NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 583

THE ROLLING FRICTION OF SEVERAL AIRPLANE WHEELS AND TIRES AND THE EFFECT OF ROLLING FRICTION ON TAKE-OFF

By J. W. WETMORE

1937

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AERONAUTIC SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Abbreviation	Unit	Abbreviation
Length	l	meter	m	foot (or mile)	ft. (or mi.)
Time	t	second	s	second (or hour)	sec. (or hr.)
Force	F	weight of 1 kilogram	kg	weight of 1 pound	lb.
Power	P	horsepower (metric)		horsepower	hp.
Speed	V	kilometers per hour	k.p.h.	miles per hour	m.p.h.
		meters per second	m.p.s.	feet per second	f.p.s.

2. GENERAL SYMBOLS

W, Weight $= mg$

g, Standard acceleration of gravity $= 9.80665$ m/s² or 32.1740 ft./sec.²

m, Mass $= \frac{W}{g}$

I, Moment of inertia $= mk^2$. (Indicate axis of radius of gyration k by proper subscript.)

μ, Coefficient of viscosity

ν, Kinematic viscosity

ρ, Density (mass per unit volume)

Standard density of dry air, 0.12497 kg-m^{-4}-s^2 at 15° C. and 760 mm; or 0.002378 lb.-ft.$^{-4}$ sec.^{2}

Specific weight of "standard" air, 1.2255 kg/m^3 or 0.07651 lb./cu.ft.

3. AERODYNAMIC SYMBOLS

S, Area

S_w, Area of wing

G, Gap

b, Span

c, Chord

$\frac{b^2}{S}$, Aspect ratio

V, True air speed

q, Dynamic pressure $= \frac{1}{2}\rho V^2$

L, Lift, absolute coefficient $C_L = \frac{L}{qS}$

D, Drag, absolute coefficient $C_D = \frac{D}{qS}$

D_o, Profile drag, absolute coefficient $C_{D_o} = \frac{D_o}{qS}$

D_i, Induced drag, absolute coefficient $C_{D_i} = \frac{D_i}{qS}$

D_p, Parasite drag, absolute coefficient $C_{D_p} = \frac{D_p}{qS}$

C, Cross-wind force, absolute coefficient $C_C = \frac{C}{qS}$

R, Resultant force

i_w, Angle of setting of wings (relative to thrust line)

i_t, Angle of stabilizer setting (relative to thrust line)

Q, Resultant moment

Ω, Resultant angular velocity

$\rho\frac{Vl}{\mu}$, Reynolds Number, where l is a linear dimension (e.g., for a model airfoil 3 in. chord, 100 m.p.h. normal pressure at 15° C., the corresponding number is 234,000; or for a model of 10 cm chord, 40 m.p.s. the corresponding number is 274,000)

C_p, Center-of-pressure coefficient (ratio of distance of $c.p.$ from leading edge to chord length)

α, Angle of attack

ϵ, Angle of downwash

α_o, Angle of attack, infinite aspect ratio

α_i, Angle of attack, induced

α_a, Angle of attack, absolute (measured from zero-lift position)

γ, Flight-path angle

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Langley Memorial Aeronautical Laboratory

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By J. W. Wetmore

SUMMARY

Tests were made to determine the rolling friction of airplane wheels and tires under various conditions of wheel loading, tire inflation pressure, and ground surface. The effect of wheel-bearing type was also investigated. Six pairs of wheels and tires were tested including two sizes of each of the types designated as standard (high pressure), low pressure, and extra low pressure. The results of calculations intended to show the effect of variations in rolling friction on take-off are also presented.

The values of rolling-friction coefficient obtained on a concrete runway varied from 0.009 to 0.035; on firm turf, from 0.023 to 0.054; and on moderately soft turf, where only the high-pressure tires were tested, from 0.064 to 0.077. Of the variables investigated, the ground-surface condition was the most important in its effect on the rolling-friction coefficient. For comparable conditions, both on a concrete surface and on firm turf, the standard wheels and tires offered the least resistance to rolling. Slightly higher values were obtained with the low-pressure wheels and tires, and the extra low-pressure type gave the highest values. The variation in rolling-friction coefficient with wheel loading and inflation pressure was generally quite small. The value of rolling-friction coefficient for wheels equipped with plain bearings was appreciably greater than that for the same wheels provided with roller bearings. The effect on take-off of all the variables, with the exception of ground-surface condition, was sufficiently small to be neglected in rough calculations of take-off performance but should be considered in more accurate work.

INTRODUCTION

In many cases when comparisons have been made between measured and calculated values of the ground-run distance in the take-off of an airplane, the results have shown considerable disagreement. A part of the discrepancy can be attributed to the inadequacy of available information concerning the forces and conditions existing during the take-off. An investigation of the rolling friction of airplane wheels and tires, one of the uncertain factors, was undertaken as a step toward augmenting this information and hence toward improving the reliability of the prediction of take-off performance.

The measurement of the rolling friction was accomplished by recording the pull between a towing vehicle and a loaded trailer equipped with the wheels and tires to be tested. The resistance thus measured included, of course, that due to the wheel bearings as well as that of the tires.

The tires and wheels tested included two sizes of each of the types generally classified as standard (high pressure), low pressure, and extra low pressure. The tests were run at various speeds under several conditions of wheel loading and tire inflation pressure. The ground-surface conditions investigated were concrete, firm turf, and soft turf.

