

ESTIMATION OF AIRFRAME SKIN-FRICTION DRAG DUE TO IMPINGEMENT OF TYRE SPRAY

1. NOTATION AND UNITS

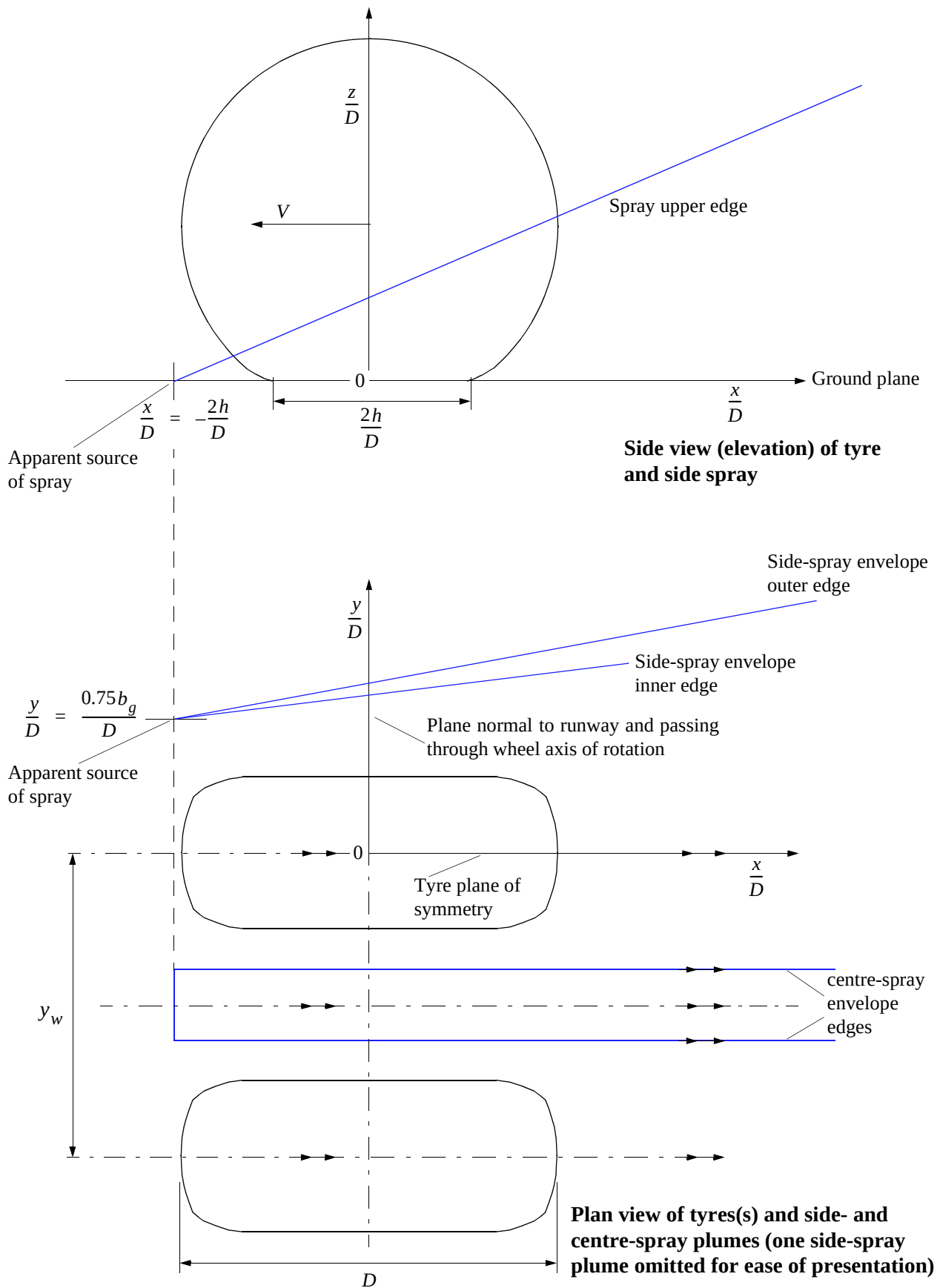
		SI	British
b_g	width of tyre-ground contact area, see Sketch 1.1 of Reference 12	m	ft
C_F	mean skin friction coefficient, see Equation (4.3)		
D	diameter of undeflected, inflated tyre	m	ft
G_{F_m}	skin-friction force due to spray impingement on m th airframe component	N	lbf
G_i	total drag force on airframe due to spray impingement	N	lbf
G_{N_n}	force normal to n th airframe component due to impact of spray	N	lbf
h	half length of tyre-ground contact area, see Sketch 1.1	m	ft
k	ratio of forward spray forward speed to aircraft ground speed		
l	reference length, see Section 4.1	m	ft
m	denotes m th airframe component giving rise to skin-friction force due to spray impingement		
n	denotes n th airframe component giving rise to normal force due to spray impingement		
q	kinetic pressure of runway contaminant, see Section 4	N/m ²	lbf/ft ²
q_0	kinetic pressure of runway contaminant at aircraft ground speed, $\frac{1}{2}\rho_w \sigma V^2$	N/m ²	lbf/ft ²
Re_l	Reynolds number for spray, VI/ν , based on reference length, l		
r	radius of circular-cross-section fuselage or afterbody	m	ft
S_{wet_m}	wetted area of m th airframe component due to spray impingement	m ²	ft ²
s_x	peripheral extent of wetted surface (measured around aircraft cross section at distance x aft of tyre)	m	ft
V	aircraft ground speed	m/s	ft/s
x	distance behind wheel axis of rotation, see Sketch 1.1	m	ft

