

ESTIMATION OF SPRAY PATTERNS GENERATED FROM THE SIDES OF AIRCRAFT TYRES RUNNING IN WATER OR SLUSH

1. NOTATION AND UNITS

Tyre geometry and associated quantities are defined in Sketch 1.1. The co-ordinate system, dimensions and angles used to define the tyre-spray envelopes predicted by this Item are illustrated in Sketches 1.2, 1.4 and 1.6.

Most equations in this Item are expressed in non-dimensional form so that any consistent set of units can be used. However, the units quoted are not coherent sets in so far as the knot is used throughout for speeds while, in British units, the inch is used for all linear dimensions and lbf/in² for tyre inflation pressure.

		<i>SI</i>	<i>British</i>
b_g	width of tyre-ground contact area, see Sketch 1.1	m	in
C_z	coefficient in expressions for tyre deflection under normal (to runway surface) load, see Section 4.1		
D	diameter of undeflected, inflated tyre	m	in
d	depth of fluid contaminant on runway (water or slush)	m	in
F_c	factor to account for effect of tyre deflection on centre-spray width		
F_{D_c}	datum factor to account for effect of speed on centre-spray width		
F_{d_γ}	factor to account for effect of contaminant depth on side- and centre-spray elevation angles γ_s and γ_c		
$F_{d_\gamma, chine}$	factor to account for effect of contaminant depth on side-spray elevation angle, $\gamma_{s, chine}$, for tyre with chine		
F_{d_λ}	factor to account for effect of contaminant depth on widths of side and centre sprays		
F_{d_θ}	factor to account for effect of contaminant depth on side-spray plan view angle θ_s		
F_{γ_s}	factor to account for effect of tyre deflection on side-spray elevation angle γ_s		
$F_{\gamma_s, chine}$	factor to account for effect of tyre deflection on side-spray elevation angle, $\gamma_{s, chine}$, for tyre with chine		
F_{θ_s}	factor to account for effect of tyre deflection on side-spray plan-view angle θ_s		
h	half length of tyre-ground contact area, see Sketch 1.1	m	in

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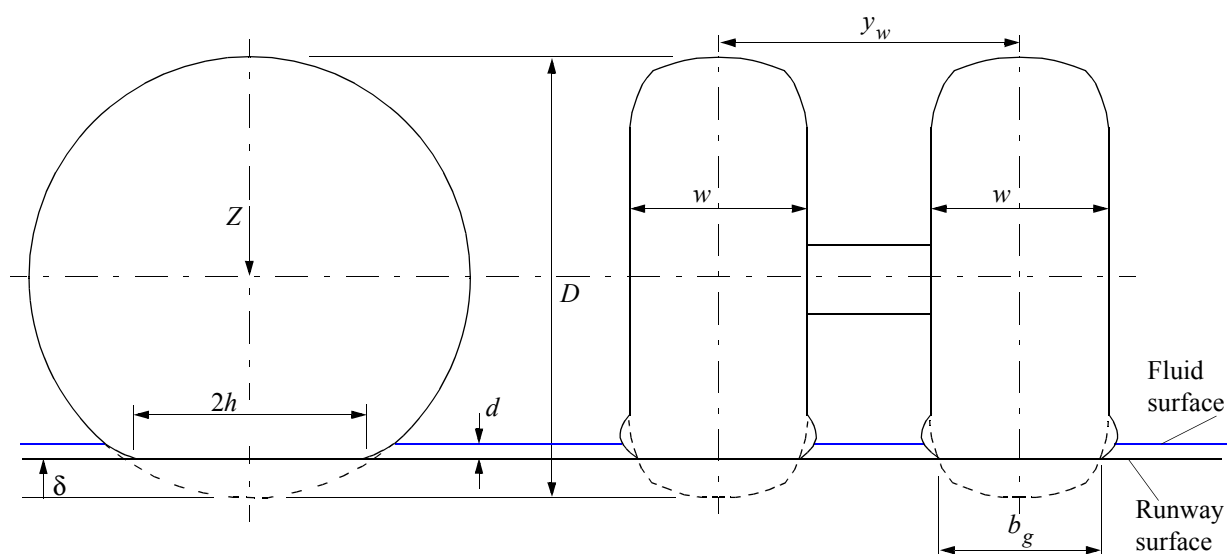
P_1, P_2, P_3	coefficients in curve-fit equations		
p	tyre inflation pressure (gauge)	N/m ²	lbf/in ²
p_r	tyre rated inflation pressure (gauge)	N/m ²	lbf/in ²
V	aircraft ground speed	kn	kn
V_p	reference speed defined in Section 4.2 for full-scale aircraft type tyres	kn	kn
u_W	head-wind velocity (<i>i.e.</i> component of wind velocity in x direction)	kn	kn
v_W	cross-wind velocity (<i>i.e.</i> component of wind velocity in y direction)	kn	kn
w	width of undeflected, inflated tyre section	m	in
x	distance behind wheel axis of rotation, see Sketch 1.2	m	in
y	lateral distance measured from tyre plane of symmetry, see Sketch 1.2	m	in
y_s	value of y at upper outer corner of side-spray envelope, see Sketch 1.4	m	in
y_w	lateral spacing of tyres, see Sketch 1.1	m	in
Z	normal (to runway) load on wheel	N	lbf
z	distance measured normal to runway	m	in
z_c	height of centre-spray envelope, see Sketch 1.6	m	in
z_s	height of side-spray envelope, see Sketch 1.4	m	in
$z_{s, chine}$	value of z_s for tyre with chine	m	in
γ_c	centre-spray elevation angle, <i>i.e.</i> angle of centre-spray upper edge when viewed from side, see Sketch 1.2	deg	deg
$\gamma_{D_c}, \gamma_{D_s}$	datum values of γ_c and γ_s used in Equations (6.2) and (5.2) respectively	deg	deg
$\gamma_{D_s, chine}$	datum value of $\gamma_{s, chine}$ used in Equation (7.4)		
γ_s	side-spray elevation angle for tyre with no chine, <i>i.e.</i> angle of side-spray upper edge when viewed from side, see Sketch 1.2	deg	deg
$\gamma_{s, chine}$	value of γ_s for tyre with chine	deg	deg
Δy_c	width of centre-spray envelope, see Sketch 1.6	m	in

