



Determination of hydroplaning speeds and corresponding hydrodynamic forces for rib tread aircraft tyres Application of ESDU 15003



**ROYAL
AERONAUTICAL
SOCIETY**

Endorsed by
The Royal Aeronautical Society

ESDU DATA ITEMS

Data Items provide validated information in engineering design and analysis for use by, or under the supervision of, professionally qualified engineers. The data are founded on an evaluation of all the relevant information, both published and unpublished, and are invariably supported by original work of ESDU staff engineers or consultants. The whole process is subject to independent review for which crucial support is provided by industrial companies, government research laboratories, universities and others from around the world through the participation of some of their leading experts on ESDU Technical Committees. This process ensures that the results of much valuable work (theoretical, experimental and operational), which may not be widely available or in a readily usable form, can be communicated concisely and accurately to the engineering community.

We are constantly striving to develop new work and review data already issued. Any comments arising out of your use of our data, or any suggestions for new topics or information that might lead to improvements, will help us to provide a better service.

THE PREPARATION OF THIS DATA ITEM

The work on this particular Data Item was monitored and guided by the Performance Committee. This Committee first met in 1946 and now has the following membership:

Chairman	
Mr G.J.R. Skillen	— Independent, UK
Vice-Chairman	
Mr K.J. Balkwill	— Independent, UK
Members	
Mr P.V. Aidala*	— Northrop Grumman ESID, Bethpage, New York, USA
Dr J.D. Avery	— Independent, UK
Mr M. Baxter	— BAE SYSTEMS, Brough, UK
Mr M. Broad	— Independent, UK
Mr E. Burdak*	— Pilatus Aircraft Ltd, Switzerland
Mr A. Dalton	— MOD, Boscombe Down, UK
Mr G. van Es	— National Aerospace Laboratory NLR, The Netherlands
Mr S.J. Hyde	— BAE SYSTEMS, Prestwick, UK
Mr L. Kornstaedt	— Airbus Industrie, Toulouse, France
Mr D.A. Law	— Civil Aviation Authority, Gatwick, UK
Mr C.J. Loughton	— Independent
Mr P.E.C.S. Magalhaes*	— Embraer, Brazil
Mr R.J. Orlowski*	— Boeing Commercial Airplane Company, Seattle, Washington, USA
Dr P. Render	— Loughborough University, UK
Mr G.E. Smith	— Independent, UK
Mr R. Storey	— Independent, UK
Mr S. Tsach*	— Israel Aircraft Industries, Jerusalem, Israel
Mr C.J. Turner*	— Boeing Commercial Airplane Company, Seattle, Washington, USA.
Mr J. Werner*	— Cessna Aircraft, Wichita, Kansas, USA.

* Corresponding Member

The construction and subsequent development of the Data Item were undertaken by

Mr R.S.D. Sayers — Senior Engineer.

The person with overall responsibility for the work in this subject area is Mr C.J. Whittaker, Head of Performance Group.

DETERMINATION OF HYDROPLANING SPEEDS AND CORRESPONDING HYDRODYNAMIC FORCES FOR RIB TREAD AIRCRAFT TYRES APPLICATION OF ESDU 15003

CONTENTS

	Page
1. NOTATION AND UNITS	1
2. INTRODUCTION	3
3. RUNWAY AND AMBIENT CONDITIONS	3
4. DESCRIPTION OF AIRCRAFT AND UNDERCARRIAGES	4
5. CALCULATION OF HYDROPLANING SPEEDS	7
5.1 Variation of Hydroplaning Speeds with Contaminant Depth	9
5.2 Variation of Hydroplaning Speeds with Runway Surface Macro-texture Depth	12
5.3 Variation of Hydroplaning Speeds with Tyre Inflation Pressure	15
5.4 Variation of Hydroplaning Speeds with Tyre Width	18
5.5 Variation of Hydroplaning Speeds with Tyre Diameter	21
6. CALCULATION OF HYDRODYNAMIC LIFT FORCE	24
6.1 Variation of Hydrodynamic Lift with Water Depth when Partial Hydroplaning Occurs	24
6.1.1 Take-off operation	24
6.1.2 Landing operation	26
6.2 Variation of Hydrodynamic Lift with Water Depth when Complete Hydroplaning Occurs	29
7. REFERENCES	30
APPENDIX A – CALCULATION OF HYDROPLANING SPEEDS FOR AIRCRAFT TYRE OPERATING ON WATER-COVERED RUNWAY SURFACE	31
A.1 Calculation of Speed at which Hydroplaning Commences	31
A.2 Calculation of Complete Hydroplaning Speed	32
APPENDIX B – CALCULATION OF HYDRODYNAMIC LIFT FORCE	33