Issued April 1998

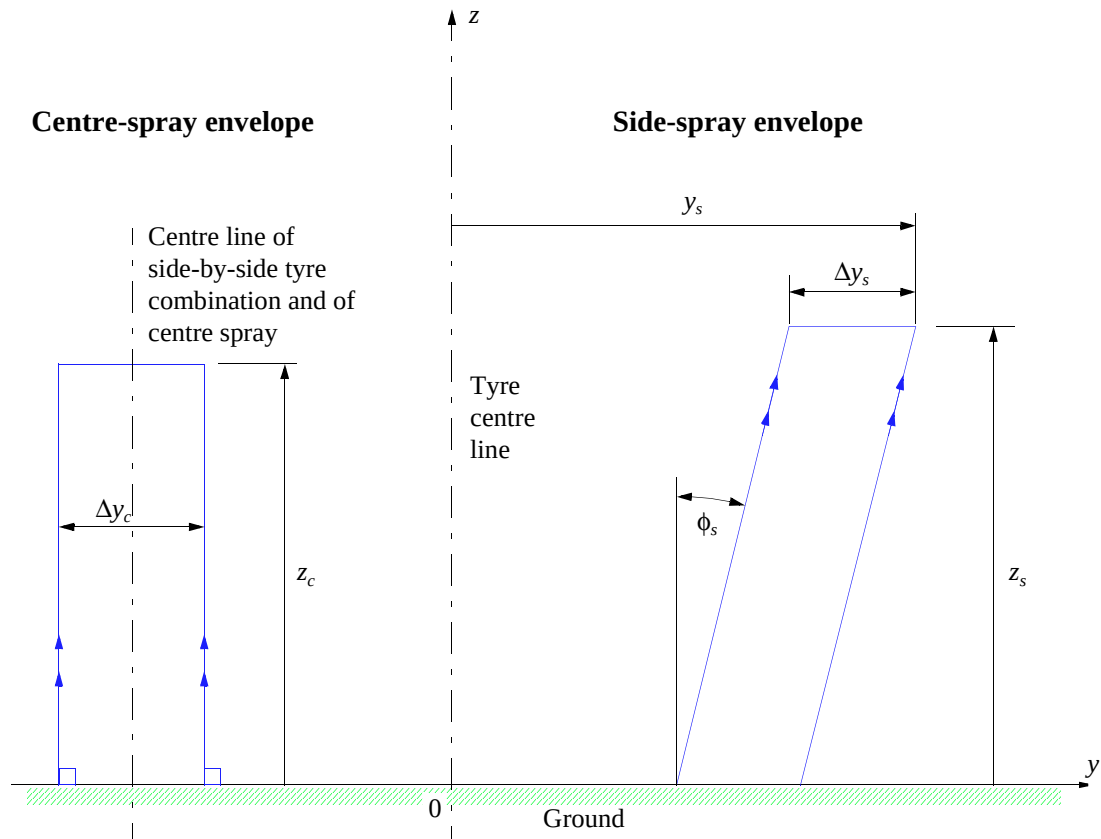
y	lateral distance measured from tyre plane of symmetry, see Sketch 1.1	m	ft
y_s	value of y at upper outer corner of side-spray envelope, see Sketch 1.2	m	ft
y_w	lateral spacing of tyres, see Sketch 1.1	m	ft
z	distance measured normal to runway	m	ft
z_c	height of centre-spray envelope, see Sketch 1.2	m	ft
z_s	height of side-spray envelope, see Sketch 1.2	m	ft
α_m, α_n	inclination of m th and n th airframe component surfaces to V direction	deg	deg
Δy_c	width of centre-spray envelope, see Sketch 1.2	m	ft
Δy_s	width of side-spray envelope, see Sketch 1.2	m	ft
μ	dynamic viscosity	N s/m ²	lbf s/ft ²
ν	kinematic viscosity, $\mu / \rho_w \sigma$	m ² /s	ft ² /s
ρ_w	density of water (taken at 10 ³ kg/m ³ , 1.94 slug/ft ³)	kg/m ³	slug/ft ³
σ	density of contaminant relative to that of water (specific gravity)		
σ_{eff}	effective specific gravity of slush, see Section 4.2.1 of Data Item No. 83042 (Reference 12)		
ϕ_s	inclination to vertical of side-spray envelope, see Sketches 1.2 and 1.3	deg	deg

