The Optimum Aeroplane and Beyond

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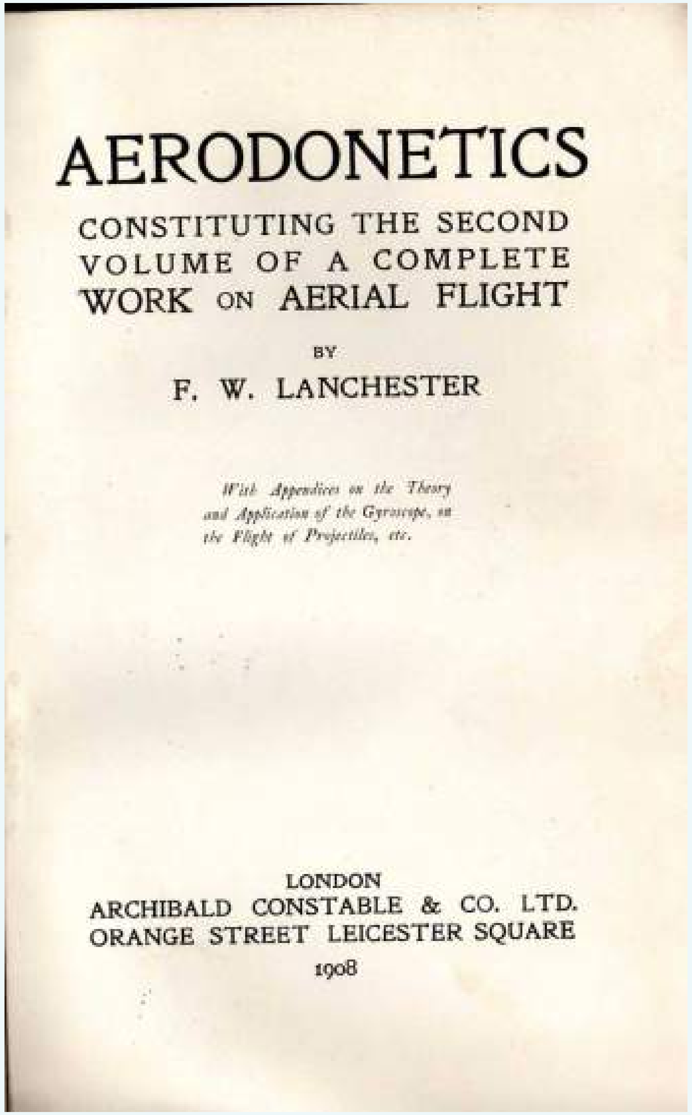
Royal Aeronautical Society, Hamburg Branch, 23rd April 2009

One hundred years of British Aviation 1908-2008

Samuel Cody 1867-1913

Alliott ("AV") Roe 1877-1958

Frederick W. Lanchester 1868-1946



AERODONETICS

CONSTITUTING THE SECOND VOLUME OF A COMPLETE WORK ON AERIAL FLIGHT

BY

F. W. LANCHESTER

With Appendices on the Theory and Application of the Gyroscope, on the Flight of Projectiles, etc.

LONDON
ARCHIBALD CONSTABLE & CO. LTD.
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1908

The Father of the Aeroplane

Sir George Cayley (1773-1857)

Why was Cayley interested in flight?

- He recognised that the industrial revolution needed transportation to bring raw materials to the factories and to take the products to market.
- He saw clearly that road, rail and sea were limited.

However, transport by air would remove many of the limitations of the other modes and would bring huge economic benefits

The Last 50 years

- Civil aviation is a major international business and has become an essential part of the world's commercial infrastructure

The reasons

- Global commerce
  - an "enabler" for wealth creation
  - access to new markets
  - speed and distance no obstacle

- Benefits to some of the poorest people in the world
  - Delicate goods to wealthy markets
  - Tourism

And

- Travel fosters
  - international understanding
  - reduces risk of conflict
  - benefits of cultural exchange

- Family and friends
  - maintains important social links

- Wider choice of holiday experiences (quality of life) for the less well off

Growth forecasts for air transport -the result of “pull” not “push”

- Passengers – 3.5 trillion seat kilometres in 1995 will increase to 12 trillion seat kilometres by 2025

- Freight - 200 billion tonne kilometers in 1995 will increase to 1.0 trillion tonne kilometers by 2025

Forcasts

- Over the next 20 years
  - 12500 aircraft replaced (47% of current fleet)
  - 16900 extra aircraft (57% growth)
  - 29400 new aircraft
    - 2510 regional jets (9%)
    - 19160 single aisle (65%)
    - 6750 twin aisle (23%)
    - 980 VLA (3%)

- In 2027 18% of the fleet will be aircraft that are in service today 82% will have been delivered new

Annual Traffic Growth (RPK)

- North America 2.8%
- Europe 3.5%
- China 8.9%
- Southeast Asia 7.8%
- North Atlantic 4.7%

World average about 5% per annum for the next 20 years

What is the target?

- In order to produce an optimum aeroplane it is necessary to know what is being optimised.

- There are several possibilities
  - Maximum payload
  - Minimum DOC
  - Minimum environmental impact

Aviation and Global Warming

- The emissions from gas turbine engines contribute to the process of global warming
- Global warming is related to climate change (precise link not entirely clear)

Emissions from kerosene burning gas turbines

- Carbon dioxide (GHG)
- Water vapour (GHG)
- Nitric oxide, Nitrogen dioxide (NOX)
- Aerosols (carbon and sulphate particulates)

How quickly are aviation emissions growing?

- This year aviation will consume about 220 million tonnes of kerosene
- The (optimistic) forecast for future growth in air transport capacity is 5% per year
- Fuel burn per aircraft decreases at about 1.5% per year as new technology aircraft enter the global fleet
- Total fuel burn could grow at 3.5% per year

Consequences

- The annual fleet fuel burn will double in 20 years
- By 2050 the annual fuel burn will be 4 times this years value
- This year the global fuel burn will be about 220 million tonnes of kerosene
- By 2050 it could be 1 billion tonnes

Carbon Dioxide

- Direct result of kerosene combustion
- EI_{co2} = kg CO2/kg fuel burned
- $EI_{co2} = 44.01/(12.01+(Y/X))$ where Y is the average number of hydrogen atoms and X the average number of carbon atoms /per "molecule" of kerosene (≈ 1.91)
- $EI_{co2} \approx 3.16$

CO_2 is such a great concern because it accumulates in the atmosphere

How serious is aviation based CO_2?

- How much air is there in the atmosphere?
  - About 5200 tera tonnes (5.2*10^15 tonnes)

- How much CO_2 is there in the atmosphere today?
  - About 3 tera tonnes

- How much extra will aviation add this year?
  - About 0.0007 tera tonnes
  - An increase of 0.023%

- By 2050 the annual fuel burn could be 1 billion tonnes of kerosene

- The amount of aviation generated CO_2 in 2050 could be 3 billion tonnes

- The total amount of CO_2 added to the atmosphere between 2008 and 2050 could be as much as 68 billion tonnes

Therefore, by 2050, aviation could increase the amount of CO_2 in the atmosphere by 2.5%

NOX

- NOX is a mixture of the various oxides of nitrogen – nitric oxide (NO), nitrogen dioxide (NO_2), nitrous oxide (N_2O)
- NO and NO_2 are toxic substances that have implications for human health
- NO reacts with O_2 to form O_3 (ozone) also undesirable
- NOX is not a greenhouse gas, but it affects the concentrations of methane and Ozone

Formation of NOX

- Produced by the combustion process
- Two forms –
  - Thermal NOX is produced by the heating of air (does not depend on the type of fuel). Production increases rapidly at temperatures above 1000ºC
  - Prompt NOX comes from a reaction of nitrogen, oxygen and hydrocarbon radicals. Fuel dependent, low temperature source.

