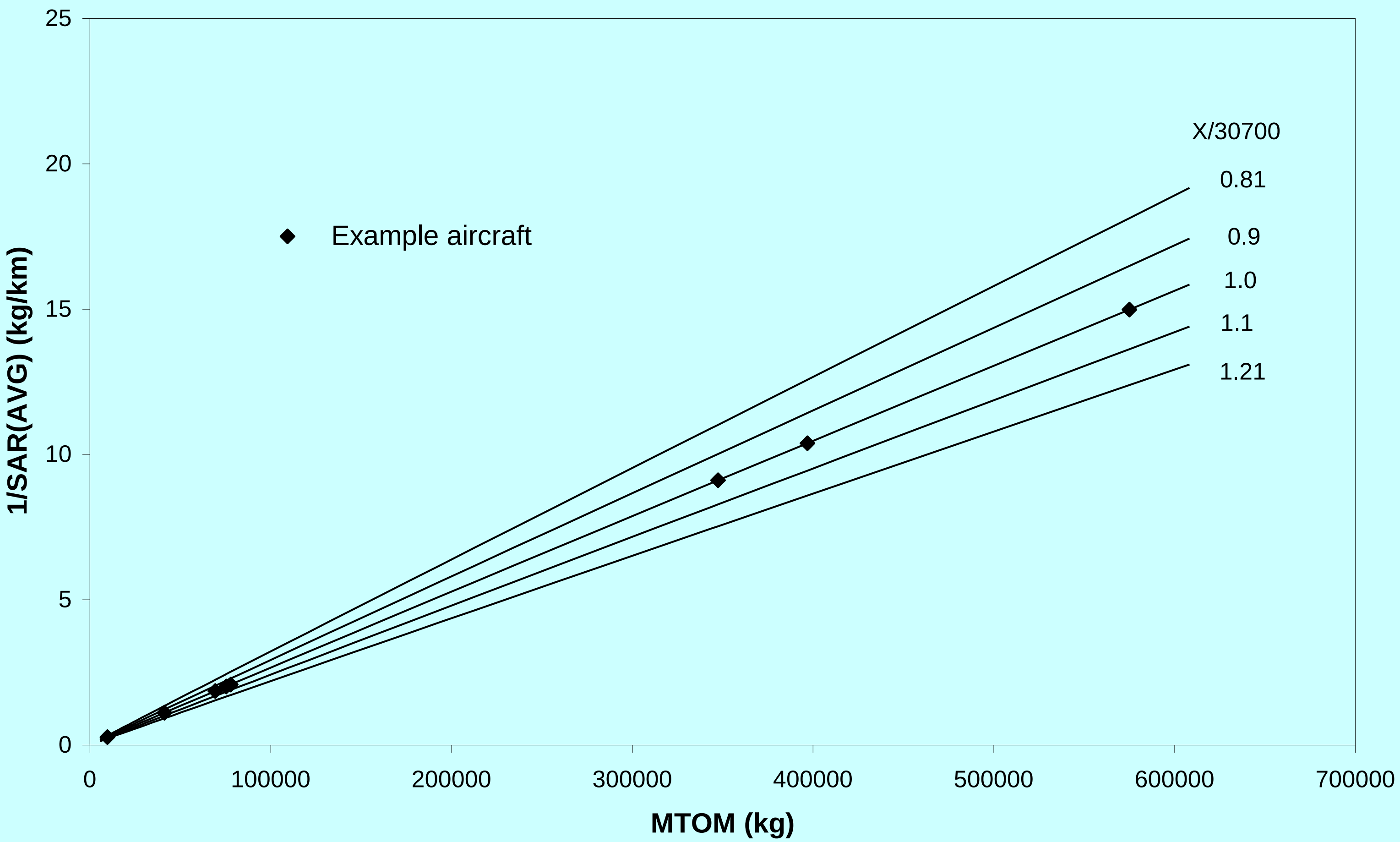
In reality, it is the combination of design range and payload that does this.

If $(1/SAR)_{AVG}$ is determined from the average of the measurements at the three reference masses, as specified in Cir 337, then