As an indication of the probable effect on take-off of the differences in rolling friction occasioned by the various conditions, calculations were made of the distances required to leave the ground for two hypothetical airplanes of different loading characteristics; for each case several values of rolling-friction coefficient, covering the range determined by the tests, were assumed.

APPARATUS AND METHODS

The trailer used in the tests (fig. 1) was a 2-wheel carriage with provision for interchanging stub axles to accommodate the various wheels. It was capable of carrying up to 3,000 pounds of load in the form of 200-pound lead weights, which, with the weight of the carriage itself, provided a maximum load on the wheels of 3,500 pounds. The carriage was equipped with airplane-type hydraulic shock absorbers to simulate an airplane landing chassis. The axles were so arranged that there was no toe-in of the wheels. A light truck was used as the towing vehicle.

The pull between the truck and the trailer was measured with a dynamometer consisting essentially of a helical spring, the deflection of which, proportional to the force, was recorded by a standard N. A. C. A. instrument of the type ordinarily used to record the position of airplane controls in flight. The force was transmitted from the trailer drawbar to the spring through a cylindrical shaft running in ball-bearing guides that confined the motion of the shaft to an axial direction. All these components were mounted in a

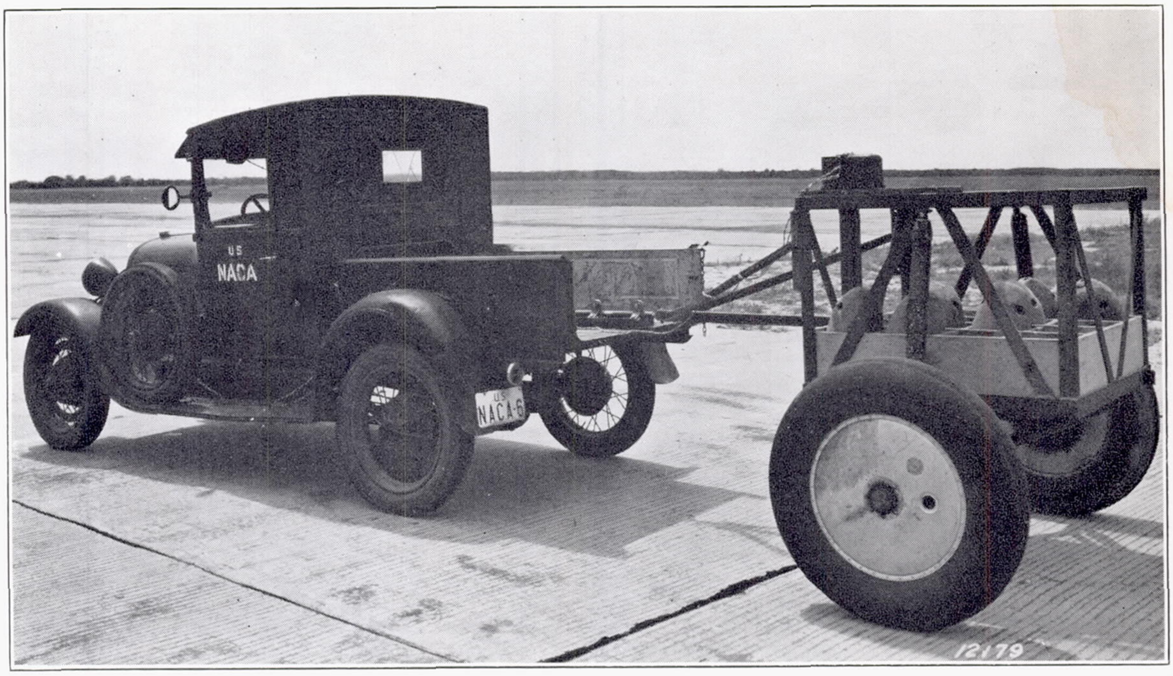

FIGURE 1.—Trailer and test equipment

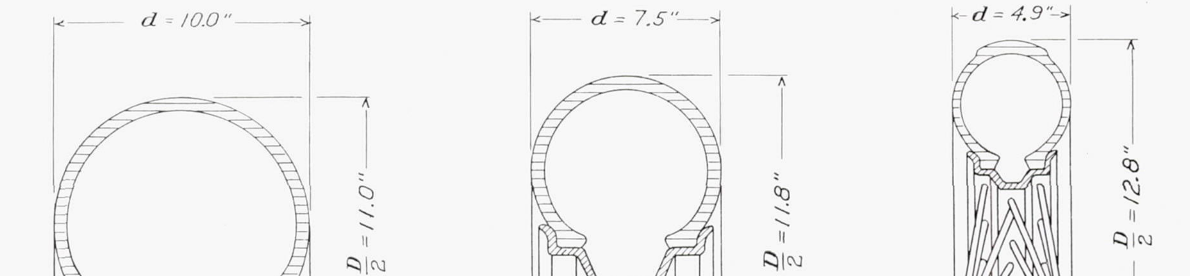

FIGURE 2.—Cross sections and dimensions of the airplane tires and wheels tested.

heavy frame to form a unit which, in turn, was bolted to the bed of the truck.

A standard N. A. C. A. recording inclinometer was mounted on the trailer to determine the horizontal acceleration. A timer was used to synchronize the records of the two recording instruments and also, in conjunction with an electrical-contact mechanism on the front wheel of the truck, to provide a means of evaluating test speeds.