Emission Index

- Not easy to calculate since it depends on the detailed characteristics of the combustion chamber

- EI_{NOx} = g NOX/kg fuel burned (NOTE difference in units)

- $EI_{NOx} \approx$ 14 g/kg

- The effects of NOX are short lived – a few years at most

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Omega
Aviation in a Sustainable World

Contrail formation

- Persistent contrails and high level contrail induced cirrus are a matter for concern
- Need to avoid the altitudes where the air is supersaturated with respect to ice – 33,000’ to 38000’

Economic Efficiency

One definition of system efficiency is

$$\eta_{econ} = \frac{revenue\ work\ done}{cost\ of\ energy\ used} = \frac{A}{B}\left(\frac{Mp.g.R}{MMF.LCV}\right)$$

where

- A = revenue/unit payload weight/unit distance travelled
- Mp = payload mass
- g = acceleration due to gravity
- R = the great circle distance flown
- B = the fuel cost/unit of energy released
- MMF = the mass of fuel consumed
- LCV = the fuel lower calorific value

- In the future, fuel prices are expected to rise and fuel cost to become increasingly important in direct operating cost (Cost Index → zero)

- Therefore, we want aeroplanes for which the ratio of energy liberated to revenue work done (*ETRW)*

$$ETRW = \frac{MMF.LCV}{Mp.g.R}$$

is as small as possible *i.e.* minimum fuel/ unit payload/unit distance travelled

Coefficient of Environmental Performance

A logical definition would be

$$CEP = \frac{emissions\ mass.LCV}{useful\ work\ done}$$

$$= (ETRW)(a.EI_{CO2} + b.EI_{NOX} + c.EI_{H2O} + d.EI_{SOX} + ...)$$

where *a,b,c,d,* etc and the *EI*s depend upon the fuel being used and the engine technology level.

e.g. for a biomass derived synthetic kerosene *a* may be less than unity and for hydrogen EI_{CO2} is zero.

However

Both the economic efficiency, η_{econ}, and the coefficient of environmental performance, *CEP*, are best when

$$\frac{MMF.LCV}{Mp.g.R} = ETRW$$

has its smallest possible value.

Therefore, the targets should be to optimise future aircraft to give minimum *ETRW* and to avoid making contrails

What determines the fuel burn?

- During the flight the engines burn fuel and the total mass of the aircraft decreases

$$\dot{M} = -\dot{m}f$$

And, in the cruise, engine thrust is equal to aircraft drag and the lift is equal to the aircraft weight

- The overall thermodynamic efficiency η_0 is given by

$$\eta_0 = \frac{(D.V_\infty)}{(\dot{m}f.LCV)}$$

where LCV is the lower calorific value for the fuel

- Now if the aircraft is flying at constant Mach number and at a fixed value of the lift to drag ratio

$$-\dot{M} = \frac{(Mg.V_{\infty})}{LCV.(\eta_0 . L/D)}$$

but $V_{\infty} = \frac{dS}{dt}$ where S is the distance flown

$$-\frac{dM}{M} = \frac{g}{(\eta_0 . L/D).LCV} \cdot dS$$

- Therefore, if the total distance flown is R, the fuel used is

$$\frac{(MF)_{cruise}}{MTO} = 1 - EXP\left(-\frac{(g.R/LCV)}{(\eta_0 . L/D)} \right)$$

For simplicity let non-dimensional range be *X* ,where

$$X = \frac{g.R}{LCV.\left(\eta_0 . L/D\right)}$$

and let the additional fuel used for taxi, climb, route deviations and descent be Δ*mf, where*

$$\frac{\Delta mf}{MTO} = \varepsilon = 1 - k$$

then the total fuel consumed for a trip between two points separated by a great circle distance R is

$$\frac{MMF}{MTO} = 1 - kEXP\left(-X\right) = \alpha$$

Mass breakdown of the aircraft

- The mass at the aircraft at the beginning of the take off run is *MTO*, where

$$MTO = MOE + Mp + MMF + MF_{NC}$$

with *MOE* = operational empty mass (mass of everything except payload and fuel)

Mp = payload mass (passengers + "belly" freight)

MMF = mass of mission fuel (fuel consumed during flight)

MF_{nc} = mass of fuel carried but not consumed (reserve fuel plus tankered fuel)

= $\beta.MTO$

- It follows that the zero fuel mass, *MZF*, is given by

$$MZF = MOE + MP = MTO(1 - \alpha - \beta)$$

- Hence, the *ETRW* is given by

$$\left(\frac{MMF.LCV}{Mp.g.R}\right)\left(\eta_0 \frac{L}{D}\right) = \frac{MMF}{MP.X} = \left(\frac{MZF}{Mp}\right)\left(\frac{1}{X}\frac{(1 - kEXP(-X))}{(kEXP(-X) - \beta)}\right)$$

Theorem 1

- For flight of a given aircraft travelling a fixed distance i.e. constant α

$$\frac{MMF}{MZF + MF_{NC}} = \frac{\alpha}{(1-\alpha)}$$

and, hence,

$$\frac{dMMF}{MMF} = \frac{d(MZF + MF_{NC})}{(MZF + MF_{NC})}$$

Therefore, the % change in fuel burnt is equal to the % change in the sum of the zero fuel mass and the fuel carried, but not used.

Theorem 2

- If *MMP* is the maximum permitted payload and LF if the load factor given by,

$$LF = \frac{Mp}{MMP}$$

- For flight of a given aircraft travelling a fixed distance, i.e. constant *α,* and carrying the legal minimum reserve fuel, i.e. constant *β,*

$$\frac{MZF}{Mp} = \frac{MOE + Mp}{MP} = \left(\frac{MOE}{MMP}\right)\left(\frac{1}{LF}\right) + 1$$

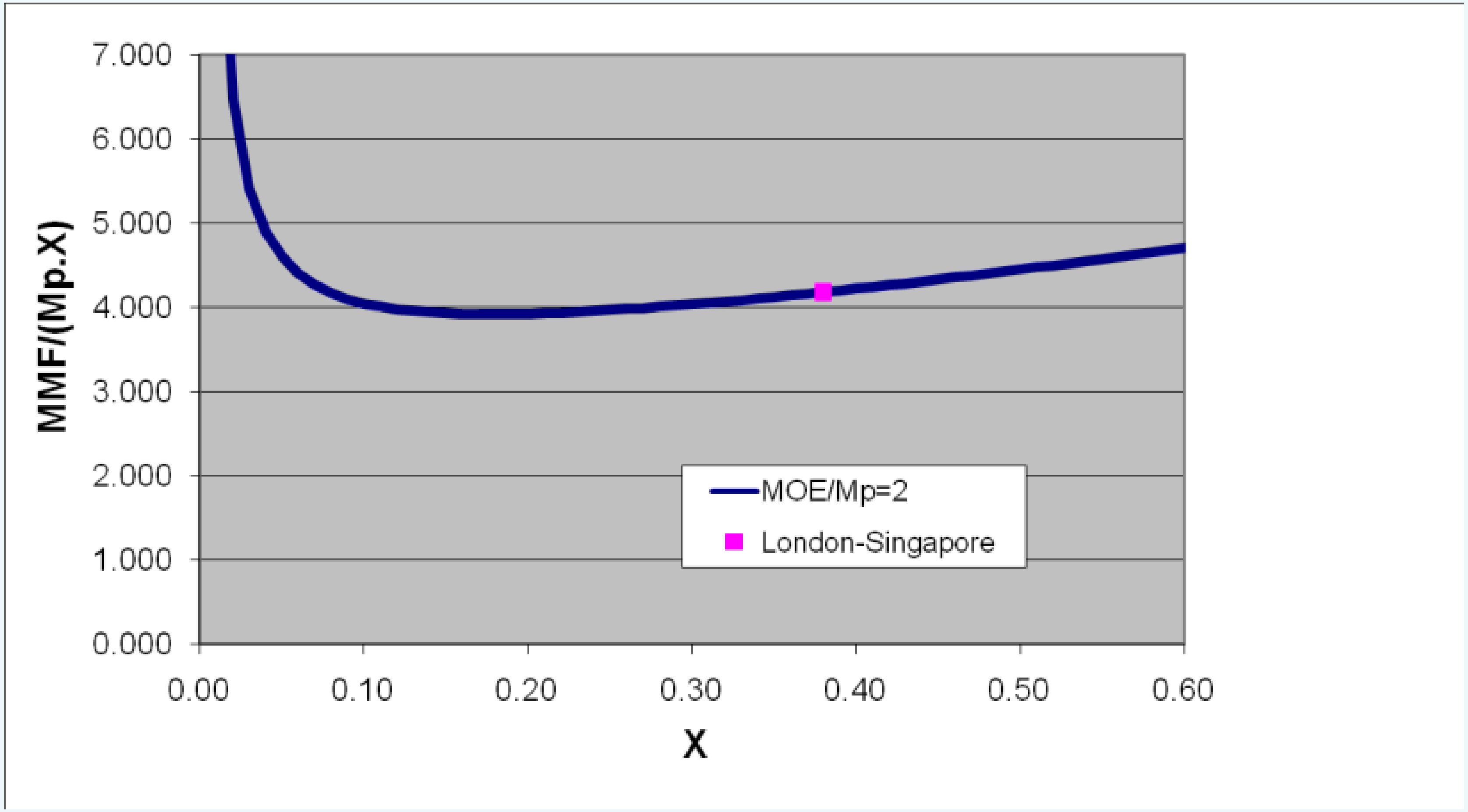
Hence, for a given aircraft travelling a fixed distance, cruising at constant ηo(L/D), the minimum value of ETRW occurs when the payload has its maximum possible value (LF is unity) and the fuel carried, but not consumed, has its minimum possible value i.e. the minimum reserve required by law.