DETERMINATION OF HYDROPLANING SPEEDS AND CORRESPONDING HYDRODYNAMIC FORCES FOR RIB TREAD AIRCRAFT TYRES APPLICATION OF ESDU 15003

1. NOTATION AND UNITS

The notation scheme from Reference 2 is followed in this document. Users should be familiar with the symbols and definitions from the reference. Additional notation relating to terms defined in this Data Item follow, along with terms from Reference 2 that are used frequently.

		Dimensions
C_L	aerodynamic lift coefficient	–
$(C_L)_H$	hydrodynamic lift coefficient	–
$c_1, c_{10}, c_{11}, c_{12}$	coefficients in decelerating-force model	–
D	inflated diameter of tyre	L
$((D)_S)_{cr}$	critical inflated diameter of tyre for partial hydroplaning. Partial hydroplaning will occur if $D \leq ((D)_S)_{cr}$	L
d_C	contaminant depth	L
$((d_C)_H)_{cr}$	critical water depth for complete hydroplaning. Complete hydroplaning will occur if $d_C \geq ((d_C)_H)_{cr}$	L
$((d_C)_S)_{cr}$	critical water depth for partial hydroplaning. Partial hydroplaning will occur if $((d_C)_S)_{cr} \leq d_C < ((d_C)_H)_{cr}$	L
d_{TEX}	depth of runway surface macro-texture	L
$((d_{TEX})_H)_{cr}$	critical depth of runway surface macro-texture for complete hydroplaning. Complete hydroplaning will occur if $d_{TEX} \leq ((d_{TEX})_H)_{cr}$	L
$((d_{TEX})_S)_{cr}$	critical depth of runway surface macro-texture for partial hydroplaning. Partial hydroplaning will occur if $((d_{TEX})_H)_{cr} < d_{TEX} \leq ((d_{TEX})_S)_{cr}$	L
d_{TREAD}	tyre tread depth	L
L	aerodynamic lift force	MLT ⁻²
L_h	hydrodynamic lift force acting on aircraft tyre	MLT ⁻²
m	number of wheels in a line-astern arrangement	–
n	number of wheels in a line-abreast arrangement	–
$(n_{UC})_{SECT}$	number of undercarriages belonging to particular section of an aircraft (for example, nose section, fuselage section)	–
p_{ABS}	inflation pressure – absolute measure	ML ⁻¹ T ⁻²

Issued July 2016 – 34 pages

$((p_{ABS})_H)_{cr}$	critical absolute tyre inflation pressure for complete hydroplaning. Complete hydroplaning will occur if $p_{ABS} \leq ((p_{ABS})_H)_{cr}$	$ML^{-1}T^{-2}$
$((p_{ABS})_S)_{cr}$	critical absolute tyre inflation pressure for partial hydroplaning. Partial hydroplaning will occur if $((p_{ABS})_H)_{cr} < p_{ABS} \leq ((p_{ABS})_S)_{cr}$	$ML^{-1}T^{-2}$
q	kinetic pressure	$ML^{-1}T^{-2}$
S_F	reference area for footprint	L^2
S_{REF}	reference area of wing	L^2
V	true air speed	LT^{-1}
V_G	ground speed of tyre	LT^{-1}
V_H	complete hydroplaning speed (see Reference 2) [†]	LT^{-1}
V_{LOF}	lift-off speed	LT^{-1}
V_S	partial hydroplaning speed (see Reference 2) [†]	LT^{-1}
V_{TD}	touchdown speed	LT^{-1}
W	aircraft weight	MLT^{-2}
$(W_{UC})_{SECT}$	vertical force acting on undercarriage belonging to particular section of an aircraft (for example, nose section, fuselage section)	MLT^{-2}
w	inflated width of tyre	L
$((w)_S)_{cr}$	critical inflated width of tyre for partial hydroplaning. Partial hydroplaning of the tyre under consideration will occur if $w \geq ((w)_S)_{cr}$	L
w/D	tyre fineness ratio	–
Z	vertical force on wheel	MLT^{-2}
$(Z_{FAC})_{SECT}$	proportion of net vertical aircraft force acting on an individual tyre that belongs to an undercarriage from a particular section of an aircraft (for example, nose section, fuselage section)	–
ρ_A	density of air	ML^{-3}
ρ_C	density of water	ML^{-3}
$1/\tau$	drainage parameter	–

[†] In this worked example, V_S and V_H values are calculated with a unit of m/s. The values are subsequently converted to, and quoted in, the unit of knot.