Δy_s	width of side-spray envelope, see Sketch 1.4	m	in
Δy_W	lateral shift of spray plume due to crosswind, positive in same direction as v_W	m	in
δ	tyre vertical deflection	m	in
θ_s	side-spray plan view angle, <i>i.e.</i> angle of side-spray upper outer edge when viewed from above, see Sketch 1.2	deg	deg
θ_{D_s}	datum value of θ_s used in Equation (5.3)	deg	deg
λ_s	incremental spray angle used in estimation of side-spray width, $\tan \lambda_s = (\Delta y_s/D)/[(2h/D) + (x/D)]$, see Sketch 1.2	deg	deg
λ_{D_s}	datum value of λ used in Equation (5.7)	deg	deg
σ	density of contaminant relative to that of water (specific gravity)		
σ_{eff}	effective specific gravity of slush for use in Equation (4.8), see Section 4.2.1		
τ	spray intensity coefficient, <i>i.e.</i> ratio of kinetic pressure in spray to kinetic pressure of water (or slush) at speed V		
ϕ_s	inclination to vertical of side-spray envelope, see Sketch 1.4	deg	deg

Subscripts

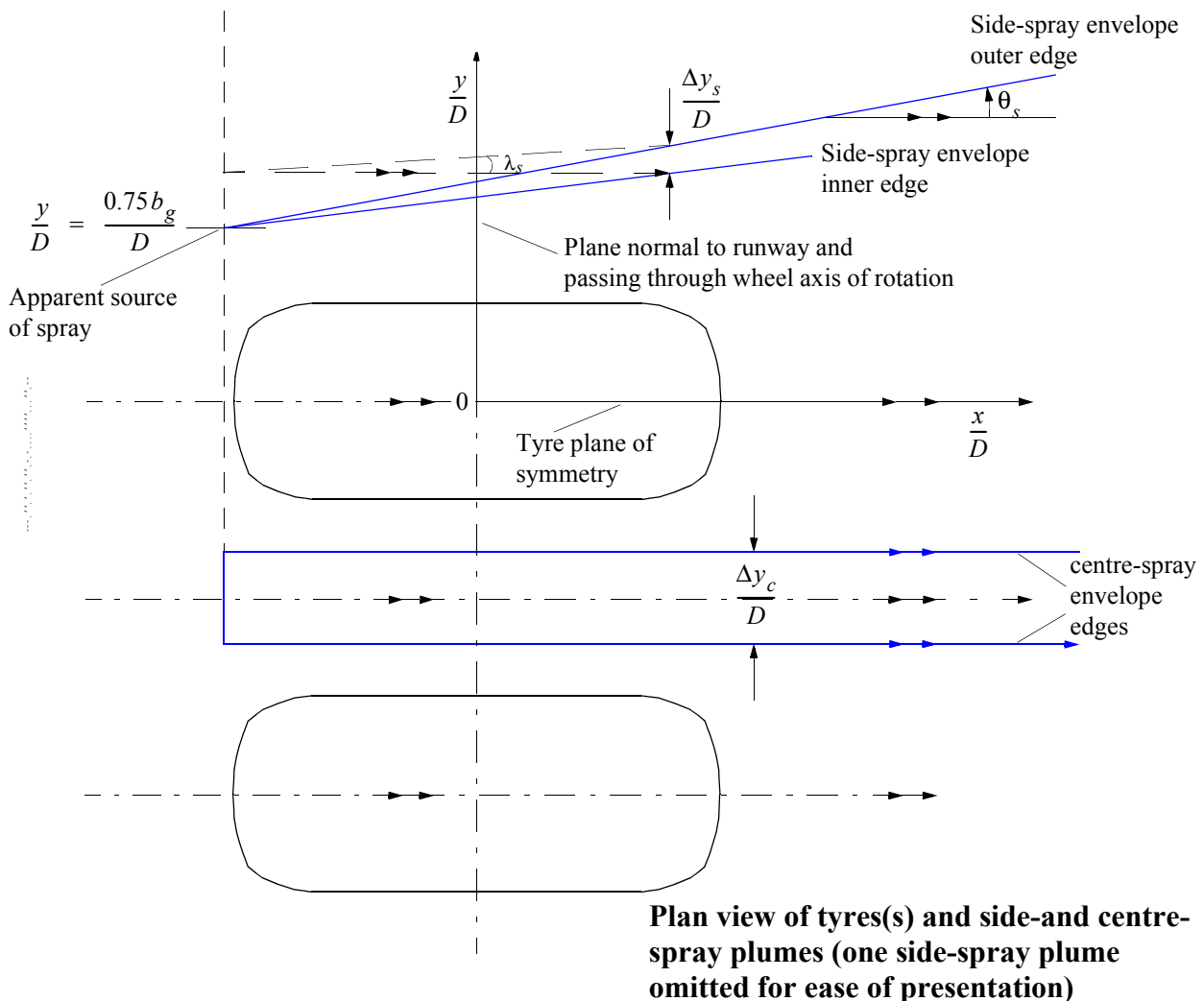
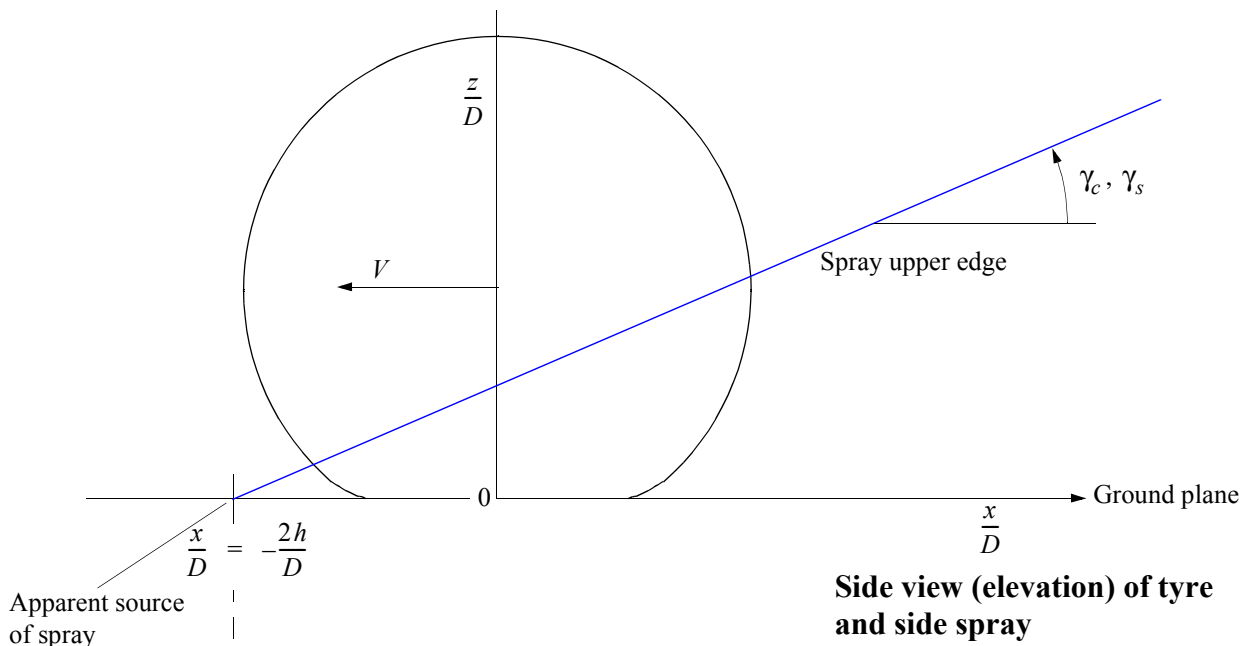
headwind denotes value in headwind