Theorem 3

- Consider what happens to the *ETRW* of an aircraft with a fixed ratio of zero fuel mass to payload mass (constant *MOE/MP*) as more fuel is added and the aircraft flies further and further.

  (NB with current technology and kerosene as the fuel, a flight half way round the world (R≈ 20,000 km) corresponds to an *X* of about 0.6)

MMF/(*MP.X*) versus *X* at fixed payload



- ***Under these conditions, the best value of ETRW occurs at a value of X that depends only upon ε (the fuel used over and above the cruise value for the same range) and β (the fuel carried, but not used).***

- Since ε is small (≈ 0.025) and *X* is typically less that 0.4,

$$\frac{MMF}{MP.X} \approx \frac{(MZF/MP)}{(1-\beta)}\left(\frac{\varepsilon}{X} + \left(1+\varepsilon\frac{(1+\beta)}{(1-\beta)}\right) + \frac{X}{2}\left(\left(\frac{1+\beta}{1-\beta}\right) + \varepsilon\left(\frac{1+4\beta+\beta^2}{(1-\beta)^2}\right)\right) + ...\right)$$

- Therefore, the range for best *ETRW* is

$$R \approx \left(\frac{LCV(\eta_o L/D)}{g}\right)(1-\beta)\left(\frac{2\varepsilon}{1-\beta^2}\right)^{1/2}\left(1-\left(\frac{1+4\beta+\beta^2}{4}\right)\left(\frac{2\varepsilon}{1-\beta^2}\right)\right)$$

and, if β is small (< 0.1),

$$R \approx \left(\frac{LCV(\eta_o L/D)}{g}\right)(2\varepsilon)^{1/2}\left(1-\frac{1}{2}(2\beta+\varepsilon)\right)$$

.

Theorem 4

- For an aircraft cruising at constant *ηo(L/D)* and carrying the maximum permissible payload, *MMP*, the best value of *ETRW* is given by

$$ETWR = \left(\frac{MMZF}{MMP}\right)\left(\frac{1+\varepsilon+\beta}{\eta_0 \frac{L}{D}}\right)\left(1+(2\varepsilon)^{1/2}\left(1+\frac{1}{2}(2\beta-\varepsilon)\right)\right)$$

- For a typical long range flight,

$$ETRW \approx 1.3\left(\frac{MMZF}{MMP}\right)\left(\frac{1}{\eta_0\left(\frac{L}{D}\right)}\right)$$

Under these conditions, the influence of the aircraft characteristics and the operational characteristics are separated and the absolute minimum value of ETRW is obtained when the product of the structural efficiency (MMP/MMZF), the propulsion efficiency (ηo) and the aerodynamic efficiency (L/D) is maximised

Theorem 5

- Consider what happens to the *ETRW* of a given aircraft operating at a fixed take-off mass, i.e. constant *MOE/MTO*, and cruising at constant *ηo(L/D)* , as more fuel is added and the aircraft flies further and further. However, since the take-off mass is fixed, as more fuel is added, the payload mass must be reduced. Hence,

$$LF = \frac{MTO}{MMP}\left(1-\left(\beta+\alpha+\frac{MOE}{MTO}\right)\right)$$

- Therefore,

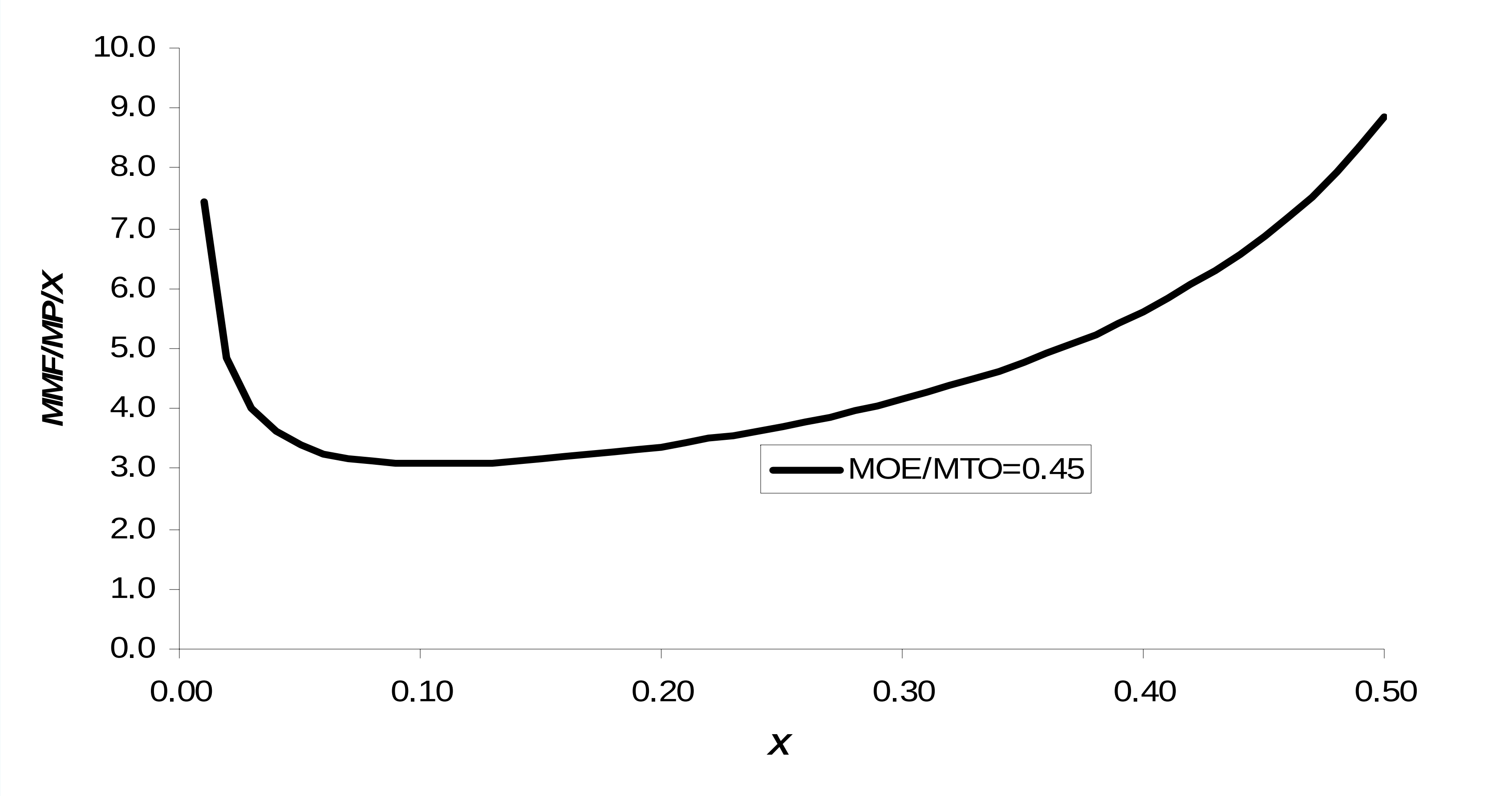
$$\frac{MZF}{MP} = \frac{1-(\beta+\alpha)}{1-\left(\beta+\alpha+\frac{MOE}{MTO}\right)}$$

and

$$\frac{MMF}{MP.X} = \left(\frac{1}{X}\right)\left(\frac{1-kEXP(-X)}{\left(kEXP(-X)-\left(\beta+\frac{MOE}{MTO}\right)\right)}\right)$$

In this case, the best ETRW occurs when MTO has its largest possible value i.e. the maximum take-off mass, MMTO, and β has its minimum possible value.

