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By

J. W. BLINKHORN, B.Sc., A.F.R.Ae.S.

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Summary.—The investigation covers all combinations of landing speed, coefficient of friction between the tyre and the ground, and harshness of landing, for any type of pneumatic tyre and wheel unit. Particular attention has been given to landing speeds between 50 and 150 m.p.h., coefficients of friction from 0 to 2·0, and landings giving vertical wheel accelerations of 1*g*, 2*g*, 3*g*, 4*g*.

It was found that for any landing, the vertical reaction at any wheel which has just finished spinning-up increases with increase in the moment of inertia of the wheel and tyre unit, and the landing speed, and decreases with increase in the free tyre radius, the aircraft weight, the time to reach the maximum vertical wheel reaction, and the coefficient of friction between the tyre and the ground. It should be noted, of course, that there is a relation between the moment of inertia, the free tyre radius and the aircraft weight,—in general the free tyre radius and the moment of inertia will increase with aircraft weight.

For any wheel and tyre unit it is shown that there are various combinations of landing speed and coefficient of friction which will cause the wheel spinning up to just cease at the same instant as the maximum vertical wheel reaction is reached, and except for very gentle landings, the maximum value of μ required is usually much less than 1·0.

Figs. 1 to 7, together with the notation given in Section 3, are self-explanatory and expand the above observations.

1. *Introduction.*—It is well-known that wheel drag loads are caused at touch down by spinning-up the landing gear wheels from rest to the speed corresponding to the landing speed of the aircraft. A limited investigation into the magnitude of these drag loads and the associated vertical loads was made some years ago in S.M.E. Department, Royal Aircraft Establishment. For various reasons it is now desirable to extend this investigation.

2. *Range of Investigation.*—The ground loads arising when spinning-up wheels at touch down have been determined in a manner which can be applied to any type of wheel and pneumatic tyre equipment fitted to undercarriages incorporating oleo-pneumatic or spring-type shock absorbers. The results of this investigation can be applied to aircraft landing at any forward speed on a surface giving any coefficient of friction between the tyre and the ground and for any practicable severity of landing, *i.e.*, very light to very heavy.

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* R.A.E. Tech. Note Mech. Eng. No. 16—received 17th July, 1948.

3. *Method of Analysis*.—Considering one wheel:

R	Vertical reaction at any instant
R_1	Unit static load at landing weight which is equal to aircraft weight ÷ number of main wheels for main undercarriage, and to static load with aircraft at rest for auxiliary tail or nose unit
μ	Coefficient of friction between tyre and ground
λ	Vertical reaction factor at any instant $= R/R_1$
λ_s	Vertical reaction factor when spinning-up ceases
λ_m	Maximum vertical reaction factor reached during any landing
V	Landing speed of aircraft
w_i	Angular velocity of wheel at any instant
r	Free radius of tyre
r_i	Radius of tyre at any instant, *i.e.*, height of axle above the ground
r_e	Effective rolling radius of tyre at any instant, *i.e.*, $= V/w_i$
I	Moment of inertia of complete wheel and tyre unit about its axle
t	Time measured from instant of touch down
t_m	Time to reach maximum vertical reaction
t_s	Time taken to spin up the wheel
T	Dynamic tyre rate (deflection per unit load)
g	Acceleration due to gravity.

Then at any instant *during* the spinning-up period we have:

$$\mu R r_i = \frac{I}{g} \frac{dw_i}{dt} .$$

Therefore,
$$\int \mu R r_i \, dt = \frac{I w_i}{g} . \qquad \text{.. .. ..} \quad (1)$$

At time $t = t_s$ when spinning-up *ceases*, *i.e.*, no slipping between the tyre and the ground, equation (1) becomes

$$\int_0^{t_s} \mu R r_i \, dt = \frac{I}{g} \frac{V}{r_e}$$

i.e.,
$$\mu = \frac{IV}{g r_e R \int_0^{t_s} \lambda r_i \, dt} . \qquad \text{.. .. ..} \quad (2)$$

Before an explicit expression for equation (2) can be obtained, substitutions will have to be made for r_e, r_i and λ in terms of time t and known constants. These substitutions can be made by the following assumptions:

(i) $\lambda = \lambda_m \sin[(\pi/2) . (t/t_m)]$, has been found to be approximately correct for a large number of landing gear units on which performance tests have been made. These units had the usual oleo-pneumatic or spring type of shock absorber, and further examination of the validity of this equation would have to be made if an unusual type of shock absorber were used.

(ii) Tyre deflection is directly proportional to the vertical load, so that

$$r_e = r - \tfrac{1}{3}RT = r - \tfrac{1}{3}\lambda R_1 T = r - \tfrac{1}{3}\lambda K r$$

and $r_i = r - \lambda K r$

where $K = \dfrac{R_1 T}{r}$.

Table 1 shows the value of K for a selection of tyres in the 'intermediate' range and in the Ministry of Supply standard tyre ranges. These show that K is of the same order for all these tyre ranges and varies from about 0·10 to 0·16, the general tendency being for K to increase as the tyre size increases.

