REPORT 1248

AN EXPERIMENTAL STUDY OF APPLIED GROUND LOADS IN LANDING[1]

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SUMMARY

An experimental investigation has been made of the applied ground loads and the coefficient of friction between the tire and the ground during the wheel spin-up process in impacts of a small landing gear under controlled conditions on a concrete landing strip in the Langley impact basin. The basic investigation included three major phases: impacts with forward speed at horizontal velocities up to approximately 86 feet per second, impacts with forward speed and reverse wheel rotation to simulate horizontal velocities up to about 273 feet per second, and spin-up drop tests for comparison with the other tests. In addition to the basic investigation, supplementary tests were made to evaluate the drag-load alleviating effects of prerotating the wheel before impact so as to reduce the relative velocity between the tire and the ground.

In the presentation of the results, an attempt has been made to interpret the experimental data so as to obtain some insight into the physical phenomena involved in the wheel spin-up process. From this study it appears that the conditions of contact between the tire and the ground, and consequently the magnitude of the coefficient of friction, vary greatly during the course of an impact and with different impact conditions. The value of the coefficient of friction appears to be appreciably influenced by a number of factors, such as the instantaneous skidding velocity, the slip ratio, the vertical load, the effects of tire heating produced by the skidding process, and the effects of contamination of the ground surface by abraded rudder. Some quantitative indications of these effects were obtained from the experimental data but the nature of the tests did not permit complete separation of all individual effects.

The investigation of the effects of wheel prerotation indicates that this means can be used to obtain appreciable reductions in the maximum drag loads; however, at very high forward speeds, because the spin-up drag loads may be of the same order as, or even less than, the drag loads caused by other design conditions, the practical advantages of prerotation could be greatly reduced.

INTRODUCTION

In recent years the problems associated with ground-impact loads during landing, particularly wheel spin-up drag loads, have assumed increased importance in the design of airplanes. Although spin-up drag loads may lead to critical design conditions for such airplane structural components as the landing gear, drag bracing, parts of the wing, engine mounts and nacelles, the afterfuselage, tail booms, and even tail surfaces, comprehensive reliable information on the magnitude and variation of the drag load is meager, and existing data are often in conflict.

The spin-up drag-loads problem may be logically resolved into two basic aspects, namely, (a) the external applied loads, which are the forces developed between the tire and the runway during the wheel spin-up process in landing, and (b) the dynamic loads induced in the landing gear and various other parts of the airplane structure by the applied loads. The applied loads serve as the forcing function which, in conjunction with the mass and flexibility characteristics of the airplane, governs the dynamic response of the structure and, thus, the loads and stresses developed in the airframe.

At the present time a number of dynamic-analysis methods exist which, while not perfect and often laborious, permit reasonable accuracy in the calculation of the dynamic response if the forcing function is known. In the case of wheel spin-up drag loads, one of the main problems is the inability to predict accurately the applied drag-load time history, because of lack of sufficient information regarding the mechanics of the wheel spin-up process, particularly the coefficient of friction between the tire and the ground, and its variation during the impact. The present investigation has therefore been undertaken primarily to study the applied ground loads in landing and the physical phenomena involved in the wheel spin-up process, with special attention to the magnitude and variation of the actual coefficients of friction between the tire and the ground.

In the past, attempts to investigate systematically the applied ground loads by means of flight tests have generally been impeded by difficulties introduced by the relatively large amount of scatter normally found in flight-test data as a result of the numerous uncontrolled and generally unmeasured variables involved and, probably most important, by the fact that such data are usually obtained with strain gages located somewhere in the landing-gear structure, which, under dynamic-loading conditions, give a measure of the local strain or response rather than of the applied ground loads. Furthermore, such landing-gear strain-gage installations are usually inherently subject to large errors due to the effects of interaction between different components of load and moment, as well as to hysteresis effects. In the case of spin-up drop tests in a jig, even though more satisfactory instrumentation is feasible, the results are also subject to question because of the artificial conditions which exist between the tire and the ground in such tests.

[1] Supersedes and extends NACA TN 3246, "An Experimental Investigation of Wheel Spin-Up Drag Loads" by Benjamin Milwitzky, Dean C. Lindquist, and Dexter M. Potter, 1954.

In an attempt to minimize the aforementioned difficulties, special instrumentation was developed for measuring the applied ground loads, as well as various other pertinent quantities involved in landing impact, and tests were made with a small landing gear under relatively well-controlled conditions on a concrete landing strip installed in the Langley impact basin. The basic investigation included three major phases. Impacts with forward speed were made at four vertical velocities between 3 and 10 feet per second over a range of horizontal velocities up to the maximum speed of the impact-basin carriage, approximately 87 feet per second. In an effort to extend the horizontal-velocity range of the investigation, forward-speed tests were made in combination with reverse rotation of the landing wheel prior to impact; in this manner horizontal velocities up to 273 feet per second were simulated. Also, stationary drop tests with reverse wheel rotation were made for comparison with the other tests. In addition to the basic investigation, supplementary tests were made to evaluate the effects of prerotating the wheel before impact so as to reduce the relative horizontal velocity between the tire surface and the runway, and thus the amount of impulse required to spin up the wheel.

This report presents an analysis of the applied ground loads measured in the aforementioned tests as well as a study of the coefficient of friction during the period of wheel spin-up. Along with the presentation of the quantitative results, an attempt is made to interpret the experimental data so as to obtain an understanding of the physical phenomena involved in the tire skidding process and the various factors which influence the coefficient of friction. Since these interpretations are based on measurements of the applied loads and the motions of the wheel and landing gear, rather than on detailed observations in the ground-contact region, they must be regarded more as inferences than as established facts, at least until such time as more detailed studies of the mechanism of the skidding process can be made.

SYMBOLS

a_{A_a} acceleration of axle parallel to shock-strut axis, ft/sec²
a_{H_a} horizontal acceleration of axle, ft/sec²
a_{N_a} acceleration of axle normal to shock-strut axis, ft/sec²
a_{H_g} horizontal acceleration of ground platform, ft/sec²
a_{V_g} vertical acceleration of ground platform, ft/sec²
F_{A_a} force on axle dynamometer parallel to shock-strut axis, lb
F_{N_a} force on axle dynamometer normal to shock-strut axis, lb
F_{H_g} horizontal force on ground dynamometer, lb
F_{V_g} vertical force on ground dynamometer, lb
F_{A_T} total force, parallel to shock-strut axis, between tire and ground, lb
F_{N_T} total force, normal to shock-strut axis, between tire and ground, lb
F_{H_T} total horizontal (drag) force between tire and ground, lb
F_{V_T} total vertical force between tire and ground, lb
g gravitational constant, 32.2 ft/sec²
K_L lift factor, ratio of lift force to total dropping weight
m_g mass of ground platform, slugs
m_w mass between axle dynamometer and ground, slugs
μ coefficient of friction, F_{H_T}/F_{V_T}
r_d deflected radius of tire, ft
r_e effective rolling radius of tire, ft
R free radius of tire, ft
s shock-strut stroke parallel to strut axis, ft
S slip ratio
t time after contact, sec
V_{axle} horizontal velocity of axle, fps
V_{car} horizontal velocity of carriage in tests with reverse wheel rotation, fps
V_{H_0} horizontal velocity in forward-speed tests, fps
$V_{H_{s_0}}$ simulated horizontal velocity in tests with reverse wheel rotation, fps
V_{skid} instantaneous apparent skidding velocity, fps
V_{V_O} vertical velocity at instant of initial contact, fps
x_{axle} horizontal displacement of axle, ft
z_u upper-mass vertical displacement, ft
δ tire deflection, ft
φ angle of inclination between shock-strut axis and vertical
θ wheel angular displacement, radians

Subscripts:
av average
max maximum
O at initial contact
su at spin-up

A dot over a symbol indicates differentiation with respect to time.

APPARATUS

EQUIPMENT

The impact-basin equipment consists primarily of a carriage which is catapulted down a horizontal track and which incorporates a dropping mechanism for controlling the descent of the test specimen with a predetermined vertical velocity and simulated wing lift while the carriage is moving horizontally. (See refs. 1 and 2.) A schematic view of the carriage equipped for landing-gear testing is shown in figure 1. For testing landing gears with forward speed a removable reinforced-concrete landing strip was installed in the impact basin, as shown in figure 2. The concrete surface of the

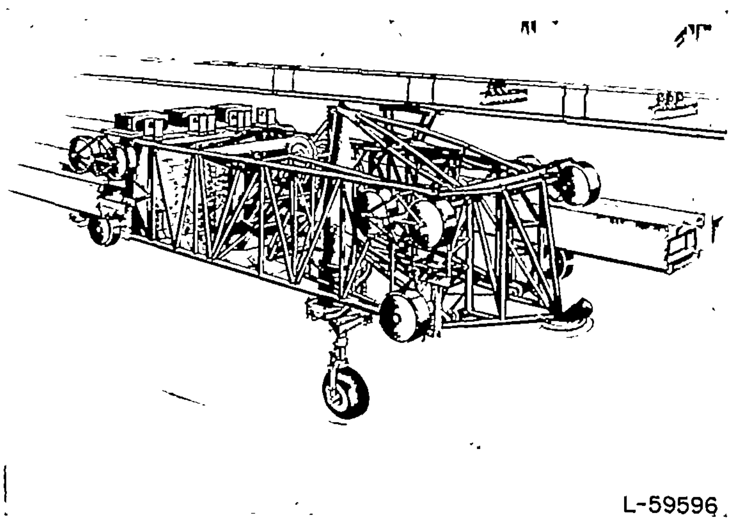


FIGURE 1.—Schematic view of impact-basin carriage and landing gear.

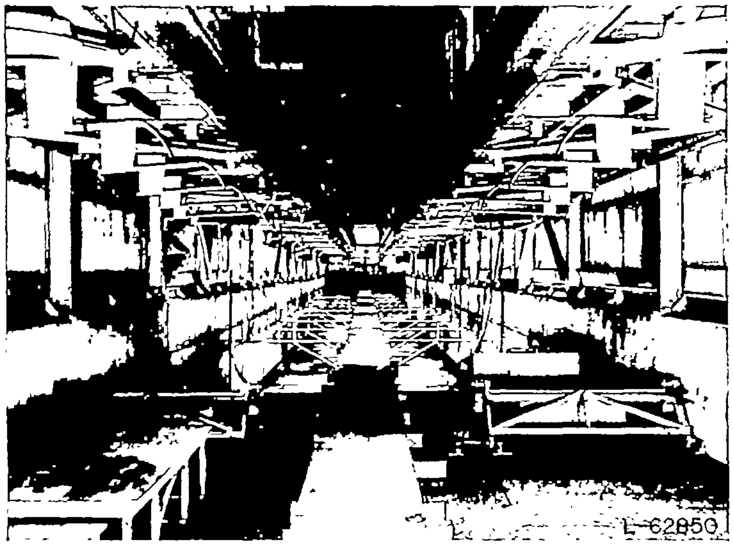


FIGURE 2.—View of concrete landing strip installed in Langley impact basin.

landing strip had a lightly broomed finish in the transverse direction.

The maximum horizontal velocity of the impact-basin carriage is about 87 feet per second and the maximum dropping weight is 2,500 pounds. In order to simulate the wing lift forces which support an airplane during landing, the carriage incorporates a pneumatic cylinder and cam system which is designed to apply any desired upward force to the dropping mass during an impact. In the present investigation all tests were made with a dropping weight of 2,500 pounds and a simulated wing-lift force of the same magnitude.

LANDING GEAR

The landing gear used in the present investigation is a main undercarriage unit designed for the T–6 and SNJ trainer airplanes, which have a gross weight of about 5,000 pounds. The landing gear is of the usual cantilever construction and incorporates a conventional type of oleo-pneumatic shock strut with metering pin and snubber valve. The wheel is fitted with a 27-inch-diameter smooth-contour (type I) tire having a nonskid tread, inflated to a pressure of 32 pounds per square inch. The brake assembly for the wheel was not installed. The original half-fork yoke was replaced by a more rigid tubular member connecting the shock strut with a specially designed strain-gage dynamometer for measuring the forces applied to the axle.

The landing gear was inclined forward at an angle of 15° with respect to the vertical, representing an airplane attitude approximately half way between the level and three-point landing conditions.

INSTRUMENTATION

A variety of time-history instrumentation was employed in the tests. In order to minimize dynamic-response errors, high-frequency instrumentation was used where feasible. The installation of the test instrumentation is schematically illustrated in figure 3. Photographs of the landing gear and instrumentation are shown in figures 4 and 5.