still air denotes value in still-air conditions



Sketch 1.1 Tyre and tyre-footprint geometry

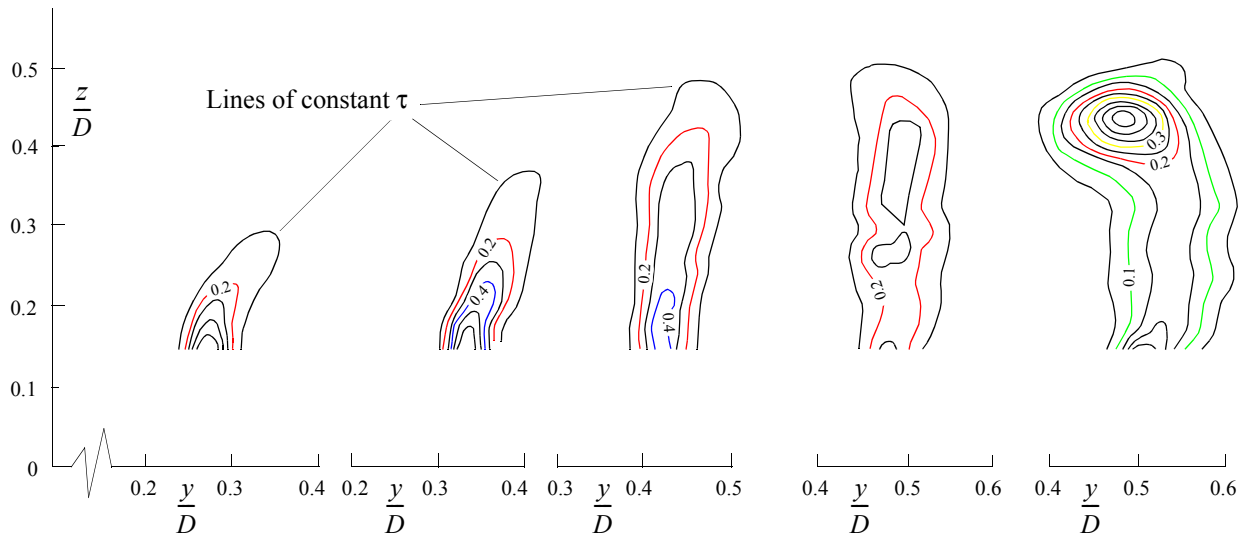
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Sketch 1.2 Co-ordinate system and angles used to define spray envelope geometries

$$\begin{array}{ccccc} \frac{b_g}{w} = 0.29 & \frac{b_g}{w} = 0.46 & \frac{b_g}{w} = 0.64 & \frac{b_g}{w} = 0.802 & \frac{b_g}{w} = 0.90 \\ \left(\frac{Z}{Z_{max}} = 0.11\right) & \left(\frac{Z}{Z_{max}} = 0.25\right) & \left(\frac{Z}{Z_{max}} = 0.47\right) & \left(\frac{Z}{Z_{max}} = 0.75\right) & \left(\frac{Z}{Z_{max}} = 1\right) \end{array}$$

