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Frictional and retarding forces on aircraft tyres Part V: estimation of fluid drag forces

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FRictionAL AND RETARDING FORCES ON AIRCRAFT TYRES PART V: ESTIMATION OF FLUID DRAG FORCES

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FRictionAL AND RETARDING FORCES ON AIRCRAFT TYRES PART V: ESTIMATION OF FLUID DRAG FORCES

1. NOTATION AND UNITS*

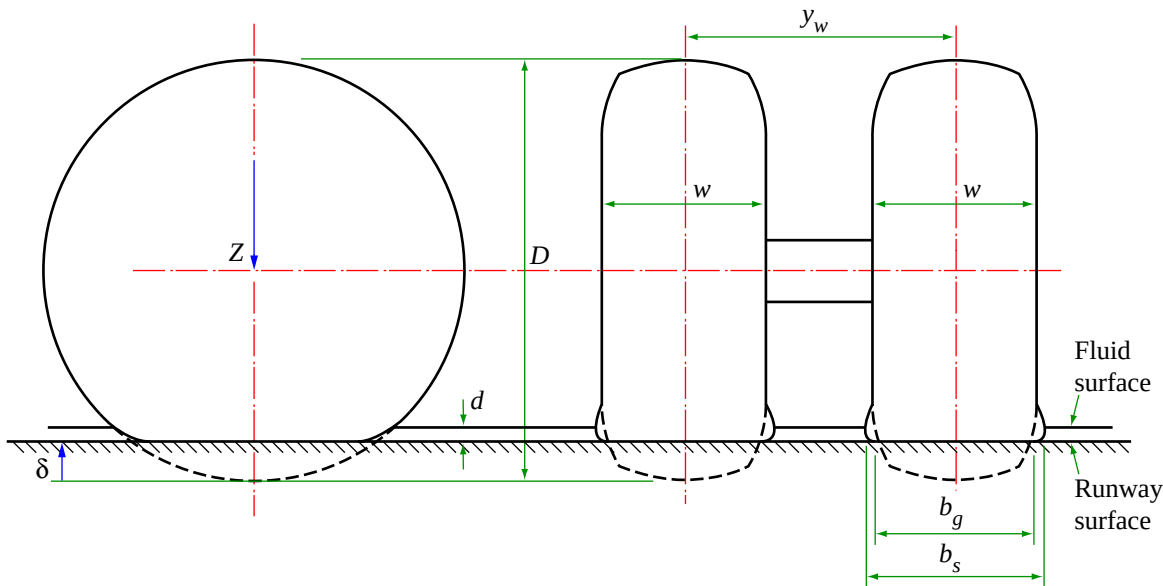
		SI	British
b_g	width of tyre-ground contact area, see Sketch 1.1	m	in
b_s	width of deflected tyre at intersection with fluid surface, see Sketch 1.1	m	in
$C_{D_{1,1}}$	drag coefficient due to fluid displacement by single tyre, $G_{F_{1,1}} / (\rho_w \sigma V^2 b_s d / 2)$, see Sketch 2.2		
C_z	coefficient in expression for tyre deflection under normal (to runway surface) load, see Section 2.3		
D	diameter of undeflected, inflated tyre	m	in
d	depth of fluid contaminant on runway (water or slush)	m	in
f_i	factor defining impingement drag of dual-tandem undercarriage relative to impingement drag at $V/V_p = 1.0$		
f_L	factor defining displacement drag of leading tyre(s) at $V/V_p > 1.0$, relative to displacement drag at $V/V_p = 1.0$		
$f_{1,2}$	factor defining drag of single-tandem undercarriage relative to displacement drag of single tyre undercarriage		
$f_{2,1}$	factor defining displacement drag of twin-tyre undercarriage relative to displacement drag of single tyre undercarriage		
G_F	fluid drag force on undercarriage (excluding leg)	N	lbf
N	number of tyres in each lateral row of undercarriage		
p	inflation pressure (gauge) of undeflected tyre	N/m ²	lbf/in ²
p_r	tyre "rated" inflation pressure	N/m ²	lbf/in ²
R	number of lateral rows of tyres in undercarriage		
V	aircraft ground speed	kn	kn
V_p	reference speed defined in Section 2.1	kn	kn

