Corso di MECCANICA DEL VOLO
Modulo Prestazioni

CAP 4 – La polare di resistenza del velivolo

Prof. F. Nicolosi

LA POLARE DEL VELIVOLO

Res. indotta (vortex drag)

Res. di scia (form drag)

Res. di attrito (friction drag)

Res. d'onda (wave drag)

Res. parassita (profile or parassite drag)

Varie forme di resistenza

LA POLARE DEL VELIVOLO

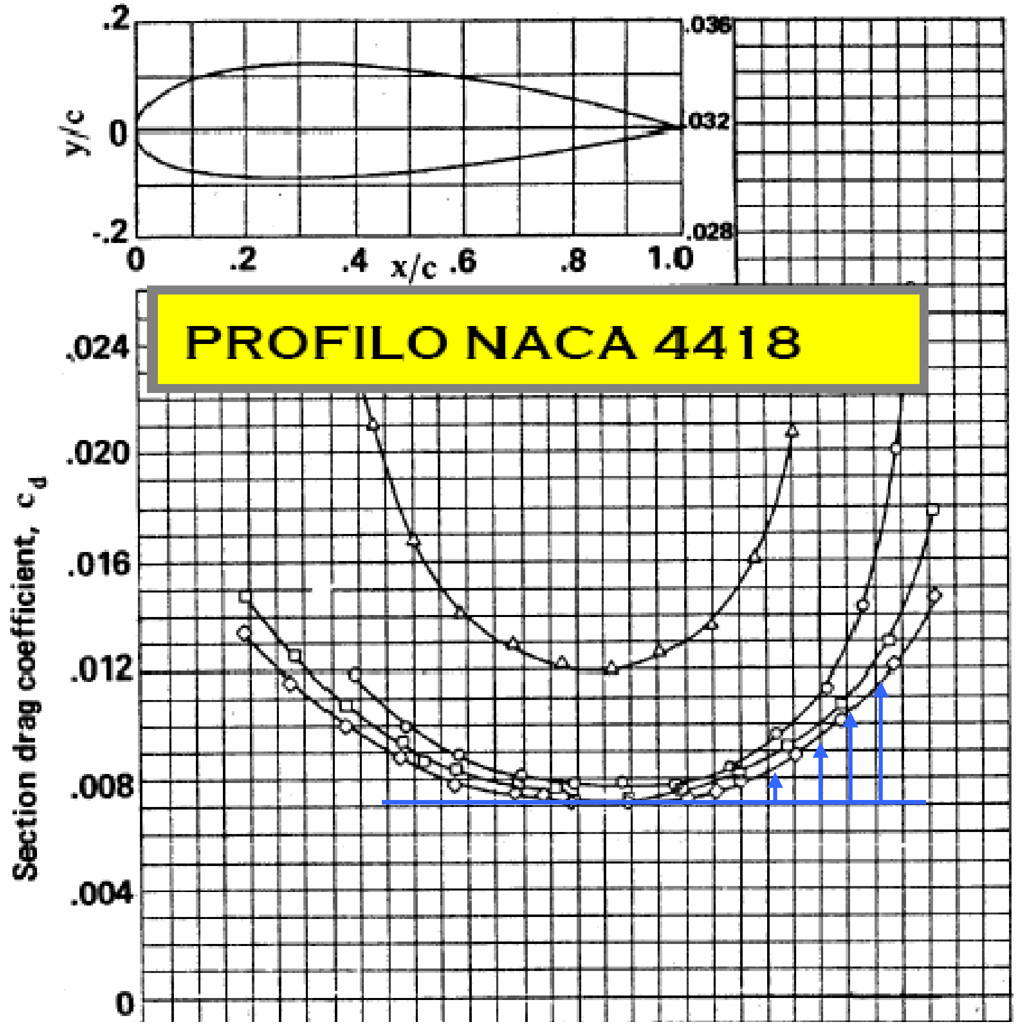
ALA

$$CD_w = CDp_w + CDi_w$$

CDp_w res. parassita dell’ala.

Sviluppando il termine di resistenza parassita :

(La res. Parassita dell’ala
È ricavabile da quella
del profilo



$$CD_w = CDo_w + Kv_w\, CL^2 + \frac{CL^2}{\pi AR}(1+\delta)$$

Il valore di Kv_w dipende dal tipo di profilo (spessore %, curvatura, tipo di profilo) ma si aggira tra un valore di 0.004 e 0.007.

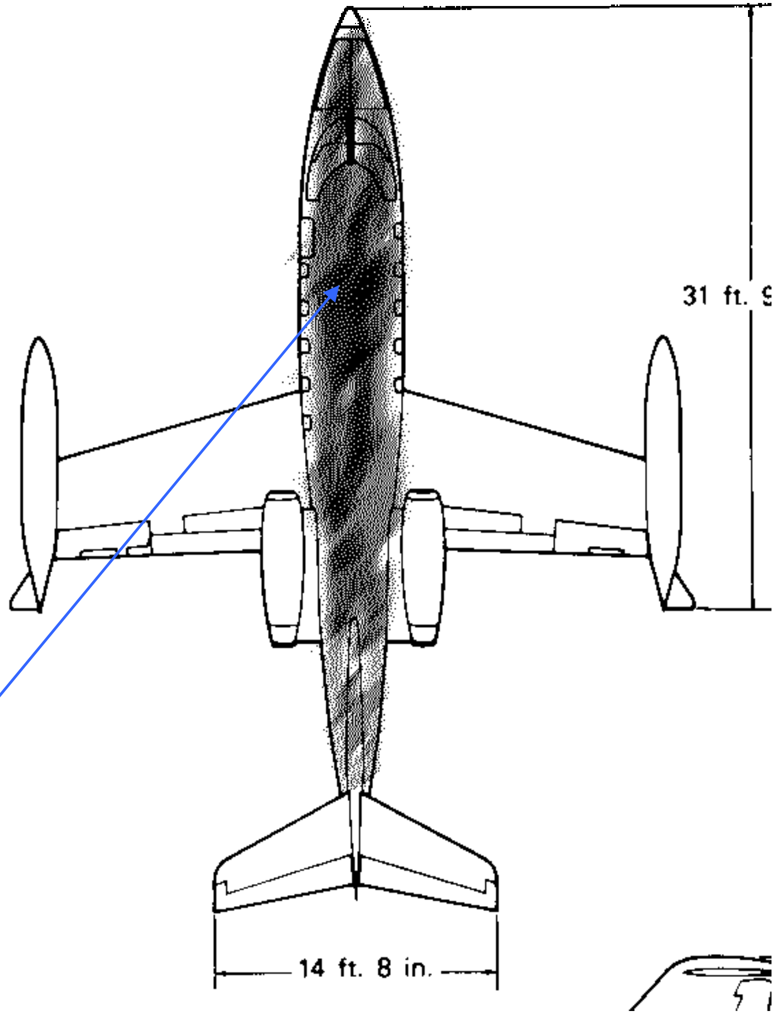
LA POLARE DEL VELIVOLO

<u>FUSOLIERA</u>

$CD_f = CDo_f + Kv_f\, CL^2$

Con Kv_f ricavabile dalla formula:

$$Kv_f = 0.004 \frac{S_{plf}}{S}$$



S_{plf}

Dove S_{plf} è la superficie in pianta della fusoliera

LA POLARE DEL VELIVOLO

GONDOLE MOTORI e PIANI

$CD_N = CDo_N + Kv_N * CL^2$

$CD_V = CDo_V$ assumiamo trascurabile la variazione di resistenza parassita

$CD_H = CDo_H$ **assumiamo trascurabile la variazione di resistenza parassita**

$CDagg = CDoagg$

Velivolo Completo:

$$CD = CDo_{TOT} + \frac{CL^2}{\pi AR}\left[1 + \delta + (Kv_w + Kv_f + Kv_N)\pi AR\right]$$

$$CD = CDo + \frac{CL^2}{\pi \cdot AR \cdot e}$$

LA POLARE DEL VELIVOLO

$$CD = CDo + \frac{CL^2}{\pi \cdot AR \cdot e}$$

Polare parabolica

$$e = \frac{1}{\left[1 + \delta + (Kv_w + Kv_f + Kv_N) \cdot \pi \cdot AR\right]}$$

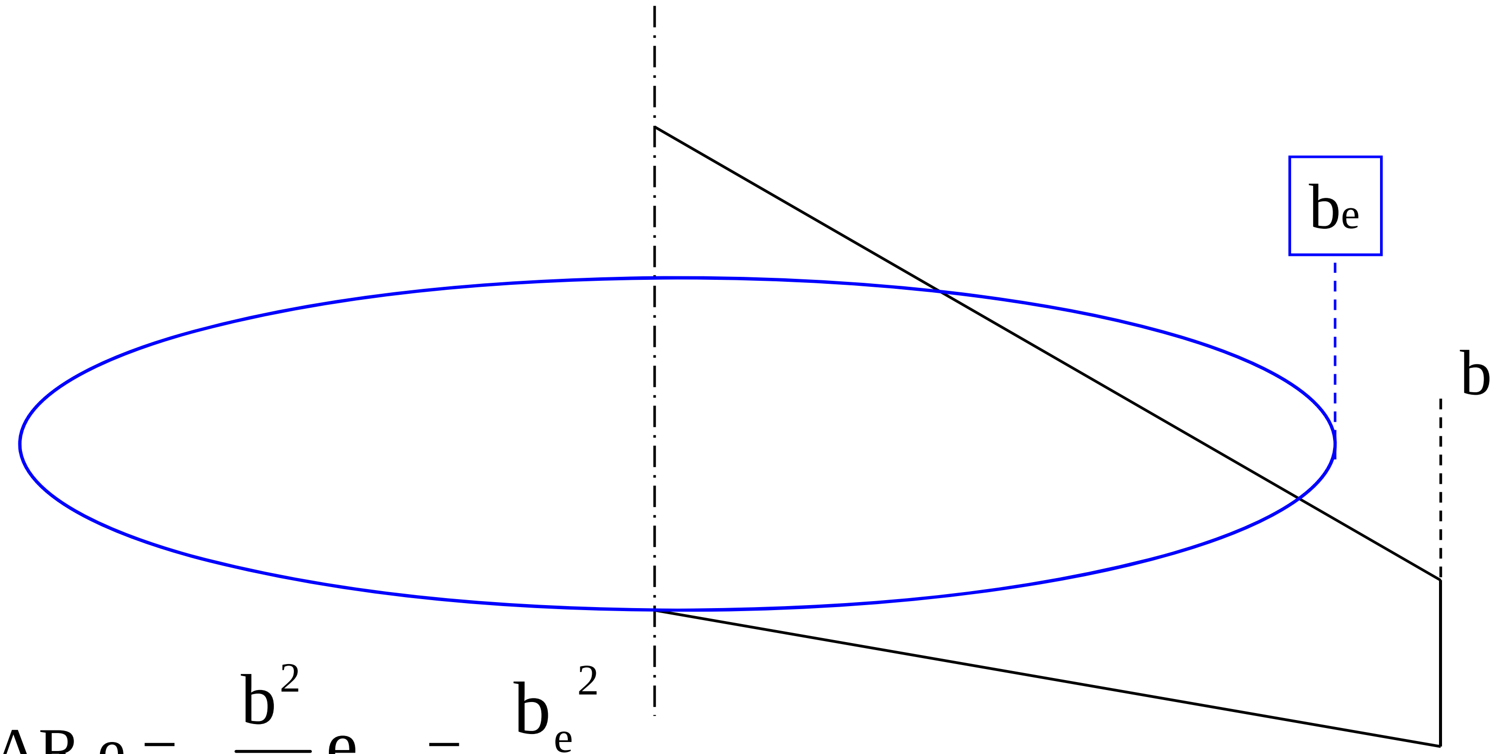
Fattore di Oswald, tipico 0.70-0.85 per velivoli da trasporto.

$$AR_e = AR\ e = \frac{b^2}{S} e = \frac{{b_e}^2}{S}$$

Avendo definito con $b_e = b\sqrt{e}$ l'apertura alare efficace.