$$\frac{1}{SAR_{AVG}} = \frac{1}{X}\left(0.685MTOM + 0.315MTOM^{0.924}\right)$$

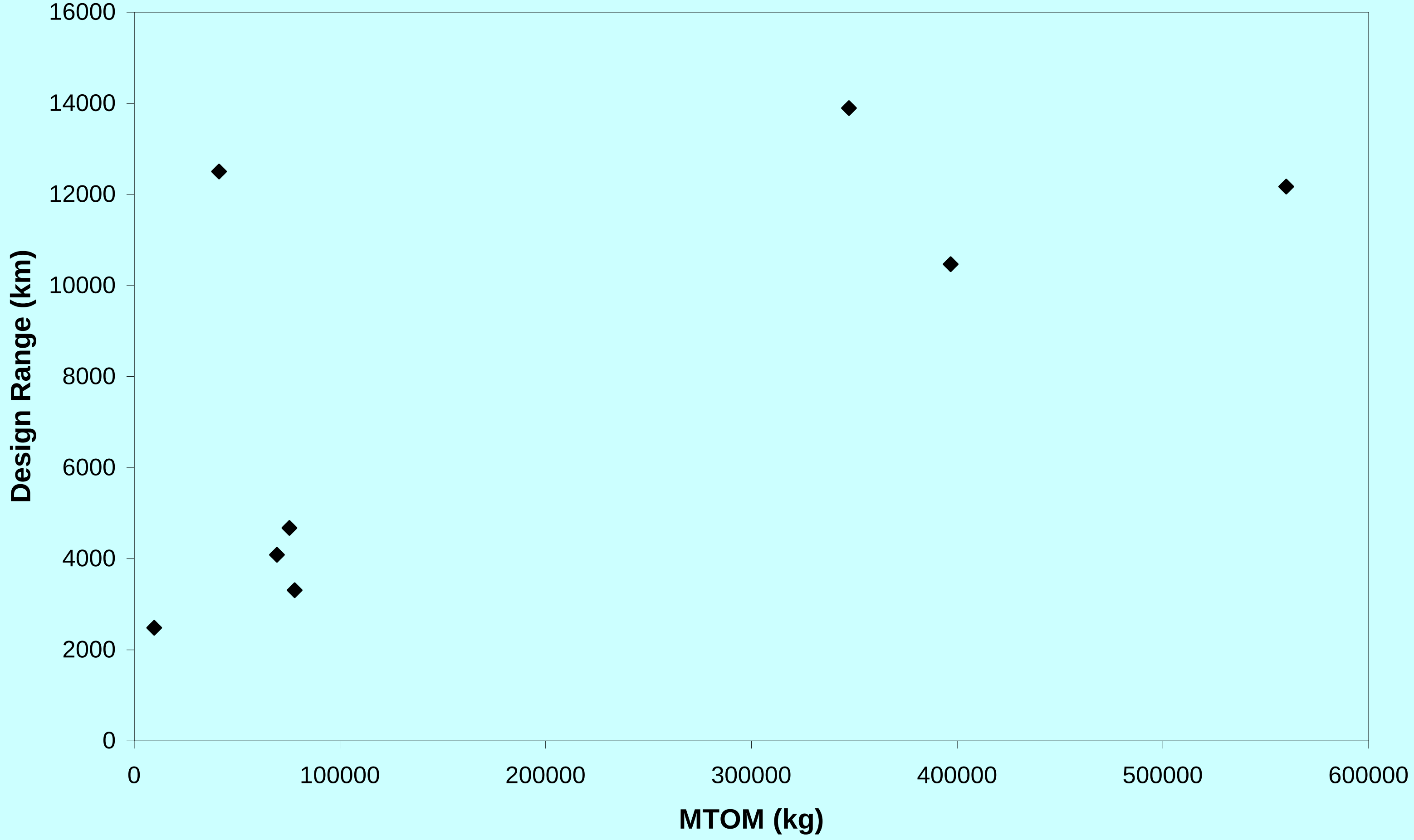
is an identity from which the combined aerodynamic-propulsion efficiency $\eta L/D$ can be determined. This is not payload-fuel efficiency.

