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AIRCRAFT DESIGN AND SYSTEMS GROUP (AERO)

Definition and Discussion of the Intrinsic Efficiency of Winglets

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$$k_{e,WL} = \left(1 + \frac{2}{k_{WL}} \frac{h}{b}\right)^2$$

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Abstract

Three simple equations are derived to define the "intrinsic aerodynamic efficiency of winglets" independent of the horizontal extension of the winglet and independent of the winglet's (relative) height. This "intrinsic aerodynamic efficiency" allows a quick comparison of purely the aerodynamic shape of winglets independent of the selected size chosen for a certain aircraft installation. The intrinsic aerodynamic efficiency is calculated in 3 steps: STEP 1: The relative total drag reduction due to the winglet is converted into an assumed contribution of the winglet only on the span efficiency factor. STEP 2: If the winglet also increases span, its performance is converted into one without the effect of span increase. STEP 3: The winglet's reduction in induced drag is compared to a horizontal wing extension. If the winglet needs e.g. to be three times longer than the horizontal extension to achieve the same induced drag reduction, its "intrinsic aerodynamic efficiency" is the inverse or 1/3. Winglet metrics as defined are calculated from literature inputs. In order to evaluate winglets further, the mass increase due to winglets is estimated in addition to the reduction of drag on aircraft level and the resulting fuel burn.