* 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 speed and, for British Units, the inch is used for all linear dimensions. These anomalies are taken into account by the inclusion of appropriate factors in equations.

w	width of undeflected, inflated tyre section	m	in
y_w	lateral spacing of tyres, see Sketch 1.1	m	in
Z	normal (to runway surface) load on wheel	N	lbf
δ	tyre deflection under normal (to runway surface) load, see Equations (2.2) and (2.3)	m	in
ρ_w	density of water (taken as 10^3 kg/m^3 , 1.94 slug/ft^3)	kg/m^3	slug/ft^3
σ	density of fluid contaminant relative to that of water (specific gravity)		
ψ_{tyre}	tyre yaw angle; angle between plane of rotation and projection of V on to ground plane	deg	deg

Subscripts

i	denotes force due to fluid impingement
N, R	denotes tyre arrangement in single undercarriage, N = number of tyres per lateral row, R = number of lateral rows, see Table 7.1 for illustrations



Sketch 1.1 Tyre Geometry

2. INTRODUCTION

This Data Item provides methods for estimating the drag force experienced by aircraft tyres running in a layer of water or slush on a runway. Single- and multiple-tyre undercarriage configurations are considered. In all cases the calculated values *exclude* the drag of the upper leg. *i.e.* that part above the axle or undercarriage chassis. Where appropriate, estimates can be made for the drag due to spray impingement on trailing tyres, brakes, undercarriage structure, *etc.* The methods do not include forces due to impingement of spray with any other undercarriage or with other parts of the airframe*.

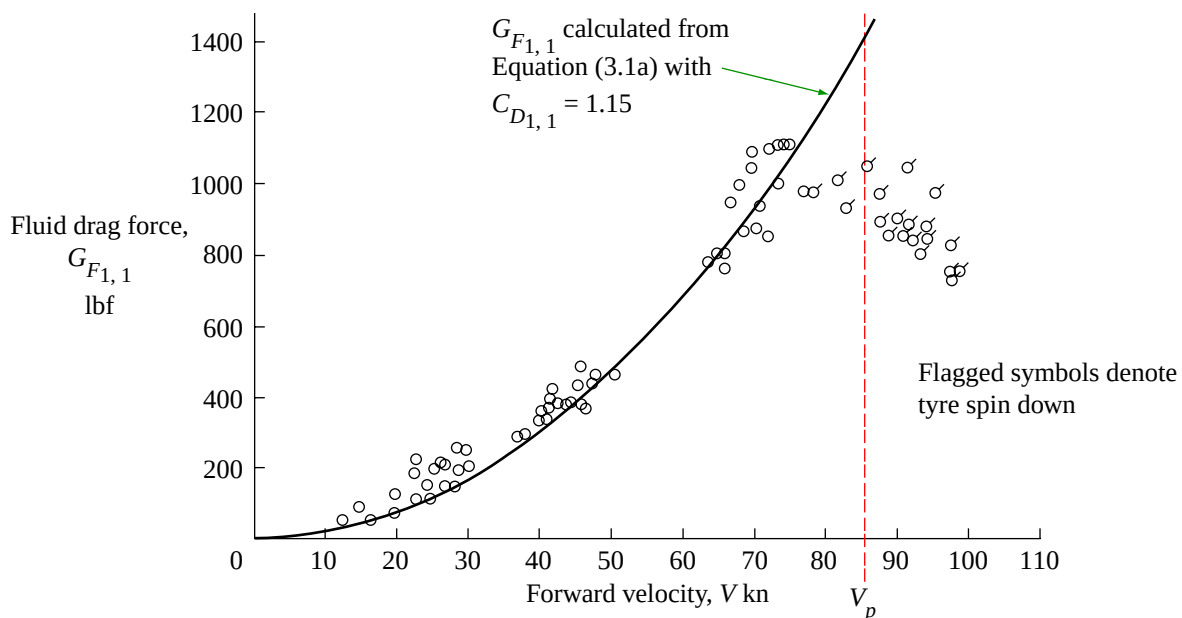
Sketch 2.1 shows a typical set of full-scale measurements for an isolated aircraft-type tyre. Where a multiple-tyre undercarriage is used, the drag force is affected by the proximity of the leading tyres to one another and, where trailing tyres are present, by impingement of spray from the leading tyres on the trailing tyres, the undercarriage structure and brake units. The drag force acts in a direction opposite to the aircraft ground speed and is present whether the wheel is braked or unbraked, yawed or unyawed.

