2. DRAG ANALYSIS OF A FIGHTER AIRPLANE

Because of the author's personal experience with that particular airplane, and on the basis of wind-tunnel investigations and flight tests carried out on and for this airplane, the maximum-speed drag of the Messerschmitt "Me-109" is presented and analyzed as follows — thus showing the application of some of the methods outlined in this book.

(a) Full-Scale Performance

The prevailing type of the Me-109 produced in 1944 was the series "G", illustrated in *figure 2.* The principal dimensions and data are

total wing area	S	=	172 ft^2
wing span	b	=	32 ft
aspect ratio	A	=	6.1 —
overall length	ℓ	=	29 ft
gross weight	W	=	6700 lb
wing loading		=	39 lb/ft^2
maximum speed	V	=	610 km/h
reciprocating engine		=	DB 601A
maximum power	P	=	1200 hp
in altitude of	z	=	22000 ft

Besides exhaust stacks and a pair of wing radiators, the airplane had the following parts exposed to the air flow: Tail wheel (14 inch diameter), antenna wire with mast on upper side of fuselage, two machine guns with portholes on top of engine cowling, partly open housings for the retractable landing gear and a comparatively blunt canopy. *Figure 2* shows size and location of these parts. The maximum speed as listed in "km/h" is 380 mph, or 330 knots.

Thrust. The efficiency of the variable-pitch propeller is estimated to be $\eta = 0.85$ at a high-speed disk loading of $C_T = T/qS_o \approx 0.07$. The effective thrust is then:

$$T = \eta \; P/V = 0.85 \; 1200 \; 550/560 = 1000 \text{ lb}$$

with "V" in ft/sec, "P" as above and "550" indicating the conversion factor for HP. To this value, the thrust produced by the exhaust of the engine is to be added. In the case of reciprocating engines, this component is in the order of

$$\Delta T_{lb} = (0.11 \text{ to } 0.13) \; P_{HP} \qquad (2)$$

provided that the exhaust pipes are adjusted in downstream direction. In case of the Me-109, the jet thrust is in the order of 140 lb. The total thrust at maximum speed is then $(1000 + 140) = 1140$ lb. Considering steady horizontal flight, the value of the total drag of the airplane is equal to that of the thrust. At a dynamic pressure $q = 184$ lb/ft^2, the "drag area" is consequently

$$D/q = C_D S = 1140/184 = 6.2 \text{ ft}^2 \qquad (3)$$

The resultant drag coefficient (on total wing area of 172 ft^2)

$$C_D = 0.036; \quad \text{or } C_{Dwet} \approx 0.0105$$

on total wetted area of 590 ft^2, indicates an airplane with comparatively poor aerodynamic efficiency (the Me-109 was first designed in 1935; size and output of the engine were ≈ doubled between then and 1944).