Subscripts

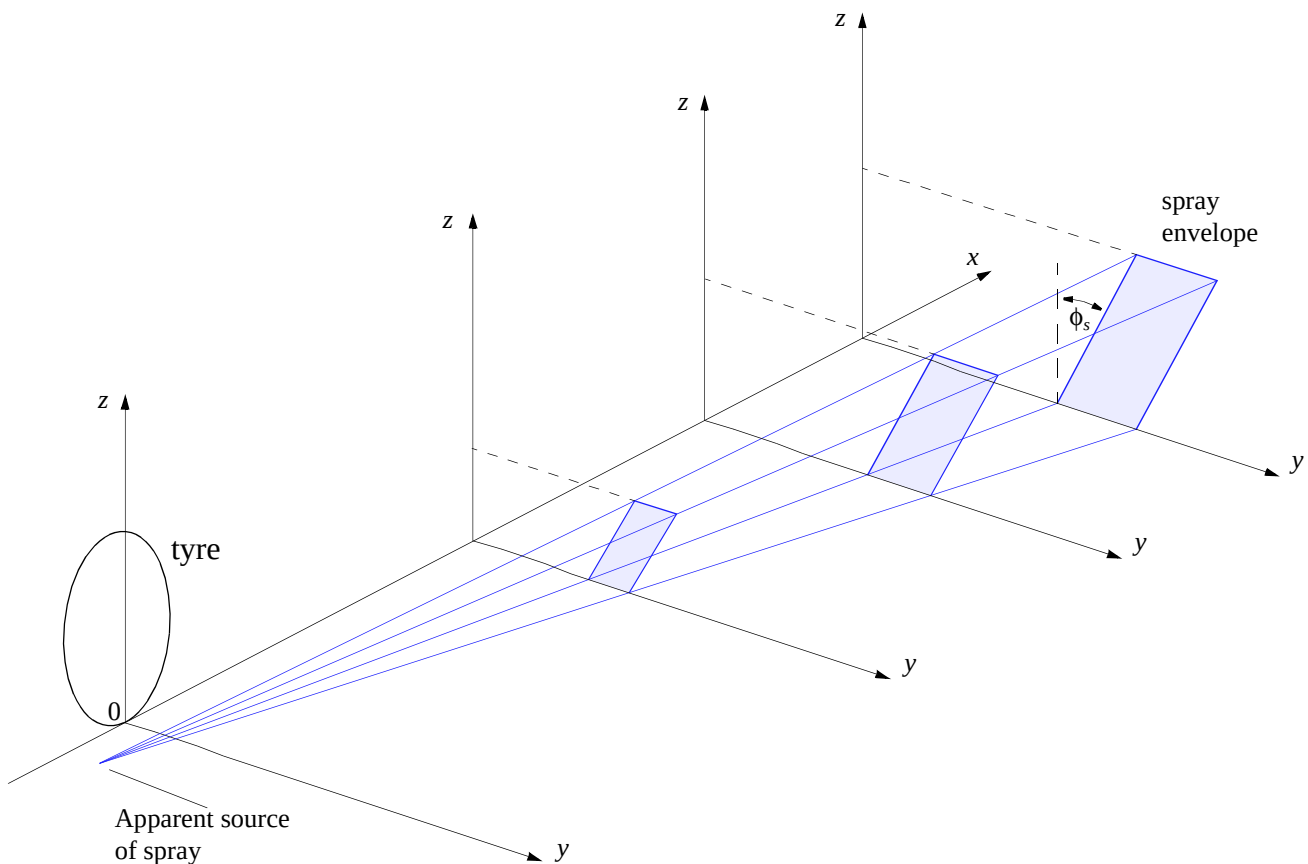
aft	denotes value for afterbody
fus	denotes value for fuselage
m	denotes value for m th airframe component giving rise to skin-friction force due to spray impingement
max	denotes maximum value
n	denotes value for n th airframe component giving rise to normal force due to spray impingement
$wing$	denotes value for wing



Sketch 1.1 Co-ordinate system used to define side- and centre-spray envelope geometries



Sketch 1.2 Side- and centre-spray envelopes in vertical plane behind tyre; as given by methods of Data Item No. 83042 (Reference 12)



Sketch 1.3 Sequence of side-spray envelopes in vertical planes aft of tyre

2. INTRODUCTION

This Data Item presents a procedure for estimating airframe skin-friction drag due to impingement of tyre-generated sprays. The procedure has been verified for tyre side- and centre-spray plumes – as described in Section 6 and illustrated in Appendix A. The spray-plume data used are those given by the methods of Data Item No. 83042 (Reference 12) – a brief review of those data is included in Section 3. No account has been taken of tyre forward-spray impingement in the verifications.