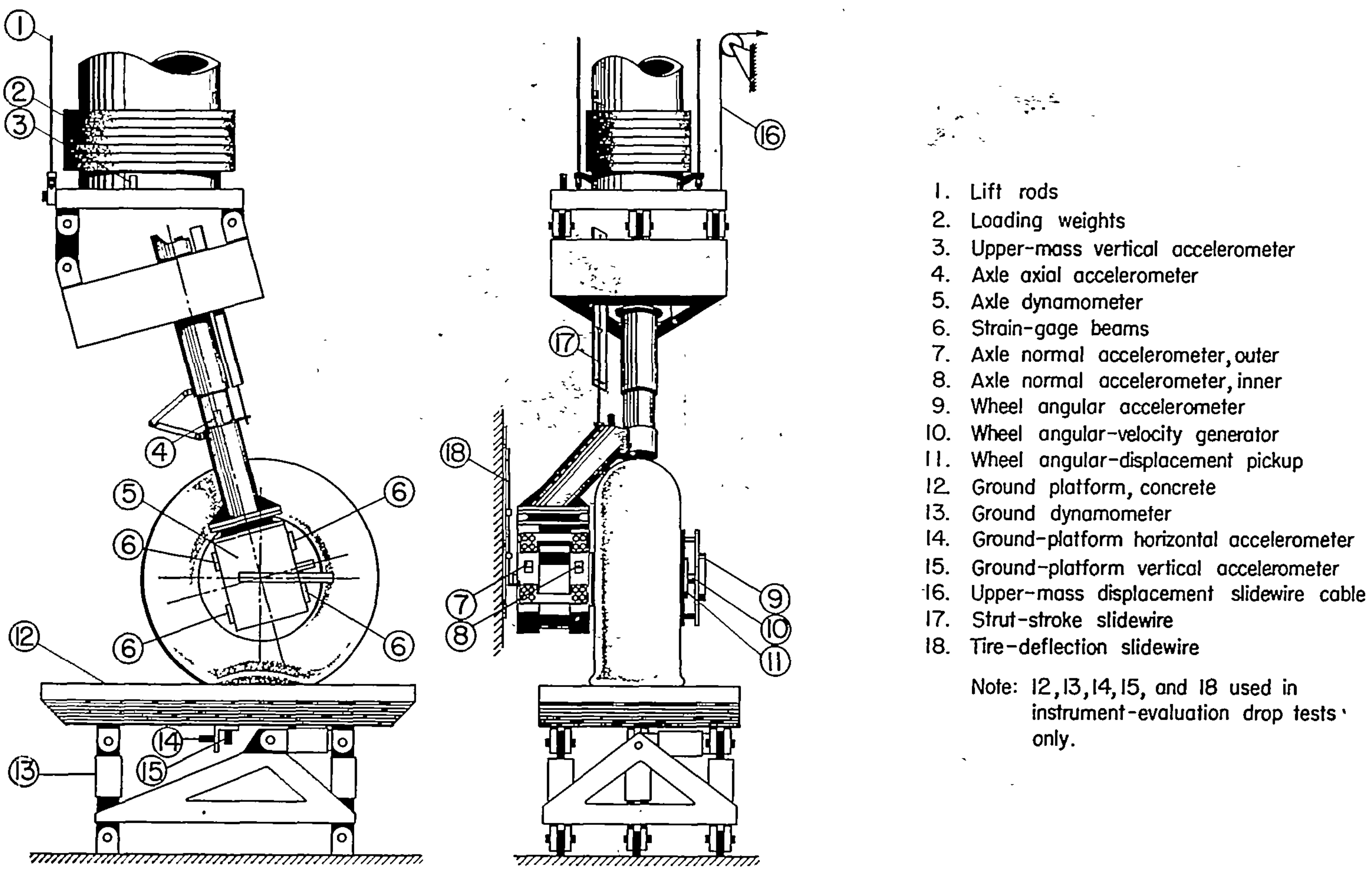


FIGURE 3.—Schematic view of landing gear and instrumentation.

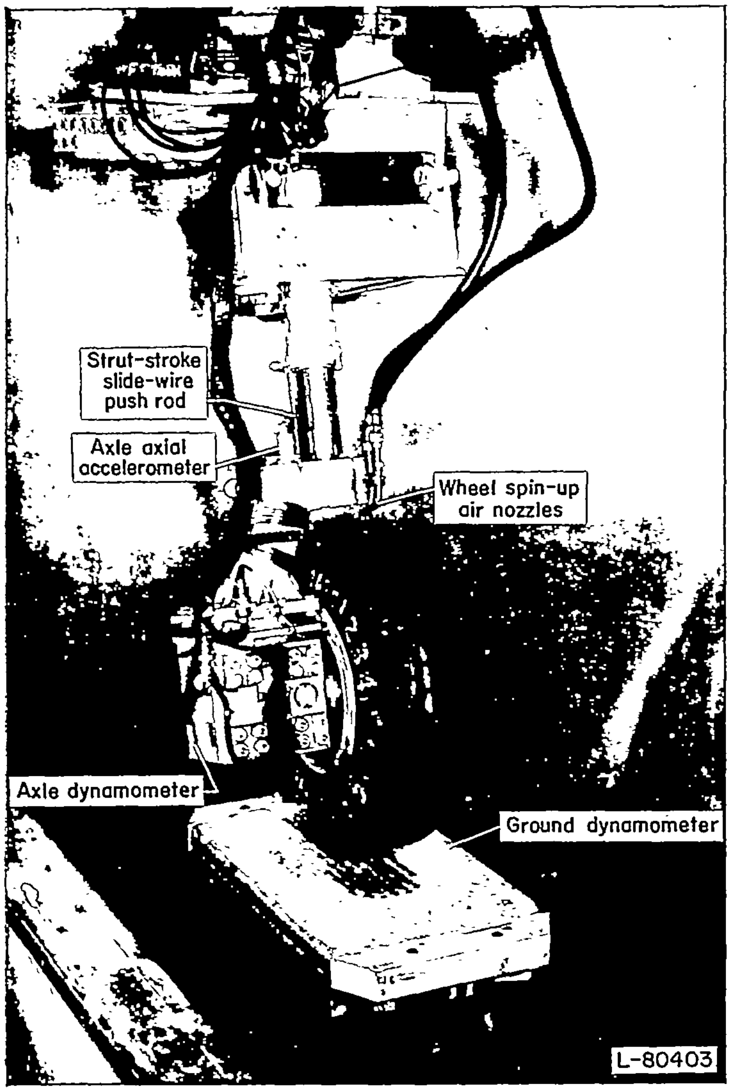


FIGURE 4.—Front view of landing gear and instrumentation.

A specially designed two-component dynamometer, installed between the axle and the fork of the landing gear, was used to measure the forces applied at the axle. This axle dynamometer, which has wire resistance strain-gage members, measured the axial (parallel to the axis of the shock strut) and normal (perpendicular to the strut axis in the plane of the wheel) forces transmitted from the axle to the fork of the landing gear, from which the vertical and horizontal forces at the axle could be determined. The axle dynamometer was designed to measure axial forces up to 10,000 pounds and normal forces up to 5,000 pounds and had natural frequencies, with wheel assembly attached, of 403 cps and 220 cps in the axial and normal directions, respectively.

The forces at the axle are, of course, not the same as the forces between the tire and the ground, the differences being the inertia reactions of the mass between the dynamometer and the ground which result from the accelerations of this mass during an impact. In order to determine these inertia forces, accelerometers were mounted on the landing-gear fork and on the dynamometer so as to measure the axial and normal components of the acceleration of the mass acting at the axle. The vertical and horizontal ground forces were then determined from the axle-dynamometer and axle-accelerometer measurements. Because of twist of the landing gear due to drag loads, it was necessary to employ two accelerometers, laterally displaced from one another, to determine the normal acceleration of the center of gravity of the mass between the dynamometer and the ground. These accelerometers are referred to as inner and outer normal accelerometers and their measurements are designated as $a_{N_{a_i}}$ and $a_{N_{a_o}}$, respectively. (See fig. 3.)

In order to evaluate the accuracy of the applied ground forces determined from the axle-dynamometer and axle-acceleration measurements under dynamic conditions, a special series of instrument-evaluation drop tests, with reverse wheel rotation to produce drag loads, was made in which the total vertical and horizontal ground forces determined from the landing-gear instrumentation were compared with data obtained simultaneously from a ground dynamometer equipped with accelerometers. The ground accelerometers were used to determine the inertia reactions of the ground platform, which were added to the forces measured by the ground-dynamometer strain gages, in order to obtain the total applied forces between the tire and the ground platform. These comparisons (see, for example, fig. 6) indicated good agreement between the applied ground forces determined from the two sets of instrumentation and

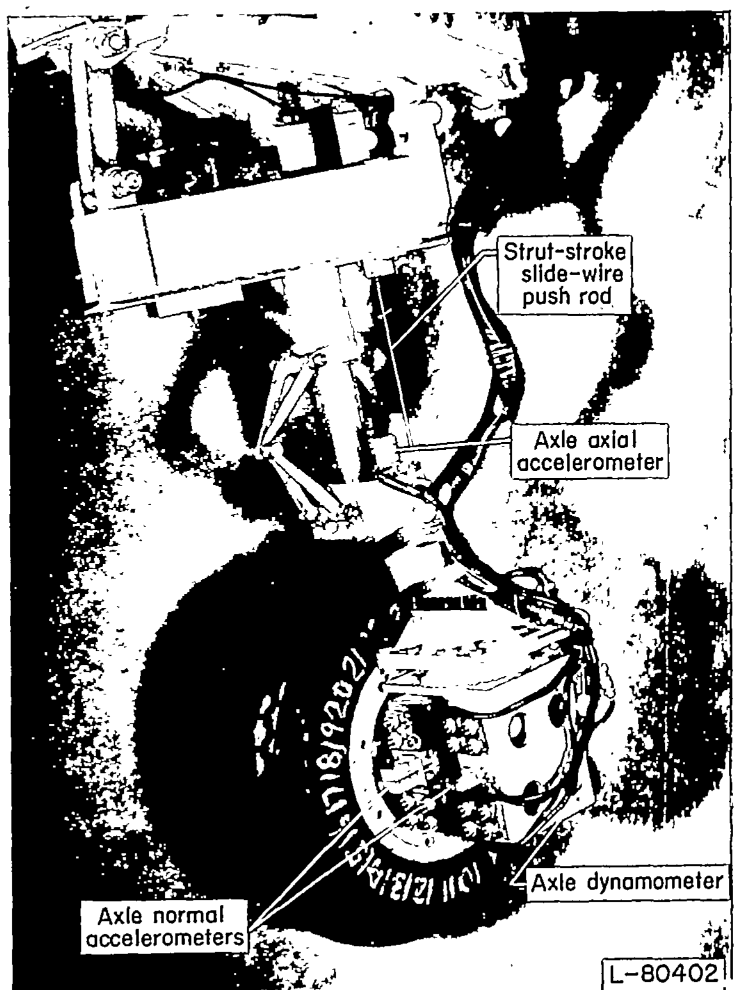


FIGURE 5.—Rear view of landing gear and instrumentation.