Therefore, equation (2) becomes

$$\mu = \frac{IV}{t_m g R_1 r^2 \left(1 - \dfrac{\lambda_s K}{3}\right) \displaystyle\int_{\frac{t}{t_m}=0}^{\frac{t}{t_m}=\frac{t_s}{t_m}} \lambda_m \sin\left(\frac{\pi}{2}\frac{t}{t_m}\right)\left(1 - \lambda_s K\right) d\left(\frac{t}{t_m}\right)} . \qquad \ldots \quad \ldots \qquad (3)$$

The integral in equation (3) becomes

$$\lambda_m \int_{\frac{t}{t_m}=0}^{\frac{t}{t_m}=\frac{t_s}{t_m}} \sin\left(\frac{\pi}{2}\frac{t}{t_m}\right) d\left(\frac{t}{t_m}\right) - \lambda_m{}^2 K \int_{\frac{t}{t_m}=0}^{\frac{t}{t_m}=\frac{t_s}{t_m}} \sin^2\left(\frac{\pi}{2}\frac{t}{t_m}\right) d\left(\frac{t}{t_m}\right)$$

$$= \lambda_m \frac{2}{\pi}\left[-\cos\left(\frac{\pi}{2}\frac{t}{t_m}\right)\right]_{\frac{t}{t_m}=0}^{\frac{t}{t_m}=\frac{t_s}{t_m}} - \frac{\lambda_m{}^2 K}{2} \int_{\frac{t}{t_m}=0}^{\frac{t}{t_m}=\frac{t_s}{t_m}} \left[1 - \cos\left(\pi\frac{t}{t_m}\right)\right] d\left(\frac{t}{t_m}\right)$$

$$= \frac{2\lambda_m}{\pi}\left[1 - \cos\left(\frac{\pi}{2}\frac{t_s}{t_m}\right)\right] - \frac{\lambda_m{}^2 K}{2}\frac{t_s}{t_m} + \frac{\lambda_m{}^2 K}{2\pi}\left[\sin\pi\frac{t_s}{t_m}\right]$$

$$= \frac{2\lambda_m}{\pi}\left[1 - \sqrt{\left(1 - \left(\frac{\lambda_s}{\lambda_m}\right)^2\right)}\right] - \frac{\lambda_m{}^2 K}{2}\left[\frac{2}{\pi}\sin^{-1}\frac{\lambda_s}{\lambda_m}\right] + \frac{\lambda_m{}^2 K}{2\,\pi}\left[2\frac{\lambda_s}{\lambda_m}\sqrt{\left(1 - \left(\frac{\lambda_s}{\lambda_m}\right)^2\right)}\right]$$

$$= \frac{2\lambda_m}{\pi}\left\{\left(1 - \sqrt{\left[1 - \left(\frac{\lambda_s}{\lambda_m}\right)^2\right]}\right) - \frac{\lambda_m K}{2}\left(\sin^{-1}\frac{\lambda_s}{\lambda_m} - \frac{\lambda_s}{\lambda_m}\sqrt{\left[1 - \left(\frac{\lambda_s}{\lambda_m}\right)^2\right]}\right)\right\}$$

Equation (3) may therefore be written

$$\frac{\mu}{\dfrac{IV}{r^2R_1gt_m}} = \frac{1}{\left(1 - \dfrac{\lambda_s K}{3}\right)\dfrac{2\lambda_m}{\pi}\left[\left(1 - \sqrt{\left\{1 - \left(\dfrac{\lambda_s}{\lambda_m}\right)^2\right\}}\right) - \dfrac{\lambda_m K}{2}\left(\sin^{-1}\dfrac{\lambda_s}{\lambda_m} - \dfrac{\lambda_s}{\lambda_m}\sqrt{\left\{1 - \left(\dfrac{\lambda_s}{\lambda_m}\right)^2\right\}}\right)\right]} \quad .. \quad (4)$$

Equation (4), then, defines the relationship between the various factors at the end of the spinning-up period, and it will be seen that the left-hand side of this equation is non-dimensional.

Fig. 1 shows the variation of $\mu/(IV/r^2R_1gt_m)$ with λ_s for values of $\lambda_m = 1, 2, 3, 4$ respectively, K being taken $= 0{\cdot}15$, these curves being obtained, of course, by substitution in the right-hand side of equation (4). Similar curves for $K = 0{\cdot}10$ and $K = 0{\cdot}20$ were practically identical with those for $K = 0{\cdot}15$ and to avoid confusion these have not been shown. The larger the value of K the slightly further from the origin the curves moved. From Fig. 1 any specific set of conditions can be examined, for $K = 0{\cdot}15$ as follows, *using lb ft sec units unless otherwise stated,* g being taken $= 32{\cdot}2$ ft/sec^2:—

(i) Figs. 2, 3, 4, 5 show, for $\lambda_m = 1, 2, 3, 4$ respectively, the variation of λ_s with μ, for values of $I/r^2R_1t_m = 0{\cdot}025, 0{\cdot}075$ and $0{\cdot}125$, and values of $V = 50$, 100, and 150 m.p.h. For nose wheel units λ_m will usually be much greater than $4{\cdot}0$ for very heavy landings, but curves for any value of λ_m can be added to Figs. 2, 3, 4, 5. Table 2 shows the values of $I/r^2R_1t_m$ for various wheel and tyre units, assuming $t_m = 0{\cdot}1$ sec which is approximately correct for all the oleo-pneumatic or spring shock absorber units on which drop tests have been made.

(ii) For $\mu = 1{\cdot}0$, Fig. 6 shows the variation of λ_s/λ_m with V, for various values of λ_m and $I/r^2R_1t_m$. Similar curves may be obtained for various values of μ.

(iii) In Fig. 7 is shown, for various values of $I/r^2R_1t_m$ and λ_m, the variation of μ with V for landings in which $\lambda_s = \lambda_m$, *i.e.,* for landings in which spinning-up ceases at the same instant as the maximum vertical reaction is reached.

The value of λ_m varies for any shock absorber unit according to the vertical velocity of descent at touch down. For dry grass surfaces μ is about $0{\cdot}45$ but increasing wetness will decrease this considerably. Dry concrete normally gives μ about $1{\cdot}0$, although for spinning-up conditions it is possible that this value may be exceeded.