LA POLARE DEL VELIVOLO

E’ come se l’ala ai fini della resistenza dovuta alla portanza (lift-dependent drag) avesse un’apertura minore. Tale resistenza è infatti uguale alla sola resistenza indotta (vortex drag) di un’ala ellittica di minore AR.

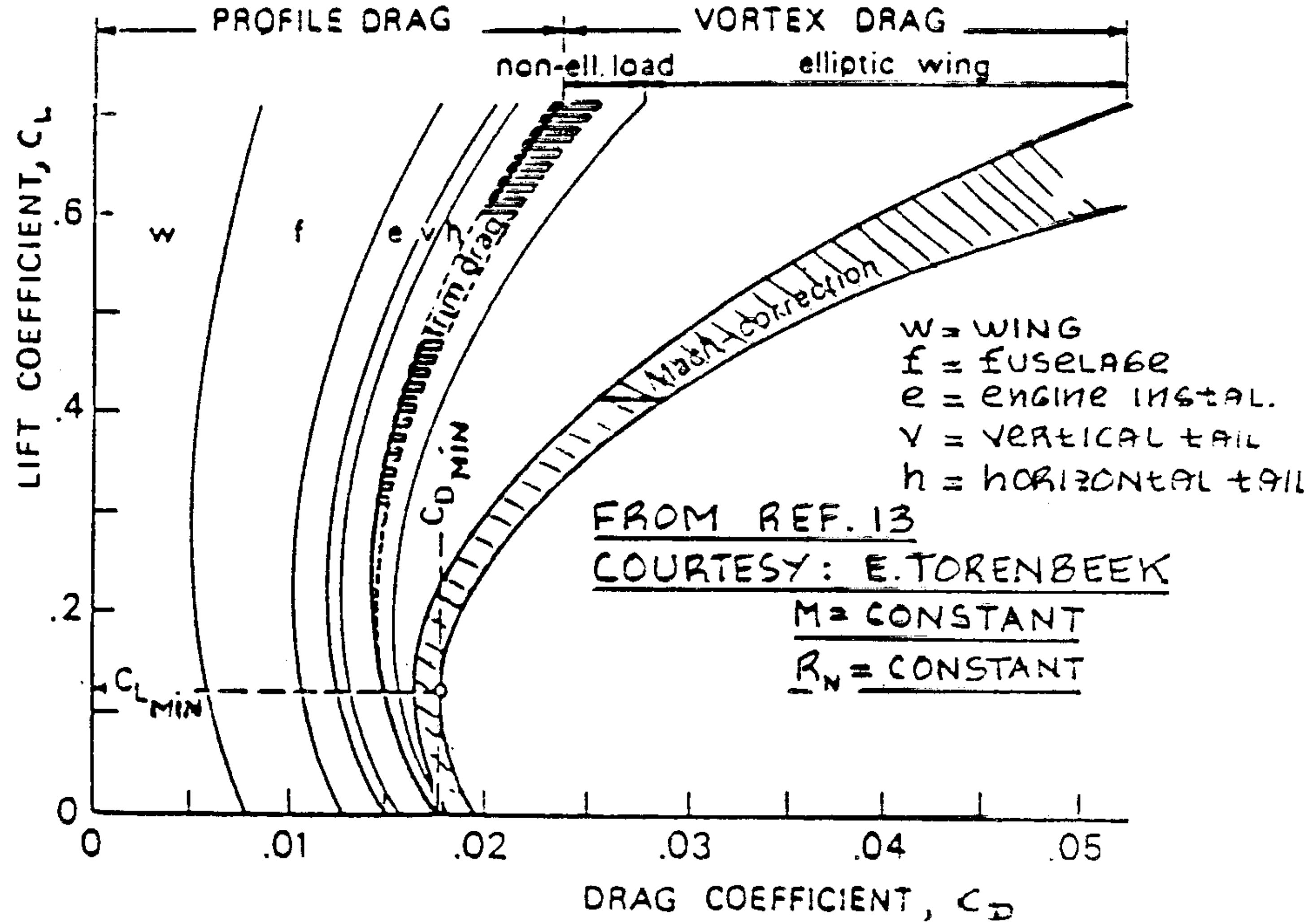


$$AR_e = AR\, e = \frac{b^2}{S} e = \frac{b_e^{\,2}}{S}$$

Avendo definito con $b_e = b\sqrt{e}$ <u>l’apertura alare efficace.</u>

LA POLARE DEL VELIVOLO

Breakdown della resistenza



Resistenza parassita - breakdown

Table 4.5 Parasite Drag Breakdown for Gates Learjet Model 25 (from Ref. 4.10)

Item	C_d (based on Wing Planform Area)	Percent of Total
Wing	0.0053	23.45
Fuselage	0.0063	27.88
Tip tanks	0.0021	9.29
Tip tank fins	0.0001	0.44
Nacelles	0.0012	5.31
Pylons	0.0003	1.33
Horizontal tail	0.0016	7.08
Vertical tail	0.0011	4.86
Interference	0.0031	13.72
Roughness and gap	0.0015	6.64
Total	0.0226	100.00

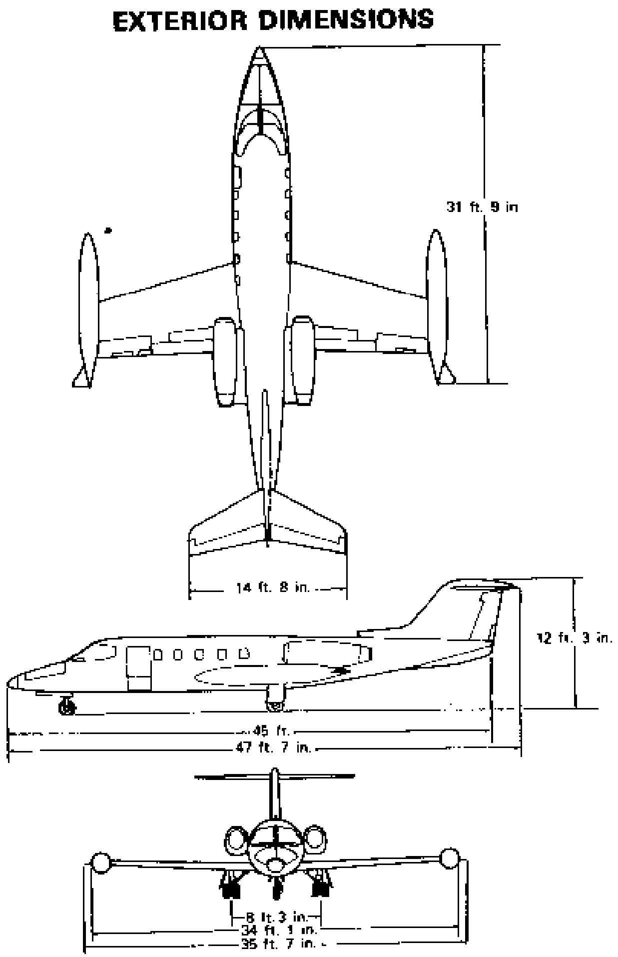


Figure 4.27 Gates Learjet Model 25. (Courtesy Gates Learjet Corp.)