2. INTRODUCTION

This Data Item is a worked example which outlines the procedure to be followed to predict the speeds associated with hydroplaning for, and the hydrodynamic forces acting on, tyres of an aircraft operating on a water-covered runway surface. Both take-off and landing operations are considered. The methods described in Reference 2 are applied to calculate these speeds and forces. It should be noted that these methods are applicable only to instances where the depth of the water layer covering the runway surface under consideration exceeds the tread depth of the tyre being analysed.

Information about the phenomenon of hydroplaning and its potential effects on aircraft performance is given in Reference 2.

IMPORTANT NOTE: The purpose of this document is to illustrate the application of the method of Reference 2, using arbitrarily chosen values for some aircraft parameters. The results shown must not be taken as representative of any particular aircraft type.

3. RUNWAY AND AMBIENT CONDITIONS

Runway data are listed in Table 3.1. Note that the surface macro-texture depth, d_{TEX} , varies from the listed value in some instances.

TABLE 3.1 Runway data

d_{TEX} (m)	Runway surface type	Gradient (per cent)
$1.27 \times 10^{-3}\dagger$	Porous friction course (Type E $\ddagger$)	0

$\dagger$ Unless stated otherwise, assume this value for the parameter listed

$\ddagger$ See Reference 1

It is assumed that the runway surface is covered by a uniformly-distributed layer of water. The properties which are relevant to the analysis are listed in Table 3.2. Note that the d_C value varies from that listed in some instances.

TABLE 3.2 Contaminant data

Contaminant type	d_C (m)	ρ_C (kg/m ³)
Water	$10 \times 10^{-3}\dagger$	1000

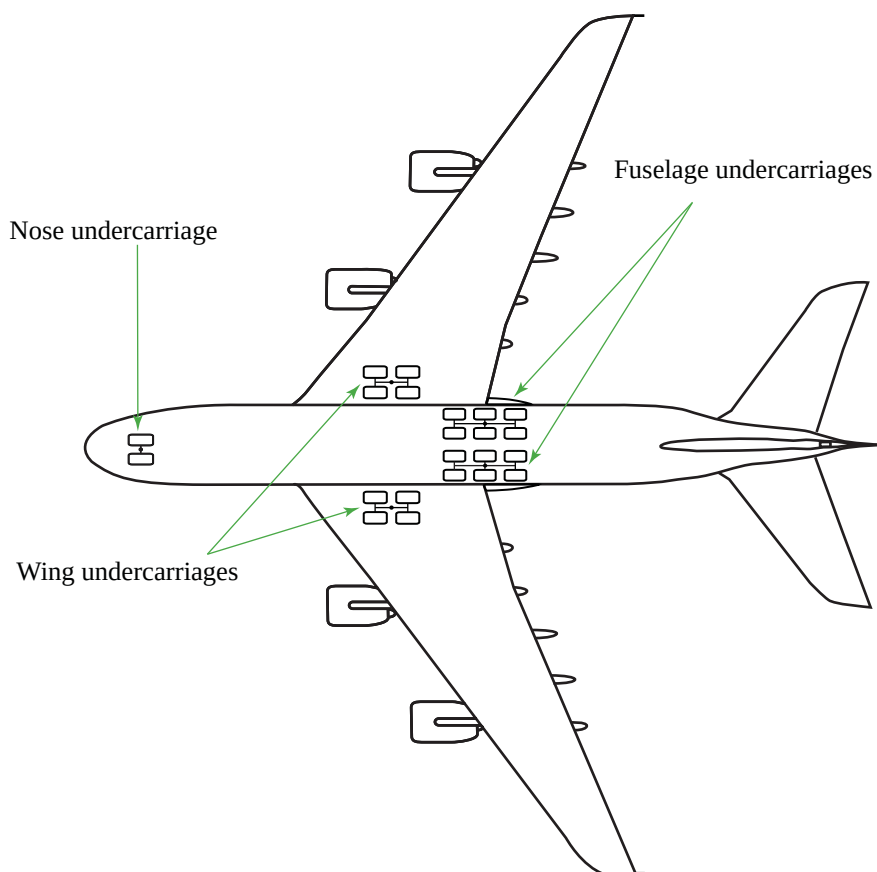
$\dagger$ Unless stated otherwise, assume this value for the parameter listed