In principle, the overall drag, G_i , due to spray impingement on an aircraft can be represented as

$$G_i = \sum_{m=1}^m G_{F_m} \cos \alpha_m + \sum_{n=1}^n G_{N_n} \sin \alpha_n . \quad (2.1)$$

The right hand side of Equation (2.1) represents the two sources of impingement drag, *i.e.* skin friction giving contributions $G_{F_m} \cos \alpha_m$, and normal (to airframe) forces giving contributions $G_{N_n} \sin \alpha_n$.

This Data Item considers only the estimation of drag due to **skin friction**. Skin-friction forces are the primary source of airframe drag due to spray impingement on the fuselage and wing and the method presented here has been applied successfully to a wide range of aircraft for which measured drag data are available. These forces act on surfaces that are more or less aligned with the aircraft fore-and-aft axis. Hence $\cos \alpha_m \approx 1$ and the total impingement drag for cases where normal force contributions can be neglected is

$$G_i = \sum_{m=1}^m G_{F_m} . \quad (2.2)$$

The second term on the right hand side of Equation (2.1) corresponds to forces G_{N_n} , acting **normal to the airframe** surface and arising as a result of impact of spray with airframe components that are essentially forward-facing. This subject has been studied extensively at model-scale in References 10 and 15 and, to a limited extent, at full-scale in Reference 4. However, apart from flap and other damage observed in tests such as References 2 and 5, no evidence exists from aircraft tests of these forces being a significant source of drag *in the take-off configuration*.

An estimation method for normal forces will be issued as a separate Data Item so as to provide a means of predicting local loads (and possible damage) on airframe components and, if required, the associated drag. The most likely such surface is a wing flap at large deflection – especially if it is fully extended as in the tests reported in Reference 4.

2.1 Applicability

The applicability of this Item is limited primarily by the tyre-spray data available. Data for tyre side spray, and for the centre spray from between side-by-side tyres, are given in Data Item No. 83042 (Reference 12) and are reviewed here in Section 3.2. The prediction of spray impingement for a given aircraft configuration requires the investigation of ranges of such operating conditions as speed, tyre normal load (which are interrelated because of the variation of wing lift with speed) and contaminant depth. The “worst” case may not be immediately obvious and may not be associated with the maximum spray angles, nor with the maximum tyre load nor with any particular value of forward speed. Any changes in aircraft pitch attitude and/or position relative to the runway surface can affect the interaction of spray plumes with the airframe and engines at any stage of the ground run. Examples are changes in aircraft weight and centre of gravity position, aerodynamic configuration and runway camber and slope.

While spray development, and hence impingement drag, is a function of contaminant depth, there is a minimum depth below which significant spray plumes are not produced. This minimum depth is a function of detail tyre design and runway surface texture but for the application of this Item a reasonable value to assume is 3 mm ($\frac{1}{8}$ inch approx.). Moreover, there is no particular reason why impingement drag should increase *linearly* with contaminant depth.

3. GEOMETRY DEFINITIONS FOR TYRE SIDE- AND CENTRE-SPRAY PLUMES AND AIRFRAME COMPONENTS

3.1 Co-ordinate System

The geometry of each spray plume and of airframe components is defined using an orthogonal axis system Ox, y, z which moves with the aircraft and is shown in Sketch 1.1. (The axis system is more frequently used for airframe design than for flight-mechanics purposes.) The origin, O , lies in the ground plane directly beneath the wheel axis of rotation and in the plane of symmetry of each tyre. The longitudinal co-ordinate, x , is taken *positive behind the tyre* and the vertical co-ordinate, z , *positive upwards*.

3.2 Side- and Centre-Spray Envelopes from Data Item No. 83042

Data Item No. 83042 (Reference 12) presents methods for estimating spray “envelopes” which define the height, width, shape and location of the following plumes generated by aircraft-type tyres.

- (i) Side-spray plumes from a single tyre,
- (ii) side-spray plumes from the outer edges of side-by-side tyre configurations,
- (iii) centre-spray plume for side-by-side tyre configurations.