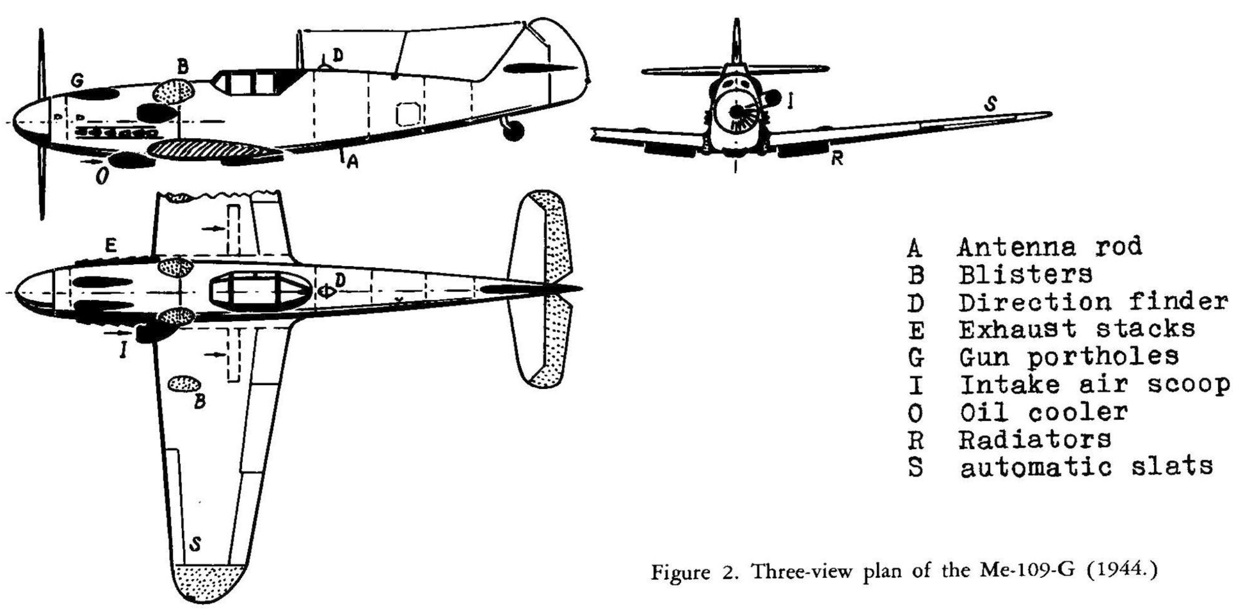

Figure 2. Three-view plan of the Me-109-G (1944.)

Induced Drag. For the given flight condition, the lift coefficient is $C_L = (W/S)/q = 0.21$. Because of flow around the wing tips (see in the "drag-due-to-lift" chapter), the effective aspect ratio is estimated to be reduced from 6.1 to 5.8. Considering planform, the induced drag is increased by some 2%. Consequently:

$$C_{Di} = 1.02\ 0.21^2/(\pi 5.8) = 0.0025$$

$$D_i/q = 172\ 0.0025 = 0.42\ ft^2 \qquad (5)$$

There is no twist built into the wing of the Me-109.- Subtracting the induced drag area from the total area, the tested parasite drag area is found to be $f = D_{par}/q = \underline{5.8\ ft^2}$.

(b) Drag Of The Wing

Skin Friction. The average wing chord of the airplane is $S/b = 5$ ft. The Reynolds number corresponding to maximum speed is thus $R_c = V\ c/\nu = 1.1\ 10^7$. The skin-friction drag coefficient of a smooth and plane surface at this R'number is approximately $C_f = 0.0028$. Because of the sheet-metal gaps behind the slats and owing to the propeller slipstream, the flow of the boundary layer past the wing surfaces of the Me-109 is "fully" turbulent, however. Furthermore, the skin of the Me-109 is coated with camouflage paint, the average grain size of which is in the order of $h \approx k = 1$ mil. This value exceeds the permissible size. The drag coefficient corresponding to a grain size of $k/l \approx h/c = 1.7\ 10^{-5}$ is in the order of $C_f = 0.0035$, as found in the chapter on "imperfections". the drag area of the wing panels (outside the fuselage) is accordingly $D/q = 1.28\ 2\ 0.0035\ 150 = 1.35\ ft^2$, where "1.28" indicates the influence of section thickness (Chapter VI). The thickness ratio is $t/c = 14.2\%$ at the roots and 11.3% near the wing tips.

Surface Imperfections. The wing surfaces of the Me-109 are covered with numerous small protuberances such as sheet-metal joints and rivet heads, and with other irregularities such as gaps and holes. Number and size of these imperfections were determined on the airplane and added up in groups, separately for the two wing sides. The *lower* side has the following:

Type of Imperfection	Area ft^2	$C_{D\cdot}$ or C_{D+}	D/q, ft^2
29 ft lateral sheet-metal edges	$S_\cdot = .16$	0.10	0.013
36 ft lateral surface gaps	$S_+ = .75$	0.05	0.038
50 ft longitudinal edges	$S_+ = .17$	.004	0.001
500 bolt heads	$S_+ = .40$	0.01	0.004
3500 flush rivet heads	$S_+ = 1.5$	.0014	0.002
several sheet-metal blisters	$S_\cdot = .07$	0.10	0.007