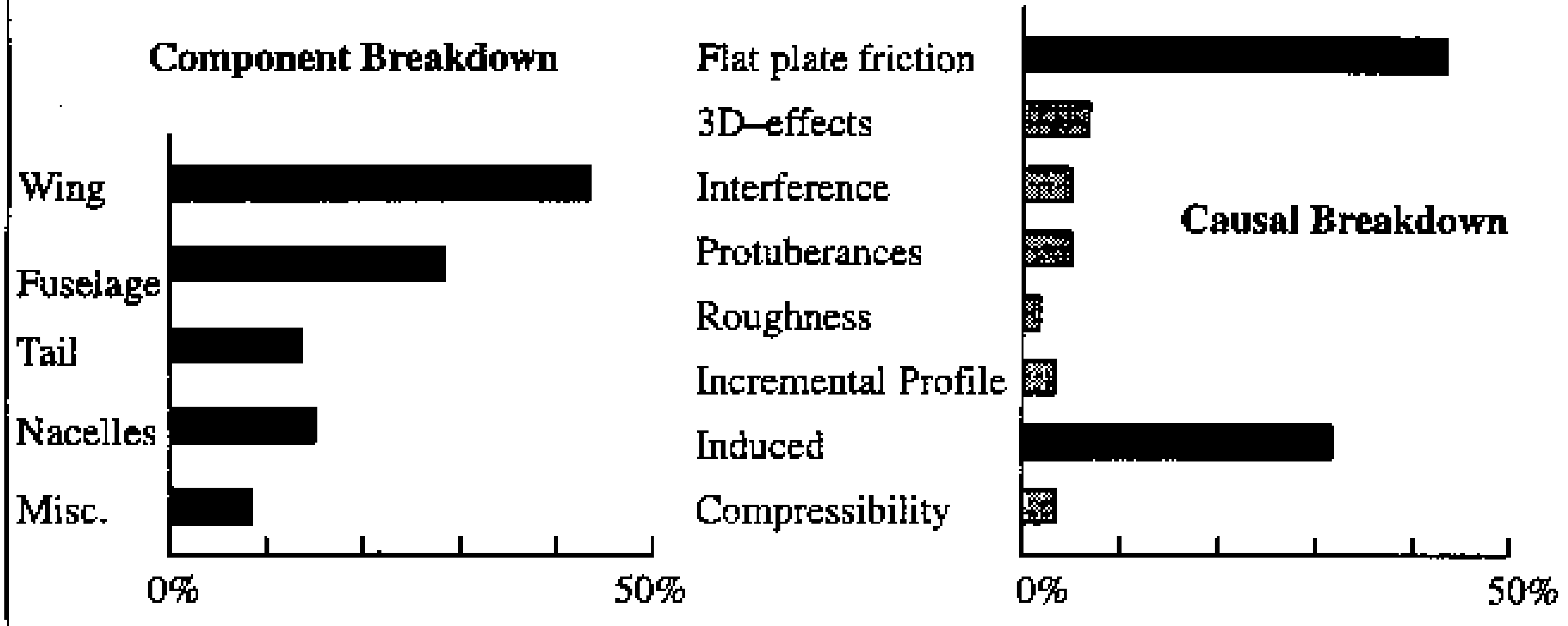


Figure 5.32 Typical Drag Build–up for Jet Transports in Cruise

Breakdown causale

Table 5.2 Cruise Drag Breakdown for the Learjet Model 25 (Ref. 5.8)		
$M = 0.75$	$C_L = 0.336$	$C_D = 0.0338$
Source	ΔC_D	% of Total
Causal Drag Breakdown:		
Profile drag (skin friction)	0.0180	53.25
Profile drag variation with lift	0.0007	2.07
Interference drag	0.0031	9.17
Roughness and gap drag	0.0015	4.44
Induced drag	0.0072	21.30
Compressibility drag	0.0028	8.28
Trim drag	0.0005	1.48
Total drag	0.0338	100.00
Profile Drag Breakdown:	$\Delta C_{D_{\text{profile friction}}} = 0.0180$	

Resistenza parassita - Breakdown sui componenti

Source	$\Delta\ C_{D_{profile\ friction}}$	% of Total
Wing	0.0053	29.57
Fuselage	0.0063	34.95
Tip tanks	0.0021	11.83
Tip tank fins	0.0001	0 .54
Necelles	0.0012	6.45
Pylons	0.0003	1.61
Horizontal tail	0.0016	9.14
Vertical tail	0.0011	5.91
Total profile drag (friction)	0.0180	100.00

Courtesy: Bombardier Learjet

ESEMPI DI POLARI

Figure 5.1 Drag Polars: Cessna 177

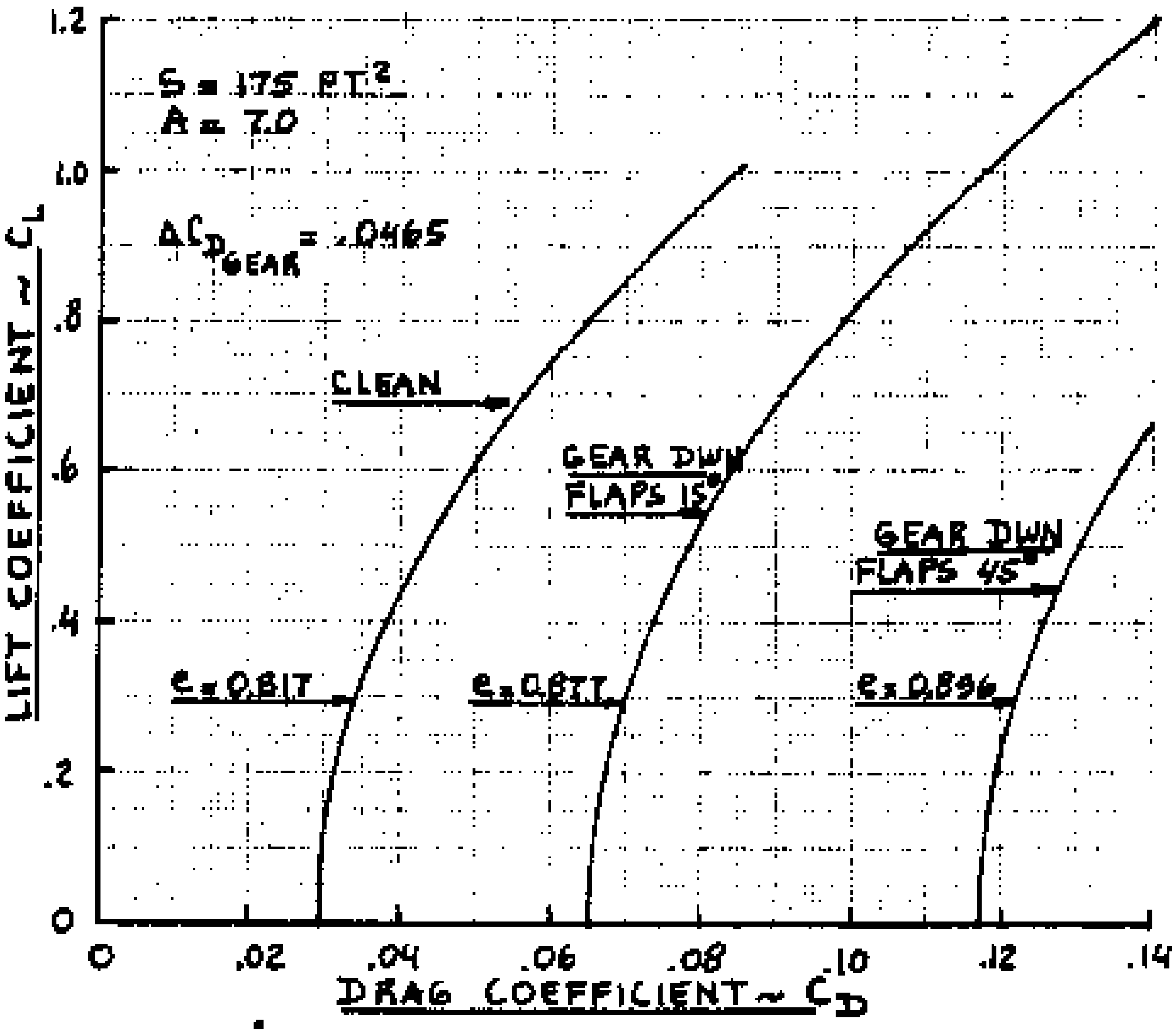


Figure 5.2 Drag Polars: Cessna 310

ESEMPI DI POLARI

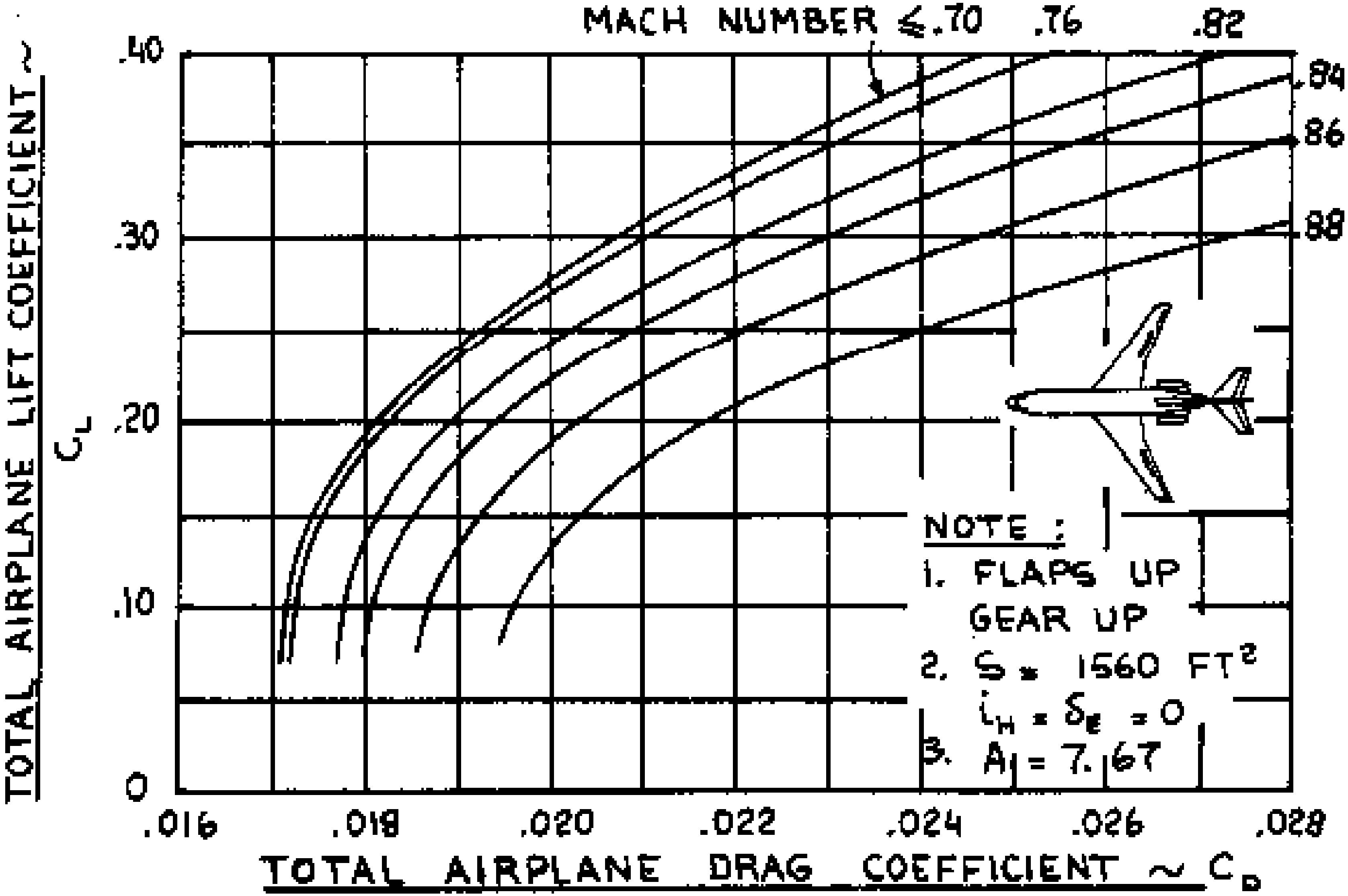
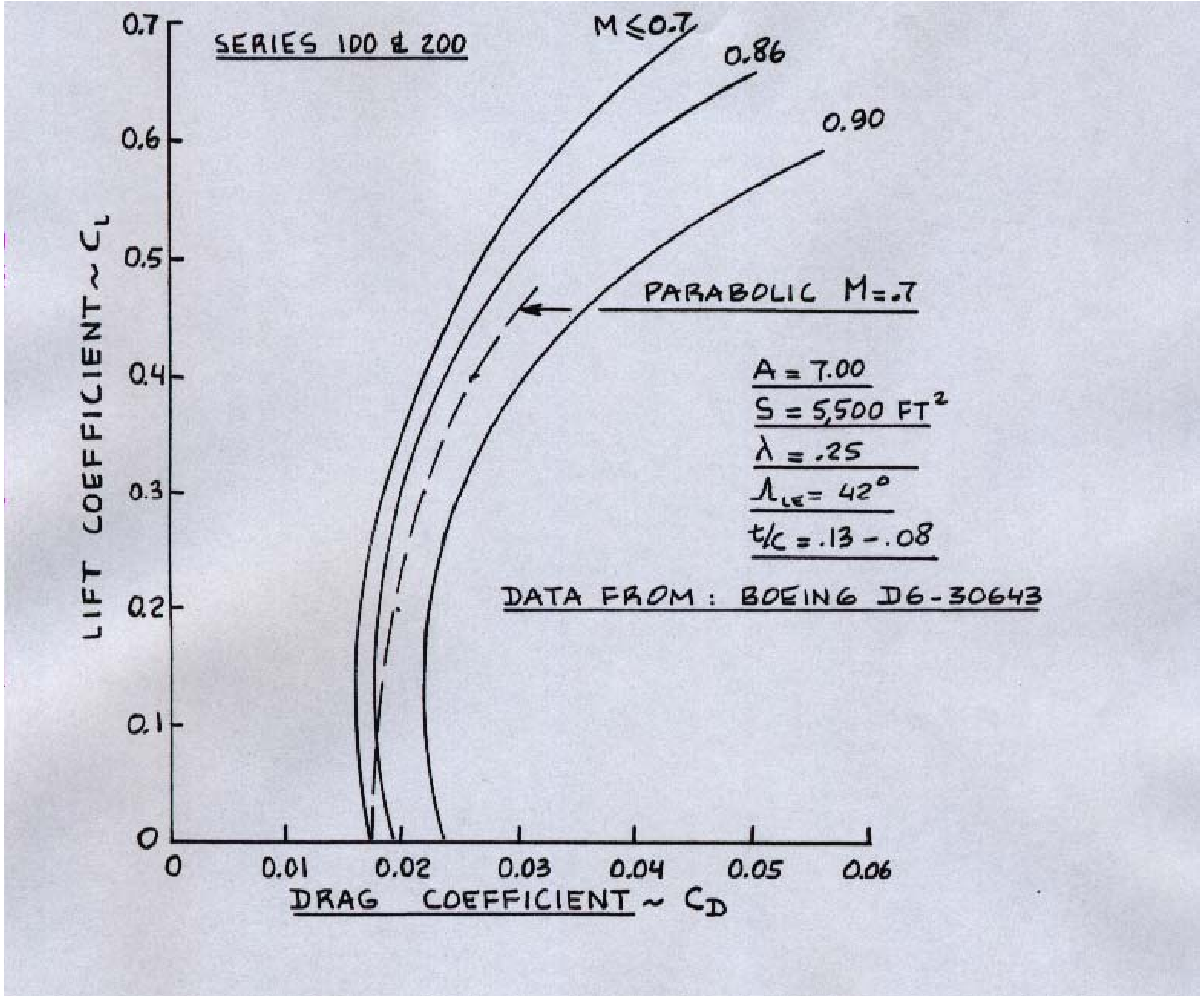