Keywords: wingtip, winglet, induced drag, wing mass, aircraft design

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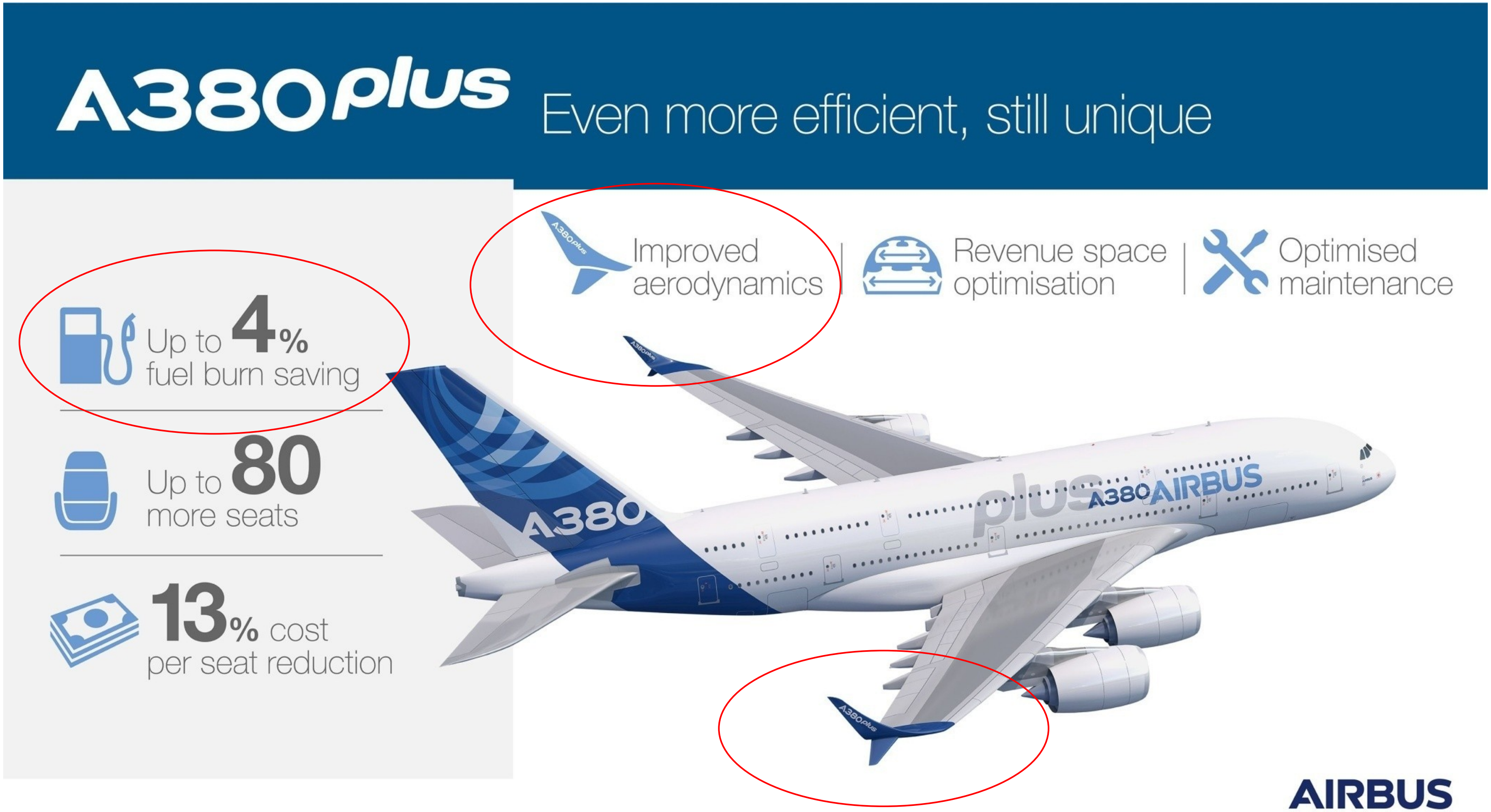
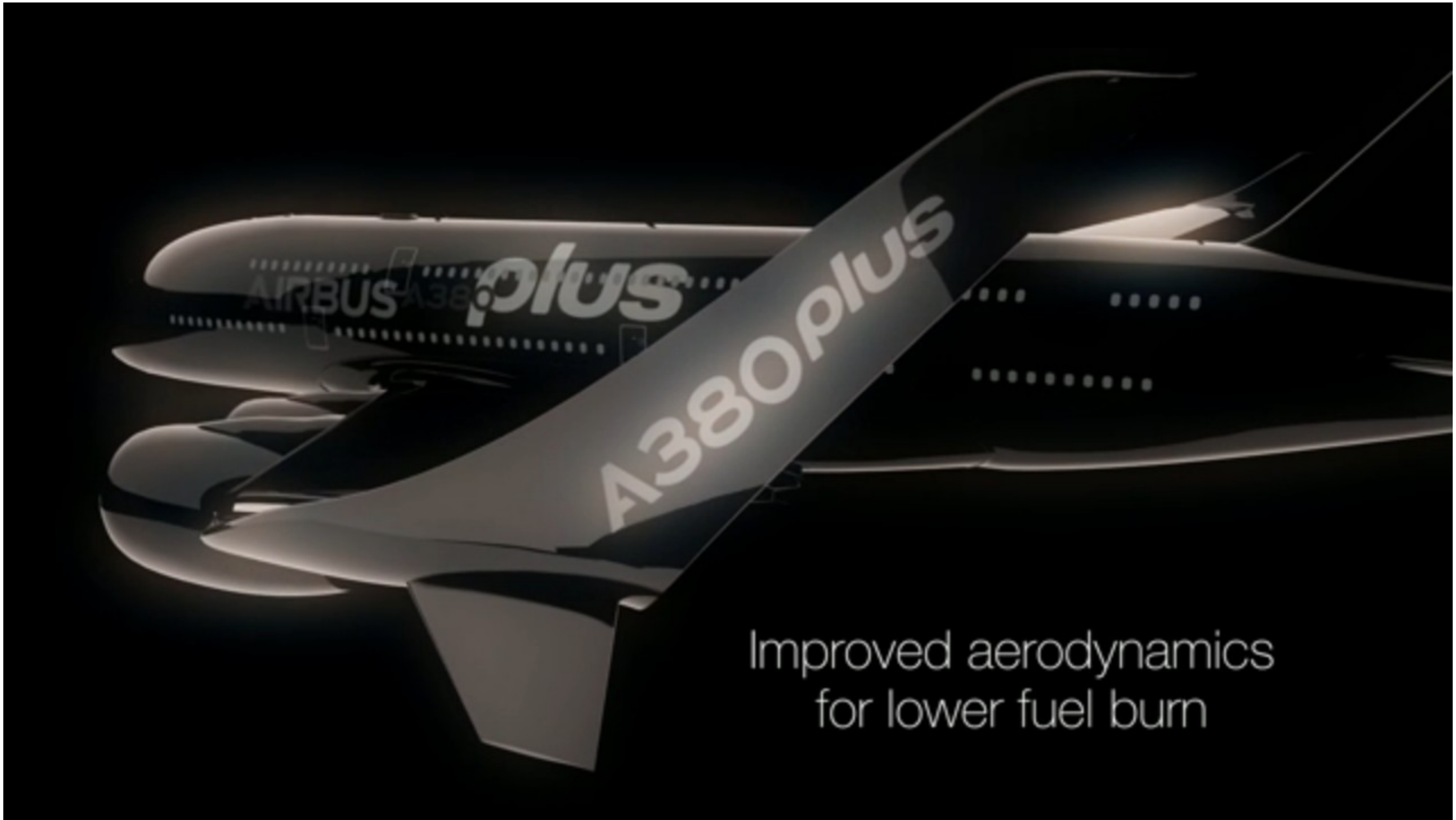