4. *Examples.*—To demonstrate the use of Fig. 1 for any particular case we will consider two hypothetical examples.

(i) An aircraft fitted with two single-wheel main undercarriage units having 17·50—18 in. patterned tread tyres at a pressure of 45 lb/in.^{2} lands at a weight of 28,200 lb at a speed of 92 m.p.h. on a runway having a coefficient of friction with the tyre of 0·75. The landing is rather severe, giving a maximum vertical acceleration of $2{\cdot}5g$ at the main wheels. We can now estimate as follows, the vertical reaction factor λ_s at the main wheels when spinning up just ceases. In Fig. 1, we know μ, r, R_1, V and g. Also I can be determined ($= 568$ lb ft^2) and t_m estimated from drop tests — say $t_m = 0{\cdot}11$ sec, compared with the overall average value of 0·1 sec assumed when obtaining curves based on Fig. 1.

Therefore, $$\frac{\mu}{(I/r^2R_1)\,(V/gt_m)} = \frac{0{\cdot}75}{(568/2{\cdot}125^2 \times 14{,}100)\,(134{\cdot}8/32{\cdot}2 \times 0{\cdot}11)} = 2{\cdot}21,$$

for which, interpolating for $\lambda_m = 2{\cdot}5$ in Fig. 1, the corresponding value of λ_s is equal to 1·97.

The time t_s taken to spin up the wheels is given by

$$1 \cdot 97 = 2 \cdot 5 \sin\left(\frac{\pi}{2}\frac{t_s}{0 \cdot 11}\right)$$

from which $t_s = 0 \cdot 064$ sec.

(ii) The above aircraft is fitted with a tail wheel unit having a 7·50—10·25 in. patterned tread tyre at a pressure of 45 lb/in.², and the static tail wheel load at the landing weight of 28,200 lb is 2,850 lb. The tail wheel touches down a few seconds after the main wheels, the landing speed being then reduced to 75 m.p.h. and the maximum vertical acceleration at the tail wheel unit is $1 \cdot 5g$. In Fig. 1 we again know or can assume the values of μ, r, R_1, V, g, I, and t_m—say t_m from drop test results is equal to $0 \cdot 095$ sec.

Therefore, $$\frac{\mu}{(I/r^2R_1)\,(V/gt_m)} = \frac{0 \cdot 75}{(15 \cdot 12/1 \cdot 01^2 \times 2{,}850)\,(110/32 \cdot 2 \times 0 \cdot 095)} = 4 \cdot 02,$$

for which, interpolating for $\lambda_m = 1 \cdot 5$ in Fig. 1, the corresponding value of λ_s is $= 1 \cdot 10$. The time t_s taken to spin up the wheel is given by:—

$$1 \cdot 10 = 1 \cdot 5 \sin\left(\frac{\pi}{2}\frac{t_s}{0 \cdot 095}\right)$$

from which $t_s = 0 \cdot 050$ sec.

TABLE 1

Values of K for Various Ranges of Tyres

Tyre Range	Tyre Size in.	Free radius r of tyre in.	Tyre pressure lb/in.^{2}	Static load R_1 lb	Dynamic tyre rate T in. per lb × 10^4	$K = \frac{R_1 T}{r}$
‘ Intermediate ’	6·00—6½	8·53	25	1,025	10·1	0·121
			35	1,325	8·17	0·127
			45	1,625	6·88	0·131
	7·00—7½	9·95	25	1,350	10·6	0·143
			35	1,750	8·49	0·149
			45	2,150	7·11	0·153
	7·50—10¼	12·13	25	1,850	7·12	0·109
			35	2,350	5·99	0·116
			45	2,850	5·18	0·122
	9·75—12	15·63	25	2,800	8·01	0·143
			35	3,800	6·58	0·160
			45	4,800	4·73	0·146
	15·00—16	22·23	25	6,000	4·81	0·130
			35	8,000	3·80	0·137
			45	10,000	3·14	0·141
	17·50—18	25·5	25	8,500	4·32	0·144
			35	11,500	3·23	0·146
			45	14,100	2·65	0·146
Ministry of Supply Standard Tyre Range (50 lb/in.^{2})	19 × 6·25—9	9·7	30	1,380	8·57	0·122
			40	1,770	6·69	0·122
			50	2,160	5·48	0·122
	21 × 6·75—10	10·65	30	1,630	7·18	0·110
			40	2,100	5·58	0·110
			50	2,570	4·57	0·110
	23 × 7·25—10	11·5	30	1,980	7·08	0·122
			40	2,540	5·52	0·122
			50	3,100	4·52	0·122
	25 × 7·75—11	12·55	30	2,360	6·51	0·122
			40	3,030	5·06	0·122
			50	3,700	4·14	0·122
	32 × 10·5—14	15·95	30	4,090	5·30	0·136
			40	5,250	4·13	0·136
			50	6,410	3·39	0·136
	37 × 13—15	18·65	30	5,985	4·56	0·146
			40	7,500	3·63	0·146
			50	9,150	2·99	0·146
	42 × 15·50—16	21·0	30	7,700	4·13	0·151
			40	9,900	3·23	0·152
			50	12,100	2·64	0·152
	48 × 18—18	23·88	30	11,750	3·23	0·159
			40	14,000	2·73	0·160
			50	16,250	2·36	0·160
Ministry of Supply Standard Tyre Range (50-70 lb/in.^{2})	22 × 6·75—11	11·2	50	2,710	4·53	0·110
			60	3,180	3·94	0·112
			70	3,650	3·44	0·112
	26 × 7·75—13	13·0	50	3,600	4·45	0·123
			60	4,250	3·55	0·116
			70	4,900	3·17	0·119
	30 × 9—15	15·0	50	5,100	3·53	0·120
			60	6,000	3·00	0·120
			70	6,900	2·61	0·120