Figure 3.12 Drag Polars: Boeing 727-100

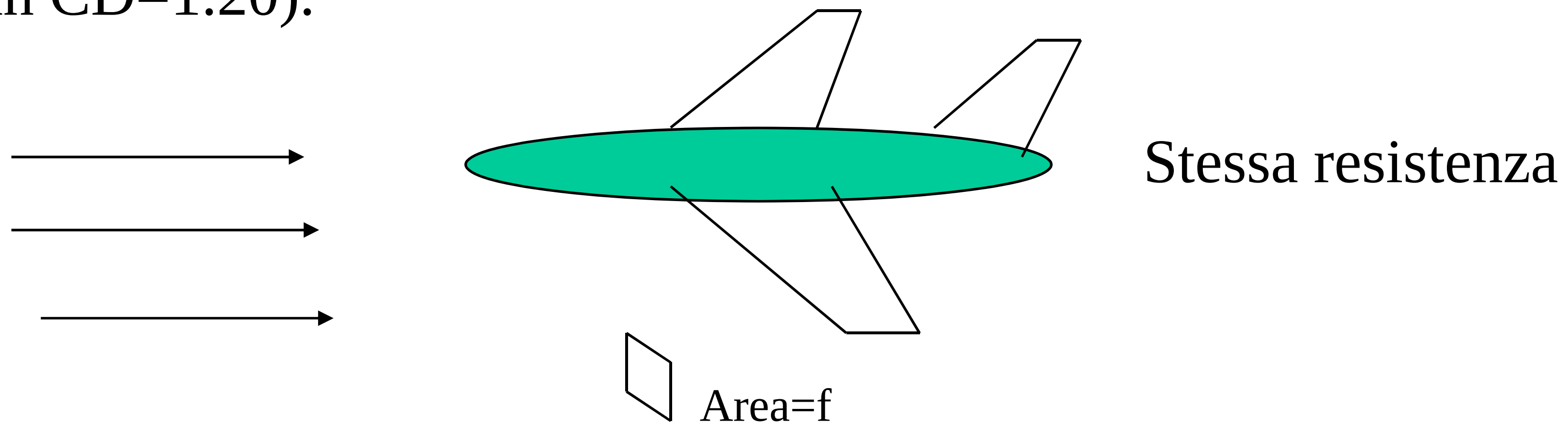
ESEMPI DI POLARI



Area Parassita Equivalente

$f = C_{D_0}\, S \quad [mq]$

Fisicamente rappresenta la effettiva resistenza del velivolo, infatti moltiplicata per la pressione dinamica fornisce la resistenza in [N] del velivolo.
E' approssimativamente pari alla dimensione di una lastra piana posta a 90° rispetto alla corrente che ha resistenza pari a quella del velivolo (infatti il CD teorico della lastra è =1, infatti si puo' vedere dalle precedenti slides che in effetti una lastra quadrata 3D ha un CD=1.20).



Area parassita equivalente f

Esempi:

Velivolo tipo Cessna : S=20 mq CDo=0.027 f=0.54 mq (lato 0.73 m)

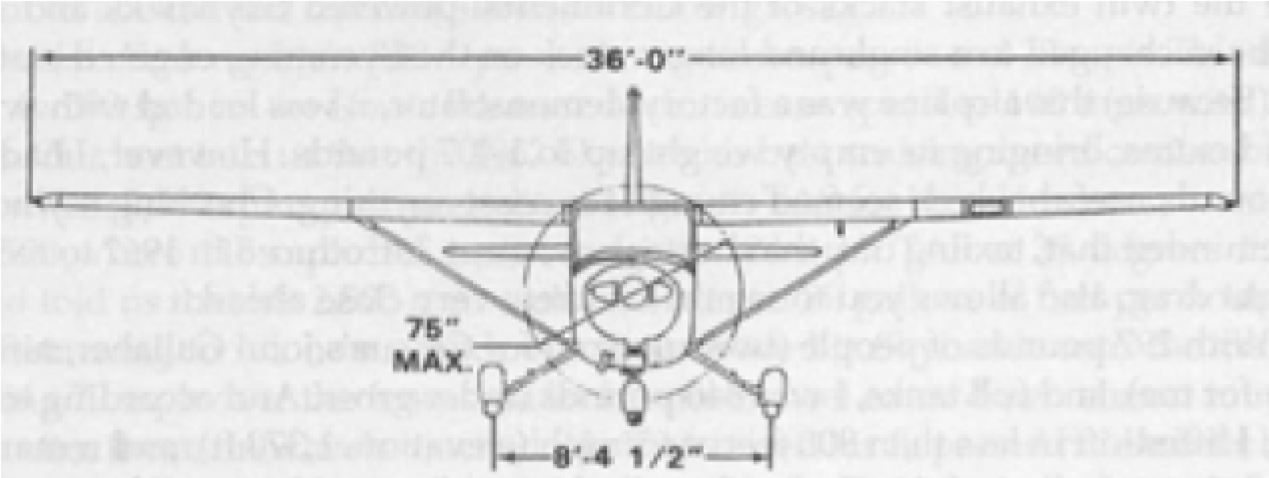
Velivolo tipo ATR : S=60 mq CDo=0.025 f=1.50 mq (lato 1.22 m)

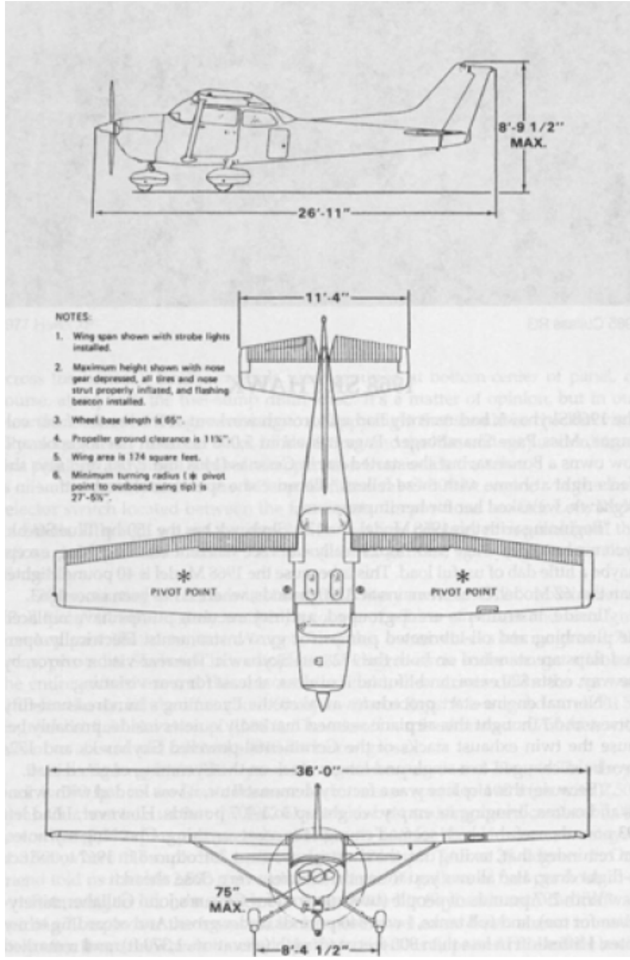
Velivolo tipo B737 : S=100 mq CDo=0.022 f=2.20 mq (lato 1.48 m)

Velivolo tipo B747 : S=500 mq CDo=0.018 f=9.00 mq (lato 3.00 m)