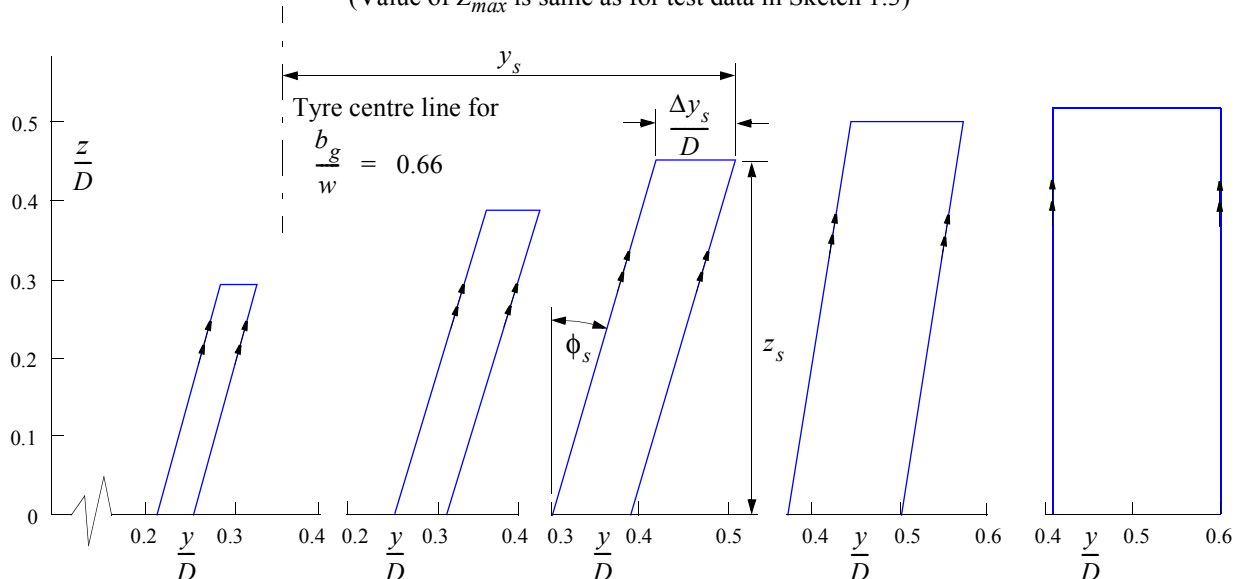
(Value of Z_{max} in test was chosen as representative of tyre maximum operating load)



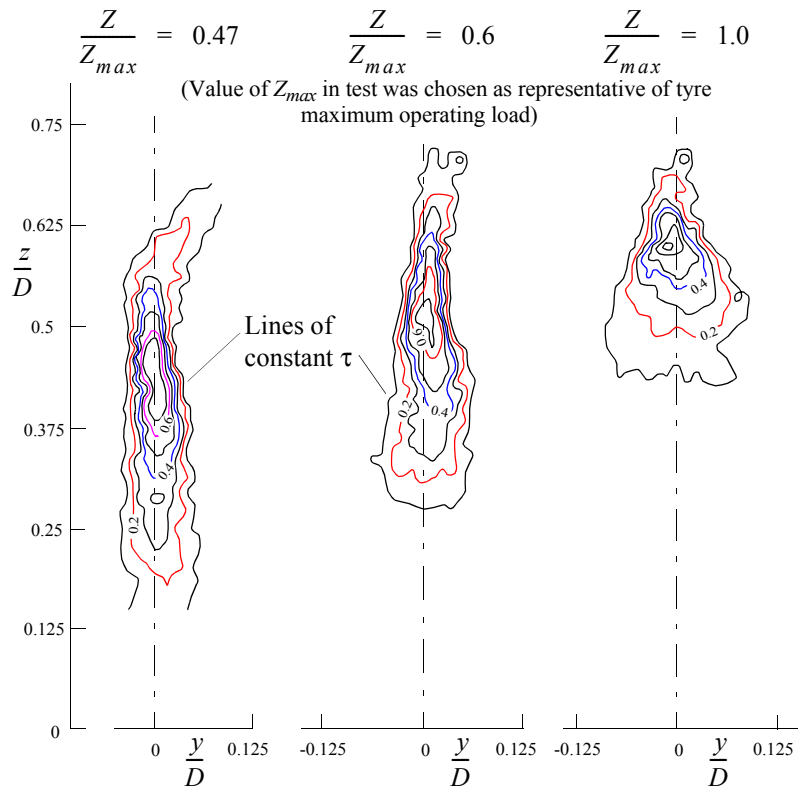
Sketch 1.3 Examples of side-spray intensity distribution patterns in a vertical plane aft of, but close to, the tyre $\left(\frac{x}{D} = 1.56, \frac{d}{D} = 0.026\right)$ (taken from Reference 21)

$$\begin{array}{ccccc} \frac{b_g}{w} = 0.29 & \frac{b_g}{w} = 0.46 & \frac{b_g}{w} = 0.64 & \frac{b_g}{w} = 0.802 & \frac{b_g}{w} = 0.90 \\ \left(\frac{Z}{Z_{max}} = 0.11\right) & \left(\frac{Z}{Z_{max}} = 0.25\right) & \left(\frac{Z}{Z_{max}} = 0.47\right) & \left(\frac{Z}{Z_{max}} = 0.75\right) & \left(\frac{Z}{Z_{max}} = 1\right) \end{array}$$

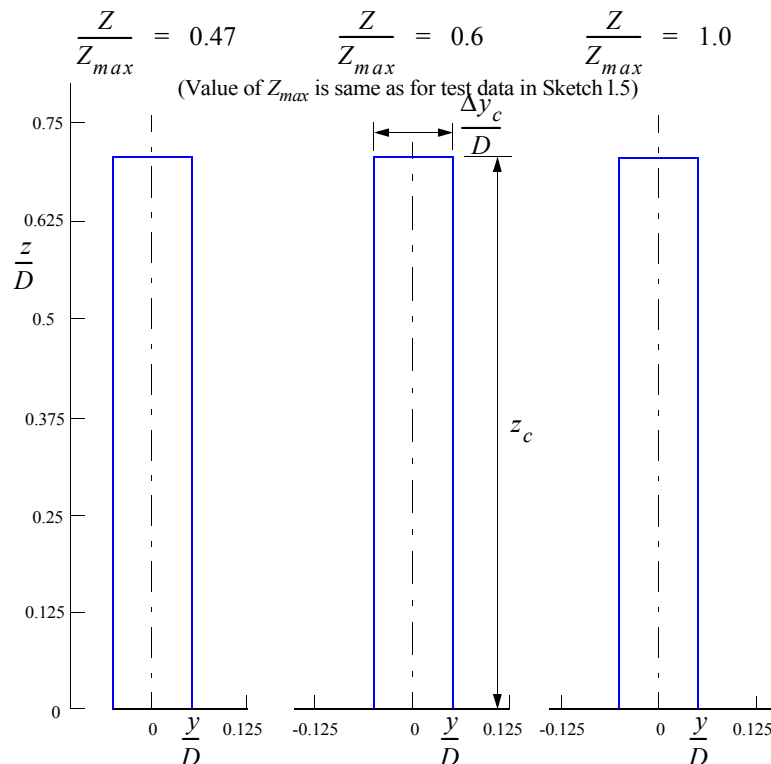
(Value of Z_{max} is same as for test data in Sketch 1.3)