Theorem 6


10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
MMF/MP/X
MOE/MTO=0.45
0.00
0.10
0.20
0.30
0.40
0.50
X

- ***For a given aircraft with a fixed take-off mass, the best ETRW occurs at a value of X that depends upon ε (the fuel used over and above the cruise value for the same range), β (the fuel carried, but not used) and the ratio MOE/MTO***
- the range for best *ETRW* is found to be

$$R \approx \left(\frac{LCV\,(\eta_0\,L/D)}{g}\right)\left(1-\left(\beta+\frac{MOE}{MTO}\right)\right)\left(\frac{2\varepsilon}{1-\left(\beta+\frac{MOE}{MTO}\right)^2+\varepsilon\left(1+4\left(\beta+\frac{MOE}{MTO}\right)+\left(\beta+\frac{MOE}{MTO}\right)^2\right)}\right)^{1/2}$$

Theorem 7

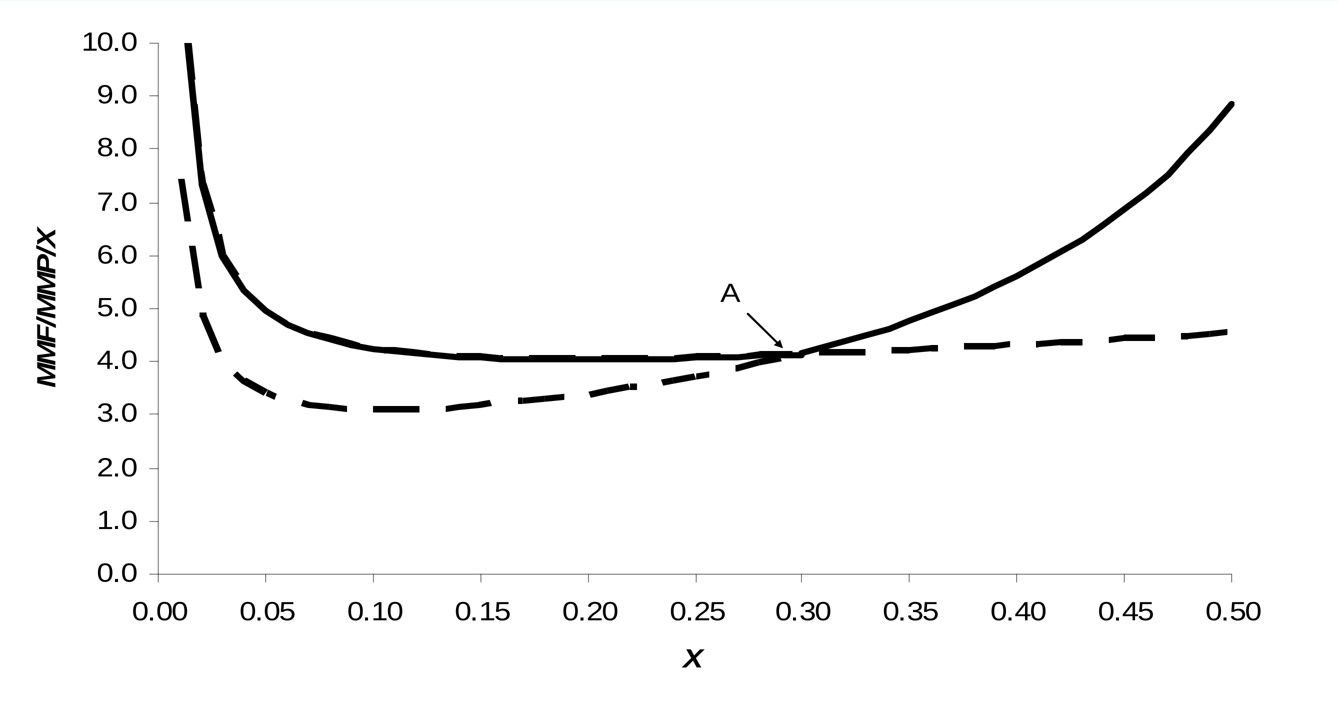
- For an aircraft operating at its maximum take-off mass and cruising at constant *ηo(L/D)*, the best value of *ETRW* is given by

$$ETRW \approx \left(\frac{1}{\eta_0 L/D}\right)\left(\frac{\left(1-\left(\beta+\frac{MOE}{MMTO}\right)+\varepsilon\left(1+\frac{MOE}{MMTO}\right)\right)}{\left(1-\left(\beta+\frac{MOE}{MMTO}\right)\right)^2}+\left(\frac{2\varepsilon\left(1-\left(\beta+\frac{MOE}{MMTO}\right)^2+\varepsilon\left(1+4\left(\beta+\frac{MOE}{MMTO}\right)+\left(\beta+\frac{MOE}{MMTO}\right)^2\right)\right)}{\left(1-\left(\beta+\frac{MOE}{MMTO}\right)\right)^4}\right)^{1/2}\right)$$

- ***Under these conditions, the influence of the aircraft characteristics and the operational characteristics are not separated and the absolute minimum value of ETRW is obtained when the structural efficiency, MMTO/MOE, and the product of the propulsive and aerodynamic efficiencies, ηo(L/D), have their largest values.***

Theorem 8

- When the payload and the take-off masses have their maximum values, the solid line defines the operating boundary for the aircraft.



$$\alpha_A = (1-\beta) - \frac{MMZF}{MMTO}$$

and

$$X_A = \ln\left(\frac{1-\varepsilon}{\beta + \frac{MMZF}{MMTO}}\right)$$

- By expanding *EXP(-X)* as a power series in ascending powers of *X* and neglecting terms of order *X3* and above, an approximation to *XA* is given by.

$$X_A \approx 1 - \left(\frac{2}{(1-\varepsilon)}\left(\beta + \frac{MMZF}{MMTO}\right) - 1\right)^{1/2}$$

- ***Therefore, for an aircraft operating at fixed values of ηo(L/D), ε and β the curves of ETRW versus X at maximum payload and maximum take-off mass cross only once. The point of intersection is determined by the ratio of the maximum zero fuel mass to the maximum take- off mass, MMZF/MMTO.***

Theorem 9

- When the distance flown is less than *XA*, the minimum *ETRW* is determined by the curve for maximum permissible payload, *LF* =1. Whilst for distances greater than *XA*, the minimum *ETRW* is determined by the curve for maximum take-off mass, *LF*<1. In the space above the solid line, both the payload mass and the take-off mass are always less than the maximum permitted values.
- At point A,

$$\left(\frac{MMF}{MMP.X}\right)_A = \frac{MMTO}{MMP}\frac{1}{X_A}\left(1-\beta-\frac{MMZF}{MMTO}\right)$$

- i.e.

$$\left(ETRW\right)_A \approx \frac{\left(MMTO/MMP\right)}{\left(\eta_0\, L/D\right)}\left(\frac{1-\beta-\left(MMZF/MMTO\right)}{1-\left(\frac{2}{\left(1-\varepsilon\right)}\left(\beta+\frac{MMZF}{MMTO}\right)-1\right)^{1/2}}\right)$$

- ***For an aircraft operating at fixed values of ηo(L/D), ε and β, the value of ETRW at point A is determined by the ratio of maximum zero fuel mass to maximum take-off mass, MMZF/MMTO, and the ratio of maximum zero fuel mass to maximum payload mass, MMZF/MMP.***

Theorem 10

- For a given aircraft, the minimum achievable *ETRW* occurs at point A when the value of *X* for minimum *ETRW* at the maximum permissible payload mass (Theorem 3) is greater than the value of *X* at point A (Theorem 8). Therefore, the best possible value of *ETRW* occurs at point A when

$$(1-\beta)\left(\frac{2\varepsilon}{1-\beta^2+\varepsilon(1+4\beta+\beta^2)}\right)^{1/2} \geq 1-\left(\frac{2}{(1-\varepsilon)}\left(\beta+\frac{MMZF}{MMTO}\right)-1\right)^{1/2}$$