The gaps are chiefly those around the covers of the retracted landing gear. Included in the sheet-metal edges are those of the many other covers of the Me-109 wing, bolted to the lower side by means of the 500 bolts as listed. The drag coefficients used in the table are selected from the various graphs in Chapter V. The total drag area of this wing side is $D/q = \underline{0.065\ ft^2}$. At the upper or suction side of the wing, the drag area due to imperfections is much smaller; $D/q = \underline{0.011\ ft^2}$. Imperfections on that side are carefully covered with filler, or they are avoided by suitable design in the first place. Referring the drag of the imperfections to the *exposed* wing area ($172 - 22 = 150\ ft^2$), additional skin-drag coefficients are obtained in the order of $\Delta C_f = 0.065/150 = 0.0005$ for the lower, and $\Delta C_f = 0.011/150 = 0.0001$ for the upper wing side. After adding these increments to the basic coefficient of 0.0035, the skin-drag coefficients are found to be 0.0040 for the lower, and 0.0036 for the upper side. Taking into account the influence of thickness as well as that of lift (as explained in the "streamline" chapter), the average dynamic pressure ratio is 1.16 at the pressure side and 1.42 at the suction side, respectively. The section drag coefficient of this "actual-construction" wing is then

$$C_{DS} = 1.16\ 0.0040 + 1.42\ 0.0036 \approx 0.010 \qquad (8)$$

The corresponding drag area is $D/q = C_D S = \underline{1.47\ ft^2}$.

Additional Components. The following sources of drag, common to both sides, are found on the Me-109 wing:

Drag Source	Area ft^2	$C_{D\cdot}$ or C_{D+}	D/q, ft^2
Aileron gaps on both wing sides	$S_+ = .70$	0.025	0.018
Aileron hinges on lower side	$S_\cdot = .06$	0.5	0.030
Balance weights on the ailerons	$S_\cdot = .09$	0.3	0.027
Gaps at the sides of the slots	$S_\cdot = .07$	1.3	0.090
Gaps beside ailerons and flaps	$S_\cdot = .06$	0.5	0.030
Air-speed Pitot-static tube	—	—	0.010
2 Position lights on wing tips	$S_\cdot = .02$	0.1	0.002
2 Blisters on upper wing side	$S_\cdot = .20$	0.1	0.020
2 Holes around landing gear	$S_+ = 3.5$	0.04	0.140

Most of the drag coefficients are again taken from the graphs in Chapter V. Others are known from specific wind-tunnel tests (10,a) on the respective parts. Including some interference drag near the trailing edge caused by the parts, the total of the additional items is in the order of $D/q = \underline{0.40\ ft^2}$.

(c) Drag Of The Fuselage

Skin Friction. Because of the propeller slipstream, the flow of the boundary layer along the fuselage may be assumed to be turbulent from the beginning. For an average grain size of the camouflage paint coat of k = 1 mil, that is for $k/l = 2.8/10^6$, the skin-drag coefficient is taken from Chapter V to be in the order of $C_f = 0.0025$. The drag of all sheet-metal joints, gaps and rivet heads is again computed according to their number and size, and through the use of the drag coefficients listed in Chapter V. The resultant drag area is $D/q = \underline{0.069\ ft^2}$. Referring this drag to the wetted surface of the fuselage, which is $S_{wet} = 250\ ft^2$, the additional drag corresponds to $\Delta C_f = 0.0003$, and the total coefficient is $(0.0025 + 0.0003) = 0.0028$. Accounting for the increased dynamic pressure along the sides of the fuselage by a factor of 1.07 (see in the "streamline" chapter), the drag coefficient (on wetted area) is increased to $C_{Dwet} = 1.07\ 0.0028 = 0.0030$. For a wetted area of 250 ft^2, the corresponding drag area is $D/q = \underline{0.75\ ft^2}$.