TABLE 1 (*Cont.*)

Tyre Range	Tyre Size in.	Free radius r of tyre in.	Tyre pressure lb/in.^{2}	Static load R_1 lb	Dynamic tyre rate T in. per lb $\times 10^4$	$K = \frac{R_1 T}{r}$
Ministry of Supply Standard Tyre Range (50-70 lb/in.^{2})	34 × 10·75—16	17·05	50	7,100	3·16	0·132
			60	8,350	2·69	0·132
			70	9,600	2·34	0·132
	40 × 13·25—17	19·8	50	10,300	2·72	0·141
			60	12,075	2·32	0·142
			70	13,850	2·02	0·142
	45 × 16—18	22·6	50	14,300	2·37	0·150
			60	16,750	2·03	0·150
			70	19,200	1·77	0·150
	52 × 18·5—21	26·1	50	19,400	2·09	0·155
			60	22,700	1·79	0·155
			70	26,000	1·56	0·155
	64 × 22·5—26	31·9	50	28,500	1·60	0·143
			60	33,500	1·41	0·148
			70	38,500	1·23	0·149
Ministry of Supply Standard Tyre Range (70-90 lb/in.^{2})	20 × 5·25—11	10·25	70	2,600	3·97	0·101
			80	2,825	3·57	0·098
			90	3,250	3·25	0·103
	24 × 6·00—13	11·9	70	3,430	3·60	0·104
			80	3,885	3·18	0·103
			90	4,340	2·85	0·104
	27 × 7·25—14½	13·75	70	4,840	3·05	0·108
			80	5,485	2·51	0·100
			90	6,130	2·39	0·107
	31 × 8·75—15½	15·65	70	6,820	2·65	0·115
			80	7,735	2·34	0·116
			90	8,650	2·09	0·116
	36 × 10·75—16½	17·8	70	10,000	2·13	0·120
			80	11,100	1·93	0·120
			90	12,200	1·76	0·120
	41 × 12·75—18	20·5	70	13,900	1·96	0·133
			80	15,550	1·75	0·133
			90	17,200	1·58	0·132
	48 × 15·00—21	24	70	19,000	1·67	0·132
			80	21,500	1·47	0·132
			90	24,000	1·32	0·132
	56 × 17·50—24	27·8	70	26,200	1·43	0·134
			80	29,700	1·26	0·134
			90	33,200	1·12	0·134
	66 × 20·75—28	32·75	70	37,500	1·18	0·135
			80	42,500	1·04	0·135
			90	47,500	0·93	0·135

TABLE 2

Value of $I/r^2R_1t_m$ for Various Wheel and Tyre Units ($t_m = 0\cdot1$ sec)

Note The values of I have been determined from the expression

$$I = 0\cdot6\, M_w r_2^2 + CM_T\,(R^2 + 1\cdot5\, r_1^2)$$

where M_W weight of wheel
M_T weight of tyre and inner tube
r_2 rim radius
$R = (r + r_2)/2$
r free tyre radius
$r_1 = (r - r_2)/2$
$C = 0\cdot95$ for tyres with thin treads and $1\cdot01$ for tyres with thick or patterned treads.

Tyre Range	Tyre Size in.	I lb ft^2	Tyre Pressure lb/in.^{2}	Static Load R_1 lb	$\frac{I}{r^2R_1t_m}$ (per sec)
' Intermediate '	6·00—6½*	2·63	25	1,025	0·051
			35	1,325	0·039
			45	1,625	0·032
	7·50—10¼	15·1	25	1,850	0·080
			35	2,350	0·063
			45	2,850	0·052
	9·75—12*	52·2	25	2,800	0·110
			35	3,800	0·081
			45	4,800	0·064
	15·00—16	274·0	25	6,000	0·133
			35	8,000	0·100
			45	10,000	0·080
	17·50—18	568·5	25	8,500	0·148
			35	11,500	0·110
			45	14,100	0·089
Ministry of Supply Standard Tyre Range (50 lb/in.^{2})	27 × 8·75—12	30·6	30	2,840	0·086
			40	3,640	0·067
			50	4,440	0·055
	37 × 13—15	114·4	30	5,985	0·079
			40	7,500	0·063
			50	9,150	0·052
	48 × 18·00—18	472·0	30	11,750	0·101
			40	14,000	0·085
			50	16,250	0·073
Ministry of Supply Standard Tyre Range (50-70 lb/in.^{2})	24 × 7·25—12	22·3	50	3,220	0·068
			60	3,740	0·058
			70	4,260	0·051
	26 × 7·75—13	39·4	50	3,600	0·093
			60	4,250	0·079
			70	4,900	0·068

TABLE 2 (*Cont.*)

Tyre Range	Tyre Size in.	I lb ft^2	Tyre Pressure lb/in.^{2}	Static Load R_1 lb	$\frac{I}{r^2 R_1 t_m}$ (per sec)
Ministry of Supply Standard Tyre Range (50-70 lb/in.^{2})	30 × 9—15	65·0	50	5,100	0·082
			60	6,000	0·069
			70	6,900	0·060
	32 × 10—15	87·3	50	6,000	0·083
			60	7,000	0·072
			70	8,000	0·063
	45 × 16—18	376·0	50	14,300	0·074
			60	16,750	0·063
			70	19,200	0·055
	64 × 22·5—26	1,985	50	28,500	0·099
			60	33,500	0·084
			70	38,500	0·073
Ministry of Supply Standard Tyre Range (70-90 lb/in.^{2})	26 × 6·50—14	28·7	70	4,050	0·061
			80	4,600	0·054
			90	5,150	0·048
	33 × 9·75—16	92·9	70	8,100	0·059
			80	9,175	0·052
			90	10,250	0·057
	43 × 13·5—19	281·5	70	15,200	0·057
			80	17,200	0·051
			90	19,200	0·045

* Smooth tread. All other tyres have patterned treads.