Area parassita equivalente f

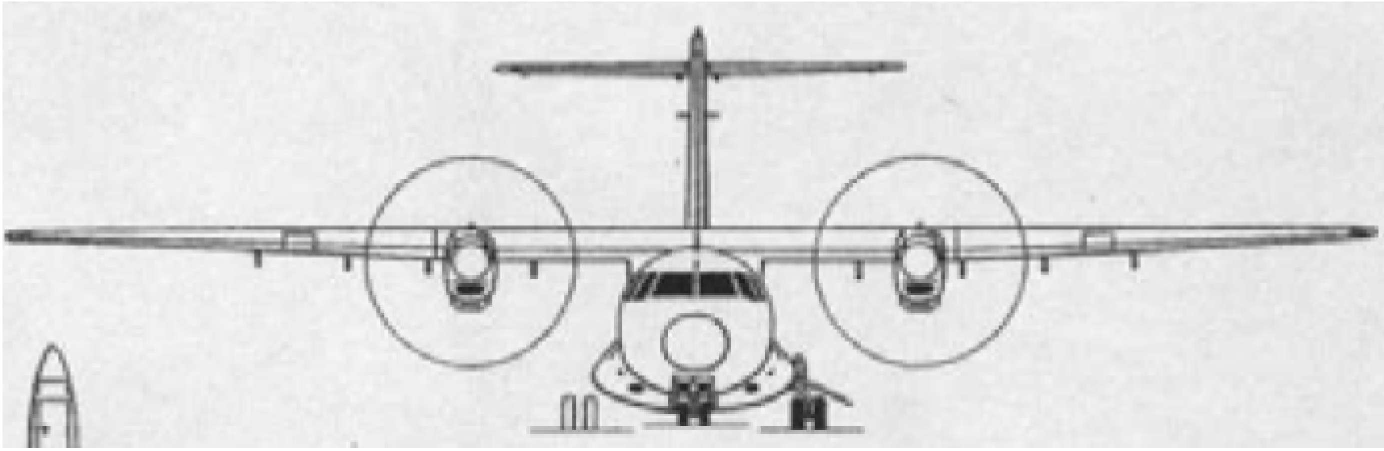
Cessna SkyHawk

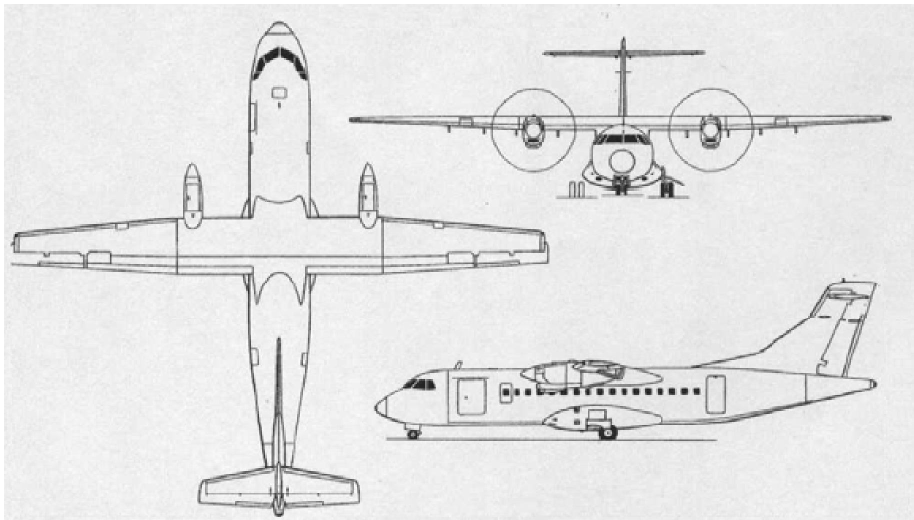




Area parassita equivalente f

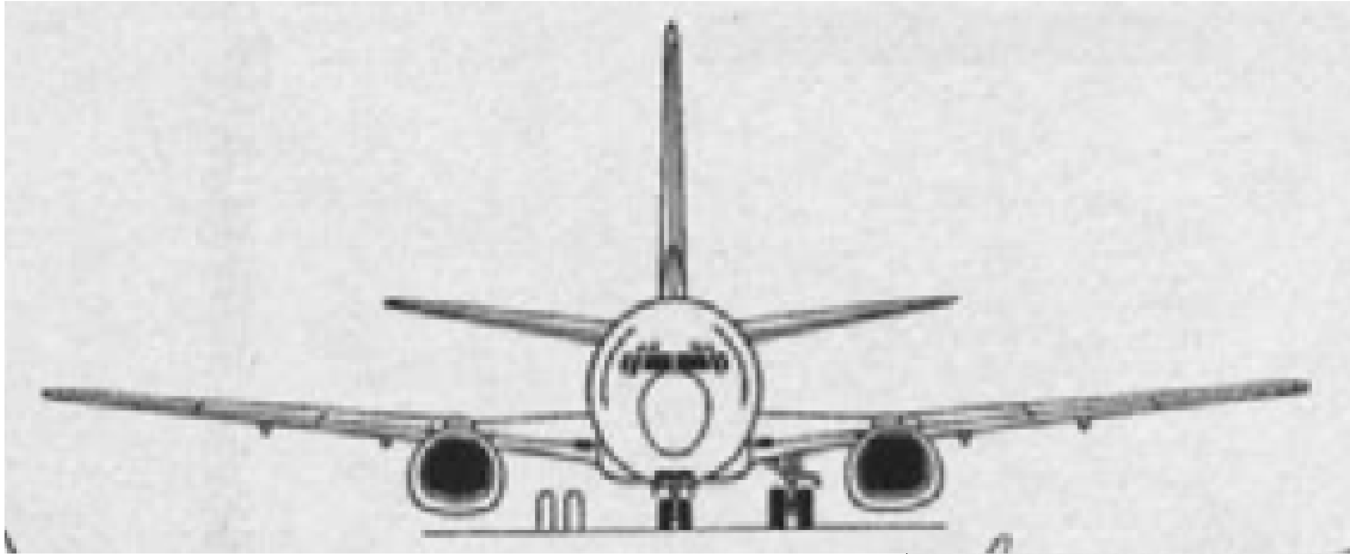
ATR 42

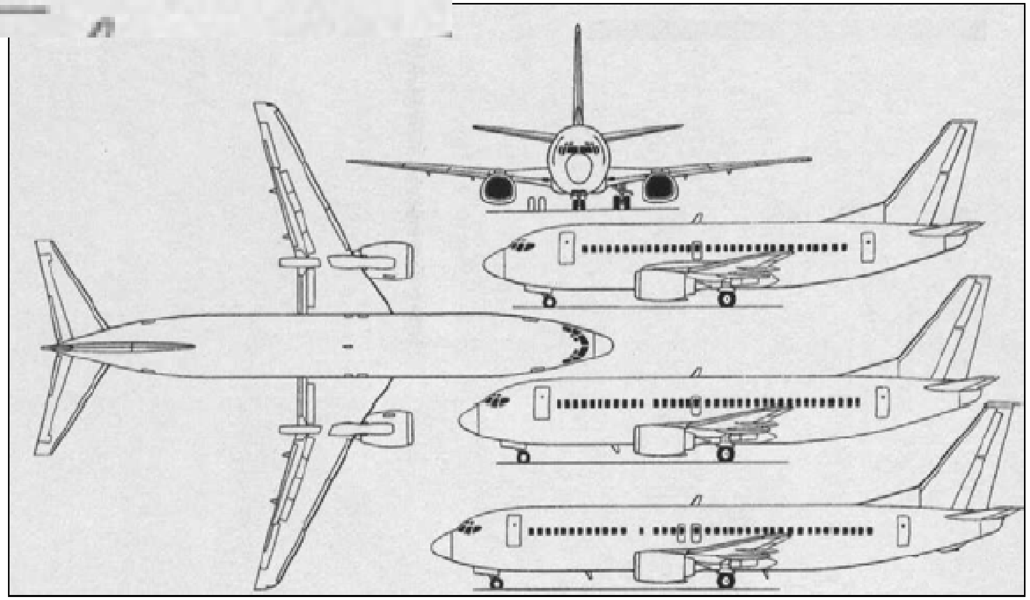




Area parassita equivalente f

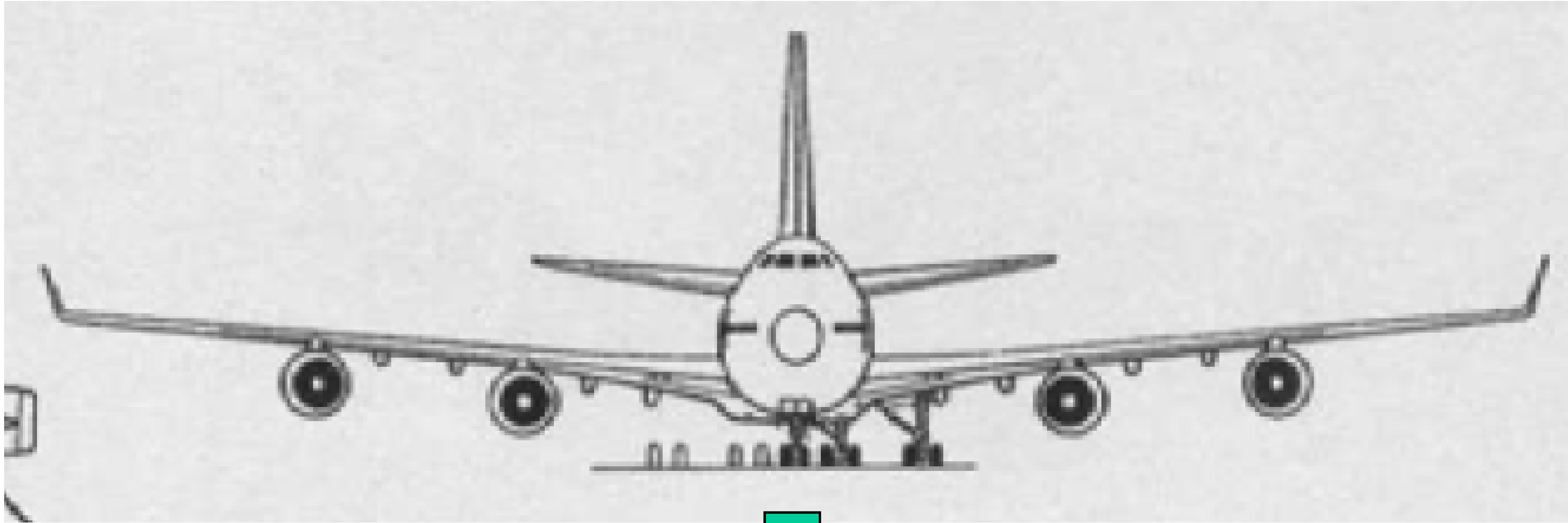
Boeing 737 - 400

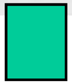


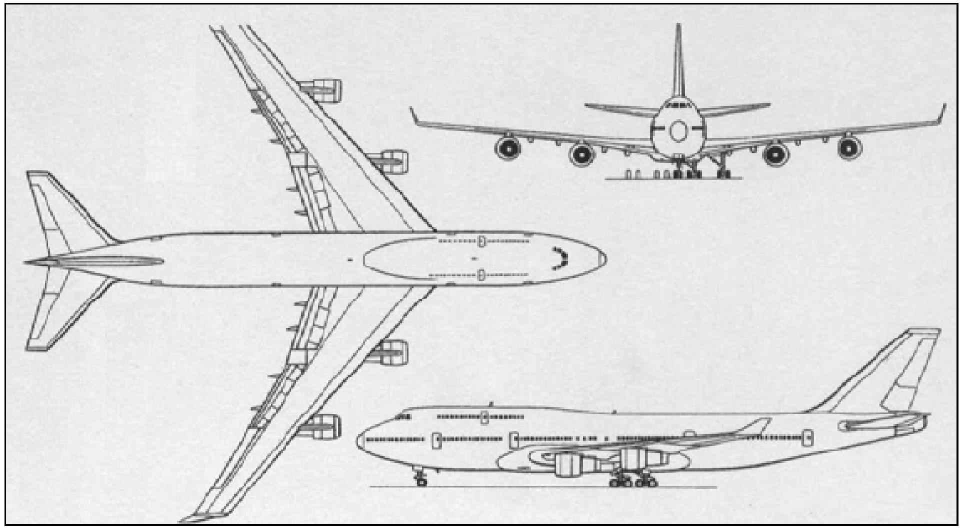


Area parassita equivalente f

Boeing 747 - 400







Area parassita equivalente f

Si può stimare f (e quindi successivamente C_{Do} , nota la S):

$f = S_{wet} * C_{fe}$ e poi => $C_{Do} = f / S$