The methods allow for the effects of variations in aircraft speed, contaminant depth and tyre deflection. Reference 12 includes advice on the use of Items (i), (ii) and (iii) for a single lateral row of more than two tyres and for multiple-row tyre configurations such as the “dual-tandem” arrangement of four tyres.

Sketch 1.2 illustrates the cross-sectional forms of the spray envelopes predicted by the methods of Item No. 83042 for side-spray and centre-spray plumes in a vertical plane at a fixed distance behind the tyre(s). Sketches 1.1 and 1.3 give illustrations of the linear development of those plumes from the following apparent spray sources.

The **apparent spray source** for the **side-spray** plume is defined in terms of tyre footprint length and width parameters (see Section 4 of Item No. 83042) and is located at the point

$$\frac{x}{D} = -\frac{2h}{D}, \quad \frac{y}{D} = 0.75 \frac{b_g}{D}, \quad \frac{z}{D} = 0.$$

The **apparent spray source** for the **centre-spray** plume is located in the line defined by

$$\frac{x}{D} = -\frac{2h}{D}, \quad \frac{z}{D} = 0.$$

No lateral co-ordinate is required because the centre spray is of constant width and located symmetrically between the tyres (thus, in Sketch 1.1, the centre line of the centre spray is at $y/D = -y_w/2D$).

4. SPRAY SKIN-FRICTION DRAG

For airframe surfaces that have only small projected areas normal to the x -axis, the drag due to spray impingement arises primarily due to skin friction. For each spray-plume/airframe-component interaction the skin-friction drag, G_{F_m} , acting in the $-V$ direction, is given by

$$G_{F_m} = C_{F_m} q S_{wet_m} . \quad (4.1)$$

The total drag force due to skin friction is given by the summation

$$\sum G_{F_m} = \sum_{m=1}^m C_{F_m} q S_{wet_m} . \quad (4.2)$$

Values of skin-friction coefficient, C_{F_m} , are given in Section 4.1.

Values of q are selected as follows.

- For side- and centre-spray plumes (as in Item No. 83042).

$$q = q_0 = \frac{1}{2} \rho_w \sigma V^2 .$$

- For forward spray* the relevant value of q is,

$$q = q_0 (1 - k)^2 ,$$

where k is the ratio of the spray and aircraft forward speeds – and so varies with distance from the tyre creating the spray.

Methods of estimating wetted areas are described in Section 5.

If more than one spray plume impinges on a particular component, the skin-friction drag is calculated for one plume only. If the estimated values of q for use in Equation (4.2) are not the same for each plume, then the higher of the two values should be used.

4.1 Skin Friction Coefficient

Reference 1 presents test data for the skin-friction force on flat plates subjected to water spray impingement. It shows that the variation of that force with forward velocity (of the plate) and plate length can be represented, approximately, by a conventional skin-friction coefficient that varies with Reynolds number based on plate length. The skin friction law used in Reference 1 and here is the Karman-Schoenherr relationship which is illustrated in Figure 1 and defined by

$$\frac{1}{C_F^{1/2}} = 4.3 \log_{10} [C_F Re_l] \quad (4.3)$$

$$\text{where} \quad Re_l = \frac{Vl}{\nu} . \quad (4.4)$$

* There is at present no method for estimating the behaviour of tyre forward spray and so no drag calculation procedure is given in this Item. Such methods will be taken into account when they become available.

The kinematic viscosity coefficient for all work in the development of this Data Item was taken as

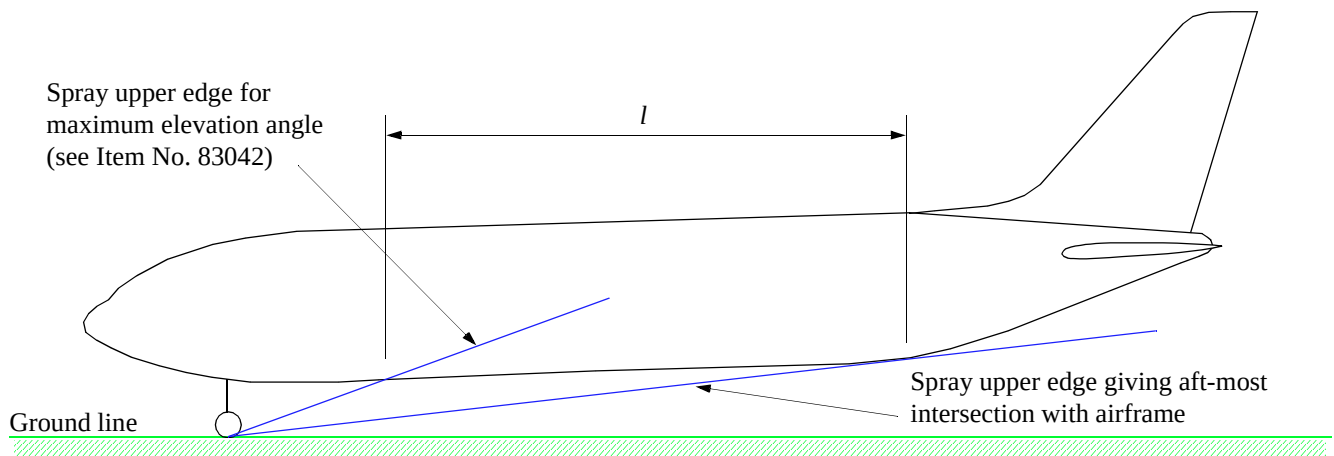
$$\nu = 10^{-6} \text{ m}^2/\text{s} (10.76 \times 10^{-6} \text{ ft}^2/\text{s}), \quad (4.5)$$