- or, if ε is small compared to 1,

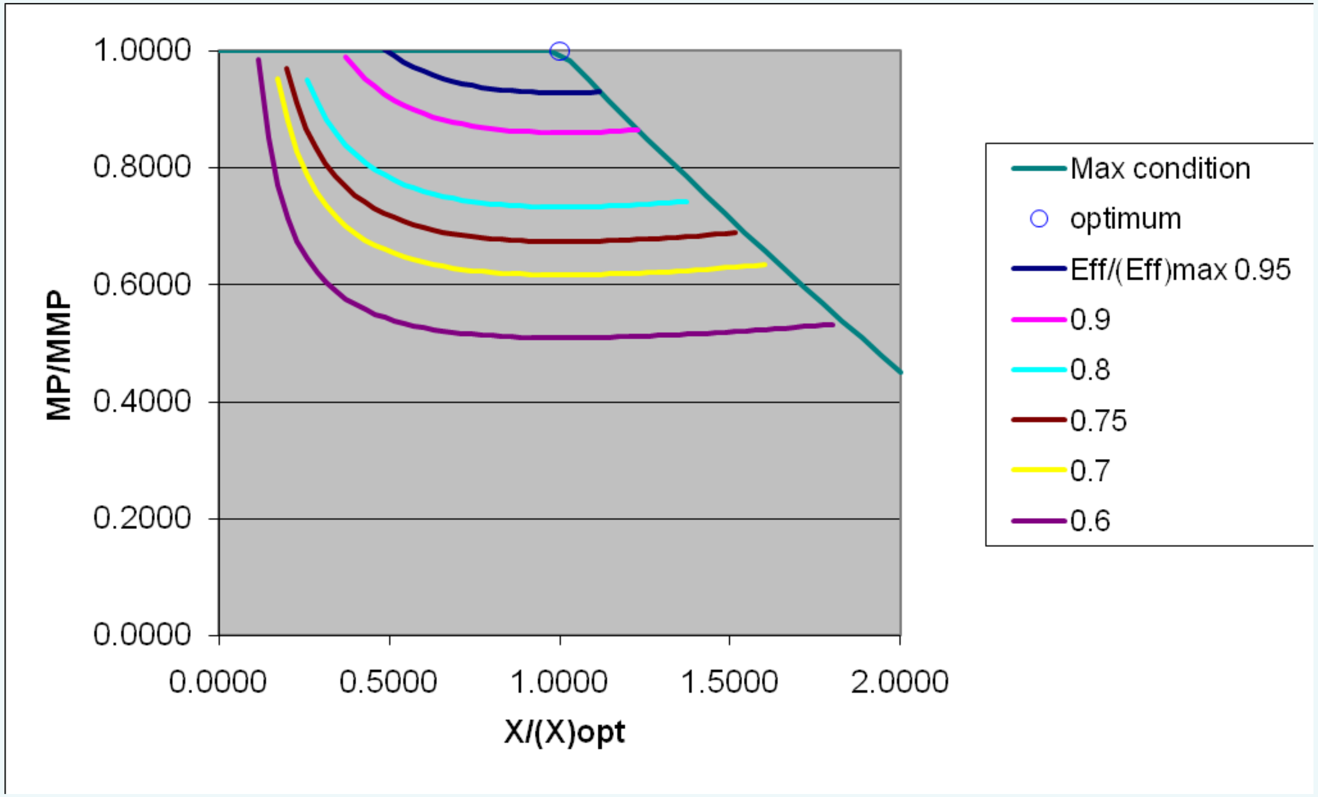
$$\frac{MMZF}{MMTO} \geq (1-\beta)\left(1-\left(\frac{2\varepsilon}{1-\beta^2}\right)^{1/2}-\beta\left(\frac{2\varepsilon}{1-\beta^2}\right)+\left(\frac{3+4\beta-\beta^2}{4}\right)\left(\frac{2\varepsilon}{1-\beta^2}\right)^{3/2}\right)$$

- ***For a given mission, the location of the point of minimum ETRW on the payload range diagram is determined by the ratio of maximum zero fuel mass to maximum take-off mass, ε (the fuel used over and above the cruise value for the same range) and β (the fuel carried, but not used).***

Sensitivity assessment

- The legal requirement to carry a minimum level of reserve fuel reduces the *ETRW* by about 6%. A 10% change in reserve fuel changes *ETRW* by about 0.5%
- The *ETRW* reduces by more than 1% for every 10% of extra fuel used to taxi, non-optimum climb, inefficient route etc.
- The Load factor is particularly important. A 10% increase in payload (passengers and belly freight) increases the *ETRW* by 7.5%

Off Optimum operation



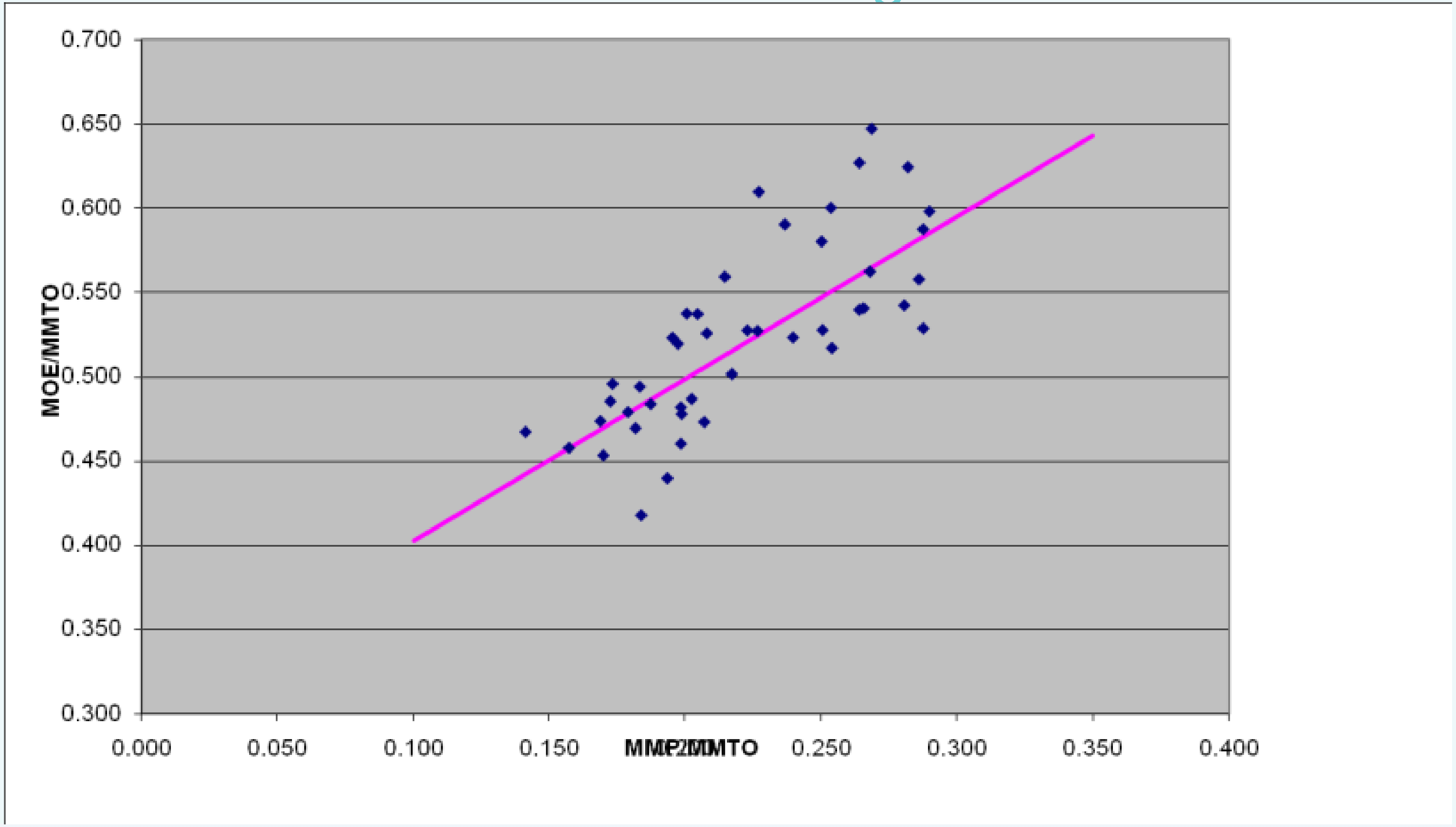
Observations

- For given aerodynamics and propulsion ($\eta_0 L/D$), the *ETRW* is determined primarily by the *MMP/MMZF* ratio.
- The range capability is determined primarily by the *MOE/MMTO* ratio.
- Once the intersection point is determined, the characteristics of the aircraft are fixed
- The *MMZF* and the *MMTO* are "certified masses" and are approved by the Regulator, whereas *MOE* is a "real" mass determined by the designer.
- All the statements made so far apply to all flying machines using conventional propulsion technology