Section 3 presents the calculation methods. **Table 7.1** summarises the methods and includes the nomenclature used to identify the various undercarriage configurations.

Section 4 describes the derivation of the methods and provides an indication of the accuracy to be expected. More details of the derivation are given in Reference 33 to 35.

Section 6 gives examples of drag calculations for typical twin-tyre and dual-tandem undercarriages.

Appendix A compares the performance of the methods for twin-tyre and dual-tandem undercarriages with the relevant parts of a widely-quoted set of test measurements (Convair 880).



Sketch 2.1 Example of measured fluid displacement drag developed by single tyre rolling unbraked in water

(Data from Reference 11; $D = 32$ in, $w = 8.8$ in, $Z = 10\,500$ lbf, $p = 90$ lbf/in², $d = 1.0$ in)

* The drag force due to tyre spray impingement of the airframe can be a significant part of the total. The magnitude of such forces is dependent on the overall aircraft configuration but can be particularly large where undercarriage legs are short and/or large flap deflections are used. The subject of tyre spray impingement forces will be dealt with in a separate Data Item.

2.1 The Reference Speed, V_p

The reference speed, V_p , is used throughout the methods in the Data Item as a convenient means of correlating and presenting the available measured data for fluid drag forces. Values of V_p are derived, customarily, from the expression*

$$V_p = 9 \left(\frac{p}{\sigma} \right)^{0.5} \text{ kn for } p \text{ in lbf/in}^2. \quad (2.1)$$

This speed is also of significance in the method of Reference 30 for predicting tyre-spray trajectories.

2.2 Runway Contaminants

For present purposes a runway contaminant is any fluid on a runway in sufficient depth and extent to produce significant drag forces on tyres passing through it. Water is the most common, true fluid contaminant. However the methods in this Data Item have been found to be equally applicable to slush – which is not a single-phase fluid – to the extent that data were available ($0.78 < \sigma < 1.0$). The methods are not suitable for use with snow but, since the distinction between wet snow and slush is indistinct, caution should be exercised if the methods are used for slush with $\sigma < 0.8$.

2.3 Values of Tyre Widths Used in Calculating Fluid Drag Forces

To use the methods presented in this Data Item, values are required for the widths b_g and b_s , of the deflected tyre at the runway surface, and at the surface of the fluid layer, respectively. Both parameters are functions of the tyre vertical deflection, δ , which, in turn, is a function of the normal load, Z , on the tyre and inflation pressure p . The load itself is dependent on aircraft weight, speed and centre-of-gravity position, although moments due to engine thrust, braking and control deflection can also influence it significantly.

Tyre vertical deflection, δ , can be expressed†, for consistent units of normal load and undeflected tyre width, diameter and inflation pressure, as

$$\frac{Z}{(p + 0.08p_r)w(wD)^{1/2}} = 2.4 \left[\frac{\delta}{w} - C_z \right] \quad \text{for } \frac{\delta}{w} > \frac{10}{3} C_z, \quad (2.2)$$

$$= 0.96 \left[\frac{\delta}{w} \right] + \frac{0.216}{C_z} \left[\frac{\delta}{w} \right]^2 \quad \text{for } \frac{\delta}{w} \leq \frac{10}{3} C_z. \quad (2.3)$$

Typical values of the coefficient C_z are:

$C_z = 0.03$ for modern cross-ply tyres, $C_z = 0.02$ for older cross-ply tyres.