Sketch 1.4 Examples of side-spray envelopes as estimated using method of Section 5



Sketch 1.5 Examples of nominally-symmetric centre-spray intensity distribution patterns in a vertical plane close to the tyre $\left(\frac{x}{D} = 1.5, \frac{d}{D} = 0.026\right)$ (taken from Reference 21)



Sketch 1.6 Examples of centre-spray envelopes as estimated using method of Section 6

2. INTRODUCTION

The take-off and landing of aircraft from precipitation-covered runways present serious problems in aircraft operations, including those associated with tyre spray.

The sprays produced by aircraft tyres running in water or slush are complex and depend on aircraft speed, the shape and dimensions of the loaded tyre and the contaminant depth. At low aircraft speeds the spray pattern is dominated by the bow-wave plume of water pushed ahead of the tyre. At these speeds there are also smaller spray plumes generated from the sides of the tyre. However, as aircraft speed increases the bow-wave plume decreases in strength and flattens while the side-spray plumes increase in strength and rise higher. At speeds near the planing condition, *i.e.* where the tyre is likely to lose contact with the runway, the side-spray plumes reach a maximum height. Further increase in speed leads to reductions in the height of the side-spray plumes and the complete suppression of the bow-wave plume. In addition, whenever a side-by-side tyre configuration is used, there is a centre-spray plume from between the tyres which varies with speed in a similar manner to the side spray. In general, the side plumes present the greatest hazard to safe take-offs and landings since they are stronger at the higher, more critical, speeds and, aft of the tyre(s), spread upwards and sideways to be encountered by many parts of the aircraft. The most serious consequence is the loss of engine power due to spray ingestion. However the performance of other systems can be disrupted and damage may be caused to airframe components. Spray impingement on any airframe component will create drag and increase the take-off ground-run.

2.1 Scope of the Item

The Item presents methods for estimating spray “envelopes” that define the height, width, shape and location of the following plumes generated by aircraft-type tyres running in water or slush.

- (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.

A single lateral row of more than two tyres is treated as generating side-spray plumes as in (ii) and an array of centre-spray plumes as in (iii).

For multiple-row tyre configurations, such as a “dual-tandem” arrangement of four tyres, only the side-spray plumes from the outer edges of the leading tyres should be considered. Spray from *between* the leading tyres of such configurations is likely to impinge on the undercarriage struts, mechanisms and trailing wheels (drag from such impingement is estimated using methods given in Data Item No. 90035 (Reference 24)).

The Item does not present data on the behaviour of the bow-wave plume.

Section 3 describes the spray characteristics and indicates how the spray “envelopes” estimated in this Item relate to the model- and aircraft-tyre test data from which they are derived. The co-ordinate system used to define the spray envelopes and associated spray angles is also presented. Section 4 gives empirical data for tyre-footprint characteristics and expressions for a reference speed used in the method. Sections 5 and 6 give the methods for estimating the spray envelopes for side and centre plumes respectively. Section 7 describes, and gives some numerical data on, the effects of a wide range of factors that affect spray plume development. The derivation of the methods is discussed in Section 8 while Section 10 gives three worked examples.

Table 2.1 collects together the terms used to characterise the spray plumes and the factors used in the various calculation procedures referenced. In general the procedures are based on a datum value, which varies with

speed, together with factors which allow for variations in tyre deflection and contaminant depth. The datum values and factors are presented in Figures 1 to 9.

TABLE 2.1 Terms used to characterise and predict spray envelopes

	Side spray				Centre spray	
	Tyres without chines			Tyres with chines		
	elevation	plan	width	elevation (only)	elevation	width
Linear dimension(s)	z_s	y_s	Δy_s	$z_{s,chine}$	z_c	Δy_c
Defining angle(s)	γ_s	θ_s	λ_s, ϕ_s	$\gamma_{s,chine}$	γ_c	–
Datum value (or factor) to account for effect of forward speed	γ_{D_s}	θ_{D_s}	λ_{D_s}	$\gamma_{D_s,chine}$	γ_{D_c}	F_{D_c}
Factor for effect of tyre deflection	F_{γ_s}	F_{θ_s}	–	$F_{\gamma_s,chine}$	–	F_c
Factor for effect of contaminant depth	F_{d_γ}	F_{d_θ}	F_{d_λ}	$F_{d_\gamma,chine}$	F_{d_γ}	F_{d_λ}
Calculation procedure	Table 5.1	Table 5.1	Table 5.2	Table 7.1	Table 6.1	Table 6.2

2.2 Applicability of the Data

The two main applications of the spray-plume data predicted using the methods given here are:

- (i) to predict the likelihood of spray ingestion into engine intakes or impingement on such airframe components as flaps, sensors, antennae or surface joints where delamination might result,
- (ii) in the prediction of forces due to impingement of tyre spray on the airframe – see Data Item No. 98001 (Reference 30) for estimation of skin-friction drag.

Use of the Item to predict the likelihood of spray ingestion into engine intakes or impingement on the airframe 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. For example, changes in tyre deflection and in the relative positions of spray plumes and engine and airframe components during aircraft rotation at take-off will alter the risk of ingestion. Other, less drastic, changes in aircraft pitch attitude and/or position relative to the runway surface, affect the interaction of spray plumes with the airframe and engines – with effects of possibly longer duration. Examples are changes in aircraft weight and centre of gravity position, aerodynamic configuration and runway camber and slope.