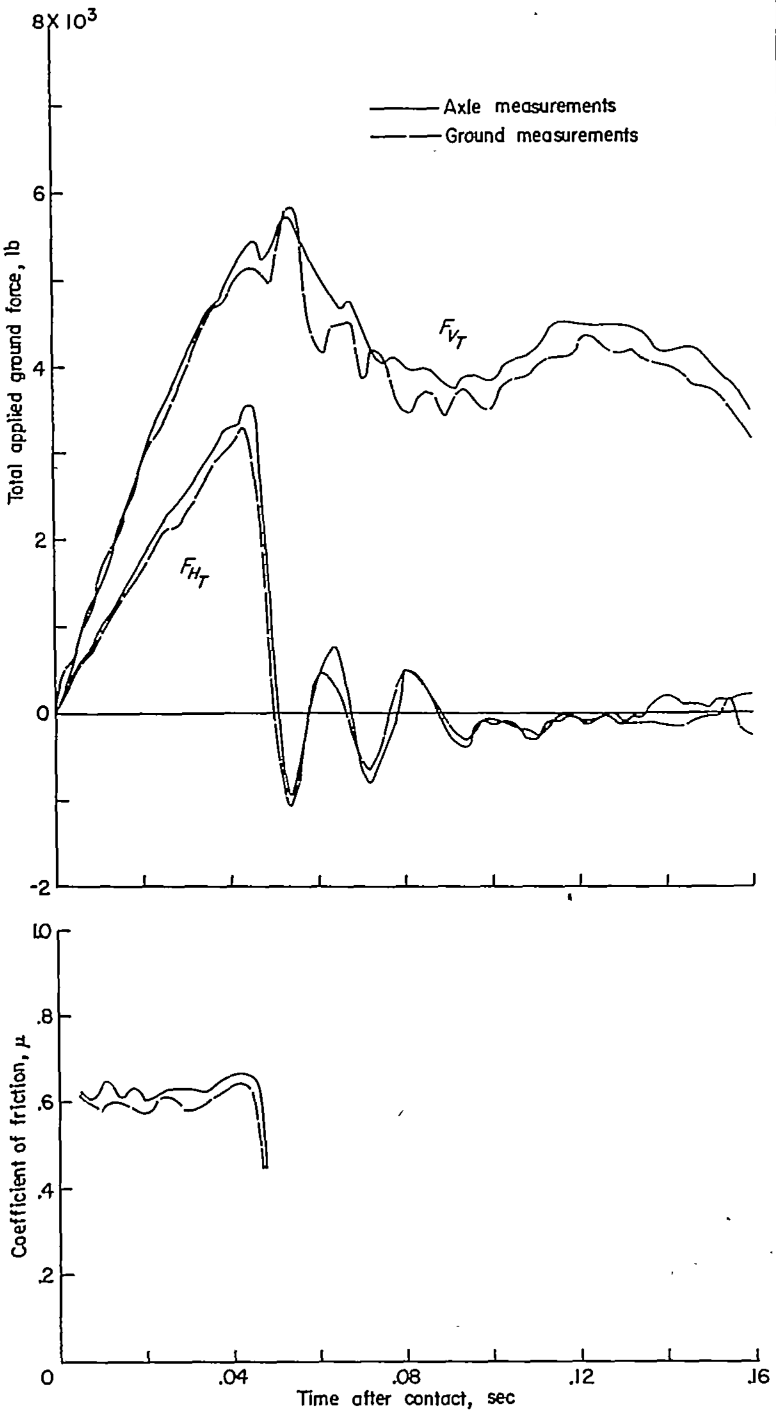


FIGURE 6.—Comparison of axle and ground measurements of applied forces in a typical instrument-evaluation test. $V_{V_O}=7.64$ feet per second; $V_{H_{g_O}}=108.5$ feet per second.

gave added confidence in the axle measurements, which were then used as a basis for the main part of the test program.

The vertical velocity at the instant of initial ground contact was determined from the output of an elemental electromagnetic generator. The horizontal velocity of the carriage in the forward-speed tests was determined from horizontal-displacement measurements obtained by means of a photoelectric cell mounted on the carriage and light-beam interrupters fixed at one-foot intervals along the track.

The lift force acting on the dropping mass was preset and its time history during the impact was measured by means of a strain-gage beam placed between the dropping mass and the rods through which the lift force is transmitted. An accelerometer for measuring the vertical acceleration of the upper mass (the mass above the shock strut) during impact was included in the test instrumentation for comparison purposes.

A two-phase induction drag-cup generator was used for measuring the angular velocity of the wheel. The angular displacement of the wheel was determined by means of a segmented ring mounted on the wheel. Brushes were attached to the axle so that electrical contact was made and broken 30 times during each revolution of the wheel. This segmented ring was also used for calibrating the angular-velocity generator. For evaluation purposes, an angular accelerometer was installed on the wheel.

The vertical displacement of the upper mass and the shock-strut stroke were measured by means of variable-resistance slide-wire potentiometers, positively driven in both directions. In order to increase the sensitivity of the upper-mass-displacement measurements, a series of separate slide wires was arranged in such a manner as to produce full-scale record deflections for each ten inches of mass displacement. Measurements of the tire deflection during impact were obtained from the difference between the values of the upper-mass displacement and the vertical component of the shock-strut stroke. In order to evaluate the accuracy of the measurements obtained by this method, a stationary slide wire was used to measure directly the tire deflection in the special series of instrument-evaluation drop tests; the data obtained by the two methods were found to be in good agreement.

The more important characteristics of the individual instruments used in the tests are given in table I, page 34. On the basis of these characteristics, the maximum errors in the derived measurements are believed to be within the following limits:

Total horizontal force on tire, F_{H_T}, lb	
Axle measurements	*±285*
Ground measurements	*±285*
Total vertical force on tire, F_{V_T}, lb	
Axle measurements	*±330*
Ground measurements	*±210*
Tire deflection, δ, ft	*±0.02*
Axle horizontal velocity, V_{axle}, ft/sec	*±6*
Carriage horizontal velocity, V_{car}, ft/sec	*±1.3*

It should be noted that the foregoing values apply to the maximum values of the measured quantities; that is, a vertical load of about 9,000 pounds, a drag load of 4,500 pounds, a tire deflection of 0.35 foot, and axle and horizontal velocities of 86 feet per second. When the measured quantities are smaller than these maximum values, the errors are, in general, proportionately reduced.

The electrical outputs from all the instruments were recorded on a 36-channel oscillograph equipped with a timer which produced timing lines on the record at intervals of 0.01 second. A typical oscillograph record is shown, reduced, in figure 7.

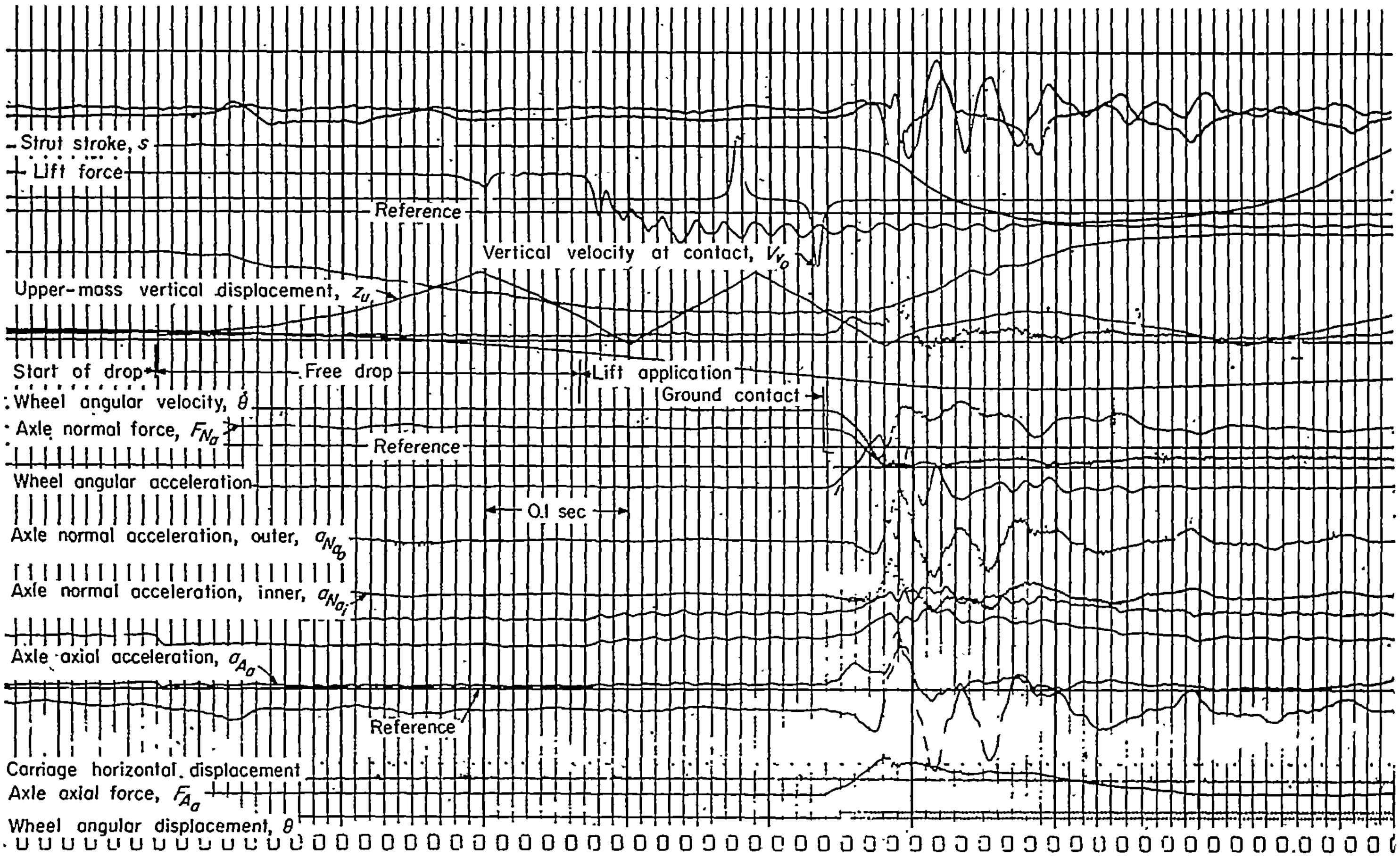


FIGURE 7.—Oscillograph record for typical forward-speed test. V_{V_O}=9.68 feet per second; V_{H_O}=84.1 feet per second.

EQUATIONS USED FOR DERIVED QUANTITIES

In view of the fact that it was not feasible to measure certain desired quantities directly (for example, the total vertical and horizontal forces between the tire and the ground), it was necessary to deduce these quantities from other closely related measurements. The equations used for this purpose are discussed in this section.

APPLIED FORCES FROM AXLE MEASUREMENTS

The applied ground forces were obtained by addition of the forces acting on the axle and the inertia reactions due to the accelerations of the mass between the axle dynamometer and the ground. From figure 8 it can be seen that

$$\left.\begin{aligned} F_{H_T}&=F_{N_T}\cos\varphi+F_{A_T}\sin\varphi \\ F_{V_T}&=F_{A_T}\cos\varphi-F_{N_T}\sin\varphi \end{aligned}\right\} \qquad (1)$$

where

$$F_{A_T}=F_{A_a}+m_w a_{A_a}$$

$$F_{N_T}=F_{N_a}+m_w a_{N_a}$$

and m_w is the mass (3.58 slugs) between the axle dynamometer and the ground. (In fig. 8, the inertia or reversed effective forces $m_w a_{A_a}$ and $m_w a_{N_a}$ are indicated by means of dashed vectors.)

The forces F_{A_a} and F_{N_a} were measured directly by the axle dynamometer. The axial acceleration a_{A_a} was obtained by means of a single accelerometer located on the modified yoke of the landing gear. (See fig. 3.) Since the yoke and axle were very rigid in the direction parallel to the shock-strut axis, the axial acceleration of the yoke was assumed equal to the axial acceleration of the center of gravity of the mass between the axle dynamometer and the ground. On the other hand, normal forces produced some twisting of the landing gear in the plane perpendicular to the shock-strut axis. For this reason it was necessary to use two accelerometers (see fig. 3) and linear extrapolation to determine the normal acceleration at the center of gravity of the mass between the axle dynamometer and the ground.

In order to illustrate the general characteristics of the force measurements, time histories of the applied ground-force components F_{A_T}, F_{N_T}, F_{V_T}, and F_{H_T}, as well as time histories of the axle forces F_{A_a} and F_{N_a} and the inertia reactions $m_w a_{A_a}$ and $m_w a_{N_a}$, from which the previously mentioned applied ground forces were calculated, are shown in figures 9 (a) to 9 (c) for a typical forward-speed test.