SAR and MTOM



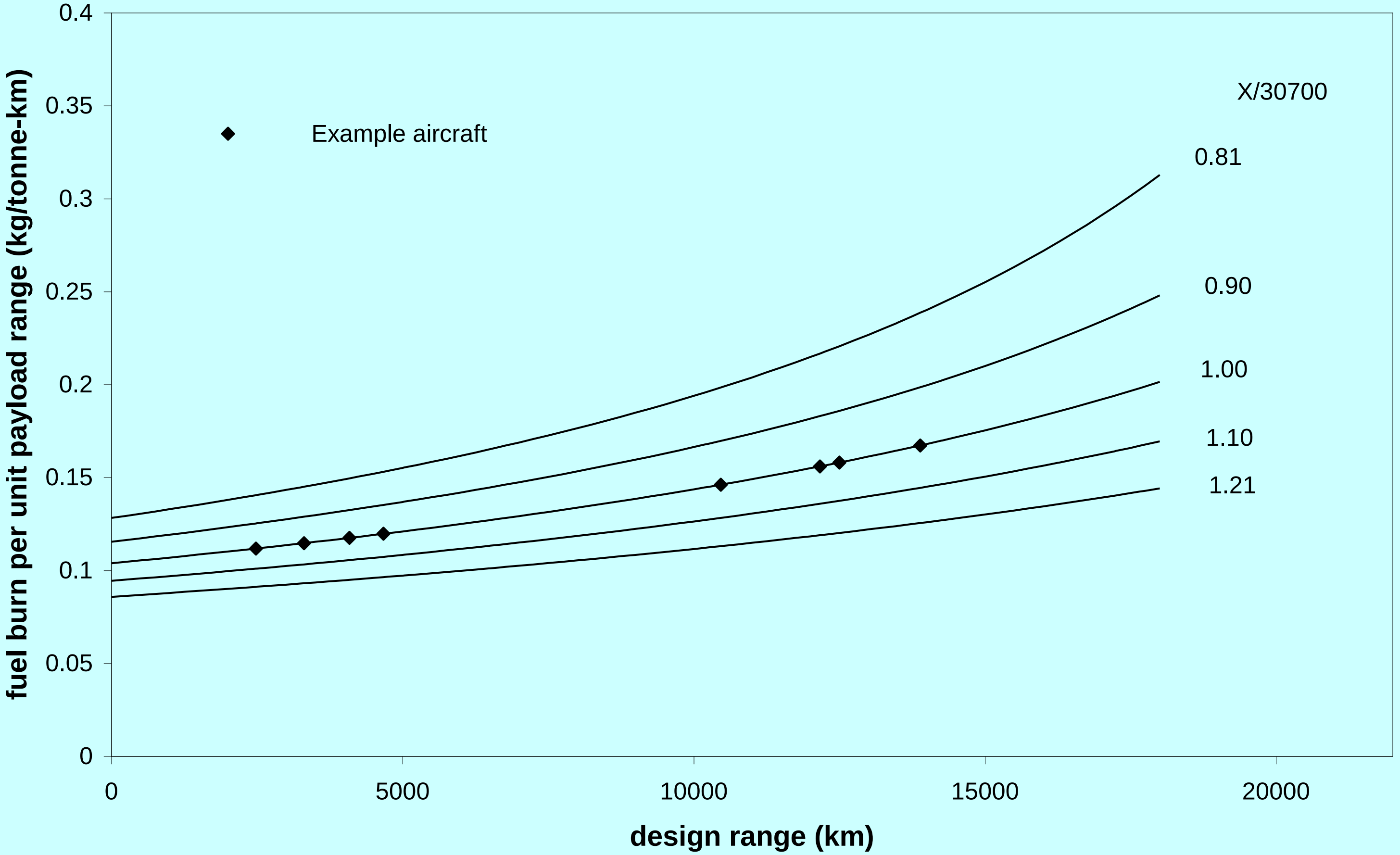
Variation of fuel burn with MTOM and X

Design range and MTOM