which corresponds to the value for water at ISA sea-level conditions. In practice ν varies with ambient temperature and pressure but there is little to be gained by taking account of such effects for the likely ranges of values of those parameters.

The reference length, l , in Equation (4.5) should, in principle, be evaluated for each interaction between a spray plume and an aircraft component so that appropriate values of Re_l and C_{F_m} can be evaluated. In practice it is likely that two values will suffice, as follows.

- (i) For a wing, put l equal to the root chord,
- (ii) for a fuselage, put l equal to the greatest length over which impingement *could* occur, Sketch 4.1 shows an example for a nose undercarriage.

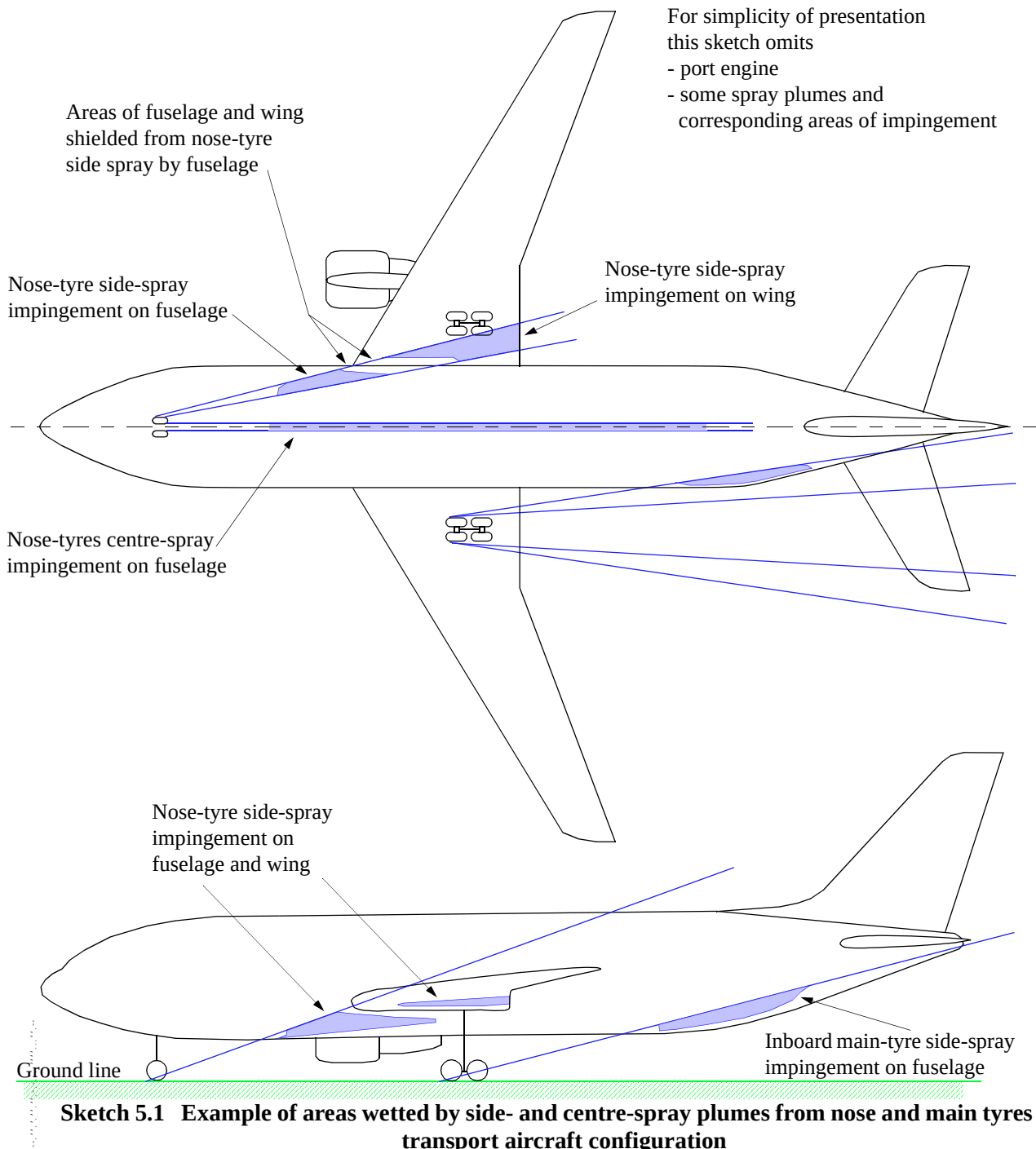
Finally, because of the limited speed range considered for some aircraft for which spray drag calculations are required, it has been found acceptable to use a mean value of Re_l for that entire speed range.