From the horizontal and vertical components of the applied ground force, the time histories of the coefficient of friction, defined as

$$\mu=\frac{F_{H_T}}{F_{V_T}} \qquad (2)$$

were determined. (See fig. 9 (d).) As used herein the term "coefficient of friction" signifies the value of the ratio of th

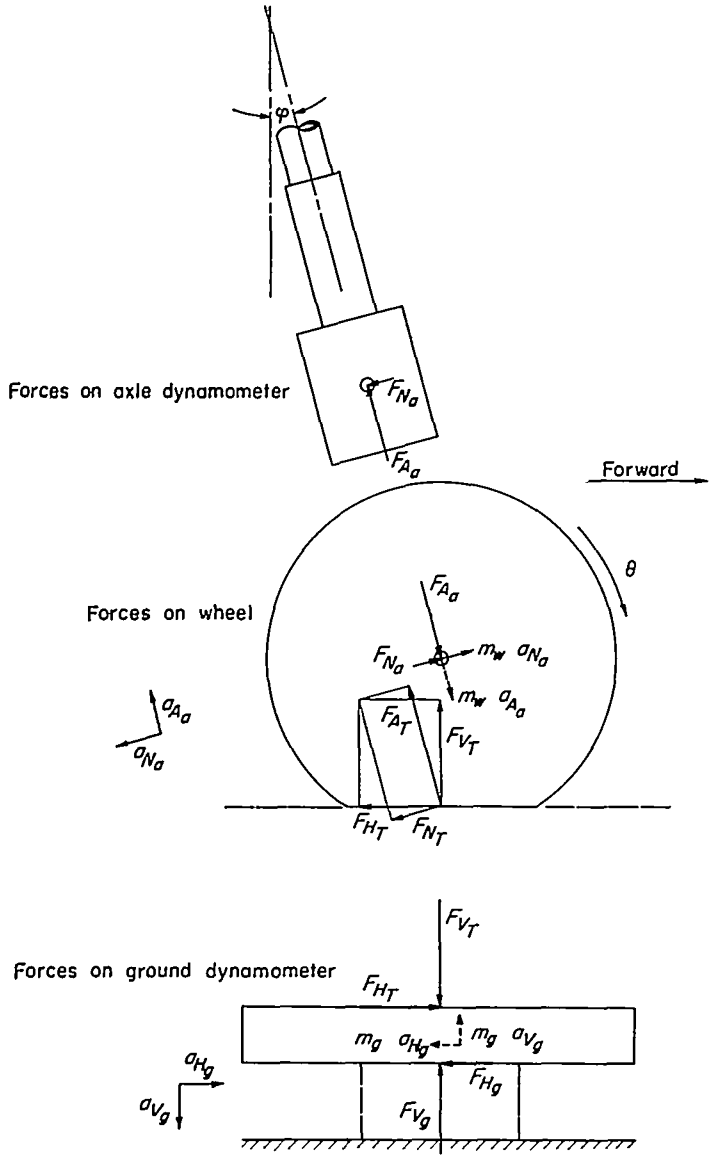


FIGURE 8.—Diagram of forces and reactions.

instantaneous applied drag force to the applied vertical force, as actually measured, and not necessarily the maximum value of this ratio that can be attained under given conditions of contact between the tire and the ground. This distinction is necessary because, under certain conditions (small slip), the drag force is governed by the circumferential distortion of the tire rather than by the limiting friction between the tire and the ground, as is discussed in a subsequent section.

APPLIED FORCES FROM GROUND MEASUREMENTS (INSTRUMENT-EVALUATION TESTS)

As previously mentioned, a ground dynamometer equipped with accelerometers was used in a special series of drop tests as an additional means of determining the applied ground loads for comparison with the values obtained from the axle instrumentation. The total applied ground loads were determined from the sum of the forces in the ground-dynamometer strain-gage members and the inertia reactions due to the acceleration of the ground-platform mass m_g (7.51 slugs). As can be seen from figure 8,

$$F_{H_T}=F_{H_g}+m_g a_{H_g}$$

and

$$F_{V_T}=F_{V_g}+m_g a_{V_g}$$

where F_{H_g} and F_{V_g} were determined directly from the ground-dynamometer strain-gage measurements and a_{H_g} and a_{V_g} were obtained from accelerometers attached to the ground platform, as shown in figure 3. (In fig. 8, the inertia forces $m_g a_{H_g}$ and $m_g a_{V_g}$ are indicated by dashed vectors.)

APPARENT SKIDDING VELOCITY

For use in studying the variation of the coefficient of friction during the spin-up process, the apparent skidding velocity V_{skid} was determined. The apparent skidding velocity is defined as the difference between the actual translational velocity of the axle and the translational velocity which would exist if the wheel were rolling freely with the same angular velocity. Since the axle velocity for a freely rolling wheel can be expressed as the product of the effective rolling radius of the tire r_e and the wheel angular velocity $\dot{\theta}$, the apparent skidding velocity during spin-up may be written as

$$V_{skid}=V_{axle}-r_e\dot{\theta} \tag{3}$$

It should be noted that the apparent skidding velocity is not necessarily the same as the actual sliding velocity between the tire and the ground, which may vary from point to point in the ground-contact area. The term "apparent" is used in recognition of the fact that equation (3) neglects the effects of the circumferential and radial distortions of the tire which, under the action of drag loads, modify the tangential velocities of the tread in the ground-contact region and thereby alter the actual local sliding velocities somewhat in comparison with the values which would apply for a circumferentially rigid wheel.

Since the applied loads during an impact cause a fore-and-aft oscillation of the landing gear, the axle velocity is not the same as the carriage velocity. Therefore, in these tests the difference between the axle velocity and the initial carriage velocity was determined by integration of the horizontal component of the axle acceleration, and the axle velocity was calculated from the expression

$$V_{axle}=V_{H_o}-\int_o^t a_{H_a}dt$$

where a_{H_a} was determined from the normal and axial acceleration components of the axle by means of the geometric relationship (see fig. 8):

$$a_{H_a}=a_{N_a}\cos\varphi+a_{A_a}\sin\varphi$$

The instantaneous value of the effective rolling radius of the tire was determined by means of the relationship (see appendix A):

$$\left.\begin{aligned} r_e&=\frac{R\sqrt{1-\frac{r_d^2}{R^2}}}{\sin^{-1}\sqrt{1-\frac{r_d^2}{R^2}}}\\ &\approx R-\frac{\delta}{3}\end{aligned}\right\} \tag{4}$$

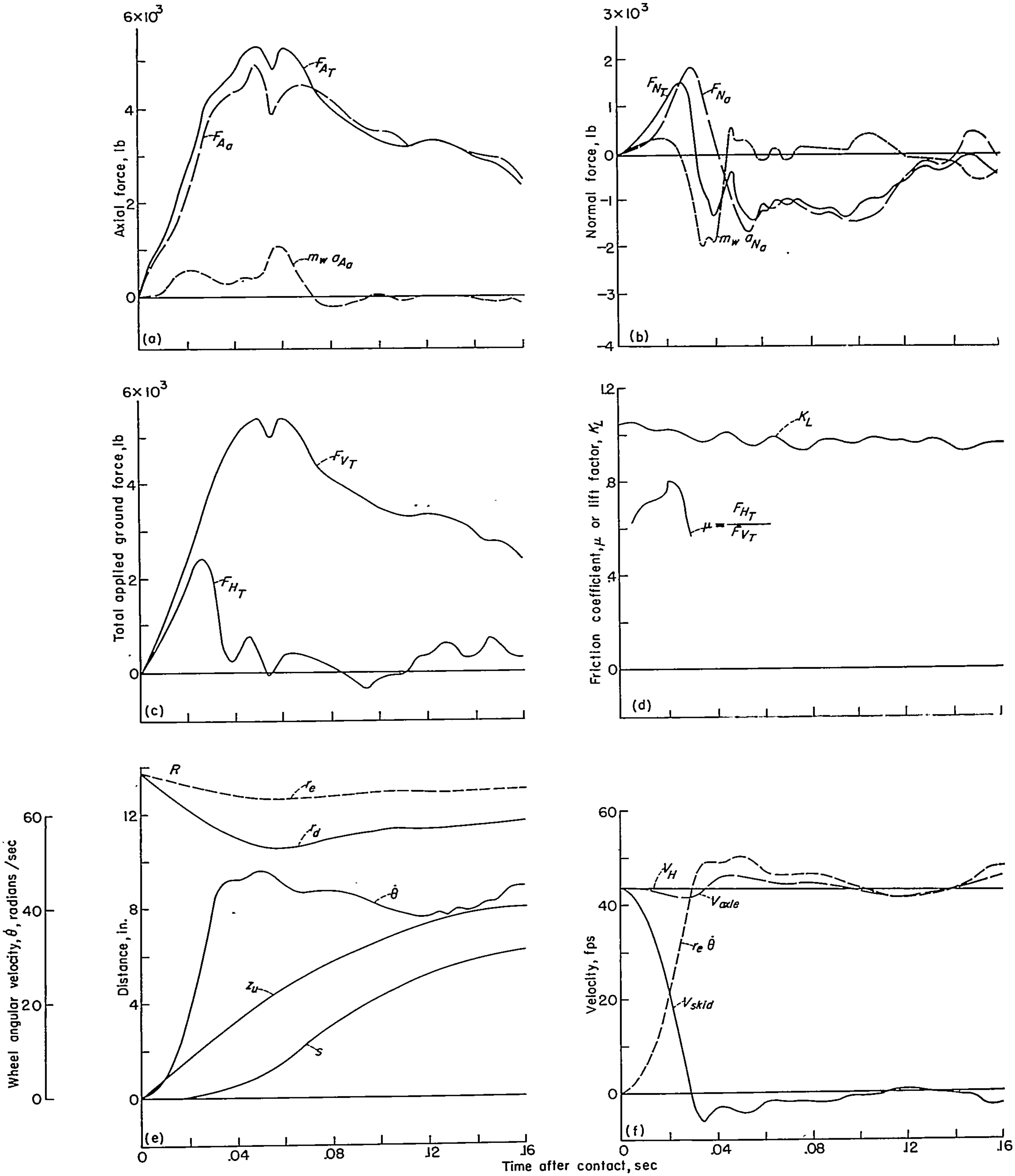


FIGURE 9.—Time histories of basic data and derived quantities from carriage instrumentation in a typical forward-speed test. V_{V_O}=7.5 feet per second; V_{H_O}=44 feet per second.

where R is the free radius of the tire, r_d is the geometric deflected radius, and δ is the vertical deflection of the tire, as determined from the measurements of the upper-mass vertical displacement z_u and the shock-strut axial stroke s by means of the geometrical relationship

$$\delta = z_u - s \cos \varphi$$

For illustrative purposes, time histories of the quantities involved in the calculation of the apparent skidding velocity are shown for a typical forward test in figures 9 (e) and 9 (f).

RESULTS AND DISCUSSION

GENERAL CHARACTERISTICS OF A TYPICAL IMPACT

In order to obtain an overall physical picture of the impact process during a landing with forward speed, it may be helpful, before proceeding to the main results of this investigation, to consider briefly, with the aid of figures 8 and 9, the manner in which the various forces are developed subsequent to ground contact and their effects on the motions of the wheel and landing gear, particularly the process whereby the conditions of contact between the tire and the ground are progressively changed from full skidding at the instant of initial contact to free rolling following the completion of spin-up.

At the instant of initial ground contact the dropping mass has essentially constant vertical and horizontal velocity components. The mechanically simulated wing-lift force is approximately equal to the dropping weight so that the lift factor K_L remains close to 1.0 throughout the impact (fig. 9(d)). Following ground contact, the deflections of the tire and the shock strut produce a vertical ground force F_{V_T} (fig. 9(c)), governed by the vertical velocity and the tire and shock-strut characteristics, which acts to dissipate the vertical momentum of the dropping mass. In the presence of this vertical force, the relative horizontal velocity between the tire and the ground, or skidding velocity, gives rise to a frictional or horizontal drag force F_{H_T} (fig. 9(c)). The moment produced by this drag force, acting through the deflected radius r_d of the tire (fig. 9 (e)), plus a small moment due to the longitudinal offset of the vertical force from the center of the wheel, causes an angular acceleration of the wheel and an increase in the angular velocity $\dot{\theta}$ with time (fig. 9 (e)), which, in turn, serves to decrease the skidding velocity with time (fig. 9 (f)).

Since the coefficient of friction μ during the spin-up process (fig. 9 (d)) is generally larger than the tangent of the angle φ between the landing-gear axis and the vertical axis, the resultant force on the landing gear has a rearward-acting component in the direction perpendicular to the landing-gear axis (normal force F_{N_T} in fig. 9 (b)). Because the landing gear has flexibility in bending, this normal force produces a rearward acceleration a_{N_a} of the axle, perpendicular to the landing gear axis (fig. 9 (b)). The axle also experiences an acceleration a_{A_a} parallel to the landing gear axis (fig. 9 (a)) as a result of the compression of the shock strut and the tire. Since the resultant of these accelerations has a rearward-acting horizontal component, the horizontal velocity of the axle V_{axle} is somewhat reduced in comparison to the velocity of the carriage V_H (fig. 9 (f)), which tends to decrease the skidding velocity slightly. During this phase of the impact the axle may experience appreciable rearward deflections. An additional increment in rearward motion of the axle is provided by the kinematic displacement due to the telescoping (shortening) of the inclined shock strut during the impact.

The process of tire skidding continues, with decreasing skidding velocity (fig. 9 (f)) as the angular velocity of the wheel $\dot{\theta}$ is increased (fig. 9 (e)), until the angular impulse becomes equal to the change in angular momentum required to bring the wheel up to ground-rolling speed. The decrease in the skidding velocity with time is accompanied by an increase in the coefficient of friction (fig. 9(d)). As the condition of free rolling is approached, the coefficient of friction passes through its maximum value, at some finite value of the apparent skidding velocity, and then rapidly drops to near zero as the final stage of the transition from skidding to free rolling is completed.