L'area parassita equivalente è il prodotto dell'area bagnata per il coefficiente di attrito equivalente o anche del C_{Do} per la superficie di riferimento.
Il **coefficiente di attrito equivalente** tiene conto delle sorgenti di resistenza diverse da quelle di attrito e dal fatto che per la distribuzione di pressione presente sul corpo (ala, fusoliera, etc) in ogni punto è presente un valore particolare del C_f.

STIMA statistica del CDo di un velivolo

Stima (o calcolo approssimato) dell'area bagnata del velivolo

Swet/S

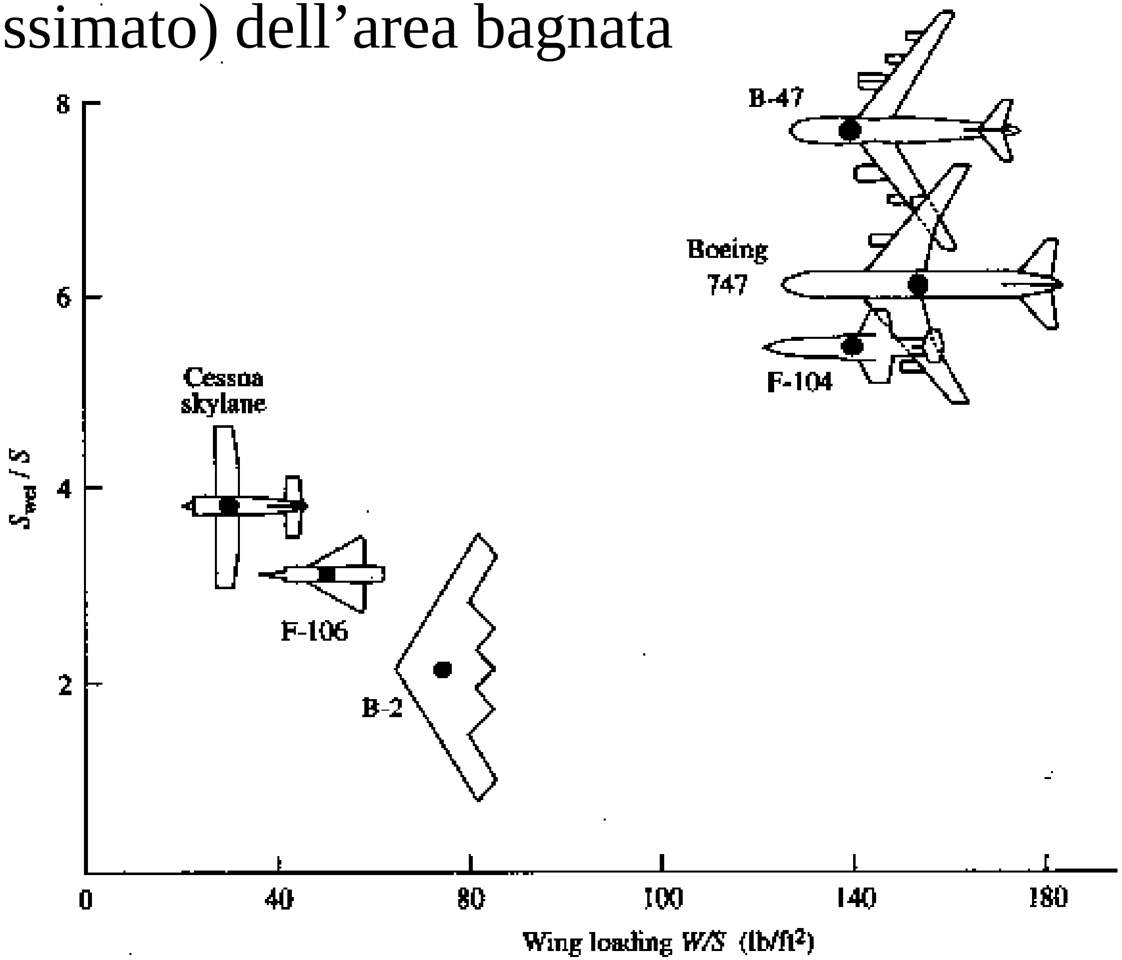


Figure 2.54 Ratio of wetted surface area to reference area for a number of different airplane configurations.