The Appendages listed in the following table present drag components, computed on the basis of frontal area and by means of drag coefficients selected from figure 3,b (for the canopy) and figure 39 (for the tail wheel) in Chapter XIII, and from reference 10,a (for the antenna mast). The *interference* drag caused by these "added" bodies is estimated on the basis of the principles and equations derived in Chapter VIII. The canopy has so many edges around the window panes, and some gaps to permit the cockpit to be opened, that its final drag value is almost twice that of the smooth shape. The total of the fuselage's appendages yields $D/q = \underline{0.63\ ft^2}$

Appendage	Area, ft^2	C_D	Interference	D/q, ft^2
Pilots Canopy	$S_• = 1.00$	0.10	19%	0.12
Irregularities	....	...	50%	0.08
Tail Wheel	$S_□ = 0.50$	0.58	0	0.29
Antenna Mast	$S_• = 0.14$	0.17	19%	0.03
Antenna Parts	---------	...	...	0.03
Antenna Stick	$S_• = 0.03$	1.50	10%	0.05
Gun Installation	. . . . . .	. . .	. . . . .	0.03

Wing Interference. Interference drag caused by adding the fuselage to the wing is twofold; induced and parasitic. The lift variation due to low-wing configuration may correspond to a $\Delta C_{Lb} = L/qb_{fus}c$ less than +0.1 (see Chapter VIII). The corresponding constant component of induced drag is negligibly small. For the parasitic interference drag, an amount is estimated equal to that of the fraction of the wing covered by the fuselage. For a ratio $b_{fus}/b = 0.1$, and for a chord of 7 ft at the wing roots, the interference drag is found to be $D/q = C_D S = (0.01\ 7\ 0.1\ 32) = 0.22\ ft^2$. Including this value and that of the appendages above, the drag area of the fuselage is found to be $D/q = \underline{1.60\ ft^2}$. Referred to the frontal area $S = 9\ ft^2$, the drag coefficient is $C_{D•} = 1.60/9 \approx 0.18$ which is more than twice the value of the bare fuselage body.

Slip Stream. The fuselage, all of its appendages and the wing roots are located within the propeller's slip stream. This means that they are subjected to an average dynamic pressure which (at maximum airplane speed) is estimated to be 10% higher than that corresponding to flight speed. Including the slip-stream effect, the fuselage's total drag area is finally found to be $D/q = 1.1\ 1.60 = \underline{1.75\ ft^2}$.

(d) Drag Of Appendages

Engine Installation. The exposed parts of the engine installation consist of a number of necessary items near the nose of the fuselage, such as the air scoop and the oil cooler for instance, and of the two radiators underneath the wings (see figure 2). The following tabulation gives their drag characteristics.

Component Part	Area ft^2	C_D	Interference	D/q, ft^2
Air Scoop	$S_□ = 0.2$	0.3	12%	0.067
Intake Momemtum	$S_□ = 0.2$	0.4	0	0.080
Exhaust Stacks	$S_• = 0.1$	0.5	12%	0.056
Oil Cooler	$S_□ = 0.75$	0.2	12%	0.168
Ventilation Cpenings	$S_□ = 0.1$	0.9	12%	0.100
Wing Radiators	$S_□ = 3.7$	0.18	---	0.660
Total of the Engine Installation	— — —	— — —	— — —	1.131

The coefficient of the air scoop is estimated on the basis of figure 18 in Chapter IX. The momentum of the air volume taken in through the air scoop presents a drag force as indicated by equation 20 in the "internal" chapter, corresponding to an estimated flow ratio of $w/V = 0.2$. The drag of the ventilation openings is determined through the use of a drag coefficient found in figure 23,b of the same chapter. The interference drag originating along the fuselage (because of engine parts), is found to be 12% of their basic drag (as per equation 9 in Chapter VIII). The drag of a radiator similar to one of the Me-109's twin wing radiators is presented in figure 4 of Chapter IX; $C_{D□} \approx 0.1$, at an assumed $w/V = 0.15$. Only 0.04 of this is expected to be momentum drag. However, flight tests carried out with and without the radiators installed (10,d) indicate drag coefficients $C_{D□}$ between 0.15 and 0.21. These comparatively high coefficients correspond to poor aerodynamic design and considerable internal leakage.—The total drag area of and due to the engine components is multiplied by the slip-stream factor "1.1" as above; thus $D/q = 1.1\ 1.13 = \underline{1.24\ ft^2}$.