A380plus
Even more efficient, still unique
Improved aerodynamics
Revenue space optimisation
Optimised maintenance
Up to 4% fuel burn saving
Up to 80 more seats
13% cost per seat reduction
A380
A380 AIRBUS
plus
AIRBUS



Video:
https://youtu.be/Fmf8YBigM1Y

Winglets – Good Looking Shapes & Space for the Logo

A350XWB Blended Winglet

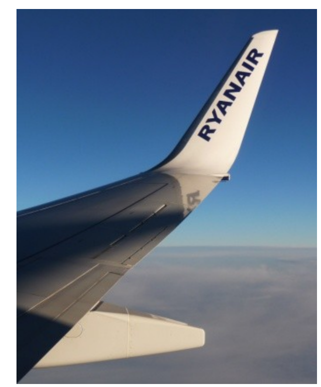
B737 MAX AT Winglet

A321 Sharklet

Southwest Airlines

Tui Fly

Air Berlin



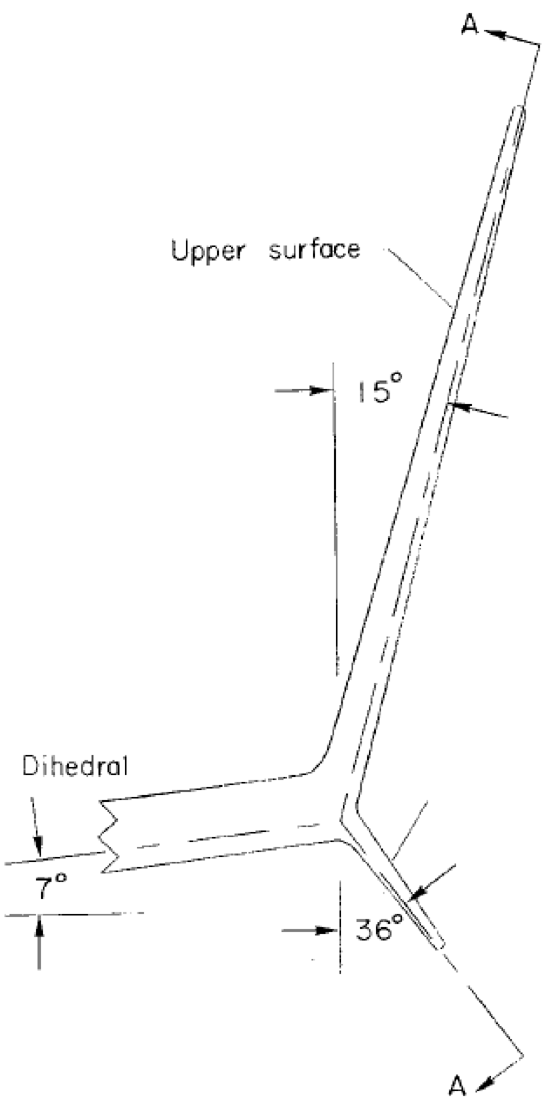
Ryanair

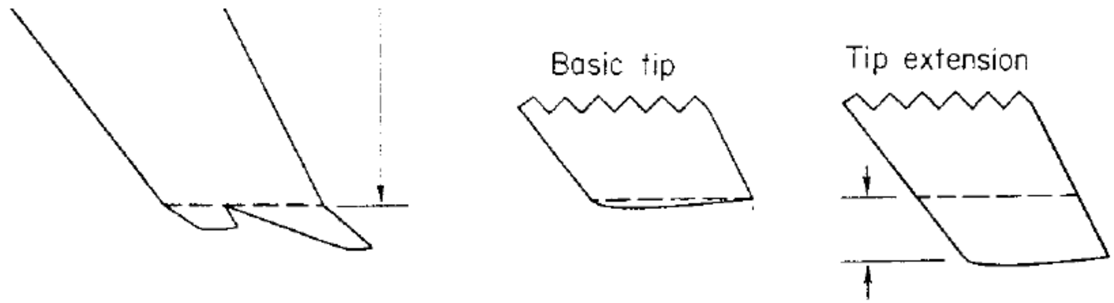
Winglets: History (selected)

- ≈1900: **Endplates** (thin flat plates) are used.
- 1976: Whitcomb works at NASA on standard **winglets** and **split winglets**.
- 1994: Patent about **blended winglets** published.
- 2001: **Blended winglets** introduced on B737NG.
- 2012 : Airbus calls the new blended winglets on the A320neo **Sharklets**.
- 2014: B737NG equipped with **Split Scimitar Winglets**.
- 2016: B737MAX has **AT Winglets**, where "AT" stands for "Advanced Technology".
  "AT winglets" are also split winglets.

Winglets get fancy names!

Winglets: History: Whitcomb (NASA)



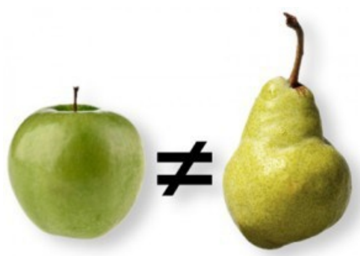


Whitcomb (NASA), 1976:

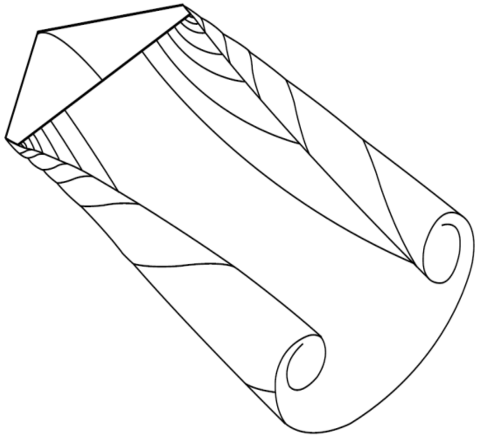
"**improvement in lift-drag ratio is more than twice** as great as that achieved with the comparable wing-tip extension."

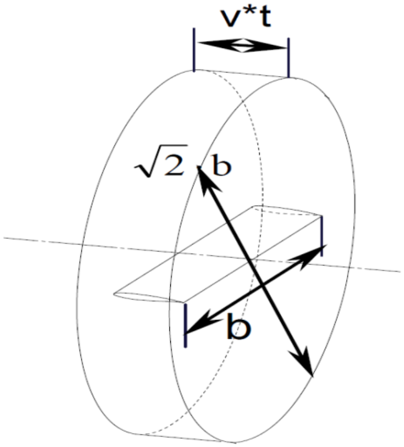
- Base Wing: Span: b = 2.753 m.
- Reference Wing: Horizontal extension: h_h = 0.076 m at tip.
- Wing with winglet: Total height of winglet: h = 0.250 m.
  Span increase: $h_{h,WL}$ = 0.054 m.

This is a "comparison of apples with pears"



Aerodynamic Fundamentals – Induced Drag





Misconceptions regarding the vortex wake and wingtip devices:

- "The vortex cores are often referred to as **wingtip vortices**, though this is a bit of a **misnomer**."
- "The **vorticity** that feeds into the cores generally **comes from the entire span** of the trailing edge, not just from the wingtips."
- We can <u>not</u> influence the induced drag by a device acting only on the wing tip on the flow.