ISA, Sea Level pressure (14.7 psi, 1013.2 mb) and ISA, Sea Level temperature (288.15 K) are assumed.

An air density, ρ_A , of 1.225 kg/m³ is assumed. There is no headwind or tailwind component.

4. DESCRIPTION OF AIRCRAFT AND UNDERCARRIAGES

The aircraft under consideration in this example has one nose undercarriage, two wing undercarriages and two fuselage undercarriages, as shown in Sketch 4.1.



Sketch 4.1 General layout of aircraft undercarriages

The nosewheel undercarriage is used to steer the aircraft, whilst the fuselage and wing undercarriages are fitted with braking systems. Note that the tyres from the final row of each fuselage undercarriage are not braked. These tyres are also used to steer the aircraft.

The aircraft net vertical force, $W - L$, is calculated using the following relationship.

$$W - L = W - 0.5\rho_A S_{REF} C_L V^2 \quad (4.1)$$

where W is the aircraft weight,

L is the aerodynamic lift force acting on the aircraft

ρ_A is the density of air,

S_{REF} is the reference area of the aircraft wing,

C_L is the coefficient of aerodynamic lift for the aircraft and

V is the true air speed of the aircraft.

As there is no headwind or tailwind component, the true air speed of the aircraft, V , is equivalent to its ground speed, V_G .

Aircraft data for take-off operations are listed in Table 4.1. These data are applicable over the ground speed range, V_G , of $0 \leq V_G$ (knot) < 145 . It is assumed that all aircraft undercarriage wheels are in contact with the runway surface over this speed range. When $V_G \geq 145$ knot, no aircraft wheel is assumed to be in contact with the runway surface.

TABLE 4.1 Data for aircraft during take-off operation

Parameter	Value	Unit
W	4.91×10^6	N
S_{REF}	845	m ²
C_L	1.62	—
V_{LOF}	145	knot

Aircraft data for landing operations are listed in Table 4.2. These data are applicable over the ground speed range of $0 \leq V_G$ (knot) < 135 . It is assumed that all aircraft undercarriage wheels are in contact with the runway surface over this speed range. When $V_G \geq 135$ knot, no aircraft wheel is assumed to be in contact with the runway surface.

TABLE 4.2 Data for aircraft during landing operation

Parameter	Value	Unit
W	3.4×10^6	N
S_{REF}	845	m ²
C_L	0.25	—
V_{TD}	135	knot

Note that the C_L values listed in Tables 4.1 and 4.2 have been selected for their suitability to the example and may not be representative of the values when the aircraft operates in its respective take-off or landing configuration.

The force acting on a tyre from an aircraft undercarriage that is operating on a runway surface is determined using the following relationship.

$$Z = (Z_{FAC})_{SECT} \times (W - L), \quad (4.2)$$

where $(Z_{FAC})_{SECT}$ is the proportion of the aircraft net vertical load, $W - L$, acting on a tyre from an undercarriage that belongs to the section of the aircraft under consideration.

For a tyre from a particular undercarriage,

$$(Z_{FAC})_{SECT} = \frac{(W_{UC})_{SECT}}{W} = \frac{(W_{UC})_{SECT}}{(n_{UC})_{SECT} \times m \times n}, \quad (4.3)$$

where $\frac{(W_{UC})_{SECT}}{W}$ is the proportion of the aircraft net vertical load acting on the undercarriages from the section of the aircraft under consideration,

$(n_{UC})_{SECT}$ refers to the number of undercarriages that belong to the section of the aircraft under consideration and

m and n refer, respectively, to the number of wheels in line-astern and line-abreast arrangement from an undercarriage that belongs to the section of the aircraft under consideration.

Relevant data for undercarriages from each section of the aircraft under consideration are summarised in Table 4.3.