In practice, Equation (2.3) is likely to be used only for such lightly-loaded tyres as may occur in the final stages of take-off rotation. Note also that δ/w has an upper limit corresponding to the deflection at which the tyre “bottoms” – typical values of this limit to δ/w are in the range 0.55 to 0.6.

* The derivation of Equation (2.1) is given in Reference 24 together with a description of the physical significance of the speed V_p . For other combinations of units the measured constant becomes

0.1084 (V in knots, p in N/m^2), 55.76 (V in m/s , p in MN/m^2), 34.28 (V in knots, p in bar).

† These expressions apply to cross-ply tyres only and are given here for convenience; their origin is given in ESDU 86005 (Reference 31). For radial-ply tyres it is necessary to consult the tyre manufacturer on a case-by-case basis.

Tyre width, b_g , at the runway surface (footprint width) can be expressed (see Reference 31) as a function of the vertical deflection parameter, δ/w , as

$$\frac{b_g}{w} = 1.7 \left[\frac{\delta}{w} - 2.5 \left[\frac{\delta}{w} \right]^4 + 1.5 \left[\frac{\delta}{w} \right]^6 \right]^{0.5} \quad (2.4)$$

Equation (2.4) can be applied to most aircraft-type tyres (for example types I, III, VII, VIII in Reference 38) but for “type H” tyres the following expression should be used

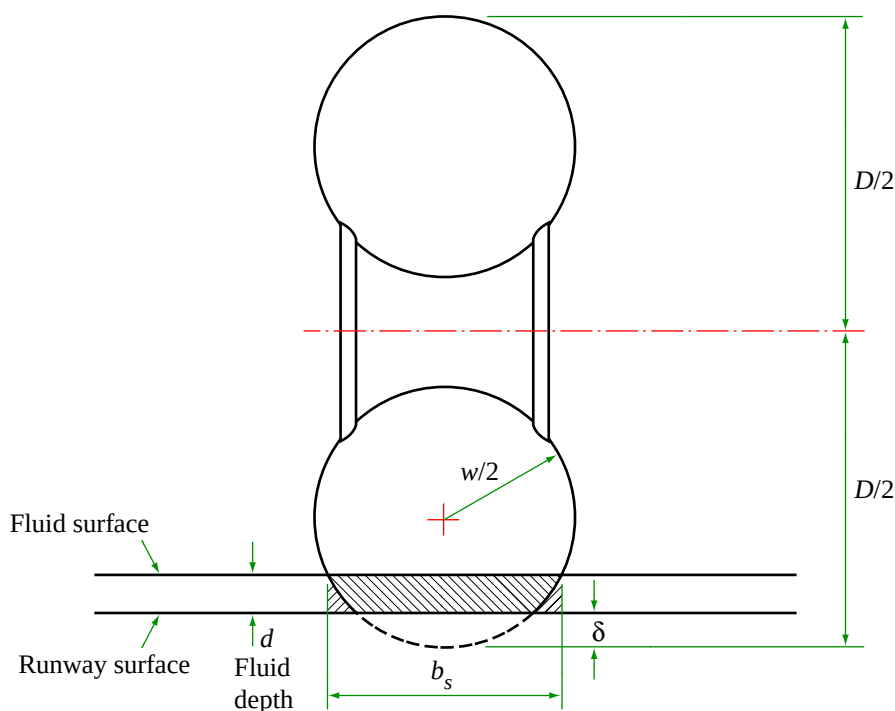
$$\frac{b_g}{w} = 1.55 \left[\frac{\delta}{w} - 1.1 \left(\frac{\delta}{w} \right)^2 \right]^{0.4} \quad (2.5)$$

Tyre width, b_s , at the fluid surface is given by the following expressions.