Sketches of the wheels and tires used in the tests are shown in figure 2. The wheels and tires tested included three types: Extra low pressure or airwheels, low pressure, and standard or high pressure. Two sizes of each type were tested. The sizes of extra low pressure tires tested were 22×10–4 and 30×13–6; the recommended tire inflation pressure for both sizes was 12.5 pounds per square inch. The recommended inflation pressure was 20 pounds per square inch for the two

Each pair of wheels and tires was tested under three loads with the tires inflated to the recommended pressure. The heaviest load in each case was determined either by the recommended maximum static load for the tires or by the capacity of the trailer; the other loads were chosen arbitrarily to provide a convenient range.

With 940 pounds per wheel, a load common to all the test series, the rolling-friction measurements were made at two inflation pressures below and in addition to the recommended value, the lowest pressure being about 50 or 60 percent of the recommended pressure. The 26×5 tires were run only at recommended inflation pressure.

All the foregoing conditions were covered in tests on a concrete runway designed for airplane operations, the surface of which had been scarified to improve its tractional qualities. Tests were likewise run for all

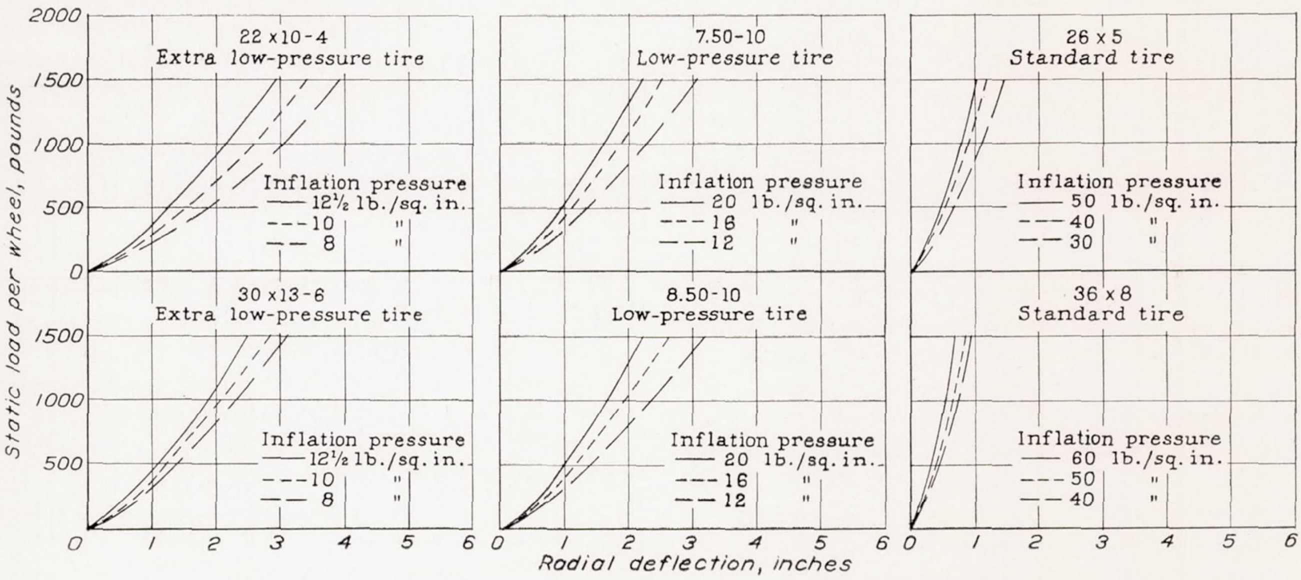

FIGURE 3.—Static load-deflection curves of tires. The highest pressure in each case is the recommended inflation pressure.

sizes of low-pressure tires, 7.50–10 and 8.50–10. The recommended inflation pressure for the 26×5 standard tire was 50 pounds per square inch; for the 36×8 size the recommended pressure was 60 pounds per square inch. All the tires had smooth treads except the 26×5 size, which had a nonskid tread. Static load-deflection curves for all the tires are shown in figure 3.

The bearings of all the standard and extra low-pressure wheels were of the plain type, i. e., bronze bushings grooved for lubrication and running on steel journals. Both sizes of the low-pressure wheels were equipped with antifriction roller bearings. The tests of the 8.50–10 low-pressure wheels and tires, however, were repeated for two loads with the roller bearings replaced by plain bearings in order to provide an indication of the effect of bearing type.

conditions on a turf surface of probably average smoothness, having a clay topsoil and covered with fairly thick grass about 6 or 8 inches in height. Most of the tests were made when the surface was very dry and firm, probably representative of the best field condition likely to be encountered. For the tests with varying load on the 26×5 and 36×8 standard wheels and tires, however, the surface was wet and moderately soft so that the truck tires left tracks between one-half and 1 inch in depth, representing fairly unfavorable conditions for normal operation but by no means the worst possible.

The measurements of rolling friction were made for each condition according to the following procedure: 3- or 4-second records were taken at several speeds between 5 and 45 miles per hour on the concrete surface or between 5 and 30 miles per hour on the turf surface, with the speed held as nearly constant as pos-

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sible during each run. The value of the mean gross pull P_m between the truck and trailer was determined from the record of dynamometer spring deflection.