While spray development 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 Data Item a reasonable value to assume is 3 mm (1/8 inch, approx.). Although spray characteristics are likely to be similar for all types of tyre, the method should be used with caution for tyres that differ significantly from typical aircraft tyres (see Section 4).

3. DESCRIPTION OF TYRE SIDE-SPRAY CHARACTERISTICS

Tyre side spray is considered here to take the form of “plumes” having trajectories that begin near the tyre and grow in height and extent with increasing distance aft. This reflects customary usage and accords with what is seen during aircraft tests and recorded in photographs and videos. The terminology is acceptable for the purposes of this Data Item but implies that the detailed motion of the water droplets displaced by the tyre is not considered. For example, in reality, the side spray is made up of droplets that have been displaced from the runway and follow trajectories that are dominated by their lateral and vertical components of velocity. (Droplets in the side spray have very small fore-and-aft velocity components – in contrast to the bow wave where droplet initial forward velocity must exceed that of the aircraft.)

3.1 Spray-Pattern Measurements at Model scale

The main parameters influencing spray plumes generated by tyres running in water or slush have been established from systematic scale-model tests in water reported in References 5, 8, 17 and 21. In those tests measurements were made using a spray-intensity probe to obtain surveys of spray kinetic pressure in vertical planes at fixed distances behind the tyre. The measurements were expressed as a non-dimensional spray-intensity coefficient, τ , *i.e.* the ratio of the kinetic pressure in the spray to the kinetic pressure of water at the wheel forward speed. Sketches 1.3 and 1.5 show examples of such surveys in the form of contours of constant τ .

3.2 Spray Envelopes

Sketches 1.4 and 1.6 show examples of the linear spray “envelopes” obtained using the estimation methods of Sections 5 and 6 (and corresponding to the spray intensity contours shown in Sketches 1.3 and 1.5 respectively). In particular, Sketch 1.4 shows how the predictions for side-spray envelope height, width and inclination vary as tyre load increases*.

The methods of Sections 5 and 6 were derived using both full-scale and model test data. Absolute values of spray angles were obtained from photographic and video records of aircraft tests while effects of systematic changes in the various tyre and operational parameters were based mainly on examination of the model data described in Section 3.1. For these purposes the model data used were for points *within about two tyre diameters* of the tyre and, because the lowest values of τ were subject to the greatest measurement uncertainty, spray intensity contours in the range $\tau = 0.05$ to 0.1 were chosen to define the edges of the spray.

3.3 Co-ordinate System and Spray Geometry

Throughout the Item the spray geometry is defined using an orthogonal axis system Ox, y, z which moves with the aircraft and is shown in Sketch 1.2. (This 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*. Sketch 1.2 also shows the angles and lengths used to define the side-spray envelope in Section 5 and the centre-spray envelope (for side-by-side tyres) in Section 6.

* Prior to the “Amendment A” version of this Data Item, a simpler treatment was given for the effect of load on side-spray envelope shape. The method presented now is a better representation of the measured data and results in a smooth variation of airframe wetted area (and hence skin-friction drag) as tyre load varies during take-off.

4. TYRE CHARACTERISTICS USED IN THE ESTIMATION METHOD

4.1 Parameters Defining the Tyre-Ground Contact Area

To use the method presented in this Data Item, values are required for the width, b_g , and length, $2h$, of the tyre-ground contact area. For applications where precise characteristics of the tyre are not known, this Section gives empirical relationships obtained from Reference 2. These relationships are valid for typical aircraft cross-ply (bias-ply) tyres* and have been confirmed by tests carried out on modern tyres and reported in Reference 22.

Tyre vertical deflection, δ , is a function of the normal load, Z , on the tyre and inflation pressure, p . The load itself is dependent on aircraft weight, flap setting, speed and centre-of-gravity position, although moments due to engine thrust, braking and control deflection can also influence it significantly. For consistent units of tyre width, diameter, normal load and inflation pressure, the vertical deflection can be expressed* as,

$$\frac{Z}{(p + 0.08p_r)w(wD)^{1/2}} = 2.4 \left[\frac{\delta}{w} - C_z \right] \quad \text{for } \frac{\delta}{w} > \frac{10}{3} C_z, \quad (4.1)$$

$$= 0.96 \left[\frac{\delta}{w} \right] + \frac{0.216}{C_z} \left[\frac{\delta}{w} \right]^2 \quad \text{for } \frac{\delta}{w} \leq \frac{10}{3} C_z, \quad (4.2)$$

where $C_z = 0.03$ for “modern” aircraft cross-ply (bias-ply) tyres* – based on data given in References 2 and 22. (For cross-ply tyres considered in Reference 1, and referred to as “older types” in Reference 2, $C_z = 0.02$.) In practice, Equation (4.2) is likely to be used only for lightly-loaded tyres, for example on some nose undercarriages, or as may occur in the final stages of take-off rotation.

Equations (4.1) and (4.2) are expressed in the form presented in Reference 2. The forms in which they are needed for calculating values of δ/w are as follows.

$$\text{For } \frac{\delta}{w} > \frac{10}{3} C_z, \quad \frac{\delta}{w} = \frac{Z}{2.4(p + 0.08p_r)w(wD)^{1/2}} + C_z \quad (4.3)$$

$$\text{For } \frac{\delta}{w} \leq \frac{10}{3} C_z, \quad \frac{\delta}{w} = \frac{1}{2} \left\{ \left[\left(\frac{0.96}{0.216} C_z \right)^2 + \frac{4ZC_z}{0.216(p + 0.08p_r)w(wD)^{1/2}} \right]^{1/2} - \frac{0.96}{0.216} C_z \right\}. \quad (4.4)$$

Tyre footprint parameters are given in Equations (4.5) to (4.7).