For $\left(\frac{\delta + d}{w} \right) \leq 0.5$, $\frac{b_s}{w} = 2 \left[\left(\frac{\delta + d}{w} \right) - \left(\frac{\delta + d}{w} \right)^2 \right]^{0.5} \quad (2.6)$

For $\left(\frac{\delta + d}{w} \right) > 0.5$ calculate b_s using Equation (2.6) with $\left(\frac{\delta + d}{w} \right) = 0.5$.

Equation (2.6) is based on the geometric representation of the deflected tyre shown in Sketch 2.2 and is the basis of values of b_s/w for those tyres used in developing the methods of this Data Item.



Sketch 2.2 Tyre cross-section assumed in Equation (2.6)

3. ESTIMATION OF FLUID DRAG FORCES ON AIRCRAFT TYRES

Sections 3.1 to 3.5 give estimation methods for fluid drag forces acting on different types of undercarriage based on the analysis of measured data from full-scale and model-scale tests. Sections 3.6 and 3.7 consider briefly the likely effects on drag of tyre yaw and of the use of spray alleviators.

The method for a single isolated tyre is given in Section 3.1 and forms the basis for drag calculations for “leading” tyres in multiple-tyre undercarriages. The subscripts denoting the different tyre arrangements are explained in Table 7.1.

3.1 Drag of Single Tyre Undercarriage

The drag force, $G_{F_{1,1}}$ due to fluid displacement by a single tyre running in a fluid layer of depth, d , and specific gravity, σ , is estimated in two parts, as follows.

For speeds where $V/V_p \leq 1.0$

For V in knots, b_s , d in inches and ρ_w in slug/ft³,

$$G_{F_{1,1}} = 0.01978 \left(\frac{\rho_w \sigma}{2} V^2 C_{D_{1,1}} b_s d \right) \text{ lbf.} \quad (3.1a)$$

For V in knots, b_s , d in metres and ρ_w in kg/m³,

$$G_{F_{1,1}} = 0.2647 \left(\frac{\rho_w \sigma}{2} V^2 C_{D_{1,1}} b_s d \right) \text{ N.} \quad (3.1b)$$

For any consistent set of units,

$$G_{F_{1,1}} = \frac{\rho_w \sigma}{2} V^2 C_{D_{1,1}} b_s d. \quad (3.1c)$$

Values of the tyre displacement drag coefficient, $C_{D_{1,1}}$, are given in Figure 1 as functions of V/V_p and b_s/b_q . Figure 1 is applicable to aircraft-type tyres for which $3 \leq D/w \leq 4$. For tyres with $D/w > 4$, there may be a reduction (of order 10 to 15 per cent) in $C_{D_{1,1}}$, see Section 4.1.1.

For speeds where $V/V_p > 1.0$ the drag force due to fluid displacement by a single tyre is given by

$$[G_{F_{1,1}}]_{V/V_p > 1.0} = f_L \times [G_{F_{1,1}}]_{V/V_p = 1.0}. \quad (3.2)$$

Values of the factor f_L are given in Figure 2 while the datum value, $[G_{F_{1,1}}]_{V/V_p = 1.0}$, is obtained from Equation (3.1).

* The numerical constants are made up as follows.

For Equation (3.1a) $0.01978 = 1.6878^2/12^2 \text{ [(ft/s)/kn]}^2/\text{[in/ft]}^2$.

For Equation (3.1b) $0.2647 = 1852^2/3600^2 \text{ [m/n.mile]}^2/\text{[s/hour]}^2$.

3.2 Drag of Twin-Tyre Undercarriage

For speeds where $V/V_p \leq 1.0$ the drag force due to fluid displacement by a twin-tyre undercarriage (*i.e.* two tyres side-by-side) is given by

$$\left[G_{F_{2,1}} \right]_{V/V_p \leq 1.0} = f_{2,1} \times \left[G_{F_{1,1}} \right]_{V/V_p \leq 1.0} \quad (3.3)$$

Values of the factor $f_{2,1}$ are given in Figure 3 while values of $\left[G_{F_{1,1}} \right]_{V/V_p \leq 1.0}$, *i.e.* the drag of a single tyre, are obtained from Equations (3.1).