STIMA statistica del CDo di un velivolo

Stima (o calcolo approssimato) dell’area bagnata del velivolo

Swet/S

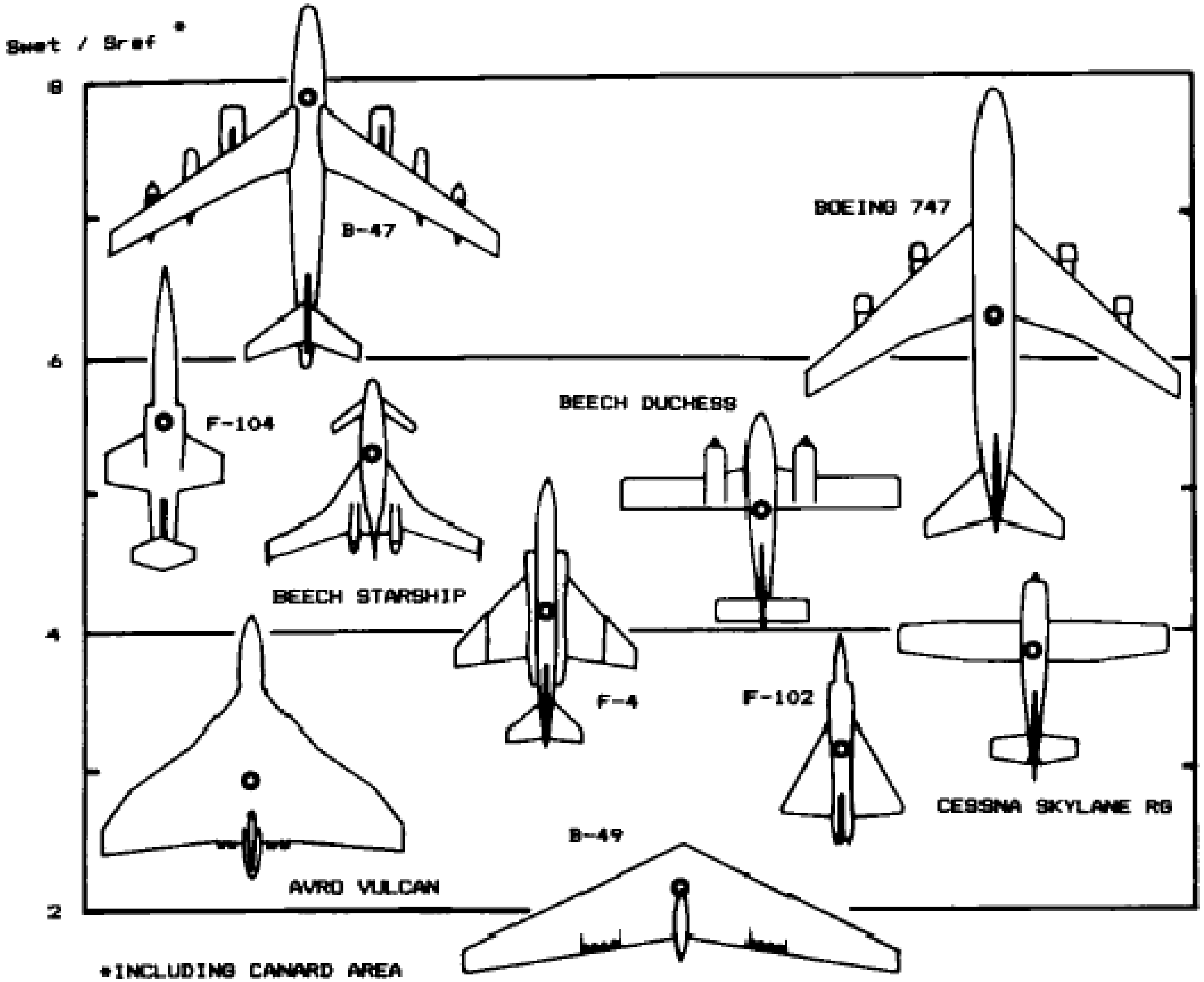


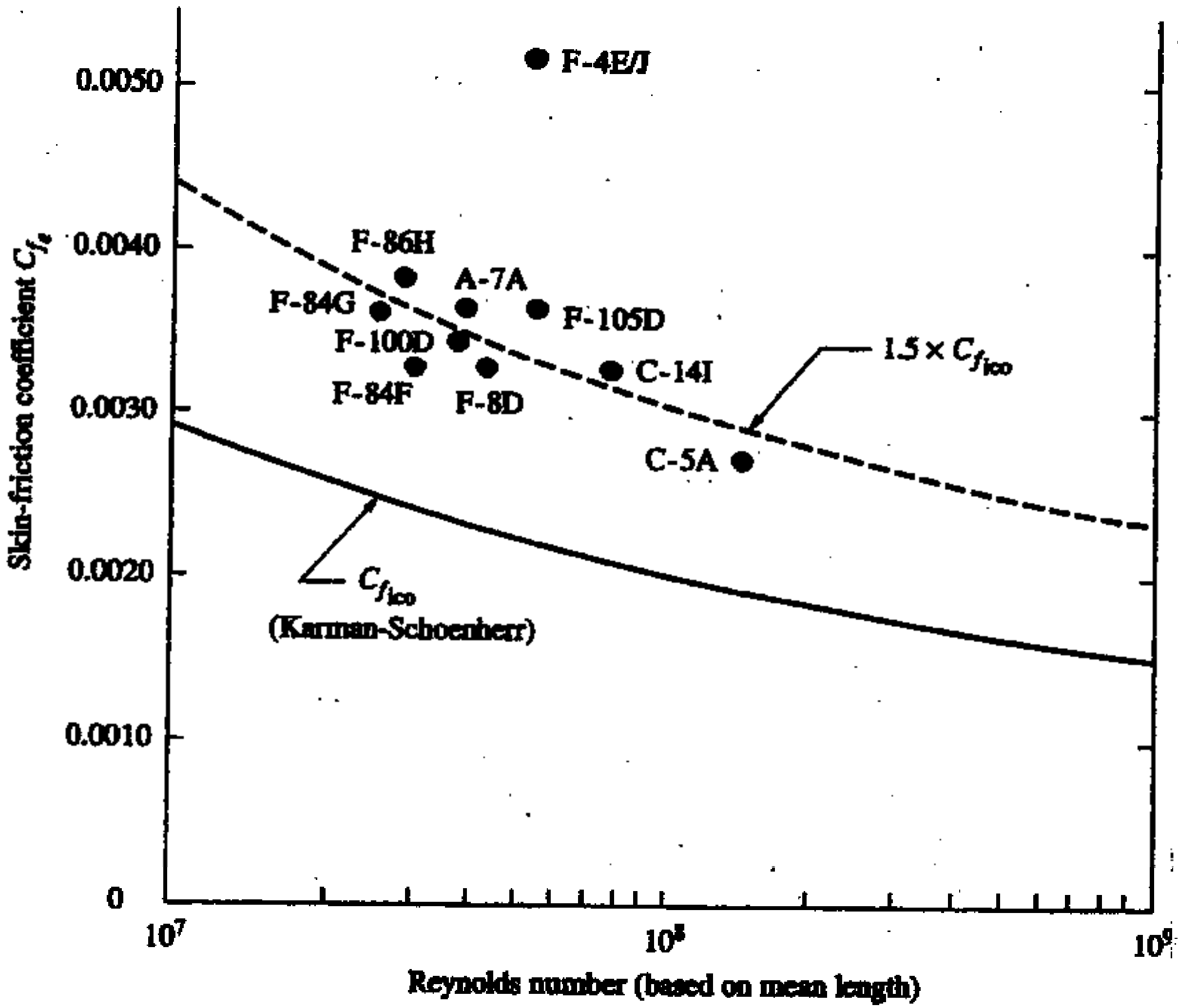
Fig. 3.5 Wetted area ratios.

STIMA statistica del CDo di un velivolo

STIMA del Cfe

Al variare del Reynolds
Varia il Cf di lastra piana.

Il Cf equivalente può essere valutato moltiplicando per 1.5 quello di lastra piana calcolato con il Reynolds basato sulla corda media e condizioni di crociera



STIMA statistica del CDo di un velivolo

STIMA del Cfe – Andamento storico del Cf equivalente

Cfe:
Attualmente varia
Tra 3 e 5 millesimi
Al variare della
categoria del velivolo

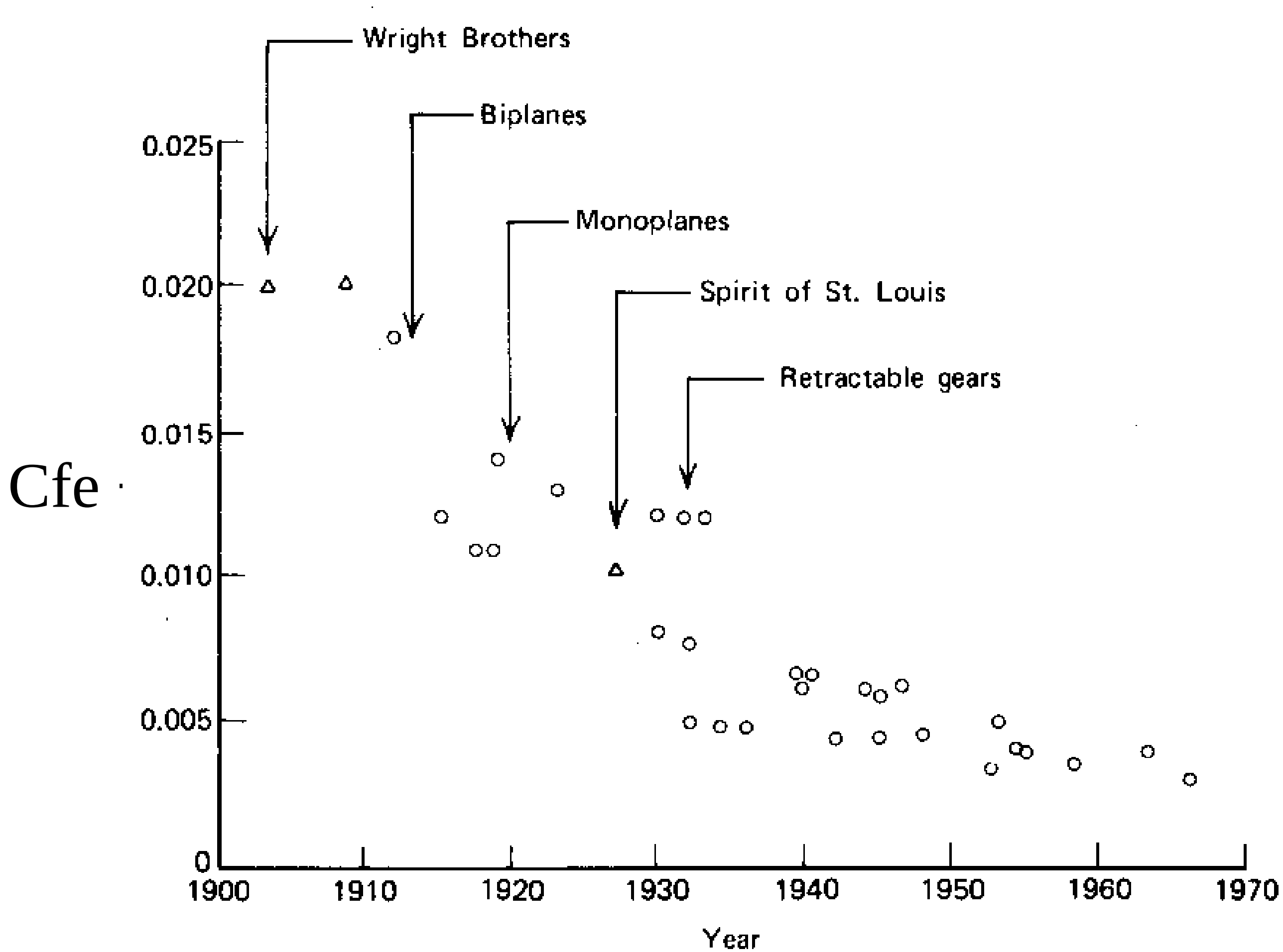


Figure 4.26 Historical survey of drag.

STIMA statistica del CDo di un velivolo

STIMA del Cfe – Base statistica

Table 4.2 Typical Overall Skin Friction Coefficients for a Number of Airplanes Built from Approximately 1940 to 1976. Data Taken from Several Sources

C_F	Airplane Designation	Description
0.0100	Cessna 150	Single prop, high wing, fixed gear
0.0095	PA-28	Single prop, low wing, fixed gear
0.0070	B-17	Four props, World War II bomber
0.0067	PA-28R	Single prop, low wing, retractable gear
0.0066	C-47	Twin props, low wing, retractable gear
0.0060	P-40	Single prop, World War II fighter
0.0060	F-4C	Jet fighter, engines internal
0.0059	B-29	Four props, World War II bomber
0.0054	P-38	Twin props, twin-tail booms, World War II fighter
0.0050	Cessna 310	Twin props, low wing, retractable gear
0.0049	Beech V35	Single prop, low wing, retractable gear
0.0046	C-46	Twin props, low wing, retractable gear
0.0046	C-54	Four props, low wing, retractable gear
0.0042	Learjet 25	Twin jets, pod-mounted on fuselage, tip tanks
0.0044	CV 880	Four jets, pod-mounted under wing
0.0041	NT-33A	Training version of P-80 (see below)
0.0038	P-51F	Single prop, World War II fighter
0.0038	C-5A	Four jets, pod-mounted under wing, jumbo jet
0.0037	Jetstar	Four jets, pod-mounted on fuselage
0.0036	747	Four jets, pod-mounted under wing, jumbo jet
0.0033	P-80	Jet fighter, engines internal, tip tanks, low-wing
0.0032	F-104	Jet fighter, engines internal, midwing
0.0031	A-7A	Jet fighter, engines internal, high wing

STIMA statistica del CDo di un velivolo

Table 4.3 Typical Total Skin Friction Coefficient Values for Different Airplane Configurations

Airplane Configuration	C_F Range at Low Mach Numbers
Propeller driven, fixed gear	0.008–0.010
Propeller driven, retractable gear	0.0045–0.007
Jet propelled, engines pod-mounted	0.0035–0.0045
Jet propelled, engines internal	0.0030–0.0035

Stima del fattore di Oswald “e”

Table 5.1 Oswald's Efficiency Factor 'e' for Several Airplanes

Single Engine Propeller

	'e'
PT-18	0.75
AT-7	0.74
AT-8	0.61
Cessna L-5	1.02
O-46A	0.80
OE-2	0.70
Cessna 180	0.75
Beech 35	0.82
Cessna 150	0.77
Cessna 172	0.77
Cessna 182	0.84
Cessna 185	0.86
Cessna 177	0.57

Prop. Fighters

	'e'
P-38J	0.76
P-40F	0.70
P-47D	1.02
P-49	0.80
P-51B	0.86
P-51F	0.80
XP-60C	0.66
P-61A	0.86

Twin Engine Prop.

	'e'
A-26B	0.79
C-46A	0.88
C-47B	0.89
B-25D	0.78
B-26F	0.76
Cessna 310	0.73
Gulfstream GI	0.78
SAAB SF 340	0.80

Jet Fighter/Trainers

	'e'
P-63A	0.86
T-37	0.78
NAA T2C	0.816

Jet Bombers

	'e'
Boeing B-47B	0.84
Boeing B-52A	0.924

Jet Transports

	'e'
Learjet M 25	0.721
Gulfstr.GII	0.950
F-28-2000	0.818
B 707-320B	0.983
L C-141B	1.067
L C-5A	1.091

Four Engine Prop.