TABLE 4.3 Undercarriage data[†]

Undercarriage	$(n_{UC})_{SECT}$	m	n	$((W_{UC})_{SECT}/W)^{\ddagger}$	$(Z_{FAC})_{SECT}^{\ddagger}$	D (m)	w (m)	p_{ABS} (N/m ²)	d_{TREAD} (m)	Tyre tread type
Nose	1	1	2	0.08	0.04	1.27	0.455	1.511×10^6	0.01	Rib
Fuselage	2	2	3	0.56	0.0467	1.4	0.53	1.601×10^6	0.01	Rib
Wing	2	2	2	0.36	0.045	1.4	0.53	1.601×10^6	0.01	Rib

[†] Unless stated otherwise, assume these values for the parameters listed.

[‡] Values are assumed to remain constant throughout take-off and landing operations.

5. CALCULATION OF HYDROPLANING SPEEDS

Reference 2 states that there are at least six conditions that can be associated with the hydroplaning of an aircraft tyre operating on a water-covered runway surface. These are,

- (i) a significant reduction of the water spray from the tyre,
- (ii) spin-down of the tyre, that is, a reduction in the rotating speed of the tyre,
- (iii) the fluid drag force acting on the tyre reaches its peak value,
- (iv) a loss of contact between the tyre footprint and the runway surface,
- (v) a loss of tyre directional stability and
- (vi) a loss of tyre braking action.

Conditions (i) to (iii) can be experienced by either a free-rolling or a braked aircraft tyre. These conditions are referred to as partial hydroplaning. The speed at which partial hydroplaning of a rib tread tyre begins, V_S , is determined using Equation (5.1). (Refer to Reference 2 for the derivation of the equation.) This refers to the speed at which tyre spin-down commences.

$$V_S = \left(\frac{c_1 \tau^2 \pi p_{ABS}}{\rho_C (\tanh[0.95])^{1/2}} \right)^{1/2}, \quad (5.1)$$

where c_1 is a coefficient,

$\frac{1}{\tau}$ is the surface drainage parameter,

p_{ABS} is the absolute inflation pressure of the tyre and

ρ_C is the density of the contaminant.

The value of the c_1 coefficient is calculated using

$$c_1 = c_{10} + c_{11} / \left(1 + \left(\frac{w/D}{c_{12}} \right)^2 \right) \quad (5.2)$$

where c_{10} , c_{11} and c_{12} are constants whose values are listed in Table 5.1.

TABLE 5.1 Non-dimensional constants used to calculate c_1 coefficient for a rib tread tyre

Constant	Value
c_{10}	0
c_{11}	1.52
c_{12}	0.3125

The surface drainage parameter is calculated from:

$$\frac{1}{\tau} = \frac{d_C}{d_C + d_{TEX}}. \quad (5.3)$$

Conditions (iv) to (vi) are assumed to occur simultaneously and are defined as complete hydroplaning. The speed at which complete hydroplaning of a rib tread tyre occurs, V_H , is calculated from:

$$V_H = 0.98 \left(1 + \frac{d_{TEX}}{d_C} \right) \left(\frac{\pi p_{ABS}}{\rho_C} \right)^{1/2}. \quad (5.4)$$

Note that $V_H > V_S$.

A coherent set of units must be used to calculate both V_S and V_H .

As is customary in aircraft performance, V_S and V_H values are always quoted in knots. However, in equations the speeds must be in coherent units such as m/s or ft/s. In this Data Item speed values are initially calculated with a unit of m/s and subsequently converted to knot.

Observing Equations (5.1) to (5.3), it is apparent that the vertical load acting on a tyre does not influence hydroplaning. Consequently, neither the weight nor the aerodynamic configuration of an aircraft will influence the likelihood that one of its tyres will experience either partial or complete hydroplaning.

Table 5.2 lists the parameters which influence both partial and complete hydroplaning of an aircraft tyre.

The influence of each of these parameters, where applicable, on V_S and V_H will be investigated in this Data Item for the aircraft described in Section 4. (It should be noted that the values of the tyre parameters which influence both forms of hydroplaning are identical for tyres from both the fuselage and wing undercarriages, consequently separate analyses are not provided.)

A detailed solution for the calculation of V_S and V_H can be found in Appendix A.

Note that Equations (5.1) to (5.4) are only valid when the contaminant depth, d_C , equals or exceeds the tyre tread depth, d_{TREAD} .