For speeds where $V/V_p > 1.0$ the drag force due to fluid displacement by a twin-tyre undercarriage is given by

$$\left[G_{F_{2,1}} \right]_{V/V_p > 1.0} = f_L \times \left[G_{F_{2,1}} \right]_{V/V_p = 1.0} \quad (3.4)$$

Values of the factor f_L are given in Figure 2 while the datum value, $\left[G_{F_{2,1}} \right]_{V/V_p = 1.0}$, is obtained from Equation (3.3).

3.3 Drag of Dual-Tandem Undercarriage

The fluid drag force, $G_{F_{2,2}}$, acting on a dual-tandem undercarriage (and others involving leading and trailing tyres, see Section 3.5) is estimated as the sum of two components,

$$G_{F_{2,2}} = G_{F_{2,1}} + G_{F_i} \quad (3.5)$$

The first component in Equation (3.5), $G_{F_{2,1}}$, represents the drag of the leading pair of tyres and is estimated in exactly the same way as for a twin-tyre undercarriage in Section 3.2.

The second component, G_{F_i} , in Equation (3.5) represents the drag due to spray from the leading tyres impinging on the trailing tyres, brake units and undercarriage structure (excluding leg).

The drag force due to fluid impingement is given by

$$G_{F_i} = f_i \times \left[G_{F_i} \right]_{V/V_p = 1.0} \quad (3.6)$$

Values of the factor f_i are given in Figure 4 while the datum value, $\left[G_{F_i} \right]_{V/V_p = 1.0}$, is given by

$$\left[G_{F_i} \right]_{V/V_p = 1.0} = \left[\rho_w \sigma V^2 b_s d \right]_{V/V_p = 1.0} \text{ for any set of consistent units.} \quad (3.7a)$$

Equation (3.7a) is a particular form of Equation (4.3) but, when combined with the definition of V_p in Section 2.1, it may be expressed as follows,

for V in knots, b_s , d in inches, p in lbf/in² and ρ_w in slug/ft³,

$$\left[G_{F_i} \right]_{V/V_p = 1.0} = 1.6024 \rho_w p b_s d \text{ lbf,} \quad (3.7b)$$

for V in knots, b_s , d in metres, p in N/m^2 and ρ_w in kg/m^3 ,

$$\left[G_{F_i} \right]_{V/V_p = 1.0} = 0.01175 \rho_w p b_s d \quad \text{N.} \quad (3.7c)$$

The derivations of Equations (3.6) and (3.7) are discussed in Section 4.2.

3.4 Drag of Single-Tandem Undercarriage

There are relatively few data for this configuration. While the trends shown by those data are similar, the spread of values is large (see Section 4.3). In the absence of better information it is suggested that values of fluid drag be estimated from

$$G_{F_{1,2}} = f_{1,2} \times G_{F_{1,1}}. \quad (3.8)$$

Values of the factor $f_{1,2}$ are given in Figure 5 (which includes upper and lower limits to reflect the uncertainty in the data) while the datum value, $G_{F_{1,1}}$, is obtained from Equations (3.1).

3.5 Drag of Other Undercarriage Configurations

There are no measured drag data available for practical undercarriage configurations other than those considered in Sections 3.1 to 3.4. However, it is believed that those methods can be used to deduce estimates for other configurations. Sections 3.5.1 and 3.5.2 present results which have been derived after making the following assumptions,

- (i) there are N identical tyres in each lateral row of the undercarriage,
- (ii) each tyre carries an identical normal load, Z ,
- (iii) all tyres are at the same lateral spacing, y_w .

3.5.1 Single lateral row of N tyres

For speeds where $V/V_p \leq 1.0$, the drag force, $G_{F_{N,1}}$, due to fluid displacement is given by

$$\left[G_{F_{N,1}} \right]_{V/V_p \leq 1.0} = \left[G_{F_{1,1}} \right]_{V/V_p \leq 1.0} \times [1 + (N - 1)(f_{2,1} - 1)]. \quad (3.9)$$

Values of the factor, $f_{2,1}$, are given in Figure 3 while values of $\left[G_{F_{1,1}} \right]_{V/V_p \leq 1.0}$, i.e. the drag of a single tyre, are obtained from Equation (3.1).