Because it was impossible to maintain the speed during the runs sufficiently steady to preclude relatively large errors due to the inertia force of the trailer, the recording inclinometer was used to provide a correction for this force. Before and after each series of runs, several records were taken of the inclinometer angle with the truck and trailer standing on a fairly level surface and heading in various directions so that the average of the readings provided a reference angle θ_0, the angle for no horizontal acceleration. Then the difference between this value and the mean angle θ_m recorded during a run defined the mean direction of the resultant force acting on the inclinometer pendulum relative to the direction of the gravity component, or

$$\theta_m - \theta_0 = \tan^{-1} \frac{a_m}{g}$$

where a_m is the mean acceleration in the direction of travel. The mean inertia force P_I was then determined from the relation

$$P_I = W \tan (\theta_m - \theta_0)$$

where W is the weight of the loaded trailer.

Owing to the deflection of the truck springs resulting from the drag of the trailer, the attitude angle of the trailer—hence of the inclinometer base—while running differed sufficiently from the static reference angle to cause an appreciable error in the acceleration as determined by the foregoing method. Moreover, a similar effect was caused at higher speeds by a reduction in the deflection of the trailer tires due to centrifugal force. The necessary corrections were found by mounting a second inclinometer between the truck axles where it was not subjected to the described effects and comparing the records of the two instruments for a sufficient number of runs under various conditions to establish a relationship between the correction and the influencing factors. The correction angle θ_c was then the difference between the mean angles recorded by the inclinometer on the truck and the inclinometer on the trailer, and the corrected inertia force became

$$P_I = W \tan (\theta_m + \theta_c - \theta_0)$$

The air resistance D of the trailer was determined as the difference between the over-all resistance measured with the trailer covered by a hood and that with the trailer uncovered. The hood consisted of a fabric-covered framework completely enclosing the trailer but entirely free of any mechanical connection with it, being supported by direct connection with the truck and running on skids. The air drag was measured in this manner at several speeds within the range covered by the tests.

The rolling friction or resistance R was evaluated from the test results according to the relation

$$R = P_m - W \tan (\theta_m + \theta_c - \theta_0) - D$$

Then the rolling-friction coefficient, the form in which the results are presented, is

$$\mu = \frac{R}{W}$$

PRECISION

The mean gross force was measured by the dynamometer to within ± 1 pound for individual runs. The mean acceleration was determined from the inclinometer records to within ± 0.06 foot per second per second. From this the inertia force is correct to within ± 2 pounds for the lightest load and within ± 6 pounds for the heaviest load. Inasmuch as each of the values presented in the table and the figures was averaged from the results of 18 runs, all but small consistent errors are largely eliminated.

In the case of the tests run on the turf surface, there is a possibility of some lack of uniformity in the condition of the surface between the different series of tests, which was not indicated by its appearance and might introduce an error into the effects attributed to the applied variables. Likewise, inasmuch as the plain bearings used in airplane wheels are of the imperfectly lubricated type and hence of somewhat uncertain frictional characteristics, it is possible that there was some difference in bearing friction between the several wheels equipped with plain bearings so that the differences observed between the over-all friction coefficients of the wheels and tires for similar conditions may not be due solely to tire size and type. These effects are believed, however, to be too small to invalidate the comparisons and conclusions drawn from the results of the tests.

RESULTS

The values of rolling-friction coefficient for all the conditions covered in the tests are presented in table I. Figures 4 and 5 give the results obtained on the concrete runway for all the wheels and tires. Figure 4 shows the effect of wheel load on the rolling-friction coefficient and also the difference between the coefficients with plain and roller bearings as determined on the 8.50–10 low-pressure tires. Figure 5 shows the variation of rolling-friction coefficient with tire inflation pressure for all but the 26×5 tires. The coefficients measured on the turf surface are plotted in figures 6 and 7. Figure 6 shows the variation of the coefficient with wheel load. For the tests of the standard-type wheels and tires, i. e., the 26×5 and 36×8, the surface was wet and fairly soft, whereas for

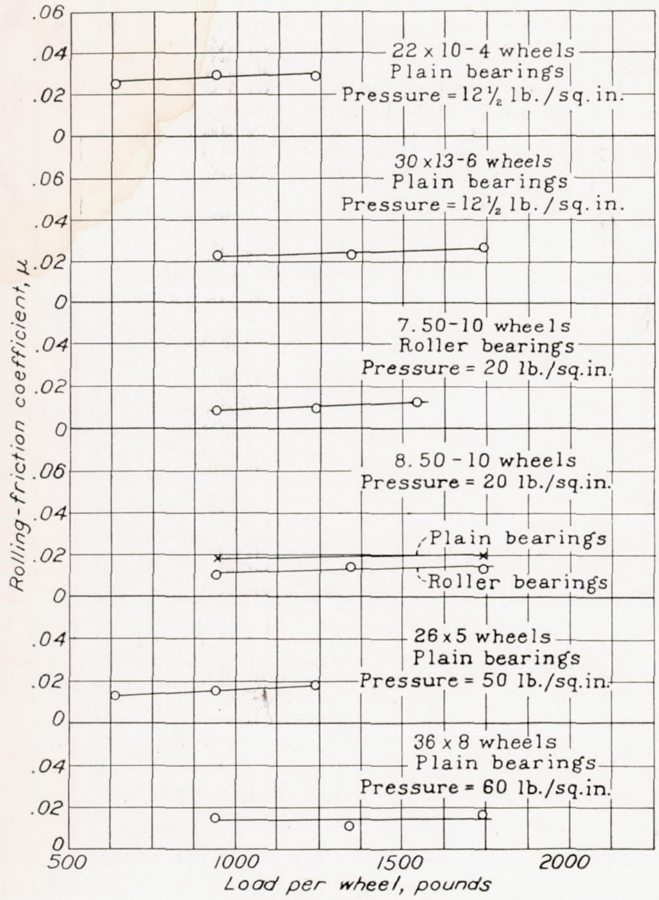

FIGURE 4.—Variation of rolling-friction coefficient with load per wheel; concrete surface; recommended inflation pressure.