This sudden decrease of the coefficient of friction causes the drag force to drop abruptly, with the following consequences. The landing gear, which had previously been deflected toward the rear by the drag force, now accelerates forward under the influence of the internal elastic forces and the vertical load, the horizontal velocity of the axle becoming larger than the carriage velocity. The landing gear passes through its undeflected position, attains large forward deflections, then again reverses its direction of motion relative to the carriage. The ensuing damped fore-and-aft oscillation, which occurs at about 11 cycles per second, is associated with the natural frequency of the landing gear in bending, including the effects of the equivalent mass of the rolling wheel.

Following the sudden drop-off of the drag force, a similar type of elastic springback and resulting torsional or circumferential oscillation, at a natural frequency of about 55 cycles per second, takes place in the tire which, because of its torsional flexibility, had been circumferentially distorted by the drag-load moment. This circumferential springback imparts a positive increment to the angular velocity of the wheel, so that it becomes larger than the angular velocity of the tire tread. The use of this larger wheel angular velocity in equation (3) leads to the calculation of negative values for the apparent skidding velocity V_{skid} (fig. 9 (f)) immediately following the decay of the drag force (fig. 9 (c)), even though the actual average skidding velocity between the tire and the ground during this period may be nominally zero or even slightly positive.

FORWARD-SPEED TESTS

Time histories of applied loads.—Figure 10 shows several typical time histories of the applied vertical and horizontal ground loads and the coefficient of friction, as measured in impacts with forward speed. The data presented are for an average initial vertical velocity of about 7.5 feet per second and horizontal velocities up to approximately 83 feet per second. (For clarity, time histories from only a few representative tests, selected from a more extensive test program, are shown in figure 10. Figure 11 summarizes the most important data from the complete series of forward-speed tests.) A number of basic effects can be seen from figure 10. As the forward speed is increased, since the impulse

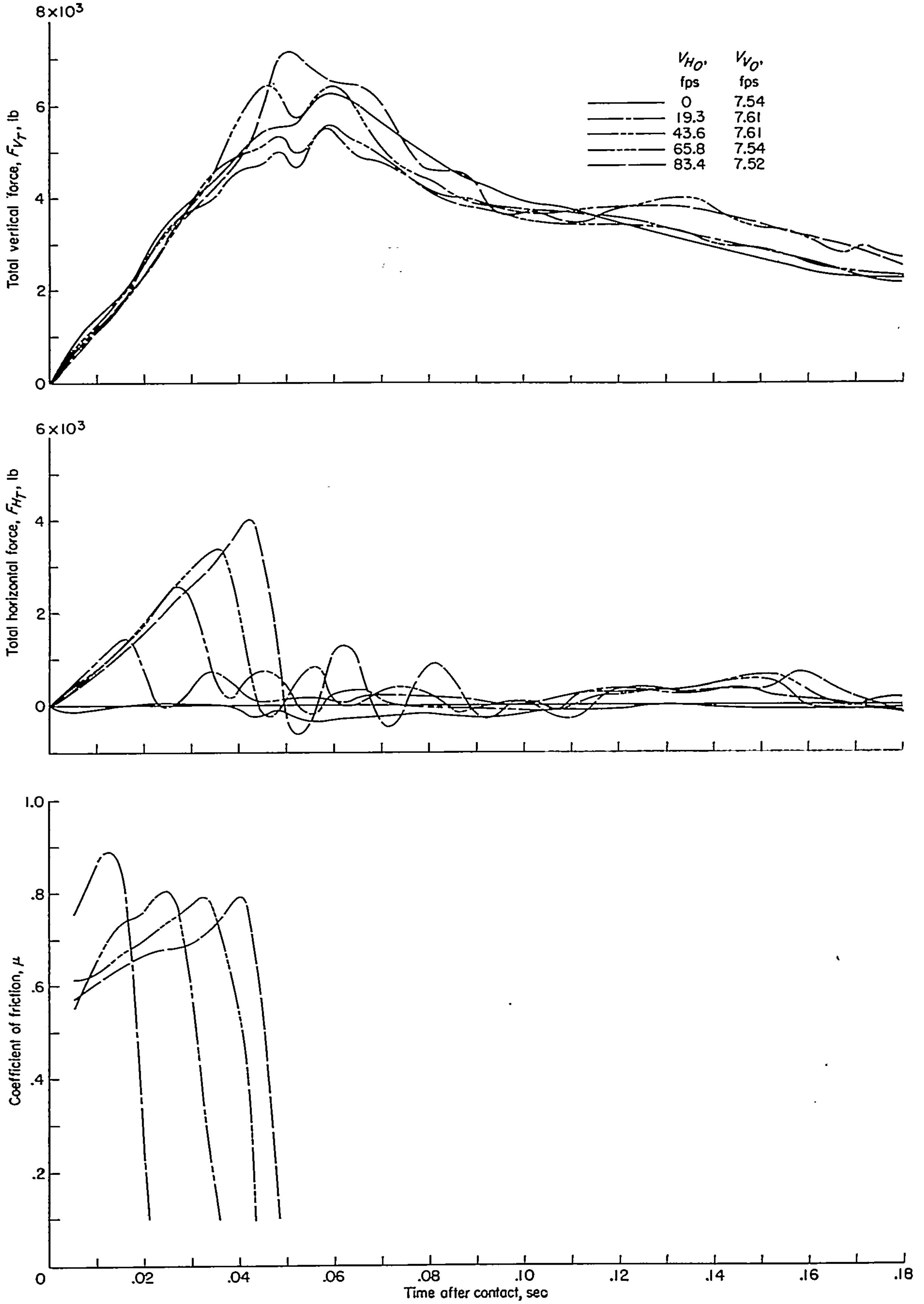


FIGURE 10.—Time histories of applied loads and coefficient of friction in typical forward-speed tests. $V_{V_{O_{av}}}=7.56$ feet per second.

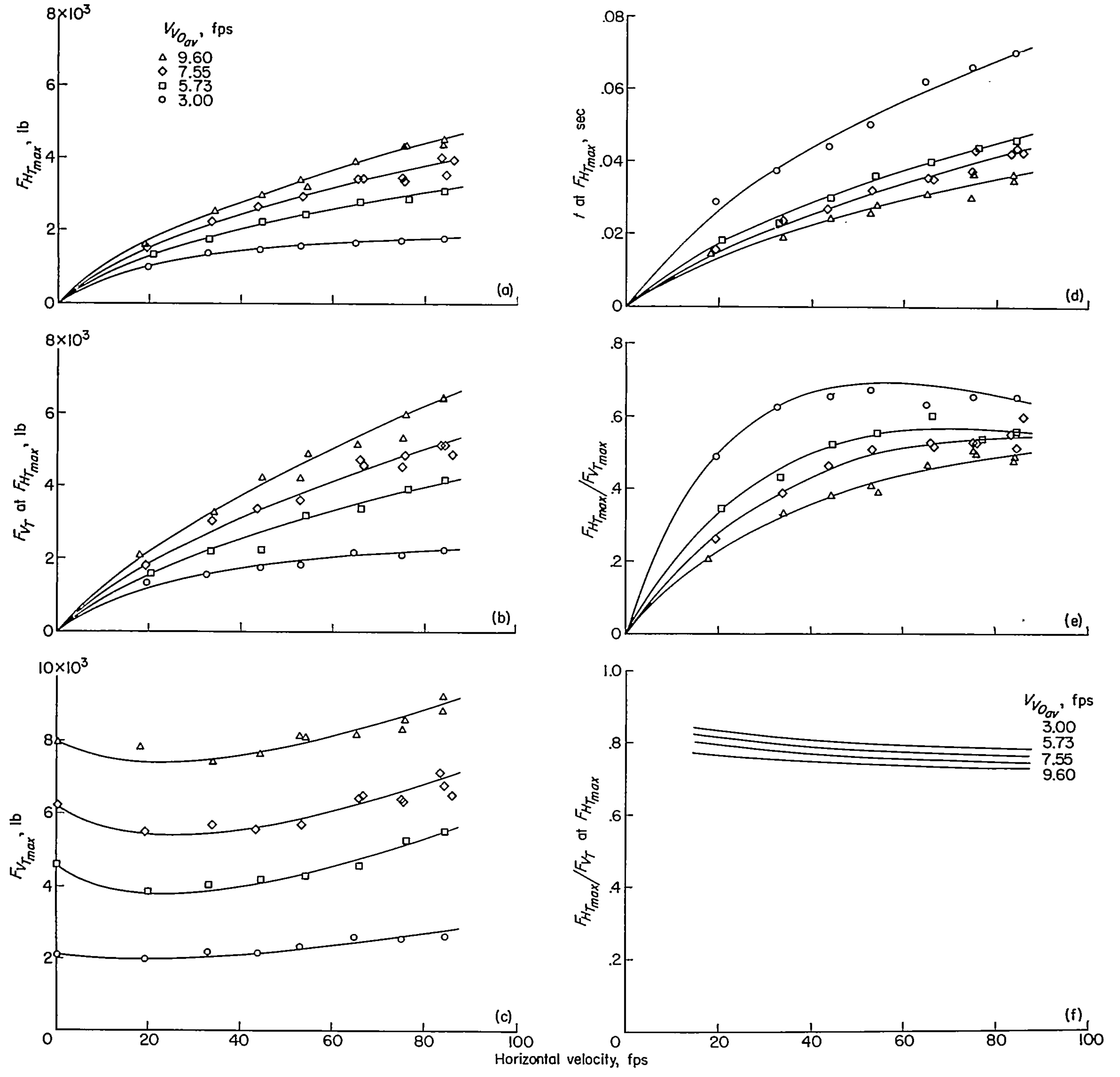


FIGURE 11.—Summary of applied loads in forward-speed tests.

required to bring the wheel up to ground-rolling speed is increased, the wheel skids for a longer time. Because the vertical load increases with time during the period of wheel skidding, as the skidding process is prolonged, there is an increase in the magnitude of the vertical load which exists at the time of spin-up and, therefore, an increase in the maximum drag load with increasing forward speed. (The generality of this result is, of course, restricted to the range of forward speeds where spin-up and the maximum drag load occur before the maximum vertical load is reached, which was the situation in these tests.) This effect of the forward speed on the maximum drag load can also be seen from figure 11 (a); the vertical load at the time of spin-up is shown in figure 11 (b).

In these forward-speed tests the wheel turned through only a fractional part of a revolution during the skidding process, the angular displacement at the instant of maximum drag load, at the highest horizontal velocity investigated, being less than 100° at a vertical velocity of 3 feet per second, and even smaller at the higher vertical velocities.

As can be seen from figure 10, two types of superimposed oscillations are evident in the drag load subsequent to spin-up. The high-frequency oscillations, at about 55 cycles per second, are due to the torsional vibrations of the wheel and tire assembly which are initiated by the circumferential spring-back of the tire at the end of the spin-up process, as previously mentioned. The low-frequency oscillations, at about 11 cycles per second, result from the alternating angular accelerations which are imparted to the rolling wheel by the fore-and-aft oscillations of the landing gear excited by the drop-off of the drag load, also previously discussed.

In the case of the impact with zero horizontal velocity, the small negative or forward-acting drag load is attributed to the kinematic displacement of the axle to the rear, which results from the telescoping (shortening) of the inclined shock strut. A forward-acting horizontal force is necessary to produce the angular acceleration of the rolling wheel required by the rearward acceleration of the axle; an additional increment in negative drag load during this period is produced by the rolling resistance of the wheel.

As can be seen from figures 10 and 11 (c), the magnitude of the maximum vertical load varied appreciably over the range of horizontal velocity covered by the tests, even when the vertical velocity was essentially constant As the horizontal velocity was increased from zero, the maximum vertical load first decreased, then increased, so that at the highest forward speeds the maximum vertical loads were considerably higher than at zero horizontal velocity. These variations of the vertical load are caused primarily by differences in the internal friction forces within the shock strut which result from the fore-and-aft bending of the landing gear during the impact. The (equivalent static) forces which cause this bending differ from the applied ground forces by an amount equal to the inertia reactions of the masses between the shock strut and the ground. In other words, the bending moments responsible for the increased shock-strut friction are those associated with the instantaneous bending deflection, or dynamic response, of the landing gear, rather than those due directly to the applied ground loads. Thus, the effects of strut friction on the vertical load under different impact conditions can be explained by consideration of the bending response of the landing gear:

In an impact with zero horizontal velocity, the resultant force is essentially vertical, so that a bending moment tending to deflect the landing gear forward is present throughout the entire impact. By the time the maximum vertical load is reached, this forward deflection has become appreciable so that substantial strut friction forces exist which cause the maximum vertical load to be greater than the value which would be obtained if bending moments were not present.