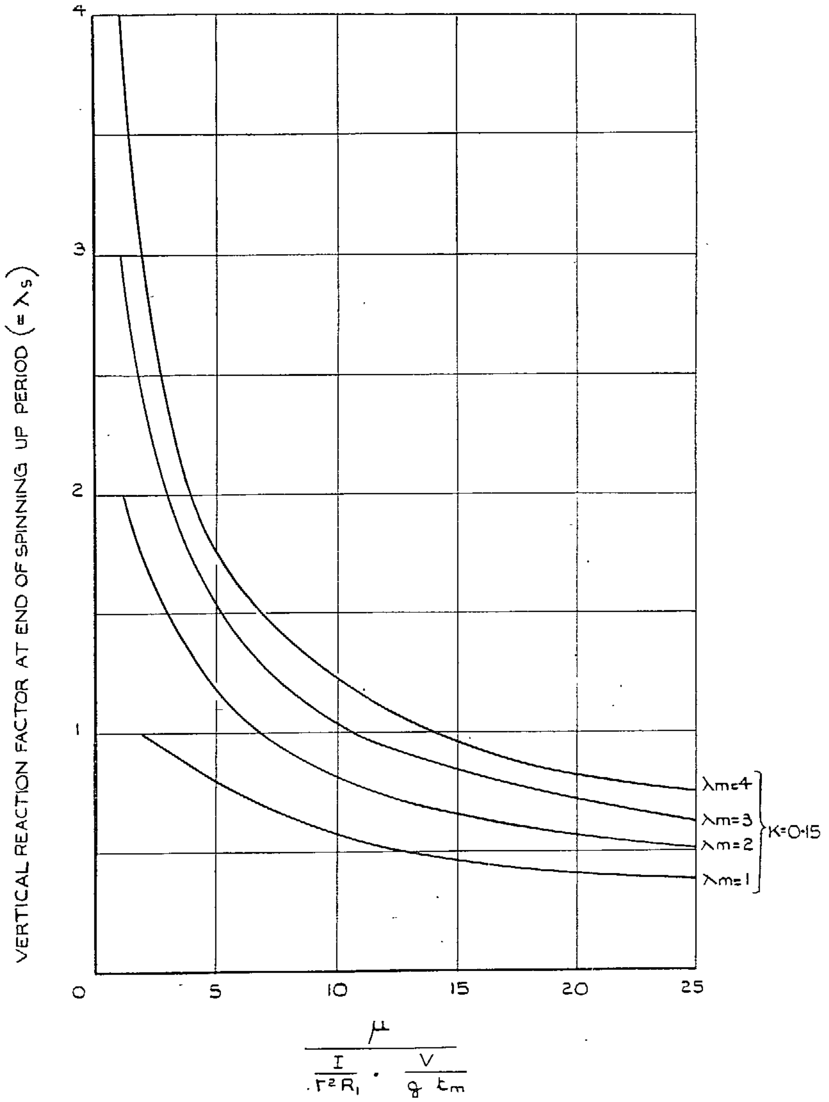

FIG. 1. Variation of λ_s with $\frac{\mu}{(I/r^2R_1)\,(V/g.t_m)}$.

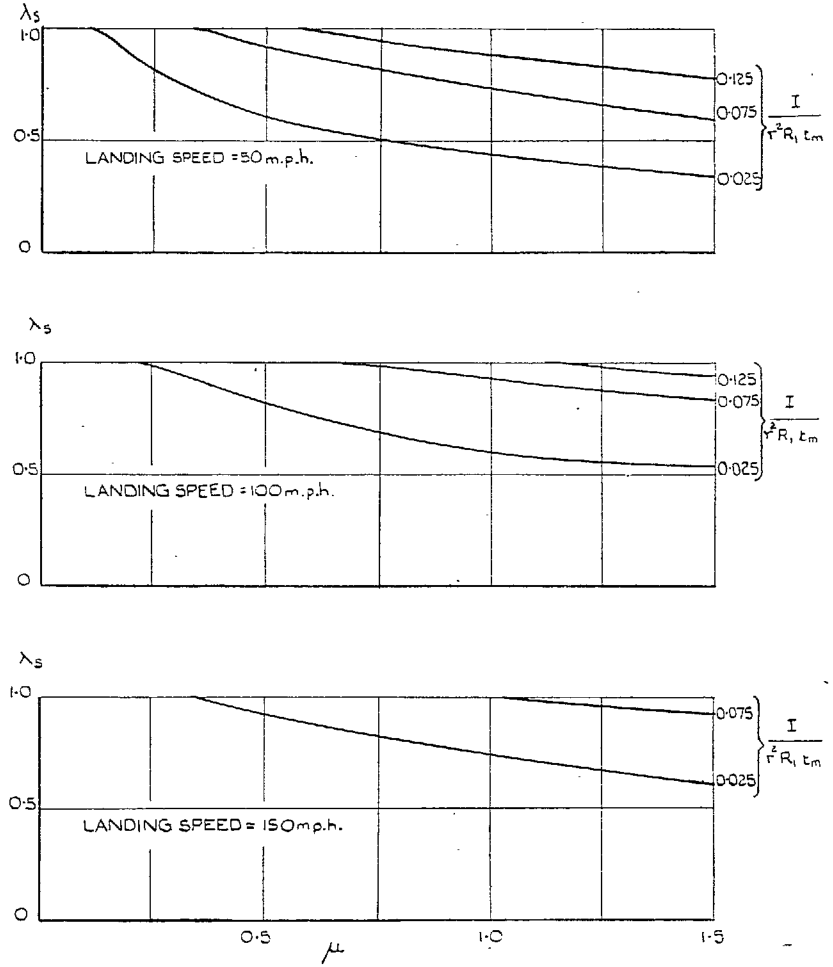

FIG. 2. Variation of λ_s with μ, for $\lambda_m = 1$.