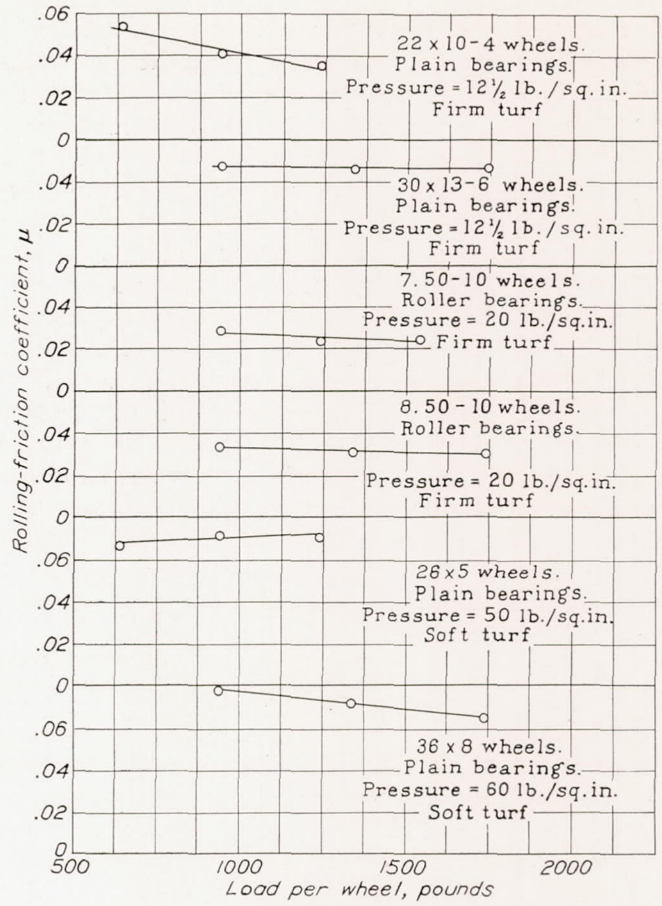

FIGURE 6.—Variation of rolling-friction coefficient with load per wheel; turf surface recommended inflation pressure.

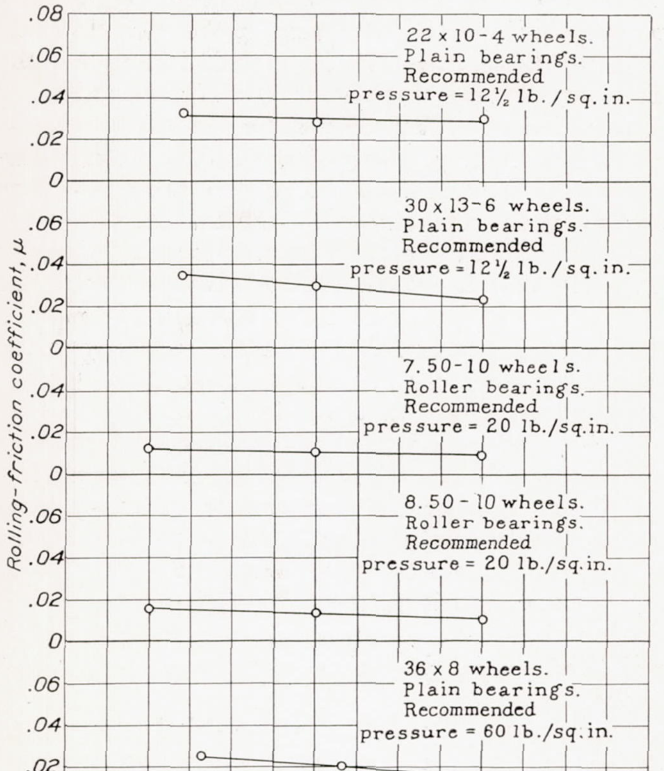

FIGURE 5.—Variation of rolling-friction coefficient with inflation pressure; concrete surface; load per wheel, 940 pounds.