Tail Surfaces. Not counting the portion covered by the fuselage, the horizontal tail surface presents an area of 25 ft^2. The vertical-surface area is 11 ft^2. For a grain size of the surface in the order of k = 1 mil, the skin-drag coefficient is $C_f = 0.004$, as found in Chapter V. Due to a thickness ratio of t/c = 10%, the section-drag coefficient is $C_{DS} = 2\ 1.2\ 0.004 = 0.0096$. Surface imperfections are accounted for in a manner similar to that as outlined above for the wing. The corresponding drag area is D/q = 0.007 ft^2 for the horizontal, and 0.009 ft^2 for the vertical tail surface. The profile-drag coefficient is increased accordingly to 0.010, including the drag of the control gaps. Considering the boundary layer originating along the fuselage, the interference drag of the junctions between tail surfaces and fuselage walls is assumed to be zero. The parasite-drag area of the tail assembly is then D/q = 0.010 (25 + 11) = 0.36 ft^2. – On account of the (negative) lift of the horizontal tail surface, a small induced drag component may exist in the high-speed condition considered, in the order of D/q = 0.01 ft^2.

(e) Results Of Me-109 Analysis

Parasite Drag Coefficient. The various drag components calculated in the foregoing paragraphs are plotted in *figure 3*. Not including induced drag, or momentum drag of the engine's air intake, and not counting the drag of the tail wheel, the resultant drag coefficient (on wing area of 172 ft^2) is $C_{Ds} = 0.028$. A coefficient of $C_{Ds} = 0.030$ was tested (10,c) in this condition in "la soufflerie la plus grande" at Chalais-Meudon near Paris in 1941 by placing a full-scale Me-109 in that tunnel. The difference in the coefficient is easily explained on the basis of Reynolds number. On wing chord, the number is $R_c = 4\ 10^6$ in the tunnel, while in flying condition $R_c \approx 2\ 10^7$.

Compressibility. The sum of all parasitic drag components considered, is D/q = 5.14 ft^2. At maximum horizontal speed in 22,000 ft altitude, the Mach number of the Me-109 is M = 0.55. As explained in Chapter XV, only a certain fraction of the total parasite drag established in the last paragraphs, increases as a function of Mach number. Assuming in this respect a fraction of 10%, that is 0.52 ft^2, the additional drag on account of compressibility, indicated by equation 55 of the chapter quoted, is

$$\Delta D/q = (('P')^3 - 1)\ 0.52 = 0.38\ ft^2 \qquad (11)$$

where the Prandtl factor "P" = 1.2. Including this component, the "synthetic" parasite drag area is D/q = 5.6 ft^2, a value that can be accepted as being sufficiently close to the 5.8 ft^2 recalculated above from the high-speed performance (thrust) of the airplane. It is possible, of course, to find values which are plus/minus 5 or more % off the correct drag area, just by assuming drag coefficients for the various component parts, somewhat higher or lower than they should be, within the range of accuracy of the information available.

Surface Imperfections. The wetted surface of the Me-109 shows transverse sheet-metal edges and gaps with a total reference area of approximately 0.4% of that surface. The average number of (flush) rivet heads (as far as they are not filled with paint) is in the order of 30 on a square foot. These figures correspond, of course, to design and construction of the Me-109 which is likely to be obsolete in comparison to modern airplanes of same or similar type. Another consequence of surface roughness (not demonstrated as such in the Me-109 analysis) is the fact that, caused by imperfections (and the propeller slip stream), the flow within the boundary layer is rendered turbulent, over practically all of the wetted surface of this aircraft. More modern airplanes most likely have less roughness in their wetted surface, and they may not have propellers any longer, so that their "skin drag" coefficient will be less than that of the Me-109.