Footprint width for most aircraft tyres (for example types I, III, VII, VIII), is given by

$$\frac{b_g}{w} = 1.7 \left[\frac{\delta}{w} - 2.5 \left(\frac{\delta}{w} \right)^4 + 1.5 \left(\frac{\delta}{w} \right)^6 \right]^{1/2}. \quad (4.5)$$

However, for “type H” tyres, the following expression should be used

$$\frac{b_g}{w} = 1.55 \left[\frac{\delta}{w} - 1.1 \left(\frac{\delta}{w} \right)^2 \right]^{0.4}. \quad (4.6)$$

* These expressions apply to cross-ply (bias-ply) tyres only. See Section 7.4 regarding the use of this Data Item with aircraft radial-ply tyres.

Tyre footprint length is given by

$$\frac{2h}{D} = 1.7 \left[\frac{\delta}{D} - \left(\frac{\delta}{D} \right)^2 \right]^{1/2} \quad (4.7)$$

4.2 Reference Speed

The reference speed, V_p , used in this Data Item is the so-called dynamic-hydroplaning speed*. It has been used in scaling model data for full-scale application and in Sections 5, 6 and 7 data for use in estimating spray angles are presented as functions of the non-dimensional speed parameter, V/V_p . The speed for dynamic hydroplaning is that at which fluid pressures beneath the tyre generated primarily by inertial effects are sufficient to produce a vertical force equal to the load on the tyre. Any further increase of speed causes the tyre to lift completely off the runway surface. Dynamic hydroplaning is also *associated with* (unbraked) wheel spin down, suppression of the tyre bow-wave spray, a peaking of the drag due to surface contaminants, and loss of all significant braking or directional-control forces. From Reference*4 for aircraft-type tyres this speed is taken as,

$$\left. \begin{aligned} V_p &= 9 (p/\sigma)^{1/2} \quad \text{kn} \quad (p \text{ in lbf/in}^2) \\ V_p &= 108.4 (p/\sigma)^{1/2} \quad \text{kn} \quad (p \text{ in MN/m}^2) \\ V_p &= 34.28 (p/\sigma)^{1/2} \quad \text{kn} \quad (p \text{ in bar}) \end{aligned} \right\} \quad (4.8)$$

In Equations (4.8) σ is the density of a *liquid contaminant* relative to that of water, *i.e.* the specific gravity.

4.2.1 Effective specific gravity of slush

For slush, which is a mixture of water, ice and air, an *effective value*, σ_{eff} , should be used in Equations (4.8) corresponding to conditions under the tyre. Reference 29 shows that values of σ_{eff} for slush are likely to be *significantly* greater than measured values due to the combined effects of two phenomena:

- (i) the compressibility of the air in the slush mixture,
- (ii) the solubility of air in water.

Both phenomena depend on the pressure developed in the contaminant beneath the tyre and the theoretical analyses of Reference 29 show that σ_{eff} varies with forward speed, V , and the undisturbed slush specific gravity, σ . Table 4.1 provides a summary of the results from Reference 29.

TABLE 4.1 Values of effective specific gravity, σ_{eff} , for slush

Undisturbed slush specific gravity, σ	Effective specific gravity of slush, σ_{eff} , for use in Equation (4.8); evaluated at following values of V in knots				
	60	80	100	120	140
0.8	0.92 to 0.98	0.92 to 1	0.92 to 1	0.93 to 1	0.93 to 1
0.6	0.83 to 0.91	0.87 to 0.96	0.92 to 0.98	0.94 to 0.99	0.96 to 1

Reference 29 suggests that measured values of $\sigma \leq 0.5$ are unlikely to correspond to a liquid contaminant. Test data for artificial slush – generated by crushing ice (see References 3, 10, 12, 13 and 14) – usually give measured values of σ between 0.8 and 0.9. Since naturally occurring slush is likely to be formed by the melting of a layer of snow, the value of σ may well be lower than for artificially-generated slush.

* See also Data Item No. 72008 (Reference 15), Section 3.1.

5. ESTIMATION OF SIDE-SPRAY ENVELOPE

The forms of side-spray envelopes, at a fixed distance behind the tyre, are illustrated in Sketch 1.4. The corresponding sets of side-spray intensity* contours are shown in Sketch 1.3.

Close to the tyre the spray trajectory is assumed to be linear so that the spray envelope can be defined in terms of the series of angles γ_s , θ_s , λ_s shown in Sketch 1.2. As the plume develops, the effects of gravity and aerodynamic drag produce a curved trajectory with, ultimately, the spray falling back to the ground. However, data from Reference 7 indicate that for aircraft applications these effects can be ignored and a linear spray trajectory assumed unless the spray plume is influenced by aircraft components or spray deflectors, see Sections 7.2 and 7.3. The spray angles are functions of tyre forward speed and deflection and contaminant depth. From these angles and the location of the apparent spray source (also shown in Sketch 1.2), the size and shape of the spray envelope can be estimated for any distance behind the tyre, see Sections 5.1 to 5.3.

5.1 Apparent Source of Side Spray

The **apparent spray source** from which the angles γ_s , θ_s and λ_s are assumed to originate is defined in terms of tyre footprint length and width parameters (see Section 4) and is located at the point

$$\frac{x}{D} = -\frac{2h}{D}, \quad \frac{y}{D} = 0.75 \frac{b_g}{D}, \quad \frac{z}{D} = 0. \quad (5.1)$$

The axis system and sign convention used here is defined in Section 3.3 and Sketch 1.2.

5.2 Location of Upper Outer Corner of Side-Spray Envelope (No chines)

For tyres *without chines* the procedure for calculating the location of the upper outer corner of the side-spray envelope is given in Table 5.1. See Section 7.3.1 regarding the effect of chines on the elevation angle, γ_s .