	'e'
C-54A	0.81
C-60A	0.63
C-64	0.97
C-69	0.82
XB-19	0.76
B-24D	0.78
B-24G	0.84
B-29A,B	0.94

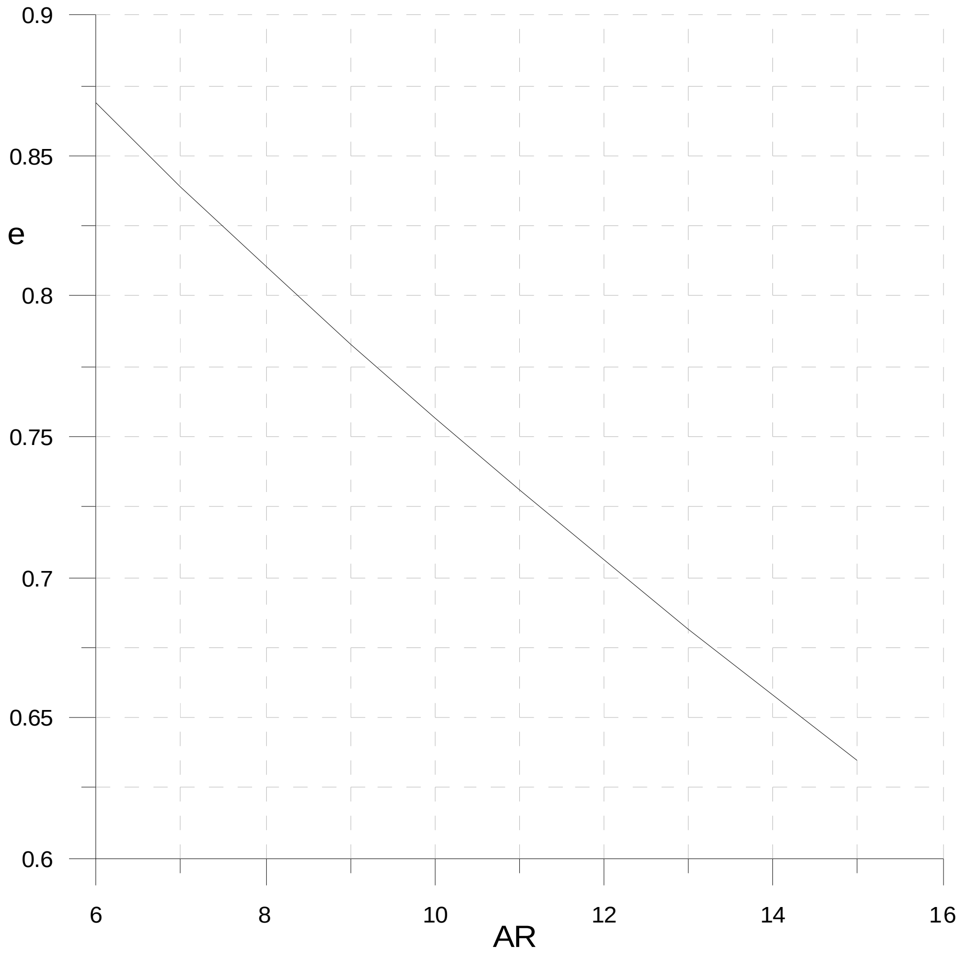
Stima del fattore di Oswald "e"

Straight-Wing Aircraft: $e = 1.78(1 - 0.045 A^{0.68}) - 0.64$

Swept-Wing Aircraft: $e = 4.61(1 - 0.045 A^{0.68})(\cos\Lambda_{LE})^{0.15} - 3.1$

(Raymer)

$(\Lambda_{LE} > 30 \text{ deg})$



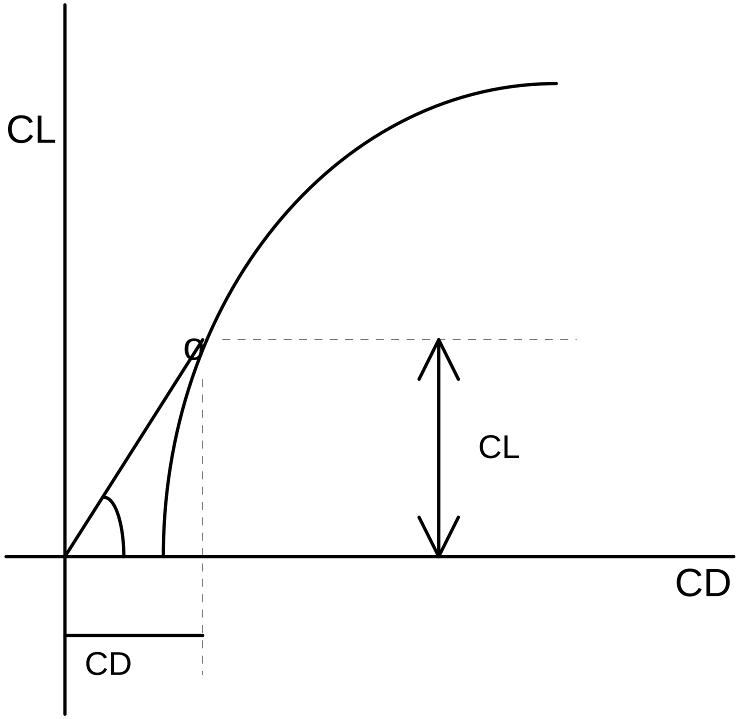
Esempi Polari

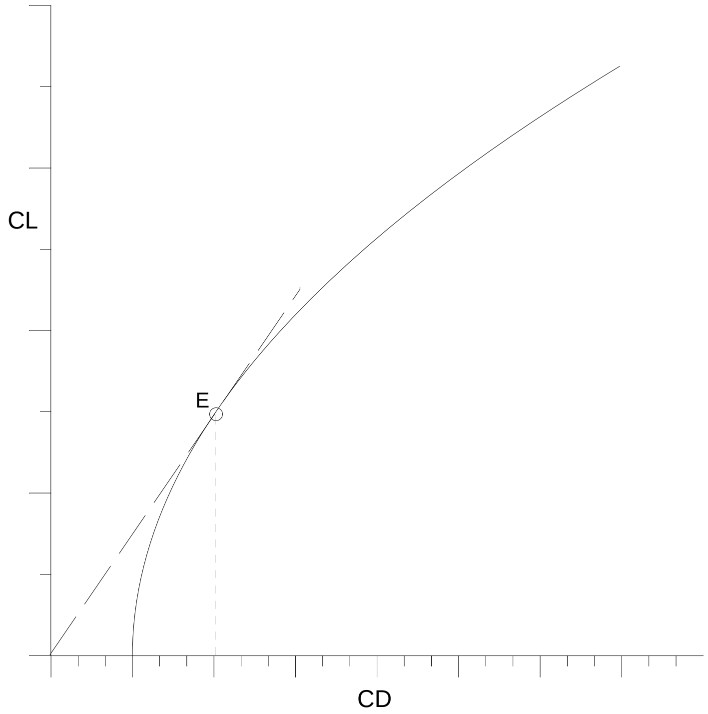
Table 5.4 Summary of Drag Data for Various Airplanes

Type	Wing Area, S	Aspect Ratio	$\frac{S_{wet}}{S}$	Drag Polar	e	$\left(\frac{C_L}{C_D}\right)_{max}$ @ C_L
	ft^2			$C_{D_0} + \frac{C_L^2}{\pi Ae}$		
C–150	160	7.0	?	$0.0327 + 0.0592C_L^2$	0.77	11.3 @ 0.74
C–172	174	7.5	3.7	$0.0281 + 0.0552C_L^2$	0.77	12.7 @ 0.71
C–180	174	7.5	?	$0.0246 + 0.0572C_L^2$	0.75	13.3 @ 0.66
C–182	174	7.5	4.0	$0.0293 + 0.0506C_L^2$	0.84	13.0 @ 0.75
C–185	174	7.5	?	$0.0207 + 0.0494C_L^2$	0.86	15.6 @ 0.65
C–310	175	7.3	4.6	$0.0263 + 0.0596C_L^2$	0.73	12.6 @ 0.66
Skyrocket	183	6.7	?	$0.0163 + 0.0579C_L^2$	0.82	16.3 @ 0.53
Saab 340	450	11.0	?	$0.0285 + 0.0362C_L^2$	0.80	15.6 @ 0.89
DC 9–30	1,001	6.8	6.5	$0.0211 + 0.0450C_L^2$	0.81	16.7 @ 0.50
B 707–320	3,050	7.1	5.0	$0.0131 + 0.0650C_L^2$	0.70	19.6 @ 0.45
A–340	3,908	9.5	?	$0.0165 + 0.0435C_L^2$	0.77	18.5 @ 0.60
B 767	3,050	8.0	?	$0.0135 + 0.0592C_L^2$	0.67	17.2 @ 0.50
C–17	3,800	7.2	?	$0.0175 + 0.0510C_L^2$	0.87	16.4 @ 0.55
Learjet M25	232	5.0	5.6	$0.0260 + 0.0078C_L^2$	0.82	10.9 @ 0.58
G–II	800	6.0	?	$0.0230 + 0.0057C_L^2$	0.93	14.0 @ 0.63

Efficienza massima

Efficienza massima Emax è dipendente sia dalla resistenza parassita che da quella indotta

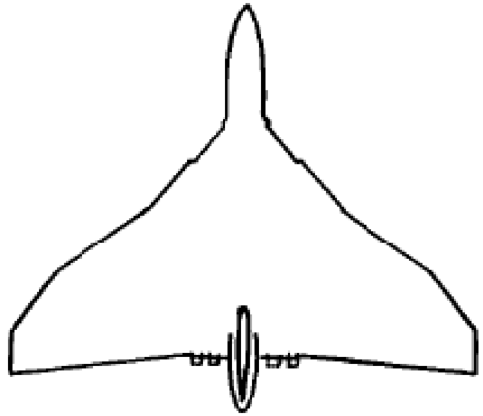




L' Efficienza massima Emax è il massimo rapporto tra CL e CD

Efficienza massima

Efficienza massima Emax è dipendente sia dalla resistenza parassita che da quella indotta



Diversi Cdo 0.0200 0.0100

	B-47	AVRO VULCAN
S reference	1430	3446
S wetted	11300	9600
SPAN	116	90
Swet/Sref	7.9	2.8
ASPECT RATIO	9.4	3.0
WETTED ASPECT RATIO	1.2	1.1
L/D max	17.2	17.0