Sketch 4.1 Illustration of maximum value of reference length for Reynolds number calculation for fuselage

5. WETTED AREAS DUE TO SPRAY-AIRFRAME INTERACTIONS

In order to predict values of skin-friction drag it is necessary that, for each spray plume, all the airframe components that it impinges on must be identified and their geometries related to the axis system used to define that plume. In general it is best that this process is carried out computationally* since the estimated value of surface area wetted by a spray plume can be quite sensitive to small changes in airframe and spray-envelope geometries. Sketch 5.1 shows an example of the areas wetted by nose and main undercarriage tyres on a typical transport aircraft configuration.



Sketch 5.1 Example of areas wetted by side- and centre-spray plumes from nose and main tyres on transport aircraft configuration

* A computer program is to be issued which implements this process as well as the procedures needed for calculating skin-friction drag due to impingement.

5.1 Definition of Wetted Areas for Skin-Friction Calculations

For each airframe component the surface area wetted by each spray plume is defined as the integral of the peripheral extent, s_x , with respect to x (s_x is measured around the wetted portion of the aircraft cross section),

$$S_{wet_m} = \int_{x=0}^{x=x_{max_m}} s_x \, dx. \quad (5.1)$$

In general, it is not permissible to deduce a value of s_x at some arbitrary value of x solely on the basis of interaction between the undisturbed spray envelope at x and the airframe cross section at x . The reason for this is that some parts of the airframe surface may be shielded from the spray by parts further forward. Three options for dealing with this are available, as follows.

- (i) If a computerised description of the aircraft geometry is available and the spray plumes are defined computationally, then the true areas where the airframe and the spray plumes intersect can be calculated by stipulating that the spray cannot pass through the airframe surface.
- (ii) Another approach is to modify the spray envelope at each cross section aft of the point where impingement first occurs so that the effect of airframe shielding is built into the spray plume itself.
- (iii) The method used successfully in the development of this Data Item is to use a simplified representation of the airframe geometry and, as part of the calculation process, to identify first all possible areas that could be shielded from the spray from each tyre. The spray plumes can then be used without modification – see Section 5.2.

5.2 Airframe Geometry Used for Verification of Spray Skin-Friction Drag Estimation Method

The airframe geometry used for verifying the method for predicting skin-friction drag due to spray impingement consists of the idealised wing-fuselage illustrated in Sketch 5.2 – details are as follows.