TABLE 5.1 LOCATION OF UPPER OUTER CORNER OF SIDE-SPRAY ENVELOPE (NO CHINES)

	<i>Spray side elevation</i>	<i>Spray plan view</i>
Spray angles	$\gamma_s = \gamma_{D_s} F_{\gamma_s} F_{d_{\gamma}} \quad (5.2)$	$\theta_s = \theta_{D_s} F_{\theta_s} F_{d_{\theta}} \quad (5.3)$
Coordinates of upper outer corner of spray envelope	$\frac{z_s}{D} = \left[\frac{2h}{D} + \frac{x}{D} \right] \tan \gamma_s \quad (5.4)$	$\frac{y_s}{D} = 0.75 \frac{b_g}{D} + \left[\frac{2h}{D} + \frac{x}{D} \right] \tan \theta_s \quad (5.5)$
Data required to estimate spray angles and coordinates of upper outer corner of spray envelope	γ_{D_s} , datum value of γ_s from Figure 1a as function of V/V_p ; see Equations (4.8) for V_p .	θ_{D_s} , datum value of θ_s from Figure 1b as function of V/V_p ; see Equations (4.8) for V_p .
	F_{γ_s} , factor from Figure 2a as function of b_g/w for normal load on tyre.	F_{θ_s} , factor from Figure 2b as function of b_g/w for normal load on tyre.
	$F_{d_{\gamma}}$, factor from Figure 3a as function of d/D for contaminant depth.	$F_{d_{\theta}}$, factor from Figure 3b as function of d/D for contaminant depth.
	$\frac{b_g}{w}$, $\frac{2h}{D}$, width and length parameters for tyre-ground contact area from Section 4.1.	

* The spray intensity, τ , both within and at the edges of the envelopes decreases with distance from the tyre.

5.3 Width and Inclination to Vertical of Side-Spray Envelope

The method given in Table 5.2 applies both to tyres without and with chines.

TABLE 5.2 INCLINATION TO THE VERTICAL AND WIDTH OF SIDE-SPRAY ENVELOPE

Tyre footprint parameter, b_g/w	$b_g/w < 0.7$	$0.7 \leq b_g/w < 0.9$	$0.9 \leq b_g/w$	Equation number
Side-spray envelope inclination, ϕ_s , to vertical, see Sketch 1.4	$\phi_s = 15 \text{ deg}$	$\phi_s = 15 - 75 \left[\frac{b_g}{w} - 0.7 \right]$	$\phi_s = 0$	(5.6)
Incremental spray angle*, λ_s	$\lambda_s = \left(-0.003 + 0.66 \frac{b_g}{w} \right) \lambda_{D_s} F_{d_\lambda}$	$\lambda_s = \left[-1.41 + 2.67 \frac{b_g}{w} \right] \lambda_{D_s} F_{d_\lambda}$	$\lambda_s = 0.993 \lambda_{D_s} F_{d_\lambda}$	(5.7)
Width, Δy_s , of spray envelope, see Sketches 1.2 and 1.4	$\frac{\Delta y_s}{D} = \left[\frac{2h}{D} + \frac{x}{D} \right] \tan \lambda_s$			(5.8)
Data required to estimate ϕ_s , λ_s and Δy_s	λ_{D_s} ,	datum value of λ_s from Figure 1c as function of V/V_p ; see Equations (4.8) for V_p .		
	F_{d_λ} ,	factor from Figure 3c as function of d/D for contaminant depth.		
	$\frac{b_g}{w}$, $\frac{2h}{D}$,	width and length parameters for tyre-ground contact area from Section 4.1.		

* From Sketch 1.2 it can be seen that λ_s is **not** equal to the angle between the spray inner and outer edges although in some cases it can be a close approximation to that angle.

6. ESTIMATION OF CENTRE-SPRAY ENVELOPE

The forms of centre-spray envelopes, at a fixed distance behind a pair of side-by-side tyres, are illustrated in Sketch 1.6. The corresponding sets of centre-spray intensity* contours are shown in Sketch 1.5.

The estimation procedure for centre-spray envelopes follows that given for side spray in Section 5. However, the procedure is simpler because of the lateral symmetry of the centre spray. The independent variables considered are tyre forward speed, tyre deflection and contaminant depth (because of a lack of measured data the effect of depth on centre spray is assumed identical with that for side spray).

6.1 Apparent Source of Centre Spray

The apparent spray source from which the elevation angle γ_c is assumed to originate is shown in Sketch 1.2, and is located in the line defined by

$$\frac{x}{D} = -\frac{2h}{D}, \quad \frac{z}{D} = 0. \quad (6.1)$$

No lateral co-ordinate is required because the centre spray is of constant width and located symmetrically between the tyres.

6.2 Location of Upper Edge of Centre-Spray Envelope

TABLE 6.1 LOCATION OF UPPER EDGE OF CENTRE-SPRAY ENVELOPE

Spray angle, γ_c	$\gamma_c = \gamma_{D_c} F_{d_\gamma}$	(6.2)
Coordinate of upper edge of spray envelope	$\frac{z_c}{D} = \left[\frac{2h}{D} + \frac{x}{D} \right] \tan \gamma_c$	(6.3)
Data required to estimate spray angle and co-ordinate of upper-edge of spray envelope	γ_{D_c} , datum value of γ_c from Figure 4 as function of V/V_p ; see Equations (4.8) for V_p .	
	F_{d_γ} , factor from Figure 3a as function of d/D for contaminant depth.	
	$2h/D$, length parameter for tyre-ground contact area from Section 4.1.	

6.3 Width of Centre-Spray Envelope

TABLE 6.2 WIDTH OF CENTRE-SPRAY ENVELOPE

Centre-spray width, Δy_c	$\frac{\Delta y_c}{D} = \frac{(y_w - w)}{D} F_{D_c} F_c F_{d_\lambda}$	(6.4)
Data required to estimate centre-spray width	F_{D_c} , datum width factor from Figure 5 as function of V/V_p ; see Equations (4.8) for V_p .	
	F_c , factor from Figure 6 as function of b_g/w for normal load on tyre	
	F_{d_λ} , factor from Figure 3c as function of d/D for contaminant depth.	
	b_g/w , width parameter for tyre-ground contact area from Section 4.1.	

* The spray intensity, τ , both within and at the edges of the envelopes decreases with distance from the tyre.