Winglets & Span Limitations

Wing span is limited at airports!
Winglets can cope.

code letter	wingspan
A	< 15 m
B	15 m but < 24 m
C	24 m but < 36 m
D	36 m but < 52 m
E	52 m but < 65 m
F	65 m but < 80 m

"FAA Airplane Design Group"
and
"ICAO Aerodrome Reference Code"

Airport Bucharest "Henri Coanda", Google Maps

Winglets do not work well
(compared to a wing span increase),
but
winglets do work at constant span.

Winglets – Simple Questions without a Good Answer Today

- What is better, a **vertical winglet or** a **span increase**?
  Alternative question: *How to get the most out of 1m extra wing?*

  Answer: **The span increase is better.**

- How can the winglet's **aerodynamic quality** be expressed independent of size?
  Note: *Larger devices save more drag, but how can concept and shape be compared?*

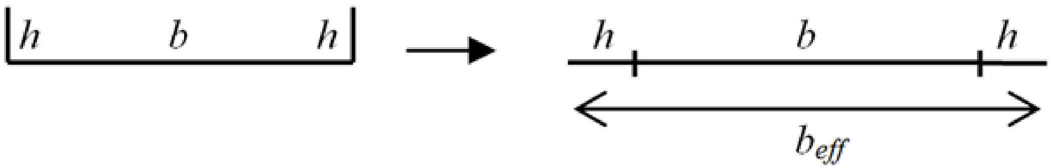
  Answer: With the **Intrinsic Efficiency of Winglets**, 1/k_WL: $k_{WL} = 2\frac{h}{b} \cdot \frac{1}{\sqrt{k_{e,WL,v}} - 1}$

- Is there an **overall benefit** in drag and fuel burn due to the winglet?
  Note: *A certain reduction in induced drag coefficient (at constant lift coefficient) can always be reached, if the winglet is high enough and installed with a cant angle such that wing span is also increased.*

  Answer: **Yes**.

$$\frac{\Delta m_F}{m_F} = \frac{\Delta D}{D}$$

Derivation of the Intrinsic Efficiency of Winglets: 1/k_WL



$$\frac{b_{eff}}{b} = 1 + 2\frac{h}{b}$$

$$C_{D,i} = \frac{{C_L}^2}{\pi A e}$$

$$C_{D,i,WL} = \frac{{C_L}^2}{\pi A_{eff} e} = \frac{{C_L}^2}{\pi A e_{WL}}$$

$$e_{WL} = \frac{A_{eff}}{A} \cdot e = \left(\frac{b_{eff}}{b}\right)^2 \cdot e$$

Hence

$$e_{WL} = \left(1 + 2\frac{h}{b}\right)^2 \cdot e \quad .$$

$$e_{WL} = \left(1 + \frac{2}{k_{WL}}\frac{h}{b}\right)^2 \cdot e = k_{e,WL} \cdot e$$

On the way to STEP 3:

$$k_{e,WL} = \left(1 + \frac{2}{k_{WL}}\frac{h}{b}\right)^2$$

The Efficiency Calculation Process

STEP 1:

$$k_{e,WL,total} = \frac{1}{1 + \frac{k_{D,WL}}{k_{Di}}}$$

Assume:

$\Delta C_{D,WL} = \Delta C_{Di,WL}$

STEP 2:

$$k_{e,WL,v} = \frac{k_{e,WL,total}}{\left(1 + 2\frac{h_h}{b}\right)^2}$$

STEP 3:

$$k_{WL} = 2\frac{h}{b} \cdot \frac{1}{\sqrt{k_{e,WL,v}} - 1}$$

ALTERNATIVE STEP 1:

$\Delta C_{D,WL} = \Delta C_{D0,WL} + \Delta C_{Di,WL}$

$$k_{e,WL,total} = \frac{1}{1 - \left(\frac{1}{k_{Di}} - 1\right) \cdot k_{D0,WL} + \frac{k_{D,WL}}{k_{Di}}}$$