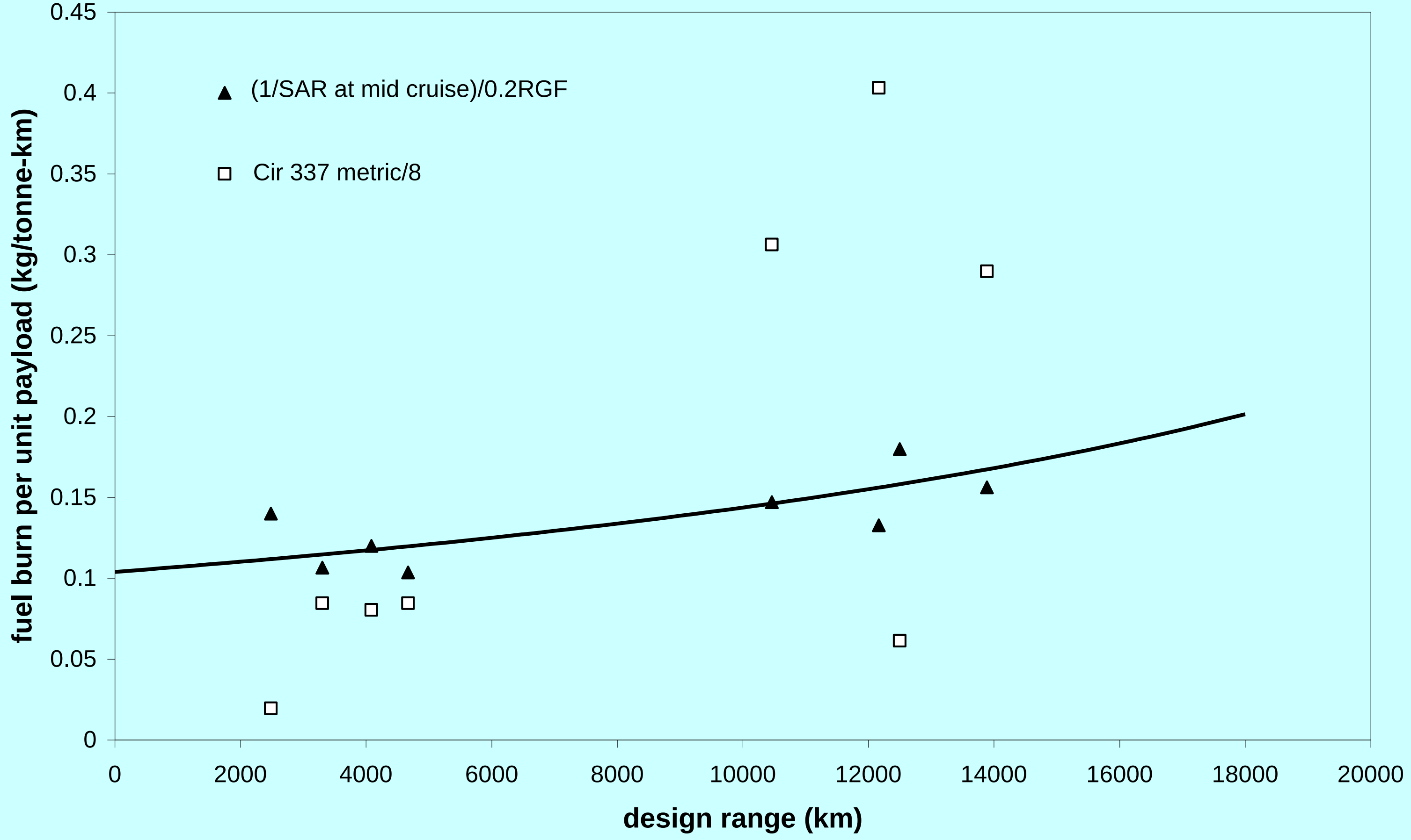
Map of design range against MTOM for eight example aircraft