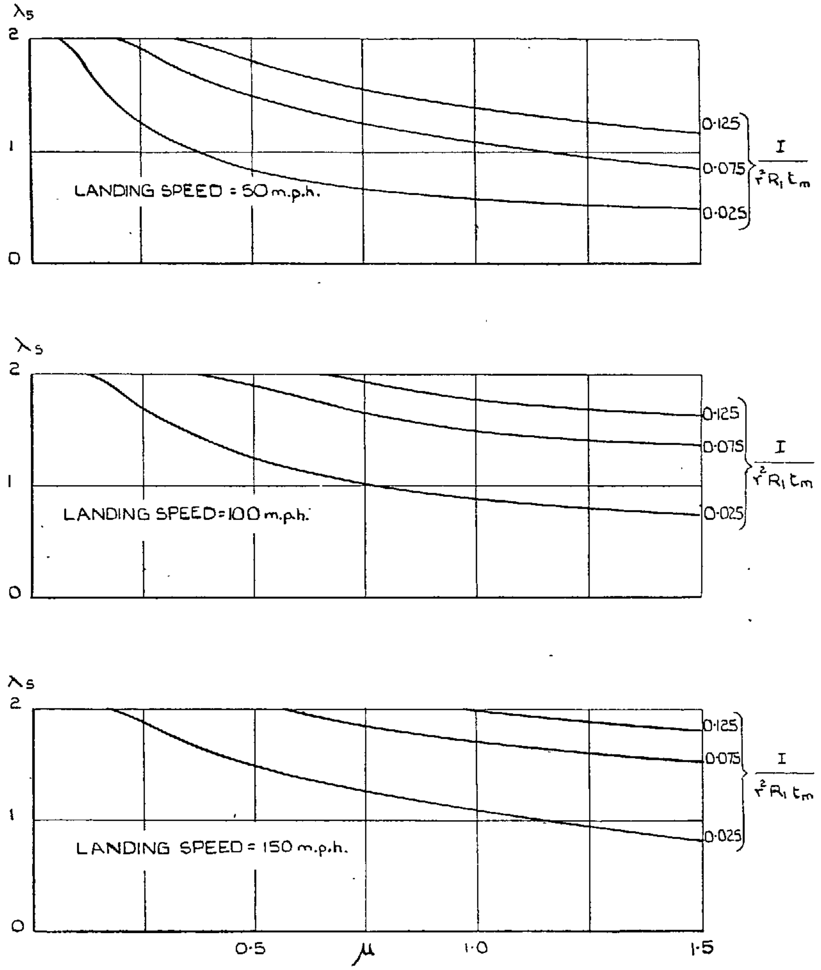

FIG. 3. Variation of λ_s with μ, for $\lambda_m = 2$.