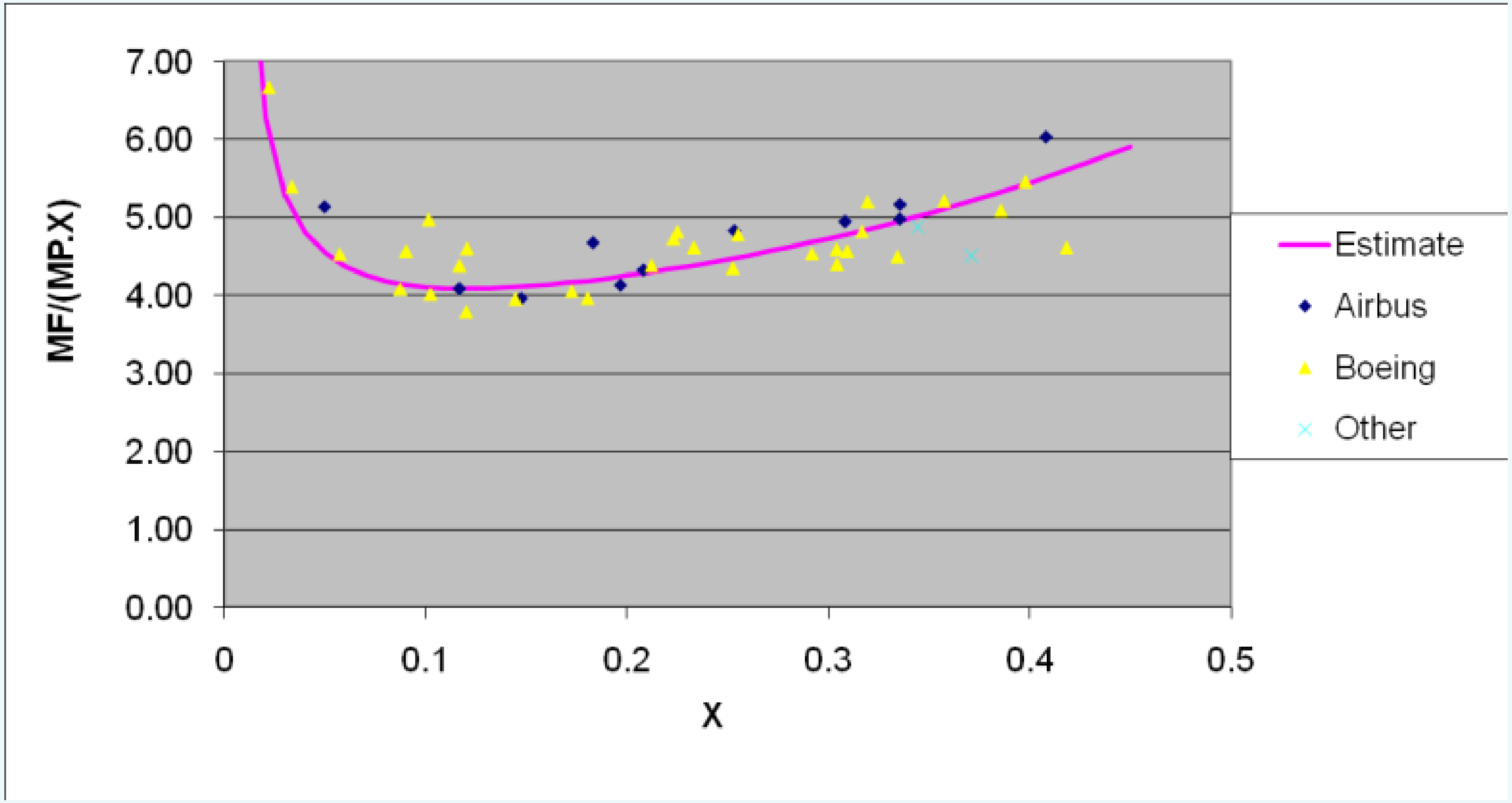
The current configuration –how good is it?

- Aircraft have not usually been designed to have the best *ETRW.*
- How good are current aircraft and can we do better in future?
- What follows involves approximation and the results are not exact.

Approximate variation of MOE/MMTO with MMP/MMTO for the current configuration



Current generation aircraft- max payload and max T/O mass



Observations

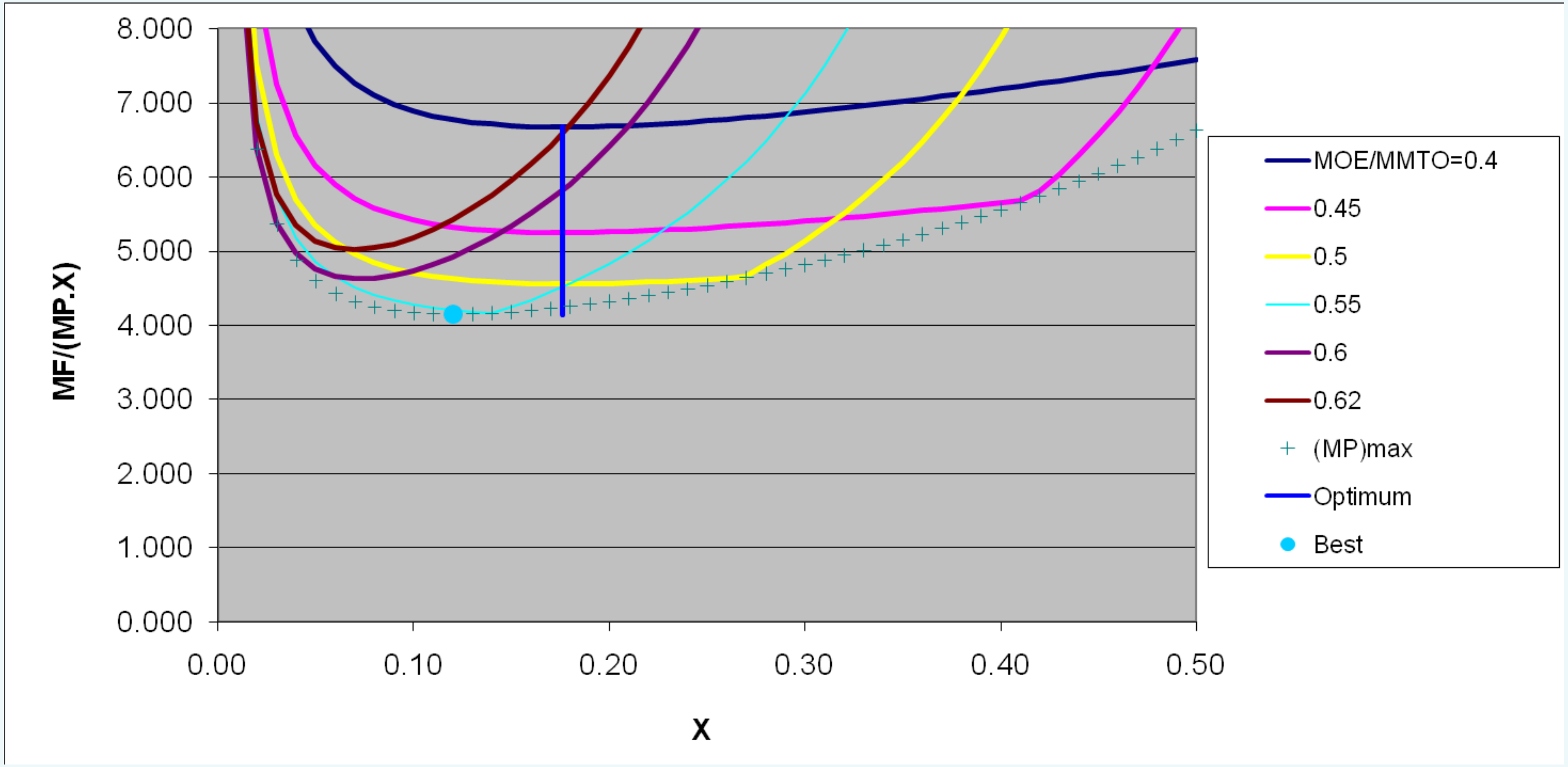
- These results indicate that on average

$$ETRW \approx \frac{4.5}{\left(\eta_0 \, {}^{L}\!/\!_{D}\right)}$$

- A typical modern value of (η_0L/D) is about 6.5. Hence

$$ETRW \approx 0.7$$

Current level of technology – current configuration



Most efficient “metal” aircraft

- The “best” aircraft has an

$$\left(ETRW\right)_{\min} \approx 4.0 \, \frac{1}{\left(\eta_0 \, {}^{L}\!/\!_{D}\right)}$$

- Provided that

$$0.07 < \left(\frac{g \times R}{LCV} \frac{1}{\eta_0} \frac{D}{L} \right) < 0.26$$

What does this aeroplane look like?