Payload-fuel efficiency and design range



Variation of mid-cruise rate of fuel burn with design range and X

Cir 337 metric and suggested alternative



Fuel burn per tonne-kilometre at mid-cruise

Cir 337 conclusions

- The two key parameters proposed in Cir 337, SAR and RGF, measured following the procedures set out in the circular, enable fuel efficiency in mid-cruise to be determined in kg/tonne-km, as called for in 2010 at the 37th ICAO Assembly
- Used with the certificated values of $MTOM$ and $MZFM$ they would enable trip fuel mass to be determined as a function of design range – an expression of flight physics
- The metric in the form proposed by CAEP/9, with RGF raised to the power 0.24 rather than unity, and plotted against $MTOM$ rather than design range, has no real basis in flight physics and its fitness for purpose is questionable

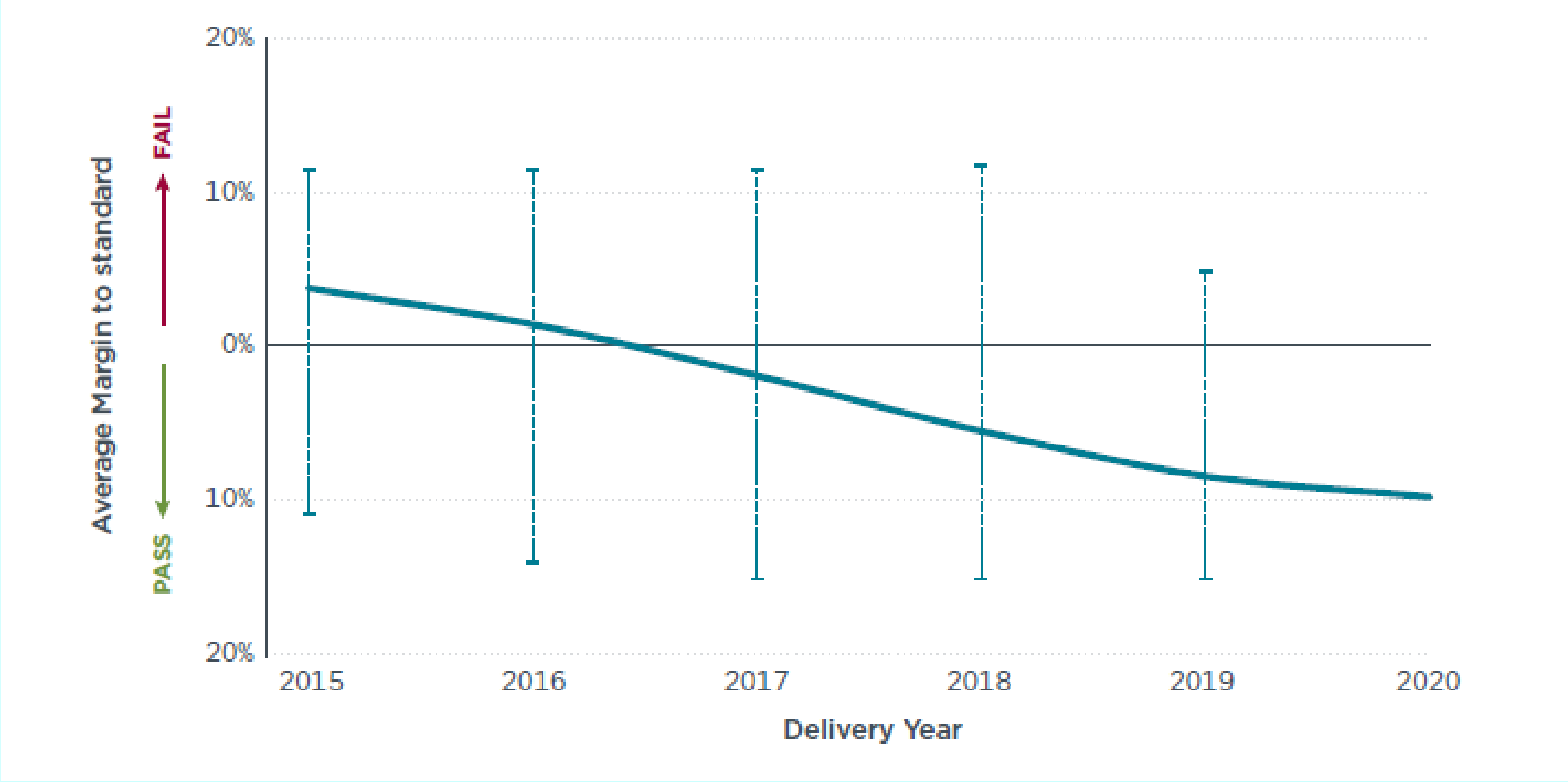
The CAEP/10 ICAO CO_2 Standard

- No published detail from CAEP/10 yet: information here taken from International Council on Clean Transportation (icct) Policy Update , February 2016 (www.theicct.org)
- "The first standard ever to impose binding energy efficiency and CO_2 reduction targets for the aviation sector"
- To be ratified by the ICAO Council (36 member states) in June 2016
- To be endorsed by the ICAO Assembly in October 2016
- The standard then has to be implemented by individual contracting states (or countries) under domestic legislation
- Countries that have certifying bodies (e.g. FAA in the US and EASA in Europe) may adopt this standard or impose tighter restrictions on CO_2 emissions from aircraft if the standard is deemed to be insufficient

The CAEP/10 ICAO CO_2 Standard

- Standard MV set as a plateau for aircraft with $MTOM$ less than 60 tonnes and as two rising lines of MV against $MTOM$, one for "New Type" (NT) and a less exacting one for "In-Production" (InP)
- NT aircraft are those which enter the type certification process after January 2020 (commercial jets) and January 2023 (bizjets) with expected entry into service around 2024 and 2027 respectively. No new aircraft that does not meet the NT MV will be certificated after 2020.
- InP aircraft, which are variants of types that already have a type certificate in 2020, will be required to meet the InP MV by 2028 with a transitional period for modified aircraft starting in 2023
- The icct analysis suggests that the standards will on average require a 4% reduction in the cruise fuel consumption of new aircraft starting in 2028 compared to 2015 deliveries (actual reductions ranging from 0 to 11% depending on $MTOM$)

icct projected margins on standard



Projected average commercial aircraft MV by delivery year 2015 to 2020, aircraft greater than 60 tonnes *MTOM*

ICAO CO_2 Standard

- GOOD: first ever to impose binding energy efficiency and CO_2 reduction targets for the aviation sector

- NOT SO GOOD:
  - metric not based on sound flight science and does not promote more efficient structural design
  - CAEP/10 standard not a significant constraint on future aircraft designs; not likely to achieve faster reductions than “business as usual”