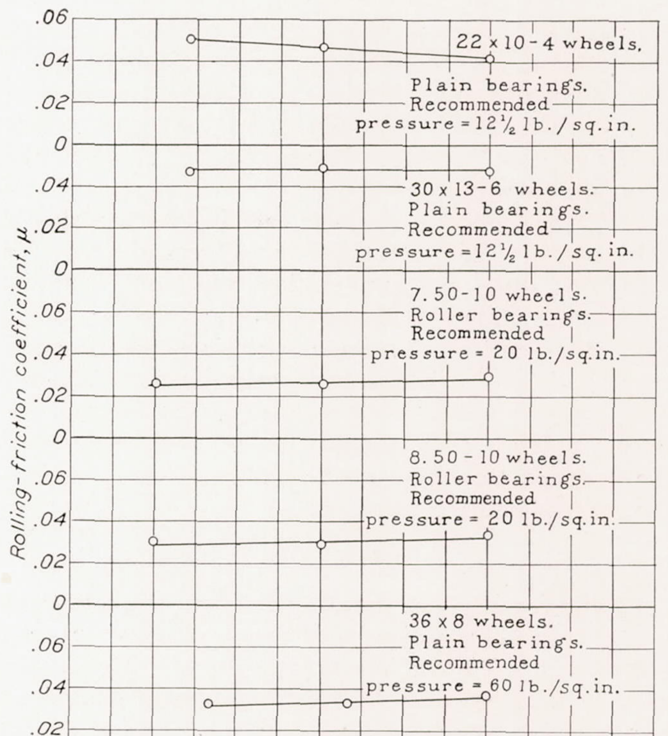

FIGURE 7.—Variation of rolling-friction coefficient with inflation pressure; firm turf surface; load per wheel, 940 pounds.

all the other tires the surface was dry and firm. In figure 7 is shown the variation of rolling-friction coefficient with inflation pressure for all tires except the 26×5 size, the surface being dry and firm in all cases.

As explained before, for each test condition a series of runs was made at different speeds with the intention of determining, if possible, the effect of speed on the rolling-friction coefficient. It is probable, however, that the heat generated by the friction caused a considerable rise in temperature in the tires during a series of runs which, according to the data of reference 1, would result in an appreciable reduction in the rolling friction. Since the runs were made with consecutive increments of speed, the effect of speed would thus be obscured by the temperature effect. The results of the present tests, therefore, do not provide a true indication of the effect of speed and are not so presented. Consideration of these results and of the data presented in reference 1, however, indicates that the effect of speed is probably slight in any case.

Each value of the rolling-friction coefficient given in the table and figures is the average of the several runs made at various speeds and with varying tire temperature, as previously mentioned. The average tire temperature was probably very nearly the same for all conditions with all tires except for those of the standard type. Tests of the standard tires were made in generally cooler weather and, consequently, the values of rolling-friction coefficient are possibly slightly higher relative to the values for the other tires than would be the case had the temperature conditions been comparable. The speed range for the tests on the concrete runway was from 5 to 45 miles per hour, whereas on the turf surface the range was from 5 to 30 miles per hour. The two groups of tests, nevertheless, are sufficiently comparable in view of the probable small effect of speed.

The results of the take-off calculations are shown in figure 8. Values of the take-off ground run were calculated for two hypothetical airplanes, one of moderate loading and the other of high loading. Several values of rolling-friction coefficient covering the range encountered in the tests were assumed for each case. Figure 8 shows the increase in ground run for given rolling-friction coefficients as a percentage of the distance required with no friction plotted against the corresponding coefficients.

DISCUSSION

Rolling-friction coefficients.—On the concrete runway the rolling-friction coefficients obtained ranged from 0.009 to 0.035. The coefficients increased somewhat with increasing load for all wheels and tires, the variation being approximately linear and of similar magnitude for all cases. Likewise, the coefficients increased almost linearly with decreasing inflation pressure, although in this case there were appreciable

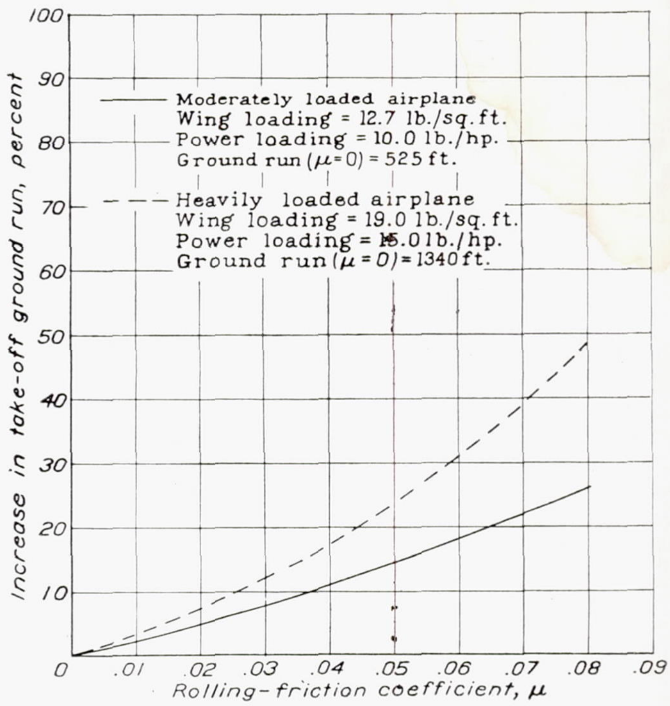

FIGURE 8.—Calculated effect of rolling-friction coefficient on take-off.

differences in the magnitude of the variation for the different tires.

The effect of replacing the roller bearings in the 8.50–10 wheels with plain bearings was to increase the over-all rolling-friction coefficient by about 0.007, the increase being sensibly independent of load and representing more than 50 percent of the original values.