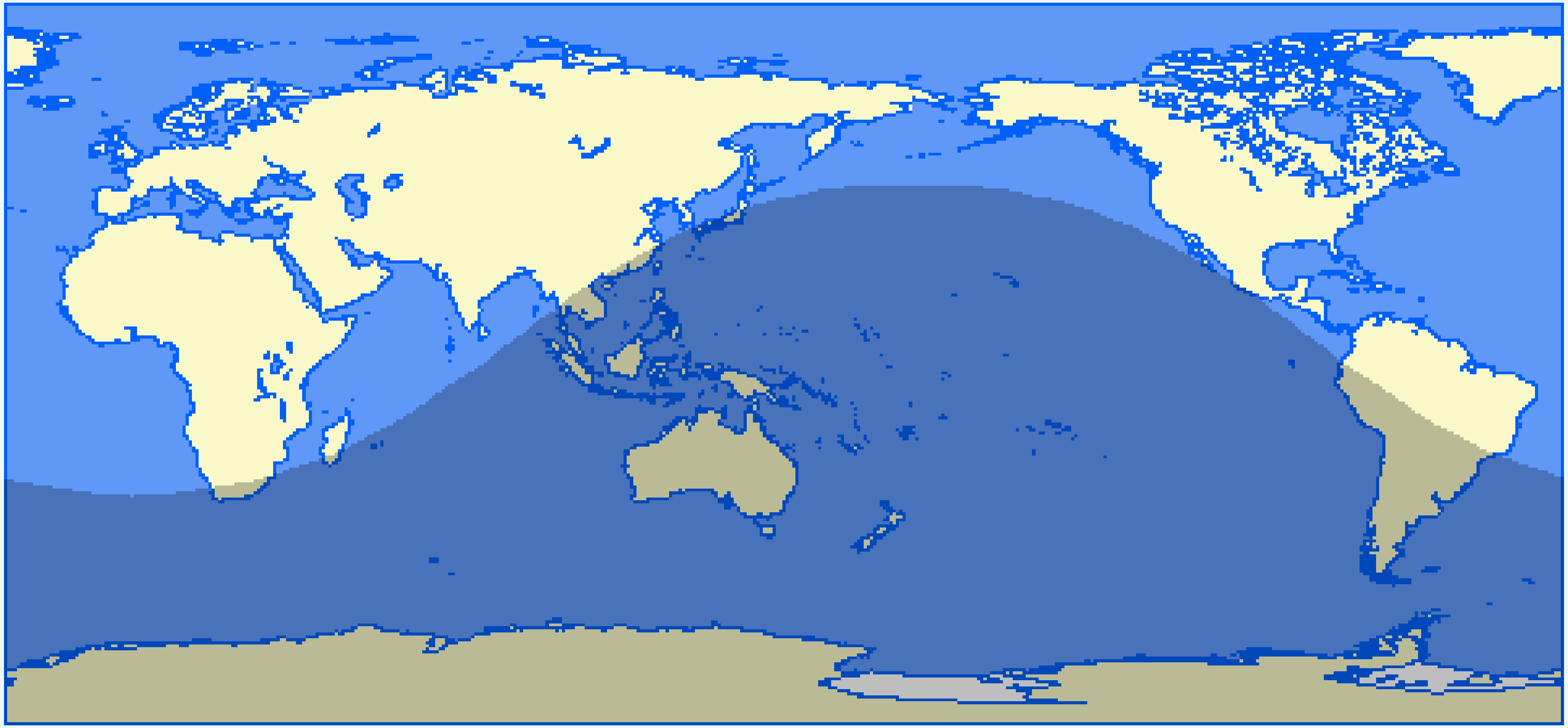
- Mission fuel - *MMF/MMTO* = 0.20
- Payload - *MMP/MMTO* = 0.25
- Disposable load (including reserve fuel) $M_{disp}/MMTO$ = 0.50
- Operational empty weight – *MOE/MMTO* = 0.50

Best trip (1500 < R (nm) < 5000)

- Distance from London to Dallas/ Mumbai/ Beijing is about 5000 nm
- Distance from London to Rhodes/Ankara/Moscow is about 1500 nm
- MMF/MP/nm ≈ 0.00028/nm
- MMF/Passenger/nm ≈ 0.026 kg/passenger/nm

All points within 1500nm of London

All points within 5000nm of London



Fleet averaged fuel burn

- The global fleet averaged fuel burn is currently about 0.45 litres/1000kg/km (source Airbus)
- This translates to an *ETRW* of 1.6
- This is more than twice the value the optimum aircraft (*ETRW* ≈ 0.7).

Where does it all go?

Reasons for the difference

- Load Factor
  - current fleet average passenger load factor is about 80%
  - current average "belly freight" is about 20%
  - overall load factor is only about 60%

This alone accounts for 50% of the efficiency loss and shows how important cargo can be to the efficient operation of passenger aircraft

- Air traffic management
  - Excess fuel is burned due to en route deviations, inefficient climb and descent, manoeuvring and holding in the departure and terminal areas.
  - On <u>average</u> an extra 9nm is flown in the origin terminal area, an extra 27nm is flown in the destination terminal area and about 20nm + 2.5% of trip distance en-route – the maximum can be up to 2.5 times these values) (Reynolds 2008)
  - For short range flights (<1500 nm), this accounts for at least 10% of the efficiency loss

- Short haul operations
  - It is clear that the majority of flights inside Europe and inside the USA are less than 1500nm
  - These flights are intrinsically less efficient than longer flights and are more sensitive to extra fuel burned due to air traffic (safety) restrictions, though slightly less sensitive to the effects of fuel carried, but not burned (tankering)

Therefore the remaining 20% of efficiency loss is probably going to be difficult to identify and to eliminate

What further developments do we need?

- If the target is to reduce *ETRW* then
  - Operate with a full passenger load and a fully cargo load
  - Reduce the mass of the structure for a given payload
  - Increase the engine efficiency (η_0)
  - Increase the airframe lift to drag ratio (L/D)
  - Increase the calorific value of the fuel
  - Optimise the combination of the above to give minimum *ETRW*

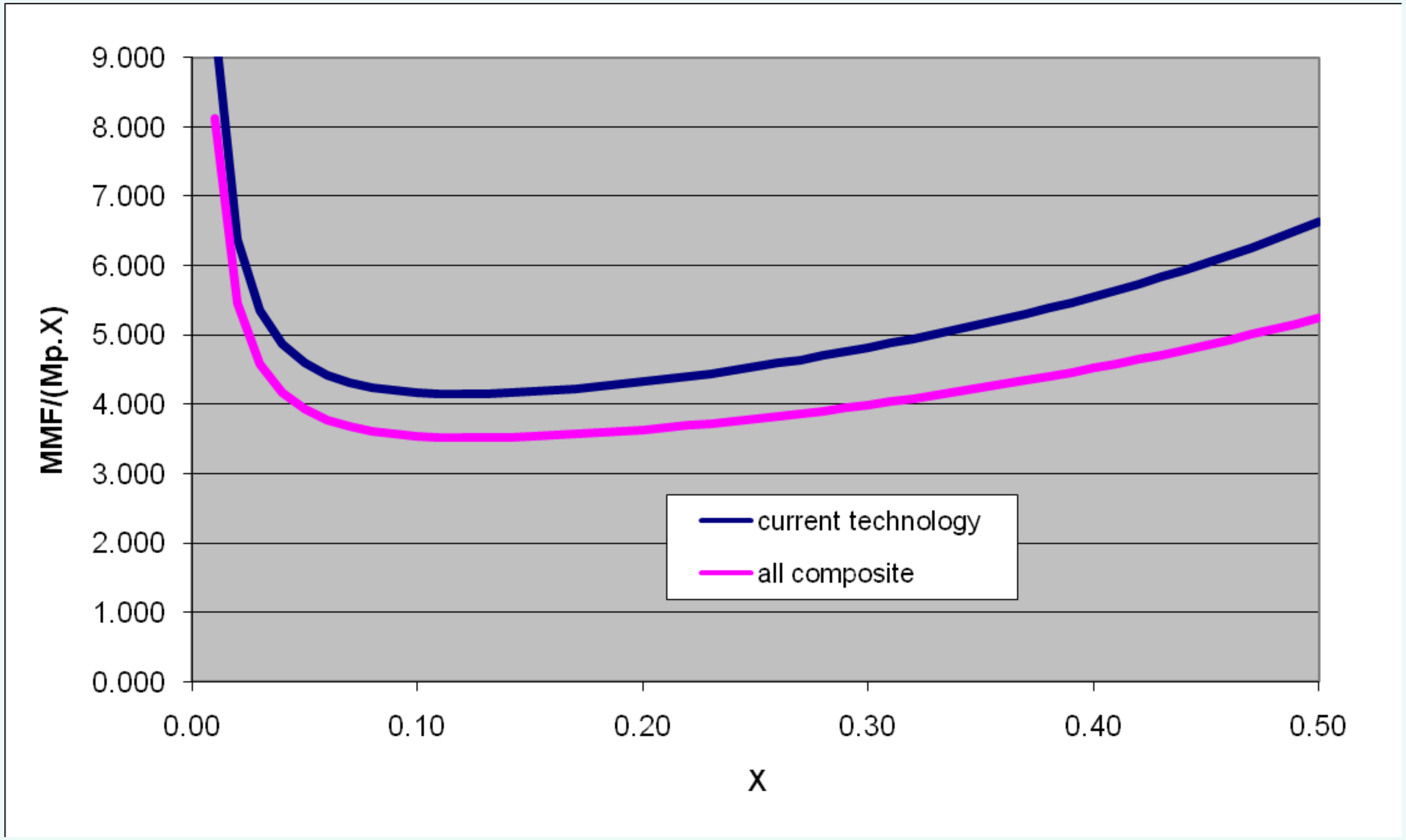
Operate with more payload

- Passenger require physical space – typically 0.85 sq.m in economy.
- A full passenger load with baggage (95 kgs each) is typically about 70% of the maximum allowable payload mass.
- On average about 75-80% of seats have passengers in them
- On average MP/MMP is about 60% - therefore, on average, the fuel efficiency is only 70% of the maximum that the aircraft can deliver.