$k_{D0,WL} = \Delta C_{D0,WL} / C_{D0} \approx 0.038$

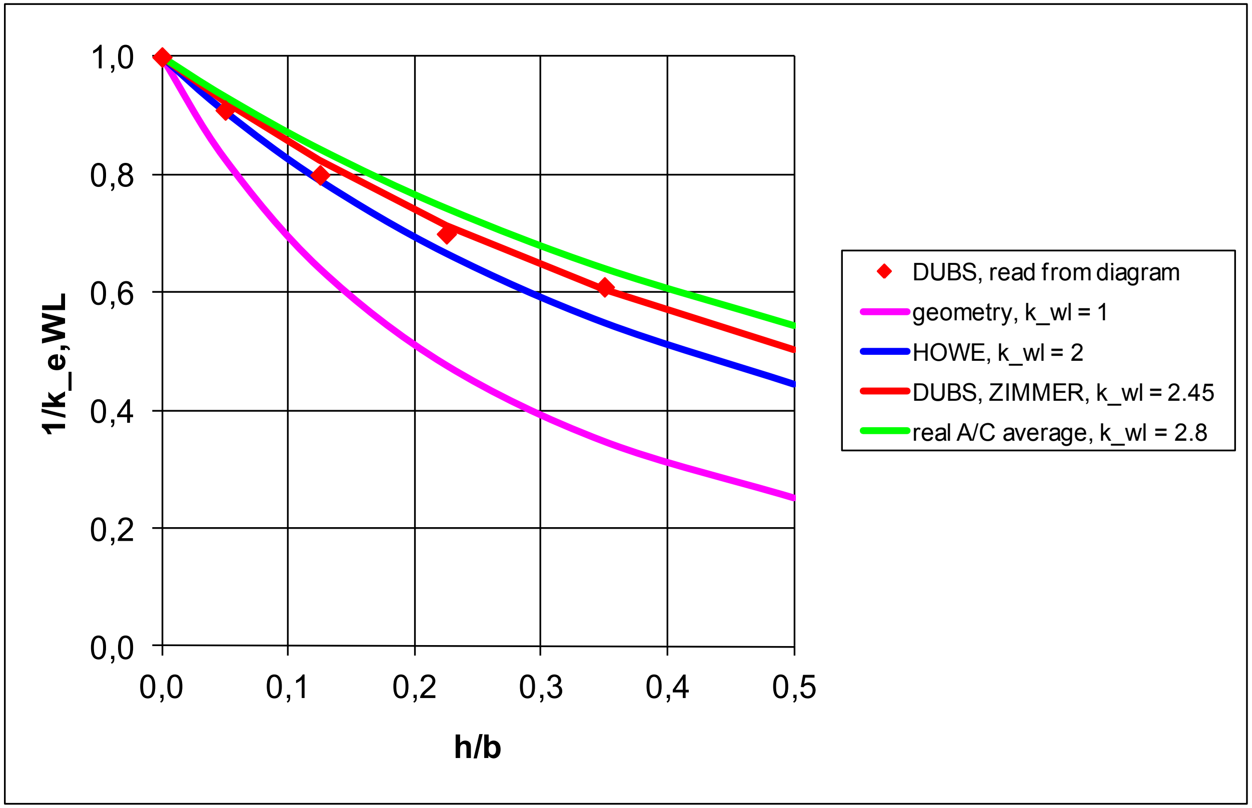
$k_{Di} = C_{Di} / C_D \approx 0.4$

$k_{D,WL} = \Delta C_{D,WL} / C_D$

k_D,WL is the relative reduction in drag due to winglets. It is given in percent. It enters the equation here as a negative value, because it is a reduction.

Example:
A321NEO: 4%. Enter -0.04 in Step 1.

First Results Calculated from Literature



Whitcomb's winglet:
k_{WL} = 2.7


A380
plus
A380
AIRBUS
A380plus
A380plus
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Airbus is presenting a **development study** for an enhanced A380, the "**A380plus**".
The study includes aerodynamic improvements in particular new, large **winglets**
and other wing refinements that allow for up to **4% fuel burn savings**.

The winglets are **4.7 m in height** (an uplet of 3.5 m, and a downlet of 1.2 m).
Today's range: 8200 nm. A380plus flies 300 nm further.

Calculated: Horizontal **span increase 1.2 m each side**.