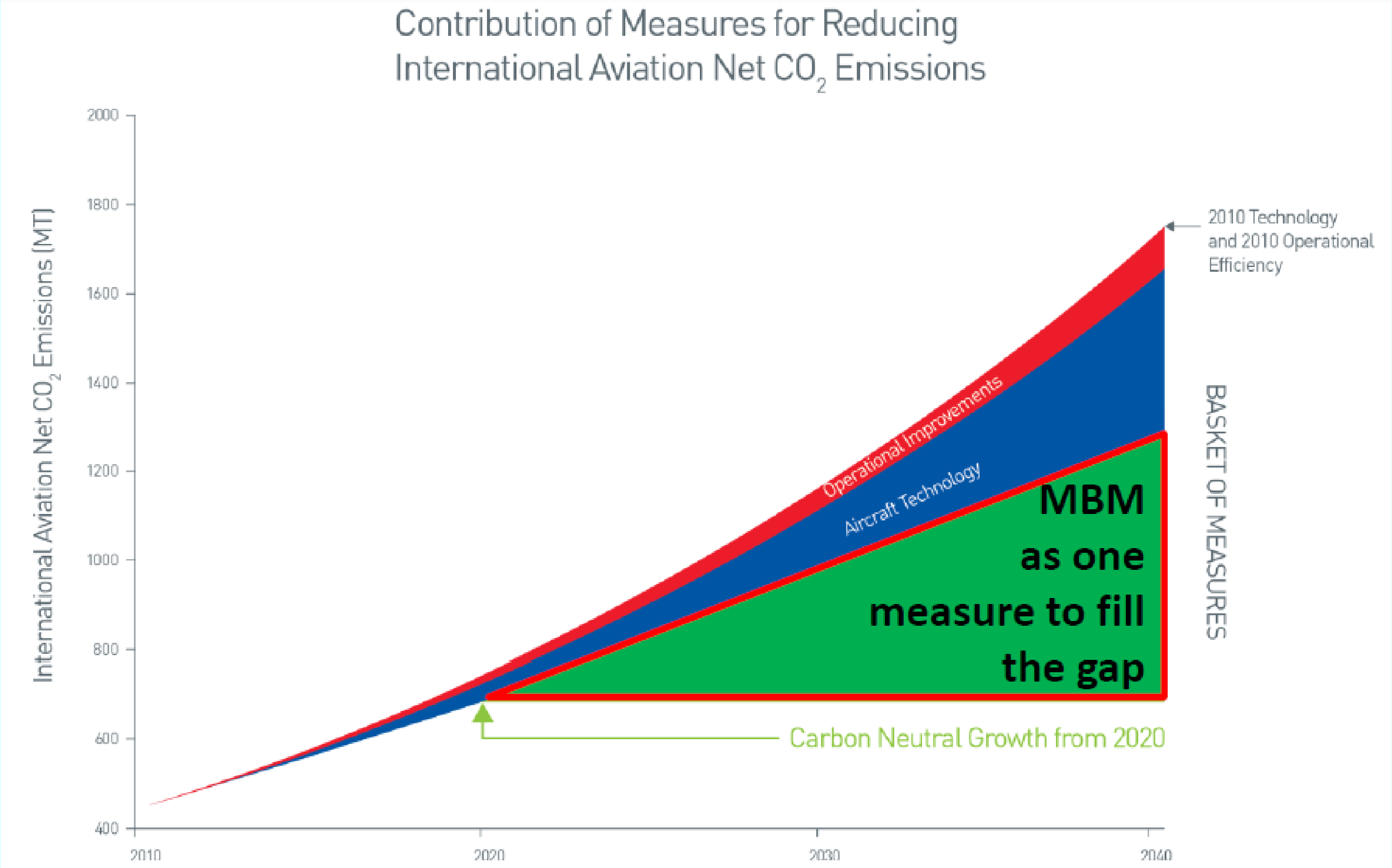
- NOT ADDRESSED
  - operational issues – load factor, cabin layout and operations beyond design range – which have greater impact on fuel economy per unit payload basic aircraft design

ICAO proposed GMBM

- “Carbon-neutral growth by 2020” was proposed as an aim by IATA in 2009 and adopted at the 37th ICAO Assembly in 2010 as an “aspirational goal” with the acronym CNG2020
- At its 38th Assembly in 2013 ICAO resolved to develop a global market-based measures (GMBM) scheme. This has now been formulated as the COSIA (Carbon Offsetting Scheme for International Aviation)
- COSIA will require airline operators to pay for CO_2 reductions in other sectors to hold the net rate of CO_2 emission from aviation at its 2020 level

- ICAO sees a GMBM scheme as a “temporary instrument”, complementary to the other elements (aircraft technologies, operational improvements, sustainable alternative fuels) in the “basket of measures” aimed at its CNG2020 aspirational goal.
- Its preference is for the other measures in the basket, but accepts that CO_2 emissions from aviation will continue to rise beyond 2020 and a GMBM is the only way of holding down net emissions

COSIA CNG2020 target



Emissions gap to be closed by further advances in technology, bio-fuels and carbon trading