Reduce the structure mass

- This can be achieved through the use of lighter materials and materials that can be tailored – easier said than done.
- Already happening through the use of carbon fibre composite – many tricky issues to be resolved including
  - Availability of raw material
  - Safe structural design
  - Through life maintenance
  - End of life disposal

Maximum impact of all composite material – current configuration with 25% reduction in mass of primary structure



- Use of all composite material could reduce the mass of the primary structure components by 25%

- The impact on the *ETRW* is between 10% and 15%

- The largest benefit occurs on the aircraft flying the longest ranges.

Increase engine efficiency

- Simply put, the engine efficiency increases as
  - Overall pressure ratio increases
  - Turbine entry temperature increases
- Both these changes tend to increase the production of NOX and an increase in thermal efficiency increases the propensity to induce contrails
  - A balance needs to be struck but where?
- Engine efficiency can also be increased by
  - Improve the propulsive efficiency (open rotor)
  - Use better ways to provide system power

Increase the lift to drag ratio

- This can be done by
  - Increasing aspect ratio
    - Improved design for pitch up at low speed stalling condition
    - Wing sections with drag rise at lower Mach number
  - Reducing interference drag between components e.g. engine and wing
  - Reducing induced drag through better load distributions
  - Using drag reduction technologies e.g. laminar flow control
  - Going to a different architecture e.g. Blended Wing Body

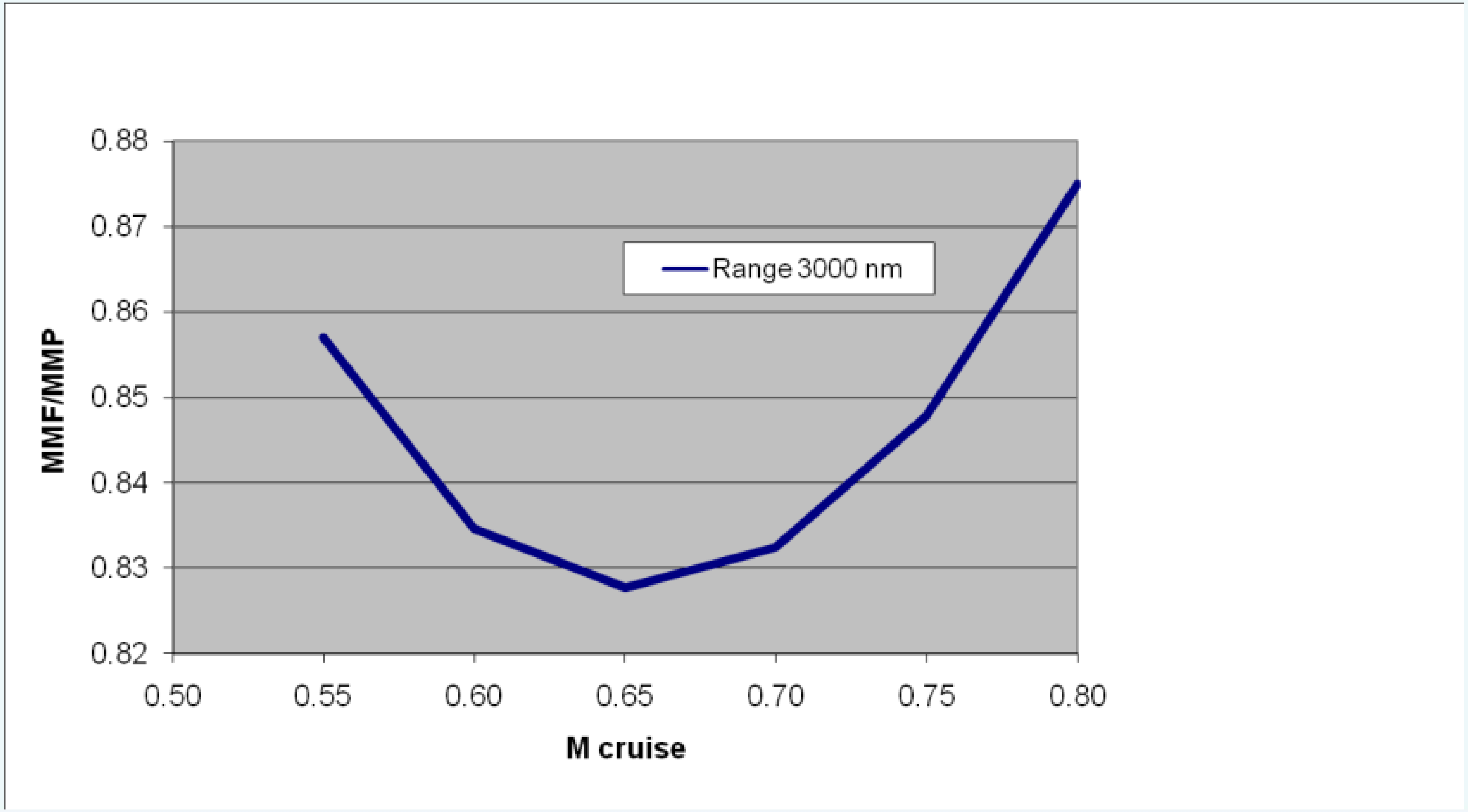
Detailed optimisation

- The optimisation should be performed for the case of maximum range at maximum payload (close to best *ETRW*)
- The requirements
  - max payload
  - range at max payload
  - cruise Mach number
  - the engine characteristics and the number of engines
  - minimum size of runway to be used
  - diversion distance (safety)

Technology

- Wing aerodynamics
  - Low speed characteristics with and without high lift systems deployed
  - Transonic drag rise characteristics
  - Low speed pitch up boundary (aspect ratio vs sweep)
  - Transonic manoeuvre maximum Cl without buffet
  - Anything fancy e.g. laminar flow control
- Brake characteristics
- Glide slope angle
- Fuel – LCV and density

Effect of cruise Mach number



"Best" aircraft –current architecture

- Cruise Mach number about 0.66
- Aspect ratio 14
- Sweep about 15 degrees
- *MMP/MMTO* about 0.23
- *MMF/MMTO* is 0.2
- *MOE/MMTO* 0.53
- *ETRW* about 0.65
- Initial cruise altitude 30,000' (no contrails)

Indications of the impact of other technologies

- Laminar flow to 50% chord on both top and bottom surface would reduce *ETRW* by 20% (no allowance for system weight)

- Composite materials would reduce *ETRW* by 10%

- Improvement in engine propulsive efficiency could produce another 10-15% reduction

Overall there could be another 40% improvement over the current situation

Find a better fuel

- Kerosene is very hard to beat
- Most other fuels have severe problems
- Hydrogen is a possibility, but it's energy density poses a design problem
- Hydrogen fuel would still leave the NOX and contrail problems

What might we do to address the climate issue?

- Short term (next 10 years)
  - Tackle the inefficiencies in the system (operational and ATM)
  - New technology coming through on Boeing 787 and Airbus A-380 and A-350 will progressively improve efficiency
- Medium term (2020-2030)
  - Maximise the opportunity presented by the replacement of the Boeing 737 and Airbus A-320 fleets
  - Introduce technology from the ACARE programme
  - Introduce new configurations if appropriate

- Long term (beyond 2030)
  - Eliminate the dependence upon kerosene to produce an air transport system that can grow without limits to meet the needs of global wealth creation!

Nuclear powered aircraft (not a crazy idea)

- We already have nuclear powered trains (French trains use electricity generated by nuclear power)
- Nuclear power could be used
  - To generate hydrogen from sea water (very little environmental impact). Hydrogen infrastructure established at about 200 airports world wide.
  - Gas turbine runs on hydrogen
  - Aircraft designed to carry high fuel volume e.g. BWB
- or
  - Small nuclear power plant developed for aircraft use (take off with hydrogen and then switch to nuclear power)

Conclusion

We are facing some big issues

The evolution of aviation into a highly efficient transportation that makes an in perpetuity contribution to a sustainable global economy is the greatest challenge yet faced by our community.

Will the aerospace and aviation communities be able to rise to it?