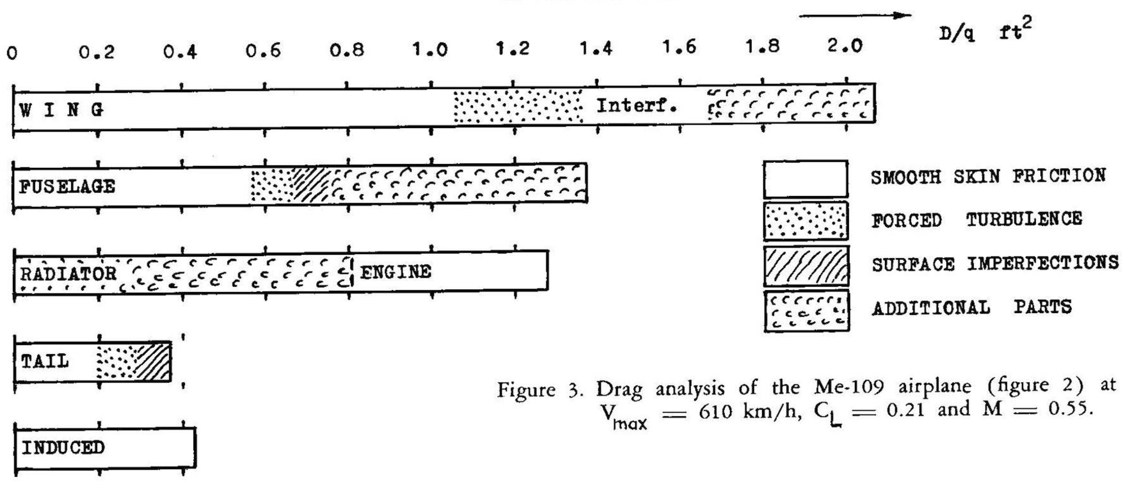

Figure 3. Drag analysis of the Me-109 airplane (figure 2) at V_{max} = 610 km/h, C_L = 0.21 and M = 0.55.

Main Components. The drag analysis of the Me-109 shows that the drag of an actual-construction airplane can realistically be predicted "from scratch", by applying the methods developed in this book, particularly in reference to surface imperfections and interference effects. Considering distribution of the total drag, percentages are found as follows:

wing, including surface roughness	37.5%
fuselage, with roughness and canopy	13.7%
tail surfaces, including roughness	6.9%
engine and radiator installation	23.3%
appendages (as armament and tail wheel)	11.4%
induced drag (at maximum speed)	7.2%

The engine installation presents more drag (in this case) than the fuselage without appendages. The share of the radiator on total parasite drag, which is almost 16%, must be considered to be very high.

Aerodynamic Efficiency. Considering drag on the basis of origin, the following breakdown is found for the Me-109:

skin-friction drag (smooth surface, turbulent)	33%
surface roughness and surface imperfections	15%
exposed parts, especially those of the engine	33%
interference drag (including that due to parts)	6%
influence of compressibility (on 10% of drag)	6%
induced drag under maximum-speed conditions	7%

Several definitions are possible for an aerodynamic "efficiency" ratio

$$\eta_{aero} = D_{useful}/D_{total} \qquad (12)$$

depending upon what is understood as "useful" or "necessary" or "unavoidable". Considering, for instance, in the last tabulation, the skin-friction drag and the induced drag as minimum limit of the useful drag, the efficiency of the Me-109 is but 40%. This figure indicates that more than half of the total drag of this airplane could theoretically be avoided by extremely clean design and faultless construction of skin and details. If rebuilding the Me-109 in a manner that η_a would reach 100%, the maximum speed would be increased from 610 to some 800 km/h, if using the same power plant.

(13) Drag characteristics of Heinkel He-70 airplane:
a) Full scale (Zts.Flugt.Motorluft Dec. 1933): $W = 3330$ kg; $S = 36.5$ m^2; $V_{max} = 235$ mph, with maximum power of 660 HP at sea level.
b) Jones and Smyth, Models, ARC RM 1709 (1936).
c) Results quoted in J.Aeron.Sci. 1940 p.425.