In impacts with finite horizontal velocity, on the other hand, the bending moments on the landing gear change sign during the impact. As a result, the landing gear is first deflected toward the rear, attains a maximum rearward deflection shortly after the maximum drag load is reached, then springs forward, passes through zero deflection, reaches a maximum forward deflection, and oscillates with decaying amplitude. The effect of strut friction on the maximum vertical load depends largely on the magnitude of the bending deflection at the instant when the maximum vertical load is reached. This, in turn, depends on the shape of the drag-load time history and the value of the maximum drag load, the amount of time elapsing between the occurrence of the maximun drag load and the maximun vertical load, and the natural frequency of the landing gear.

For example, when the forward speed is small, because the time to spin up is short, the maximum rearward deflection is small and occurs early in the impact, considerably before the maximum vertical load is reached. Thus, the landing gear is already in the process of fore-and-aft oscillation when the maximum vertical load is reached, the bending deflections at this instant being either positive or negative, depending on the factors previously mentioned. The minimum effect of strut friction, and thus the smallest value of the maximum vertical load, is obtained for the condition where the landing gear passes through zero deflection at the instant of maximum vertical load. In these tests, this situation occurs at a horizontal velocity of approximately 20 feet per second. (See fig. 11 (c).) At lower horizontal velocities the landing gear has larger forward deflections at the instant of maximum vertical load since it has been subject to a forward acceleration for a longer time. At higher horizontal velocities, because the time to spin up is increased, the maximum rearward deflection increases and occurs at a later time after contact; as a result, the amount of rearward deflection, and thus the magnitude of the strut friction forces, at the time of maximum vertical load increases with increasing forward speed (for the range of conditions where the maximum drag load occurs before the maximum vertical load). Since the maximum rearward deflection occurs after the maximum drag load is reached, the effect of strut friction on the maximum vertical load can be very large, even though the applied (ground) drag load has already dropped to low values at the instant of maximum vertical load. This situation exists at the highest forward speeds for which data are shown in figures 10 and 11. Of course, if there were no strut friction, the vertical load would be almost independent of the forward speed and the drag load; in this case, the only effect of the drag load would arise from the relatively small component parallel to the axis of the shock strut, which would tend to increase the rate of closure of the strut somewhat and thereby cause a slight increase in the axial force produced in the strut.

Coefficient of friction.—Figure 10 also shows the variation of the instantaneous value of the coefficient of friction (as defined previously) between the tire and the ground during the spin-up process. As can be seen, the coefficient of friction in each test started out at an intermediate value immediately after initial contact, increased steadily with time, attained a maximum value just before the maximum drag load was reached (at a finite value of the apparent skidding velocity), then dropped very rapidly toward zero as the transition from skidding to rolling was completed.

The variations of the coefficient of friction during any given impact and from one set of conditions to another can be explained qualitatively by consideration of several effects which appear to influence the characteristics of the contact between the tire and the ground; namely, the phenomenon called "slip," the effects of changes in the instantaneous value of the skidding velocity, the effects of variations in the vertical load, and the effects of heating of the tire running surface produced by the skidding process.

Some insight into these effects can be obtained from the results of previous investigations of the braking of the rolling wheels of automobiles. (See, for example, ref. 3.) In the case of a rolling wheel, if a braking torque is applied, the angular velocity is reduced, even though the horizontal velocity of the axle may be held constant. This reduction in angular velocity under the action of a torque gives rise to the concept of slip. (The term "slip" may be somewhat misleading since, at low values of torque, the reduction in angular velocity occurs almost exclusively as a result of the circumferential and radial distortions produced in the tire by the tangential forces developed between the tire and the ground, rather than through actual sliding of the tire contact surface over the ground.) The ratio of the change in angular velocity of the wheel under torque to the angular velocity of the freely-rolling wheel for the same axle velocity is called the slip ratio. As is discussed in appendix A, the slip ratio may also be expressed as the ratio of the apparent skidding velocity of the tire to the horizontal velocity of the axle.

The relationship between the slip and the horizontal force developed between the tire and the ground can be easily understood if one first considers the situation which exists when an elemental block of rubber, in contact with the ground, is subjected to an increasing horizontal force in the presence of a vertical force. As the horizontal force is applied, at first, because of the interlocking or adhesive nature of the contact between the block and the ground, no appreciable relative motion takes place between the contacting surfaces and an opposing equal tangential force is developed in the contact region. Under the action of these forces, however, an elastic deformation of the block in bending and shear occurs, essentially proportional to the horizontal force. Because of this elastic deformation, a relative motion is produced between the top of the block and the surface in contact with the ground, even though no actual sliding motion exists in the ground-contact area. This relative motion between the top and bottom of the block is analogous to the relative circumferential motion between the bead and the tread which is the basis of deformation slip in the case of the tire. As the horizontal force is increased, a point is reached where the tangential stress between the tire and the ground reaches the limiting value which can be maintained by the interlocking or adhesive forces. Any further increase in the applied horizontal force causes the block to slide relative to the ground. Following the onset of sliding, since the interlocking bond between the contacting surfaces has been broken, the tangential force immediately becomes appreciably smaller than its value at the instant of incipient sliding and continues to decrease with further increase in the velocity of sliding.

The variation of the tangential force developed when a rolling wheel is subjected to a braking torque can be visualized if each section of the tire in contact with the ground is assumed to behave in more or less the same way as the elemental block just discussed. In the case of the tire, of course, the situation is much more complicated; since the effective stiffness and the distortions of the casing differ considerably from point to point, the distributions of the vertical ground pressure and the tangential stresses vary appreciably over the contact area.

At low values of torque, that is, at small slip ratios, the tangential stresses are mostly below the level at which local sliding occurs, so that the contact between the tire and the ground is basically of an interlocking or adhesive nature. In this region finite slip is due primarily to elastic deformation of the tire, since little or no actual sliding occurs between the tire contact area and the ground; as a result, in this region the slip is essentially proportional to the torque. As the torque is increased, the deformations and the tangential stresses become larger, so that the slip and the total horizontal force increase. With further increase in torque, an increasingly greater part of the ground-contact area reaches the limiting stress level that can be maintained by adhesion, so that more and more points in the contact area begin to slide. As soon as a given tire element begins to slide the tangential force which can be developed by that element is considerably reduced, and a transfer of tangential stress takes place to load up elements which have not yet begun to slide. As a result, as more and more elements begin to slide, a point is reached where the total horizontal force begins to decrease with further increase in brake torque. From the foregoing considerations it is clear that, after the horizontal ground force has reached its maximum value, the process is unstable with further increase in brake torque. Since the ground force becomes increasingly insufficient to balance the brake torque, the wheel rapidly decelerates to zero angular velocity (slip ratio equal to 1.0) and locks. At this point, full skidding, at a velocity equal to the axle velocity, exists over the entire ground-contact area.

As a result of the physical process just described, the drag force (and, therefore, the ratio of the drag force to the vertical force) for a braked wheel increases rapidly with slip ratio, reaches a maximum at a relatively low value of the slip ratio (the so-called "point of impending skidding"), and decreases with further increase in slip ratio until the locked-wheel condition is reached at a slip ratio of 1.0, as may be seen from figure 12, which is taken from reference 3.

In the literature on tire friction the ratio of the horizontal force to the vertical force is generally referred to as the coefficient of friction. It should be recognized that this usage is not strictly correct over the entire range of slip

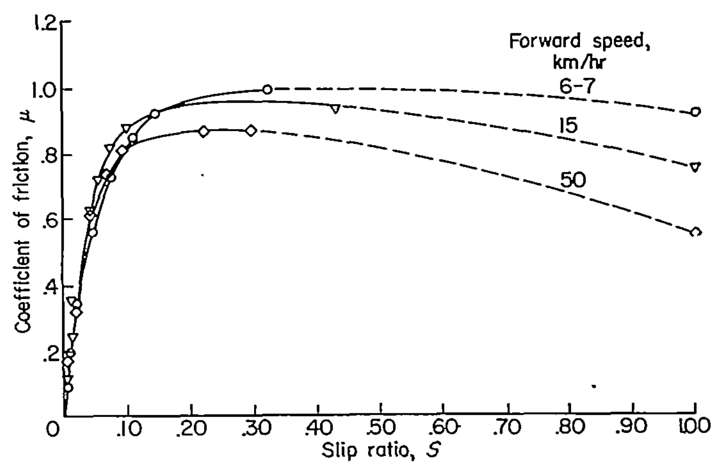


FIGURE 12.—Variation of coefficient of friction with slip ratio. Braking tests on dry concrete (from ref. 3).

ratio, inasmuch as at slip ratios below the "point of impending skidding" the horizontal force developed depends solely on the resisting torque or, what amounts to the same thing, on the deformation of the tire and not on the ground friction since, in this region, the horizontal force is less than the limiting value which can be maintained by friction between the tire and the ground. For slip ratios above the "point of impending skidding," on the other hand, the horizontal force developed is the maximum value which can be maintained by friction under the particular conditions of contact involved, so that in this range the ratio of the drag force to the vertical force is more properly termed the coefficient of friction of the tire. The friction at the "point of impending skidding" is analogous to, though not identical with, the classical static friction, whereas the friction for the locked-wheel condition corresponds to what is commonly called kinetic or sliding friction. Between these two limits the friction appears to involve both types in combination.

In addition to the effects of slip ratio previously discussed, it is also evident from figure 12 that the magnitude of the forward speed has an appreciable influence on the value of the coefficient of friction. This influence can be seen even more clearly from figure 13, also taken from reference 3, which shows the effects of the forward speed on the coefficient of friction at slip ratios in the primarily adhesive and sliding regions. (Figure 13 appears to be a cross plot of the data from the same series of tests on which fig. 12 is based. The curves labeled "adhesive friction" and "sliding friction" correspond with the data for "impending skidding" and slip ratio of 1.0, respectively, in fig. 12.)

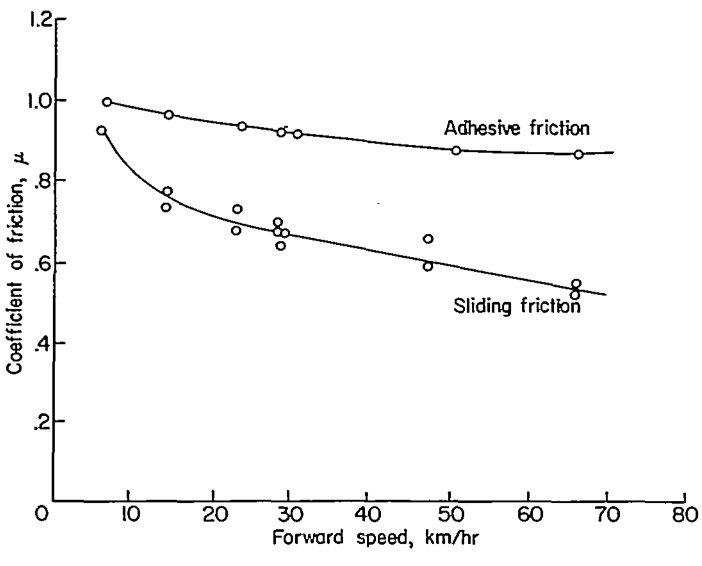


FIGURE 13.—Effect of forward speed on coefficient of friction. Braking tests on dry concrete (from ref. 3).

The effects of the forward speed on the coefficient of friction arise primarily through changes in the magnitude of the local skidding velocities in the regions of sliding in the ground-contact area. At a given slip ratio, an increase in the forward speed causes an essentially proportional increase in the skidding velocities at points in the ground-contact area where sliding already exists. Also, because of inertia and hysteresis effects associated with the rate of deformation of tire elements passing through the ground-contact area, which tend to reduce the effectiveness of the mechanical interlocking between the tread and the ground, an increase in the forward speed tends to reduce the level of tangential stress at which sliding begins, so that a greater proportion of the contact area is in a state of sliding. As a result of the foregoing effects and the fact that the local coefficient of friction at any point within the ground-contact area where sliding exists decreases with increasing skidding velocity, it follows that, for slip ratios beyond the "point of impending skidding," where a large part of the contact area is in a state of sliding, an increase in the forward speed causes an appreciable decrease in the overall coefficient of friction for the tire as a whole. Also, since an increase in forward speed tends to accelerate the transition from adhesion to sliding, as previously noted, the value of the slip ratio at which the maximum overall coefficient of friction occurs is somewhat decreased at the higher forward speeds. On the other hand, at low slip ratios, below the value at which the maximum overall coefficient of friction appears, since the horizontal force is developed primarily through adhesive ground contact and tire deformation, a change in horizontal velocity has relatively little effect on the overall coefficient of friction.