ICAO chart

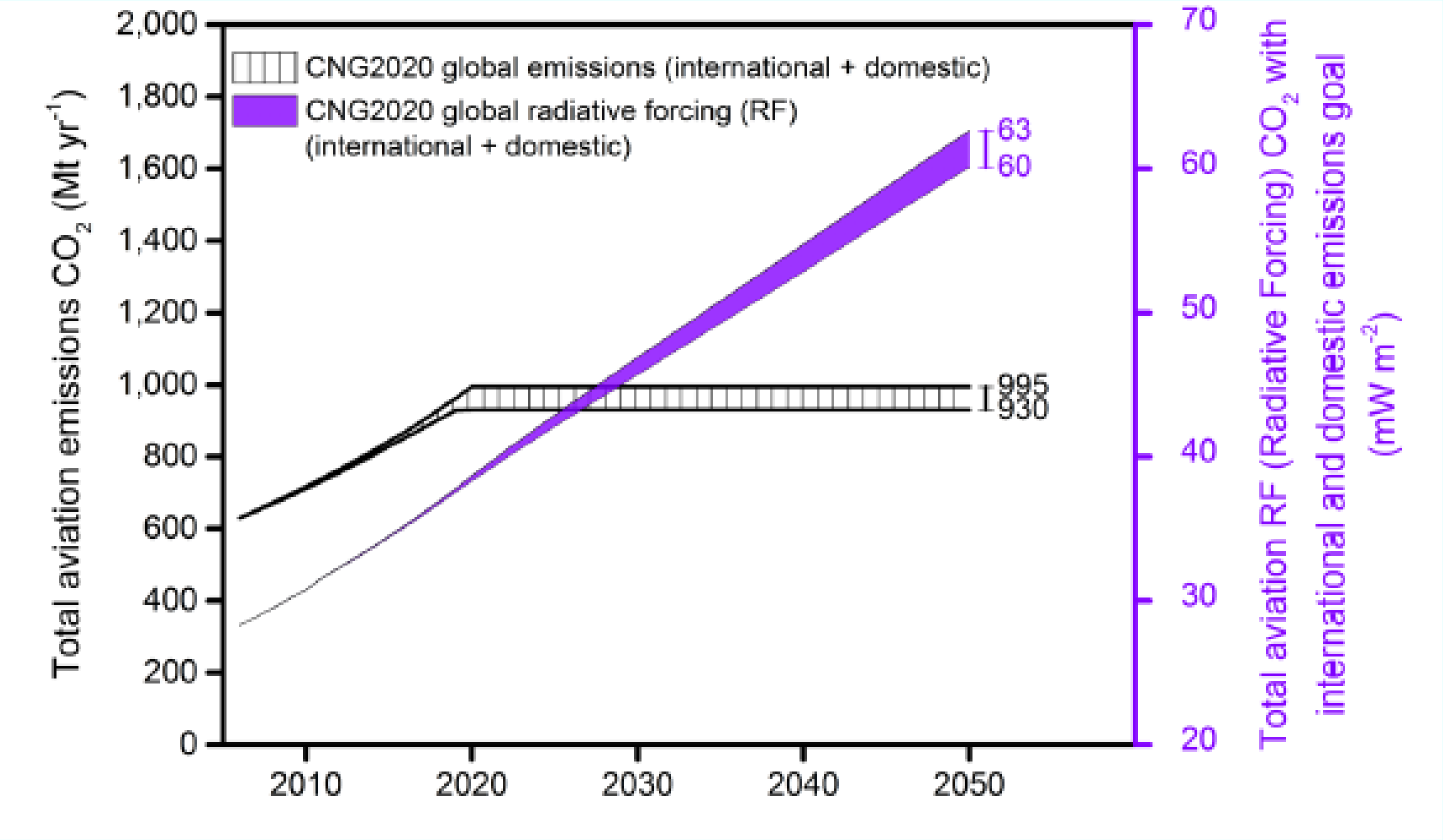
ICAO proposed GMBM

- Pilot implementation and testing 1 Jan 2018
- Full first phase implementation 1 Jan 2020 for all “high income” states, capturing 80% of international travel
- Second phase implementation 1 January 2025 to include “upper-middle income” states, capturing 95% of international travel

- Review progress every 3 years, starting 2022
- In 2032, special review to determine whether to terminate or continue beyond 2035

- High Level Meeting to agree draft resolution, 11 to 13 May 2016
- Review by ICAO Council in June, adoption by 39th Assembly September-October

CNG2020 is not good enough



With aviation net CO_2 capped from 2020 onwards, radiative forcing from aviation CO_2 will increase by 2050 to three times its level today and will be rising steadily