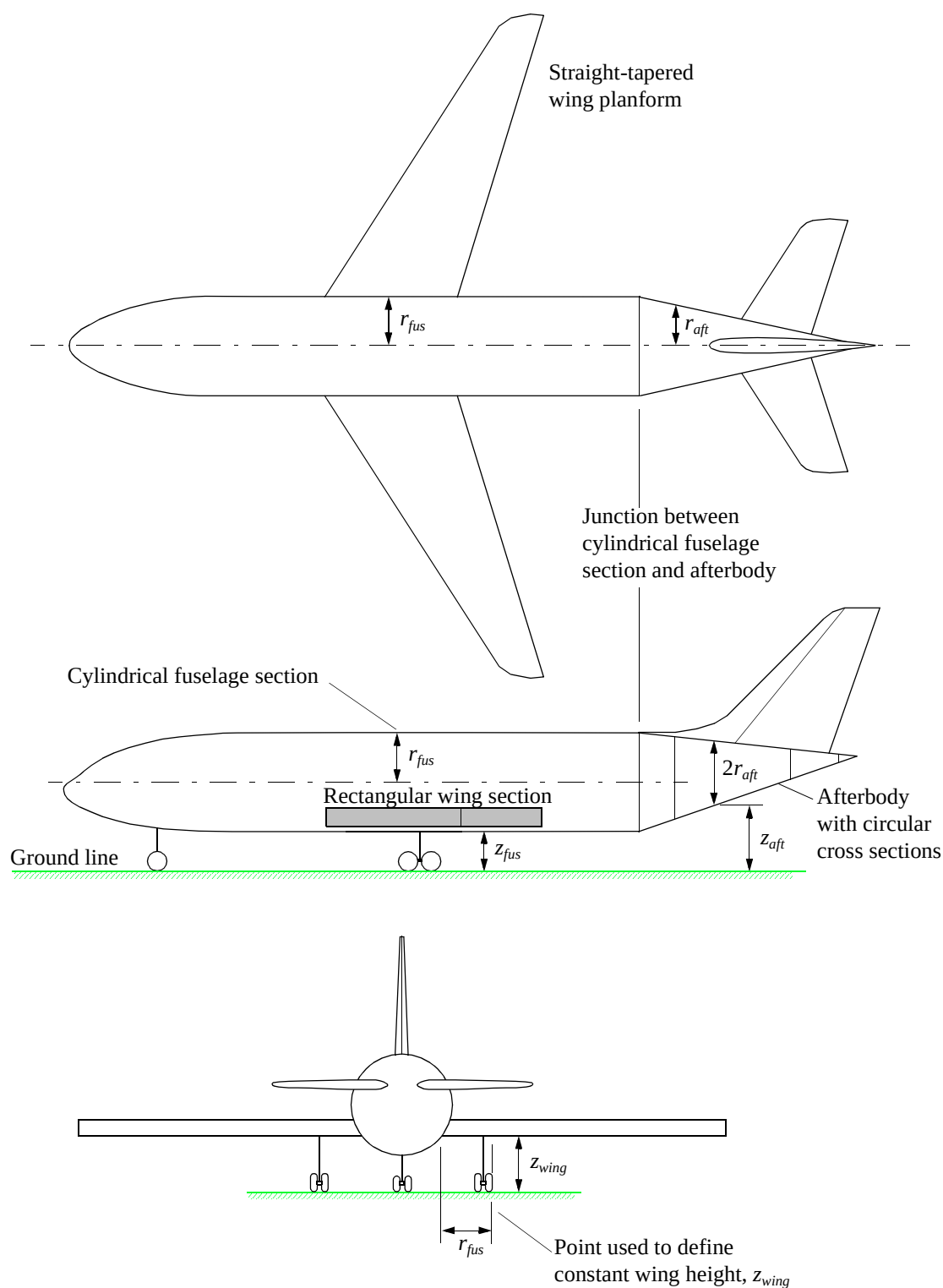
The fuselage is represented as a cylinder of constant radius, r_{fus} , at a constant height, z_{fus} , from the runway. This is followed by an afterbody made up of a sequence of circular sections of radius r_{aft} , which are located so as to position the bottom of the fuselage at the correct height, z_{aft} , above the runway.

The wing is represented as a straight-tapered trapezium planform having a constant thickness (this is used to determine the shielding of the upper fuselage from spray; no skin-friction drag is attributed to the wing upper surface). For simplicity, the wing height, z_{wing} , is taken as a single value corresponding to the height of the lower surface at a distance equal to r_{fus} outboard of its intersection with the fuselage.

Section 5.1 emphasises the need to consider that some parts of the airframe surface may be shielded from the side- and centre-spray by parts further forward and identifies three methods of dealing with the problem. The method adopted here is to identify, for the simplified geometry of Sketch 5.2, all possible areas that could be shielded from the spray from each tyre, as follows.

Nose tyre spray: No spray from a nose tyre can impinge on the upswept rear fuselage. The combination of spray envelopes from Item No. 83042 and a constant radius circular-section fuselage is such that, at any distance x aft of the tyre, there is a maximum height at which impingement is possible – based on line-of-sight from the apparent source of spray (see Section 3.2). In addition, the presence of the fuselage may result in the shielding of the inboard parts of the wing lower surface from the spray – the effect is greatest for a wing mounted on top of the fuselage. A low-mounted wing can shield parts of the fuselage above and behind it from the nose tyre side spray.

Main tyre spray: Side and centre spray from underwing tyres rarely impinges on the wing itself – unless flaps are deflected to a large extent*. Impingement on the cylindrical parts of the fuselage of side spray from the main tyres will not be subject to shielding. However it is possible for the cylindrical section part of the fuselage to shield part, if not all, of the afterbody from the main-tyre side spray.



Sketch 5.2 Airframe geometry used for verification of spray skin-friction drag method

* In which case skin-friction alone is likely to give an underestimate of the resulting drag force.