In the preceding discussion the influence of the slip ratio on the coefficient of friction has been considered as a primarily mechanical effect. On the other hand, from observation of tires subjected to drag loads, it would appear that another aspect should be considered; namely, the effects of heating of the tire tread surface which results from the work done in sliding. It is known (see, for example, ref. 4) that the coefficient of friction of tire tread rubber on concrete decreases markedly with increasing temperature. On the basis of elementary considerations, it is shown in appendix B that the sliding work per unit of tire area in contact with the ground, which may be taken as a qualitative index of the heat concentration in the tire ground-contact area, depends to a great extent on the slip ratio, as well as on other factors, such as the vertical load, the tire pressure, and the coefficient of friction; the greatest heating effect, everything else being equal, occurring at a slip ratio of 1.0. These considerations suggest that at least part of the effect of slip ratio is a heating effect. This aspect is discussed in more detail subsequently in connection with the forward-speed tests with reverse wheel rotation.

The concepts just discussed permit some interpretation of the variations of the coefficient of friction in the tests of the present investigation. In the forward-speed tests (fig. 10) the process is reversed from that in braking; that is, the process begins, at the instant of initial contact, when the tire is not rotating, so that the slip ratio is equal to 1.0 and full skidding, at a velocity equal to the horizontal velocity of the axle, exists over the entire ground-contact area of the tire, just as in the case of the locked wheel in the braking process. For this condition, because of the high skidding velocity, the absence of any adhesive contact, and the large heat concentration per unit of tire contact area, the coefficient of friction immediately following ground contact is comparatively low; in fact, lower than at any other stage of the skidding process. As the wheel begins to rotate under the influence of the moment produced by the drag load, the angular velocity increases so that the slip ratio and the local skidding velocities in the ground-contact area are reduced; also, the rate of introduction of fresh tire-tread area into the ground-contact region is increased so that the heat generated per unit time by the skidding is distributed over a larger tire-tread area. As a result of the combination of the foregoing effects, the coefficient of friction increases with time from its initial value. As the angular velocity approaches the value for free rolling, an increasingly greater part of the ground-contact area passes from sliding to adhesive contact. The maximum value of the overall coefficient of friction is reached when virtually all of the tire contact area has attained a state of adhesive contact and the tangential stresses due to tire distortion reach their highest values. With further increase in the angular velocity of the wheel, the deformations of the tire and the slip arising therefrom are rapidly reduced, so that the tangential stresses, and thus the total drag force and the overall coefficient of friction, drop to near zero as the final stage of the transition from sliding to rolling is completed.

From the foregoing discussion it appears that the variation of the coefficient of friction in an impact with forward speed can be explained, at least qualitatively, by consideration of the effects of slip ratio, skidding velocity, and heating of the tire surface. The effect of the skidding velocity is particularly evident at the beginning of the spin-up process where the slip ratio is the same for all tests and the skidding velocity is equal to the horizontal velocity; it can be seen from figure 10 that, in general, the coefficient of friction decreases progressively with increasing skidding velocity. A slight, though systematic, decrease in the maximum value of the coefficient of friction with increasing forward speed is also evident. This latter result may be largely due to inertia and hysteresis effects, previously mentioned, which tend to reduce the effectiveness of the interlockng contact at low slip ratios corresponding to the "point of impending skidding."

Effect of vertical velocity.—The effects on the applied loads caused by changes in the vertical velocity at contact are summarized in figure 11. The usual, not quite linear, increase in the maximum vertical load with vertical velocity is evident (fig. 11 (c)). It can also be seen that the effects of forward speed on the vertical load were less pronounced at the lowest vertical velocity. This result appears due to the fact that the strut friction is appreciably reduced at low vertical velocity since the bending moments on the gear, and thus the bending deflections, are smaller. Also, the tire can compensate more readily for the effects of strut friction, that is, reduced shock-strut travel, by deflecting somewhat more, with relatively little increase in vertical force, since the slope of the tire force-deflection curve is comparatively flat at small deflections.

As would be expected, the maximum drag load at any given horizontal velocity increased with the vertical velocity (fig. 11 (a)). Since an increase in vertical velocity resulted in an increased rate of rise of the vertical load, and since the amount of impulse required for wheel spin-up is essentially constant for any given horizontal velocity, the time to spin up decreased with increasing vertical velocity (fig. 11 (d)). Even though the time to spin up was reduced, this effect was offset by the higher rate of rise of the vertical load, which caused the vertical load at the time of spin-up to be increased with increasing vertical velocity (fig. 11 (b)), so that the maximum drag load increased with vertical velocity. Also, because of the higher rate of rise of the vertical load, the rate of increase of the maximum drag load with horizontal velocity was greatest at the high vertical velocities (fig. 11 (a)). In the tests at a vertical velocity of 3 feet per second, relatively little increase in the maximum drag load with horizontal velocity is noted at speeds above about 40 feet per second. This result occurs because the characteristics of the landing gear are such that, at low vertical velocity, the vertical load is essentially constant over a large part of the impact time; thus the vertical load which exists at the time of spin-up is essentially unchanged with variations in the time to spin up. As a result, changes in time to spin up, within this essentially constant vertical-load region, produce only small differences in the maximum drag load.

Figure 11 (e) shows how the ratio of the maximum drag load to the maximum vertical load varies with the vertical and horizontal velocities. The highest values of the drag load relative to the vertical load, of course, were obtained at the high horizontal velocities where spin-up occurs when the vertical load is near its maximum value. As can be seen, a large reduction in load ratio, most pronounced at low horizontal velocities, occurred as the vertical velocity was increased. This reduction results from the decreased time to spin up at the higher vertical velocities, previously discussed. At a given horizontal velocity, since the drag impulse required for spin-up is essentially constant, whereas the total vertical impulse increases directly with the vertical velocity, it follows that the ratio of the vertical load at the time of spin-up to the maximum vertical load will be reduced with increasing vertical velocity, so that the ratio of the maximum drag load to the maximum vertical load consequently is also decreased with increasing vertical velocity.

Figure 11 (e) also shows that the curves for the different vertical velocities tend to converge at the higher horizontal velocities. This result is explained by the fact that, at the higher horizontal velocities, spin-up occurs when the vertical load is near its maximum value, as previously indicated, so that the ratio of the maximum drag load to the maximum vertical load approaches the value of the coefficient of friction at the time of spin-up. When the maximum drag load coincides exactly in time with the maximum vertical load, the ratio of these two loads is the coefficient of friction at the time of spin-up. Since the time to spin up decreases with increasing vertical velocity, the horizontal velocity at which $F_{H_{T_{max}}}/F_{V_{T_{max}}}=\mu_{su}$ increases with increasing vertical velocity. For horizontal velocities beyond this value, because spin-up occurs subsequent to the peak vertical load, the ratio $F_{H_{T_{max}}}/F_{V_{T_{max}}}$ should decrease with further increase in horizontal velocity. As a result of the foregoing considerations, the curves of $F_{H_{T_{max}}}/F_{V_{T_{max}}}$ for different vertical velocities have to cross one another somewhere in the horizontal-velocity region beyond the range of these forward-speed tests. The vertical spread of the curves in figure 11 (e) at the highest horizontal velocities shown may thus be attributed to two effects due to changes in the vertical velocity; namely, differences in the value of the horizontal velocity at which $F_{H_{T_{max}}}/F_{V_{T_{max}}}=\mu_{su}$ and differences in the value of the coefficient of friction at the time of spin-up.

The latter effect is indicated in figure 11 (f), which shows the ratio of the maximum drag load to the vertical load at the same instant, that is, the coefficient of friction at the time of maximum drag load. As can be seen, there was some decrease in the coefficient of friction with increasing vertical velocity. Several factors apparently combine to produce this result. With increasing vertical velocity, since the rate of rise of the vertical load is increased, the rate of rise of the drag load is increased. Consequently, the amount of angular displacement of the wheel between the instant of contact and full spin-up is decreased. Thus, more skidding energy is transferred to the tire per unit time and this energy is distributed over a smaller area of the tire periphery, so that the concentration of heat and, thus, the temperatures of the tire tread surface are increased. In addition, higher tangential stresses are produced in the tire contact area as a result of the larger vertical deflections of the tire, so that the remaining amount of tangential stress available for the production of drag load in the interlocking contact regime is reduced. Also, the vertical ground pressures are increased and the rates of loading are higher. Each of the foregoing effects tends to cause a reduction in the coefficient of friction as the vertical velocity is increased.

FORWARD-SPEED TESTS WITH REVERSE WHEEL ROTATION

Time histories of applied loads.—In order to obtain an indication of the characteristics of the applied loads for the range of forward speeds beyond the maximum velocity of the impact-basin carriage, forward-speed tests were made with reverse rotation of the landing wheel. In these tests the carriage horizontal velocity was approximately 86 feet per second and the landing wheel was spun up backward before impact so as to produce relative velocities between the tire and the landing strip at the instant of contact up to about 273 feet per second. Figure 14 shows a number of typical time histories from such tests at an average vertical velocity of about 7.5 feet per second, and also includes data (solid-line curve) from one test with no reverse wheel rotation. For clarity, the results of only a few selected tests are shown in figure 14. The maximum values of the applied vertical and drag loads for the complete series of forward-speed tests with reverse wheel rotation are shown in figure 15. Also shown in figure 15, for comparison, are the results obtained in the forward-speed tests without reverse rotation previously discussed (long-dash curves).

Before these results are considered in detail, it should be pointed out that the use of reverse wheel rotation in combination with forward speed does not yield complete simulation of actual impacts at high forward speeds. For example, even though the relative velocity between the tire periphery and the ground is made the same at the instant of contact, the slip ratios during the first part of the spin-up process in the reverse-rotation tests are, of course, higher than in corresponding true forward-speed impacts, the amount depending on the difference between the simulated horizontal velocity and the speed of the carriage. Thus, for the highest simulated horizontal velocity in these tests (273 fps), the initial slip ratio is about 3.2; whereas, in an actual forward-speed impact the initial slip ratio would be 1.0. As a result, the variations of the slip ratio during the spin-up process are different in these tests than in true forward-speed impacts. Also, because of the higher slip ratios during the first part of the spin-up process, the amount of rubber removed from the tire per unit time by the skidding process is distributed along a shorter length of ground travel than in an actual forward-speed impact, so that the concentration of abraded rubber in the ground-contact area is greater in these tests. The differences in the slip ratio also influence the amount of tire periphery coming in contact with the ground and the heating of the tire during the spin-up process. All of the foregoing differences, which are, of course, greatest at the highest simulated horizontal velocities (highest initial slip ratios), influence the coefficient of friction and the applied loads. Nevertheless, the results obtained, although not completely realistic, do serve to indicate, at least qualitatively, the manner in which the applied loads would vary if the forward speed were increased to high values. With the foregoing restrictions, the results presented in figure 14 may be considered to be a continuation of those shown in figure 10.

As in the case of the forward-speed tests previously discussed, an increase in the relative velocity between the tire and the ground at the instant of initial contact (simulated horizontal velocity) causes the duration of the skidding process to be increased, so that a longer time is required for the completion of spin-up. At the lower simulated horizontal velocities, where spin-up occurs before the maximum vertical load is reached, the maximum drag load increases with increasing simulated horizontal velocity, just as in the forward-speed tests and for the same reasons previously discussed.