Of the three types of wheels and tires tested, the extra low-pressure type gave the highest values of rolling-friction coefficient and the low-pressure type with roller bearings provided the lowest values. The coefficients for the standard wheels and tires were slightly higher than those for the low-pressure type. Increasing the values for the low-pressure tires by the difference in coefficients observed between the values for the plain and roller bearings in order to obtain a fairer comparison would, however, raise the values for these tires somewhat above those for the standard tires. For different sizes of wheels and tires of a given type, the results do not show any consistent relation between tire size and rolling-friction coefficient.

For the tests on the turf surface, there were, of course, factors contributing to the over-all resistance that were not present on the smooth hard surface, such as the energy loss incurred by depressing the grass and earth and also the energy loss to the shock absorbers and tires associated with the unevenness or roughness of the surface.

In general, the values of rolling-friction coefficient derived from the tests on the firm turf surface averaged about twice those obtained on the concrete runway for corresponding conditions, the range of coefficients found being from 0.023 to 0.054. The coefficients decreased slightly with increasing load for the low-pressure wheels and tires and for the 30×13–6 extra low-pressure wheels and tires. The 22×10–4 extra low-pressure size showed a considerably greater variation in the same sense. The effect of varying load was not determined for the standard-type wheels and tires on the firm turf surface.

Decreasing the inflation pressure resulted in a small reduction in the friction coefficient in the case of the standard and low-pressure tires. The values for the 30×13–6 tires appeared to be very nearly independent of inflation pressure, whereas the 22×10–4 tires showed a fairly large increase in the coefficient with decreasing inflation pressure.

The different types of wheels and tires were in the same order of merit, as regards rolling-friction coefficient, for the firm turf condition as for the concrete runway. In general, the larger tires of each type offered greater resistance to rolling than the smaller size for comparable conditions.

Only the 26×5 and the 36×8 standard-type wheels and tires were tested on the soft turf surface and these only for various loading conditions. The values for this condition were about twice those obtained with the 36×8 wheels and tires on the firm turf surface and were of approximately the same general magnitude for both sets of tires, the coefficients ranging from 0.064 to 0.077. The larger size showed decreasing rolling-friction coefficients with increasing load whereas the values for the smaller tires increased slightly with increasing load.

Effects on take-off.—Some indication of the effects on the take-off ground run that would result from the differences observed in the rolling-friction coefficients corresponding to the various conditions may readily be obtained by cross reference between figure 8 and figures 4 through 7. It may be seen from figure 8 that the effect of rolling friction on the take-off will be much greater for a heavily loaded airplane than for one of moderate loading even when considered, as in the figure, on a percentage basis. For convenience, only the heavily loaded airplane will be considered in this discussion.

Obviously the ground-surface condition is the variable having the greatest effect on the rolling-friction coefficient, and hence on the take-off distance. The distance required to take off on the firm turf would average about 9 percent longer than on the concrete runway, while on the soft turf surface it might be as much as 35 percent longer.

The variation in rolling-friction coefficient on the concrete surface between the highest and lowest loads tested would result in a difference of only 1 or 2 percent in the take-off distance. On the turf surfaces, the effect of varying load on the take-off would likewise be very small in most cases although, for the 36×8 tires on the soft turf surface, the variation in friction coefficient with load is sufficient to cause about 11 percent difference in take-off distance. Inasmuch as the load on the wheels of an airplane is continually decreasing during the take-off ground run, the rolling-friction coefficient will likewise be changing. In most cases, however, this variation can be neglected in take-off calculations without serious error or can be allowed for satisfactorily in any case by assuming a constant value of rolling-friction coefficient corresponding to the load intermediate between the static load and the load at the end of the run prior to the pull-off.

The effect on the take-off of moderate differences in the inflation pressure of a given set of tires would obviously be very small in most cases, probably resulting in a difference of only 1 or 2 percent for as much as 35 or 40 percent underinflation. For the cases showing an unusually large variation of friction coefficient with inflation pressure, the effect might be as high as 6 percent.

Under similar conditions on the concrete runway the take-off distance that would be required with the extra low-pressure tires would be between 4 and 6 percent longer than that with the standard tires. For the low-pressure tires equipped with roller bearings, the take-off distances would be slightly less than with the standard tires, within 2 percent, and with plain bearings about 1 percent greater. The same conclusions apply approximately to the firm turf condition.

In view of the generally small effect on take-off of all the variables with the exception of the ground-surface condition, the assumption of an average rolling-friction coefficient corresponding to a given surface condition should be satisfactory for ordinary routine calculations. Where the greatest possible accuracy is desired in calculating take-off performance, the other factors—type and size of the wheels and tires, wheel load, inflation pressure, and wheel-bearing type—should also be considered.

CONCLUSIONS

1. The values of rolling-friction coefficient obtained on the concrete runway varied from 0.009 to 0.035; on the firm turf surface, from 0.023 to 0.054; and on the soft turf, where only the high-pressure tires were tested, from 0.064 to 0.077.

2. The most important factor affecting the rolling-friction coefficient was the character of the ground surface.

3. For comparable conditions, either on a concrete runway or on firm turf, the standard-type wheels and tires had the lowest values of rolling-friction coefficient; the values for the low-pressure tires were only slightly higher. The highest coefficients were obtained with the extra low-pressure wheels and tires.

4. In general, the variation in rolling-friction coefficient with either wheel load or tire inflation pressure was fairly small.

5. The rolling-friction coefficient was appreciably greater for wheels equipped with plain bearings than for the same wheels having roller bearings.