In Equation (3.9), in addition to assumptions (i) to (iii) in Section 3.5, the flow is assumed to be symmetric about each tyre so that the drag of a lateral row of N tyres is equal to the drag of a single tyre plus $(N - 1)$ times the differences between the drags of a twin- and of a single-tyre undercarriage.

For speeds where $V/V_p > 1.0$,

$$\left[G_{F_{N,1}} \right]_{V/V_p > 1.0} = f_L \times \left[G_{F_{N,1}} \right]_{V/V_p = 1.0}. \quad (3.10)$$

Values of the factor f_L are given in Figure 2 while the datum value, $\left[G_{F_{N,1}} \right]_{V/V_p = 1.0}$, is obtained from Equation (3.9).

3.5.2 Multiple lateral rows of N tyres each

Each of the undercarriage configurations considered here is presumed to consist of a leading lateral row of N tyres followed by one or more trailing lateral rows of N tyres arranged in-line with those in front – see Table 7.1.

For the leading lateral row of N tyres, the drag due to fluid displacement is calculated using the method of Section 3.5.1.

For a single trailing lateral row of N tyres, the drag force, $[G_{F_i}]_N$, due to fluid impingement, is given by

$$[G_{F_i}]_N = f_i \times (N - 1) [G_{F_i}]_{V/V_p = 1.0} \quad (3.11)$$

Values of the factor f_i are given in Figure 4 while the datum value, $[G_{F_i}]_{V/V_p = 1.0}$, is obtained from Equations (3.7).

For multiple trailing lateral rows of tyres, it is unlikely that the impingement drag force will follow exactly the same trends as are defined for a single trailing row by Equations (3.11) and Figure 4.

In analysing data for the dual-tandem configuration in Section 4.3, the decrease in values of f_i shown at the higher speeds in Figure 4 is associated with a reduction in elevation angle of spray generated by the leading tyres (see Reference 34). However, this reduction in spray elevation angle will have a less pronounced effect the greater the number of rows of tyres. Thus, one conservative method of allowing for the drag due to fluid impinging on trailing tyres, etc, where there is a large number of lateral rows of tyres, is to assume that, for the particular value of tyre pressure, the value of f_i to be used in Equation (3.11) follows the trend with speed given by Figure 4 until it reaches its maximum value and thereafter remains at that value.

3.6 Effect of Yaw on Tyre Drag

There are few measured data available for the effect of yaw on the fluid drag force on tyres. For small angles of tyre yaw angle, ψ_{tyre} , it is suggested that the dimension b_s be replaced by $[b_s/\cos\psi_{tyre}]$ in Equations (3.1) and (3.7).

3.7 Effect of Tyre-Spray Alleviators on Drag

Most spray alleviators and deflectors are installed with the aim of preventing fluid ingestion into engine intakes, but a limited amount of information is available on associated drag forces (Reference 12) and pressures (Reference 26). Further information has been obtained indirectly from aircraft tests reported in Reference 25.

Sketch 3.1 shows two views of a device tested with a dual-tandem undercarriage in Reference 12. When only the vertical “splitter” plate was installed, there was no significant change in the measured drag (even when the “splitter” plate was extended almost to the runway surface). When both the “splitter” plate and curved “capping” plate were installed, the drag was reduced by a significant amount. This is illustrated in Sketch 3.2 as the ratio of the impingement drag forces experienced with and without the alleviator installed. Given the size and extent of this device, it seems likely that further reductions in drag using this kind of alleviator would be small.

Sketch 3.2 also includes results deduced from aircraft tests in which the main (dual-tandem) undercarriages were fitted with spray suppressors. These tests are reported in Reference 25 and the method of analysis