The Intrinsic Aerodynamic Efficiency Calculated for the A380plus and other Aircraft

No.	aircraft	$\lvert\Delta D / D\rvert$	b_{old} [m]	b_{new} [m]	b_{ICAO} [m]	h [m]	h_h [m]
1	747-400 winglet	3.5%	59.63	64.40	65	3.73	2.39
2	737-800 blended winglet	3.8%	34.32	35.79	36	2.60	0.73
3	MD-11 extended winglet	3.5%	51.52	51.97	52	2.87	0.23
4	A320neo Sharklet	4.0%	35.80	35.80	36	2.43	0.00
5	A380plus split winglet	4.0%	79.75	82.15	80	4.70	1.20

1


2

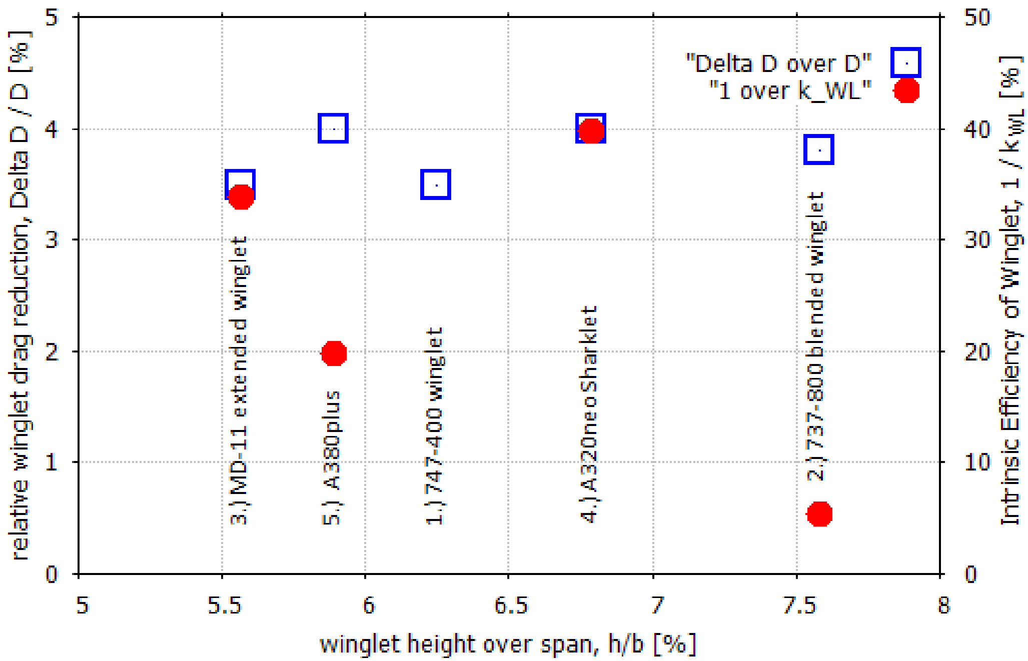

3


4


5


The Intrinsic Aerodynamic Efficiency Calculated for the A380plus and other Aircraft

No.	aircraft	h/b	h_h/b	$k_{e,WL,total}$	$k_{e,WL,v}$	k_{WL}	$1/k_{WL}$
1	747-400 winglet	6.25%	4.00%	1.096	0.940	---	---
2	737-800 blended winglet	7.58%	2.14%	1.105	1.016	18.94	5.3%
3	MD-11 extended winglet	5.57%	0.44%	1.096	1.077	2.95	33.9%
4	A320neo Sharklet	6.79%	0.00%	1.111	1.111	2.51	39.8%
5	A380plus split winglet	5.89%	1.50%	1.111	1.047	5.06	19.8%



Summary

- A method has been presented to calculate the "**intrinsic aerodynamic efficiency of winglets**" $1/k_{WL}$.
- The method lumps **all aerodynamic winglet characteristics** (from zero-lift drag and from induced drag) **into** this **single parameter**.
- A constant typical cruise lift coefficient is assumed because **changes in aircraft mass are not considered**.
- If e.g. the winglet needs to be 3 times larger compared to a horizontal span increase with the same overall aerodynamic effect ($k_{WL} = 3$), its intrinsic aerodynamic efficiency would be the inverse or 1/3.
- **Find more in the paper**:
  - Methods to calculate **wing mass increase due to bending and winglet mass**.
  - Method to **calculate fuel mass increase due to winglets**.

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