Lee et al MMU CATE report

So where do we go from here? Non-CO_2 impacts

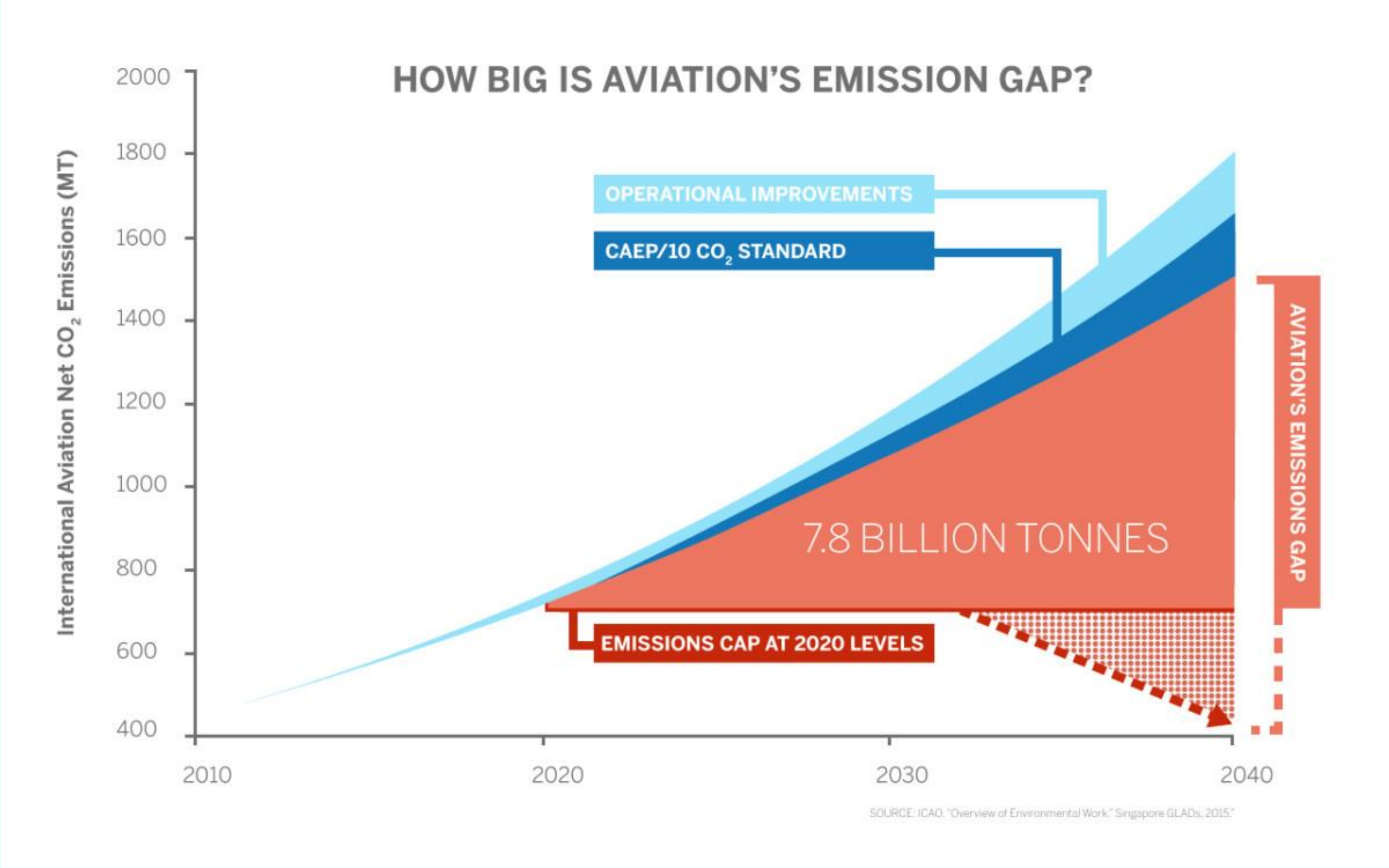
- Contrails and contrail-cirrus: tactical flight path changes to manage climate impact: potentially important mitigator
  - Involves increases in CO_2 emission, fuel burn and costs and may disrupt schedules. Time now ripe for in-depth study of ATM and operational practicalities. Will eventually require action by regulators
- NO_X at altitude
  - Reduction at source by adoption of low NO_X combustors
  - Reduction at source by reducing engine OAP to trade NO_X for fuel burn and CO_2
  - Reduction of climate impact by reducing cruise altitude of future designs
  - Action by regulators needed
- Further scientific study needed

So where do we go from here? Fuel burn and gross CO_2 emissions

- Medium term
  - Tube, swept wing, turbofan, nothing radical, today's designs with more advanced technology, fuel includes some proportion of sustainable alternative fuel. How much improvement by 2030 EIS?
- Mid-long term
  - Laminar flow control on wings
  - Contra props
  - Novel configurations (eg HWB, TTBW) and hybrid turbo-electric propulsion. Increased proportion of sustainable alternative fuel.
  - Novel configurations EIS when??
- Obstacles
  - Airline and manufacturers business models
  - Uncertain fuel price (12.5 - 140 $/bbl) and very weak carbon price (0.84$/bbl equiv on 12 May 2016)

Net CO_2 - how to improve on CNG2020?

- At some future date – say 2032 – set aviation net CO_2 to be reduced by GMGM to zero by, say, 2050
- This would stabilise RF from aviation CO_2 at around 55 mWm^{-2} compared with around 33mWm^{-2} currently – only a 67% increase!



ICAO chart adapted by Transport & Environment

What else can regulators do?

- Take action to bear down on the non-CO_2 contributors to climate change by
  - regulating to reduce NO_X emissions in cruise through the introduction of state of the art low NO_X combustors
  - reducing contrail cirrus by introducing contrail control into ATM regimes
- Take action to bear down on gross CO_2 emissions by
  - reformulating the CO_2 Standard around a soundly based metric, derived from the Breguet range equation with design range as the independent variable
  - re-setting the targets to force faster fuel burn reduction than "business as usual"
  - requiring aviation fuel to include an increasing proportion of sustainable alternative fuel
  - promoting fleet renewal by forcing withdrawal of older aircraft
  - regulating to promote greater operational efficiency (load factor, seating, operating range)
  - regulating to promote design for min climate impact rather than min DOC
- How much of this likely, and in what timescale???