6. The effect on take-off of all the variables, with the exception of the ground-surface condition, was generally quite small; so that, for ordinary calculations of take-off performance, the assumption of an average value of rolling-friction coefficient corresponding to a given ground-surface condition would probably be satisfactory. Where greater accuracy is desired, however, the other factors, although of less consequence, should nevertheless be considered.

LANGLEY MEMORIAL AERONAUTICAL LABORATORY,
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., *September 19, 1936.*

REFERENCE

1. Holt, W. L., and Wormeley, P. L.: Power Losses in Automobile Tires. Tech. Paper No. 213, Bur. Standards, 1922.

TABLE I.—ROLLING-FRICTION COEFFICIENTS

Wheels	Bearings	Load per wheel	Inflation pressure	Static tire deflection	Rolling-friction coefficient, μ		
					Concrete	Firm turf	Soft turf
		Pounds	*lb. sq. in.*	*Inches*			
Extra low pressure.							
22×10–4	Plain	1,240	12.5	2.55	0.029	0.035	------
		940	12.5	2.06	.030	.041	
		640	12.5	1.58	.025	.054	
		940	10	2.50	.028	.047	
		940	8	2.92	.033	.050	
30×13–6	do	1,740	12.5	2.82	.027	.046	------
		1,340	12.5	2.29	.024	.046	
		940	12.5	1.74	.023	.047	
		940	10	1.96	.029	.049	
		940	8	2.19	.035	.047	
Low pressure:							
7.50–10	Roller	1,540	20	2.26	.013	.025	------
		1,240	20	1.90	.010	.023	
		940	20	1.52	.009	.029	
		940	16	1.78	.010	.026	
		940	12	2.18	.012	.026	
8.50–10	do	1,740	20	2.52	.013	.030	------
		1,340	20	1.93	.014	.031	
		940	20	1.56	.010	.034	
		940	16	1.83	.013	.029	
		940	12	2.22	.015	.030	
	Plain	1,740	20	2.52	.020	------	------
		940	20	1.56	.018		
Standard:							
26×5	do	1,240	50	.94	.018	------	0.070
		940	50	.76	.015		.071
		640	50	.58	.013		.066
36×8	do	1,740	60	.80	.017	------	.064
		1,340	60	.67	.011		.072
		940	60	.53	.015		.077
		940	60	.53	------	.037	------
		940	50	.62	.020	.033	
		940	40	.69	.025	.033	

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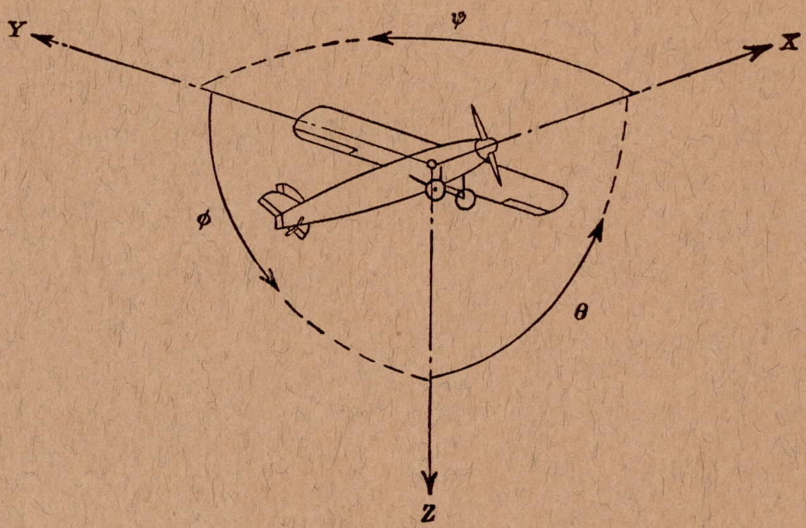

Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	Rolling	L	$Y \longrightarrow Z$	Roll	ϕ	u	p
Lateral	Y	Y	Pitching	M	$Z \longrightarrow X$	Pitch	θ	v	q
Normal	Z	Z	Yawing	N	$X \longrightarrow Y$	Yaw	ψ	w	r

Absolute coefficients of moment

$C_l = \frac{L}{qbS}$ (rolling) $C_m = \frac{M}{qcS}$ (pitching) $C_n = \frac{N}{qbS}$ (yawing)

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D, Diameter
p, Geometric pitch
p/D, Pitch ratio
V', Inflow velocity
V_s, Slipstream velocity
T, Thrust, absolute coefficient $C_T = \frac{T}{\rho n^2 D^4}$
Q, Torque, absolute coefficient $C_Q = \frac{Q}{\rho n^2 D^5}$

P, Power, absolute coefficient $C_P = \frac{P}{\rho n^3 D^5}$
C_s, Speed-power coefficient $= \sqrt[5]{\frac{\rho V^5}{P n^2}}$
η, Efficiency
n, Revolutions per second, r.p.s.
Φ, Effective helix angle $= \tan^{-1}\left(\frac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS

1 hp. = 76.04 kg-m/s = 550 ft-lb./sec.
1 metric horsepower = 1.0132 hp.
1 m.p.h. = 0.4470 m.p.s.
1 m.p.s. = 2.2369 m.p.h

1 lb. = 0.4536 kg.
1 kg = 2.2046 lb.
1 mi. = 1,609.35 m = 5,280 ft.
1 m = 3.2808 ft.