(14) Full-scale performance of airplanes:
a) Richards, "Cleanness", J.Roy.Aeron Soc. 1950 p.137.
b) Hoerner, Skin Friction Analysis, Lufo 1935 p.188.
c) Collection of Airplane Data in Aviation Week, 14 March 1955.
d) Jane's "All the World's Aircraft", Volumes since 1909.
e) RAE, "Spitfire" and "Mustang", ARC RM 2535 (1951).
f) Sinclair, Vickers Viscount J.SLAE May 1956 p.3.
g) Military Aircraft, Flight 1956 p.699.
h) Clarkson, Efficiency, The Aeroplane 1938 p.474.
i) NACA, Qualities of Douglas DC-3, Tech Note 3088.
k) DeHav."Comet", The Aeroplane, 6 Jan, 6 July 1956.
l) Fahey, U.S. Army Aaircraft 1908 to 1946 and USAF Aircraft 1947 to 1956, by "Ships and Aircraft", Falls Church (Va.).
m) Hall, Ryan "Spirit of St. Louis", NACA T.Note 257
n) Fischer-Poturzyn, Junkers and World Aviation, Munich 1935.
o) Littlewood, Trends in Transport, J.A.Sci.1953 p.225.
p) From publications in aeronautical magazines.

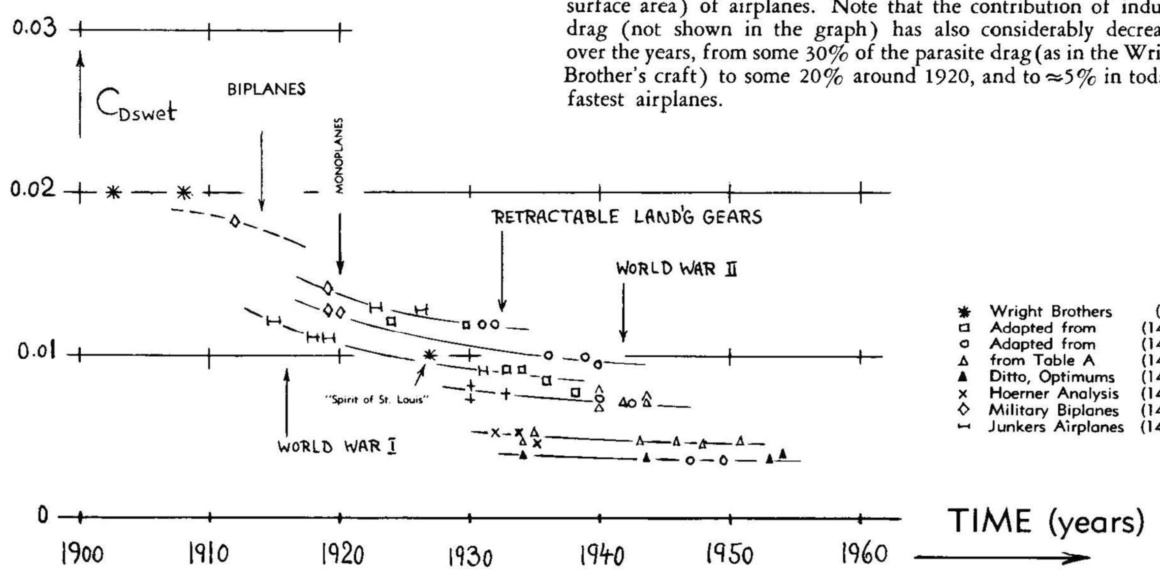

Figure 4. Historical survey of parasite drag coefficient (on wetted surface area) of airplanes. Note that the contribution of induced drag (not shown in the graph) has also considerably decreased over the years, from some 30% of the parasite drag (as in the Wright Brother's craft) to some 20% around 1920, and to ≈5% in today's fastest airplanes.