TABLE 5.2 Parameters that influence partial and/or complete hydroplaning of an aircraft tyre

	Parameter	Form of hydroplaning influenced by parameter	
		Partial	Complete
Tyre properties	Tread type (rib or smooth)	✓	✗
	Diameter (D)	✓	✗
	Width (w)	✓	✗
	Inflation pressure (p_{ABS})	✓	✓
Runway properties	Texture depth (d_{TEX})	✓	✓
Contaminant properties	Contaminant density (ρ_C) [†]	✓	✓
	Contaminant depth (d_C)	✓	✓

[†] Note that the density of water is considered to remain constant in value.

5.1 Variation of Hydroplaning Speeds with Contaminant Depth

The influence of water depth, d_C , on V_S and V_H for a tyre from the nose undercarriage and from a fuselage or wing undercarriage is summarised in Table 5.3 for a number of d_C values within the range $10 \times 10^{-3} \leq d_C \text{ (m)} \leq 20 \times 10^{-3}$. These results are also illustrated in Sketch 5.1. (Note that the marker points for the d_C values used to determine V_S for a tyre from the nose undercarriage in Sketch 5.1 differ from those listed in Table 5.3. These alternative values were used in Sketch 5.1 in order to distinguish the V_S curves for a tyre from the nose undercarriage from the V_S curves for a tyre from a fuselage/wing undercarriage.)

It is apparent that, for each type of tyre, both V_S and V_H decrease as the contaminant depth increases. Additionally, for each type of tyre the speed at which hydroplaning commences, V_S , for the range of contaminant depths considered is always less than the lift-off and touchdown speeds for the aircraft. Consequently, partial hydroplaning of each aircraft tyre always occurs for the water depths considered. During the take-off operations, tyre spin-down will always occur over the aircraft ground speed range $V_S \leq V_G \leq V_{LOF}$. During landing operations, the hydrodynamic forces will cause one or more tyres from each type of undercarriage to separate from the runway surface when $V_G \geq V_S$, which is likely to have a detrimental influence on the stability and control of the aircraft.

If partial hydroplaning will result in a loss of directional control of the aircraft, the results imply that the aircraft should not be operated on the runway when its surface is covered by a layer of water in the range $10 \times 10^{-3} \leq d_C \text{ (m)} \leq 20 \times 10^{-3}$.

The V_S value for a tyre from the fuselage or wing undercarriage is slightly lower than the V_S value for a tyre from the nose undercarriage for a given contaminant depth. A fuselage (or wing) undercarriage tyre has fineness ratio, w/D , of 0.3786, which is larger than the value of 0.3583 for a nose undercarriage tyre. This has the effect of lowering the speed at which hydroplaning commences. Although the inflation pressure, p_{ABS} , for a tyre from the fuselage or wing undercarriage is greater than that for a tyre from the nose undercarriage, which has the effect of raising the V_S value, the margin is not sufficient to compensate for the larger fineness ratio value of these tyres.

In order to avoid the partial hydroplaning of any tyre belonging to the aircraft, it will be necessary to ensure that the V_G of the aircraft does not equal or exceed the V_S value for a tyre from the fuselage or wing undercarriage for the depth of water that is covering the runway.

The speed at which complete hydroplaning occurs, V_H , is higher for a tyre from the fuselage or wing undercarriage than for a tyre from the nose undercarriage in each instance. This is because tyres from fuselage and wing undercarriages are inflated to a higher value of p_{ABS} . Complete hydroplaning of a tyre from the nose undercarriage occurs when the water depth equals or exceeds 12.11×10^{-3} m during a take-off operation. Complete hydroplaning of such a tyre is not observed for the range of water depths considered during a landing operation. Complete hydroplaning of a tyre from a fuselage or wing undercarriage occurs during take-off operations when the runway is covered by a layer of water whose depth equals or exceeds 17.31×10^{-3} m.

The maximum speed that an aircraft tyre will travel at is V_{LOF} for a take-off operation and V_{TD} for a landing operation.

The critical contaminant depth which corresponds to the case where $V_S = V_{LOF}$ or V_{TD} for an aircraft tyre is denoted as $((d_C)_S)_{cr}$. Partial hydroplaning of the tyre under consideration will not occur if $d_C < ((d_C)_S)_{cr}$.