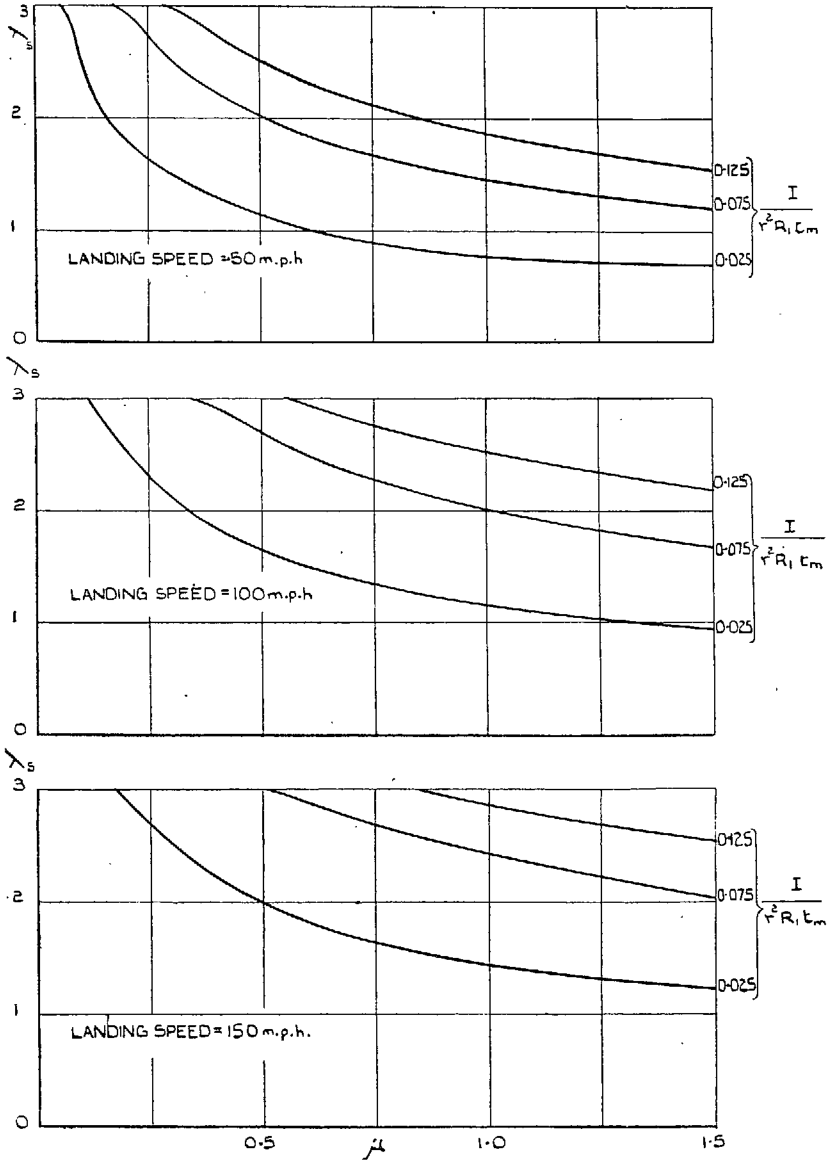

FIG. 4. Variation of λ_s with μ, for $\lambda_m = 3$.

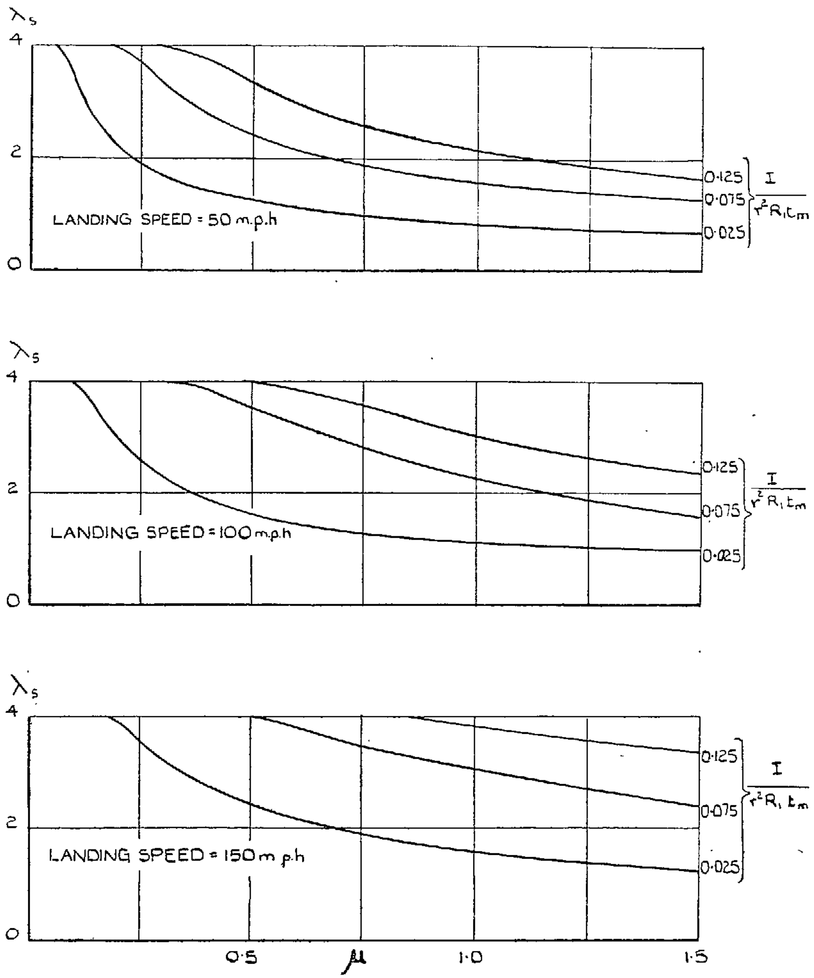

FIG. 5. Variation of λ_s with μ, for $\lambda_m = 4$.

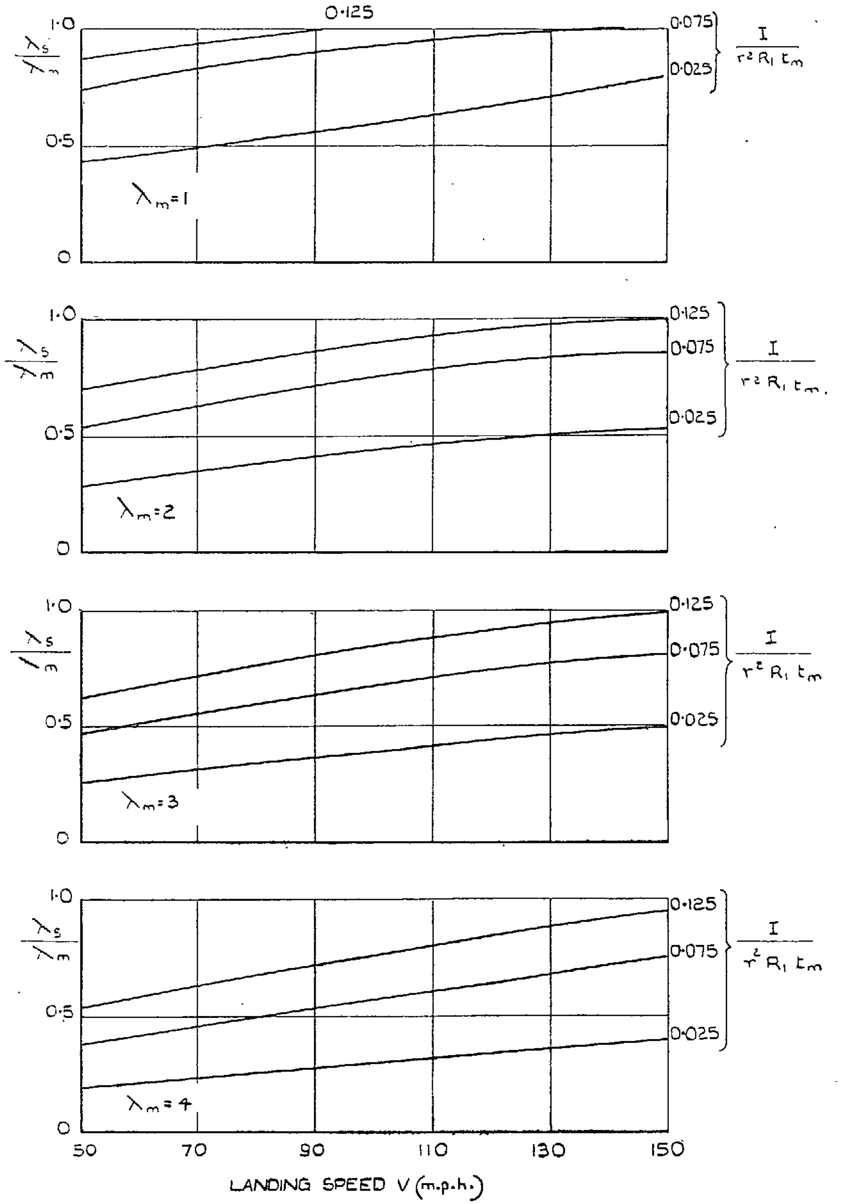

FIG. 6. Variation of λ_s/λ_m with V for $\mu = 1 \cdot 0$.

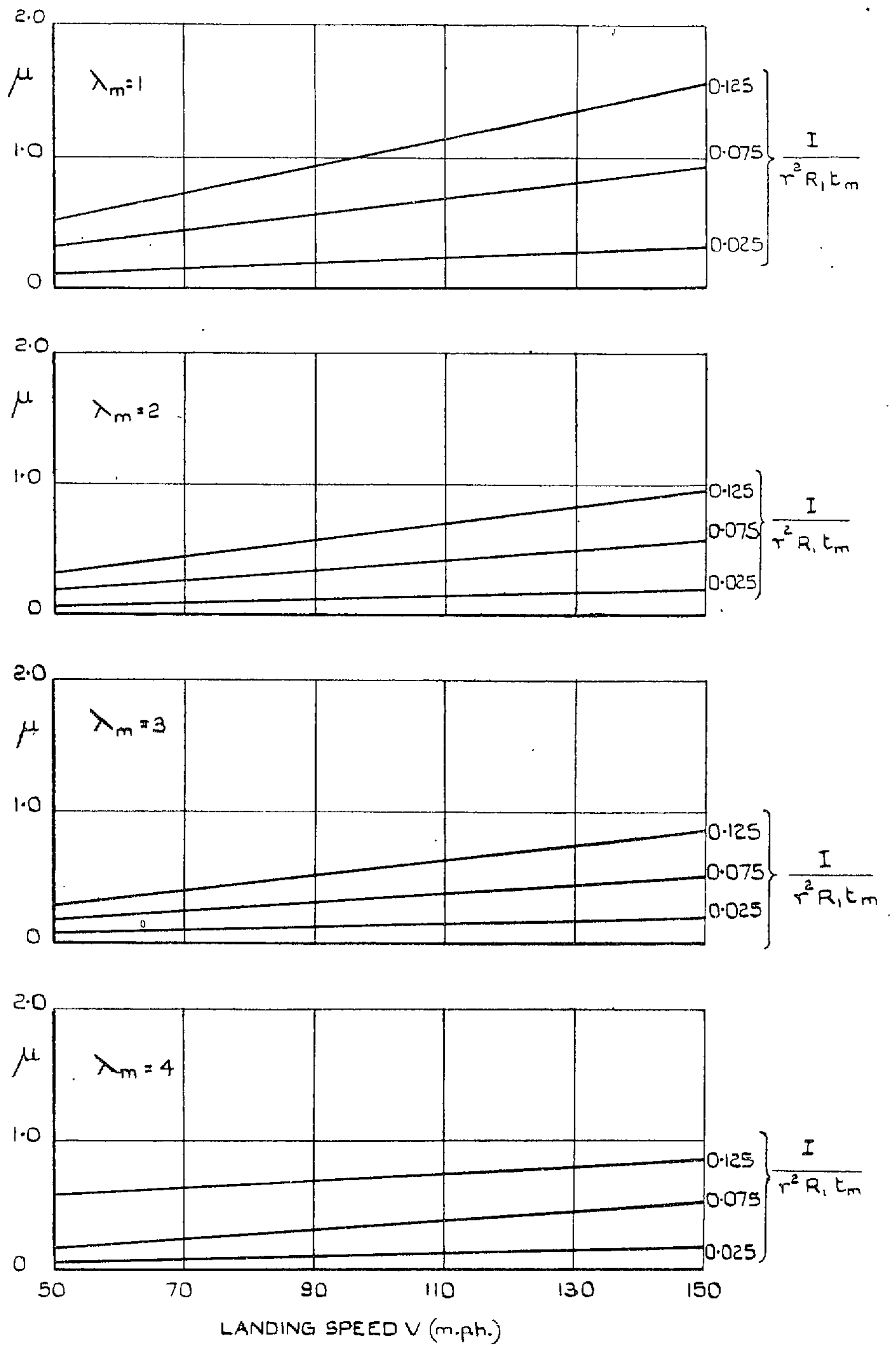

FIG. 7. Variation of μ with V for $\lambda_s = \lambda_m$.

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