For the higher simulated horizontal velocities, spin-up occurs after the maximum vertical load is reached. In this region, since the vertical load is decreasing with time, the vertical load which exists at the time of spin-up is reduced as the duration of skidding is increased; as a result, the drag load at the time of spin-up decreases with increasing simulated horizontal velocity, since the coefficient of friction at the instant of spin-up is more or less the same for all tests in this series. In figure 14, the drag-load time histories for the higher velocities are seen to exhibit two peaks; the first occurring when the vertical load is at a maximum, the second at the time of spin-up, when the coefficient of friction is at a maximum. Because the coefficient of friction was so much larger at the time of spin-up, when the skidding velocities and the slip ratios were small, than at the time of maximum vertical load, when the slip ratios and the skidding velocities were larger, the maximum drag load in these tests always occured at the time of spin-up, rather than at the time of maximum vertical load. Consequently, the maximum drag load reached its highest value for the condition where the completion of spin-up coincided with the occurrence of the maximum vertical load and decreased with further increase in simulated horizontal velocity. Figure 15 shows that the maximum drag load reached its highest value at a simulated horizontal velocity of about 112 feet per second and dropped to about 60 percent of this value at the higher test velocities. Although the maximum drag load

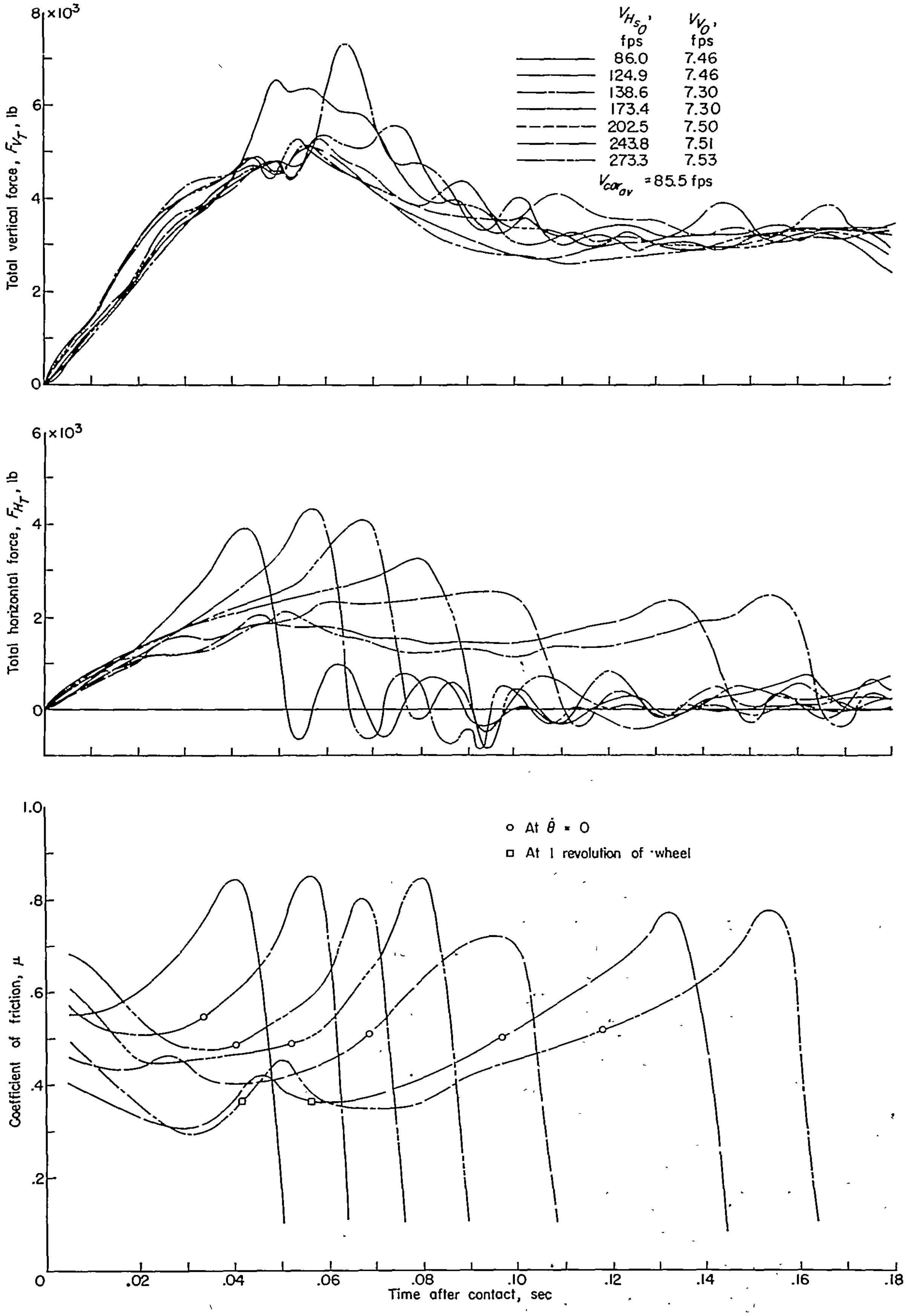


FIGURE 14.—Time histories of applied loads and coefficient of friction in typical forward-speed tests with reverse wheel rotation. $V_{V_{O_{av}}}$=7.44 feet per second; $V_{car_{av}}$=85.5 feet per second.

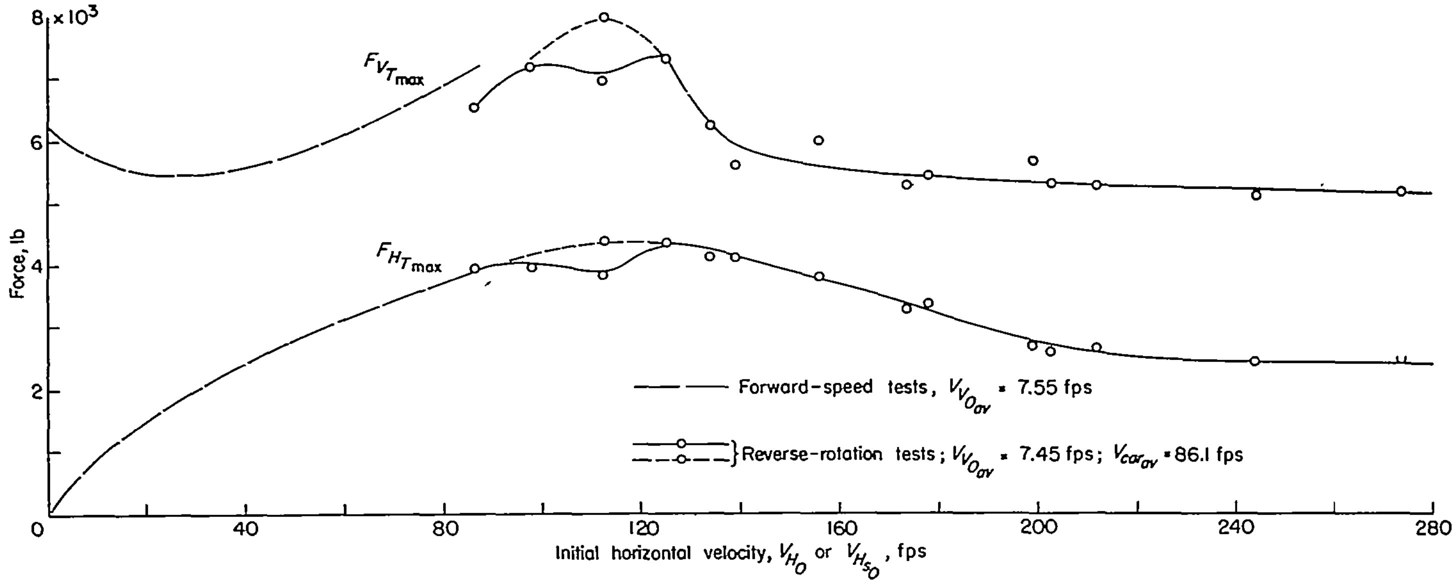


FIGURE 15.—Comparison of maximum applied loads in forward-speed tests with reverse wheel rotation and loads in true forward-speed tests.

always occurred at the time of spin-up in these tests, it appears that, if the horizontal velocity were high enough, spin-up would be delayed until the vertical load was small enough that the drag load would be smaller at the time of spin-up than at the time of maximum vertical load, even though the coefficient of friction were larger at the time of spin-up.

In these tests, as in the forward-speed tests, circumferential springback of the tire and bending springback of the landing gear occurred following the drop-off of the drag load; the ensuing torsional oscillations of the wheel and fore-and-aft bending oscillations of the landing gear resulted in the oscillations evident in the drag-load time histories of figure 14 subsequent to the time of spin-up.

The effects of the drag load on the vertical load were as would be expected from the previous discussion of the forward-speed tests. For those conditions where spin-up occurred just before the maximum vertical load was reached (for example, at horizontal velocities of 86.0 and 124.9 fps in fig. 14), the large dynamic bending deflection of the landing gear at the time of maximum vertical load resulted in large shock-strut friction forces which greatly increased the maximum vertical load. At higher simulated horizontal velocities, because the coefficient of friction decreased, the shapes of the drag-load time histories were greatly changed so that the drag impulse at the instant of maximum vertical load was reduced. As a result, the bending deflections at the time of maximum vertical load, and consequently the strut friction forces, were smaller so that the maximum vertical loads were considerably reduced at the higher horizontal velocities. Even in these cases, however, the bending response of the landing gear resulted in a momentary rise of the vertical load slightly after the maximum drag load occurred, when the bending deflection reached its maximum value, as can be seen from the individual time histories in figure 14.

The overall variation of the maximum vertical load with simulated horizontal velocity is shown in figure 15. The highest values of the maximum vertical load occurred at a simulated horizontal velocity of about 112 feet per second. In this region, because of the irregularities in the vertical-load time history, caused by the sudden changes in the shock-strut-orifice area resulting from the metering-pin displacement, the exact phasing between the drag load and the vertical load appears to be critical. As a result, relatively small differences in the initial conditions or in the time to spin up caused fairly large differences in both the maximum vertical and maximum drag loads, as can be seen from the solid and short-dash curves in figure 15.

Coefficient of friction.—The variations of the coefficient of friction during the spin-up process in these tests were considerably different from those in the forward-speed tests. As can be seen from figure 14, the coefficient of friction in the reverse-rotation tests started out at relatively high (for the high skidding velocities involved) values at the beginning of each impact, decreased with time, then increased until a maximum value was reached just prior to the completion of spin-up. The later phases of the time histories are similar in appearance to those obtained in the forward-speed tests. As an aid in interpreting these variations, the points at which reversal of the wheel rotation takes place ($\dot{\theta}=0$) are shown. At these points the slip ratio is, of course, equal to 1.0. Also shown, for the two highest speed tests, are the points at which the wheel rotation passed through a complete revolution. At the lower speeds the wheel angular displacement was always less than a full revolution.

As previously noted, the values of the coefficient of friction at the beginning of the impacts were relatively high, even though the skidding velocities were large. This result is apparently due to the very high slip ratios during the first part of the skidding process. At these high slip ratios, because the large angular velocity of the wheel contributes a major part of the total skidding velocity, the rate of introduction of tire-tread area is relatively large compared with the rate at which work is done in skidding; thus, the skidding energy is distributed over a larger area of the tire running surface so that heating of the tire surface is reduced. (See appendix B.) As a result, the transition which the ground-contact surface of the tire undergoes from its initially cold condition to the higher temperatures characteristic of normal operation requires an appreciable length of time in the reverse-rotation tests. In an actual forward-speed impact, on the other hand, since the wheel would be turning slowly during the early part of the spin-up process, the skidding energy would be much more highly concentrated in the tire surface, the transition from cold to hot rubber would be greatly accelerated, and the coefficients of friction during this stage of the impact would be much lower.

The variation of the coefficient of friction during the remainder of the spin-up process in the reverse-rotation tests appears to be governed primarily by the combined effects of the slip ratio and skidding velocity, both of which decrease with time, as well as by changes in the vertical load. As was previously indicated, a reduction in the skidding velocity tends to increase the coefficient of friction. On the other hand, because of the effects of tire heating, a reduction in the slip ratio tends to decrease the coefficient of friction for slip ratios greater than 1.0 and tends to increase the coefficient of friction for slip ratios less than 1.0, as is indicated in appendix B. As a result of the combination of the foregoing effects, the coefficient of friction first decreases with time, reaches a minimum value at a slip ratio greater than 1.0, then increases until a maximum value is reached at very small slip ratios, where local sliding in the ground-contact area is transformed into adhesive contact just prior to the completion of spin-up. The process during the interval between a slip ratio of 1.0 and full spin-up appears to be very similar to the complete spin-up process in the forward-speed tests previously discussed, except for differences in the magnitude of the vertical load during this period and possible effects of the residual elevated temperature of the tire resulting from the previous skidding.

The time histories of the coefficient of friction for the higher simulated horizontal velocities in figure 14 indicate a momentary peak during the early stages of the spin-up process. These peaks do not appear to be directly connected with the rotation of the wheel through one revolution and their cause is not evident.

In addition to the effects of the slip ratio and the skidding velocity, variations in the vertical load on the tire appear to have an influence on the coefficient of friction. Some indications of the effect of the vertical load may be obtained from the values of the coefficient of friction at the points where $\theta=0$. At these points the slip ratio is equal to 1.0 and the skidding velocities are more or less the same for all tests in this series. Therefore, differences in the coefficients of friction at these points may be indicative of the effect of vertical load. This effect is discussed in a subsequent section.

From the foregoing discussion it appears that, because of the artificially high slip ratios, the variations of the coefficient of friction in the reverse rotation tests may differ appreciably from those which would be obtained in a true forward-speed impact. In particular, it would appear that the coefficients of friction at the beginning of the spin-up process would be considerably lower in an actual forward-

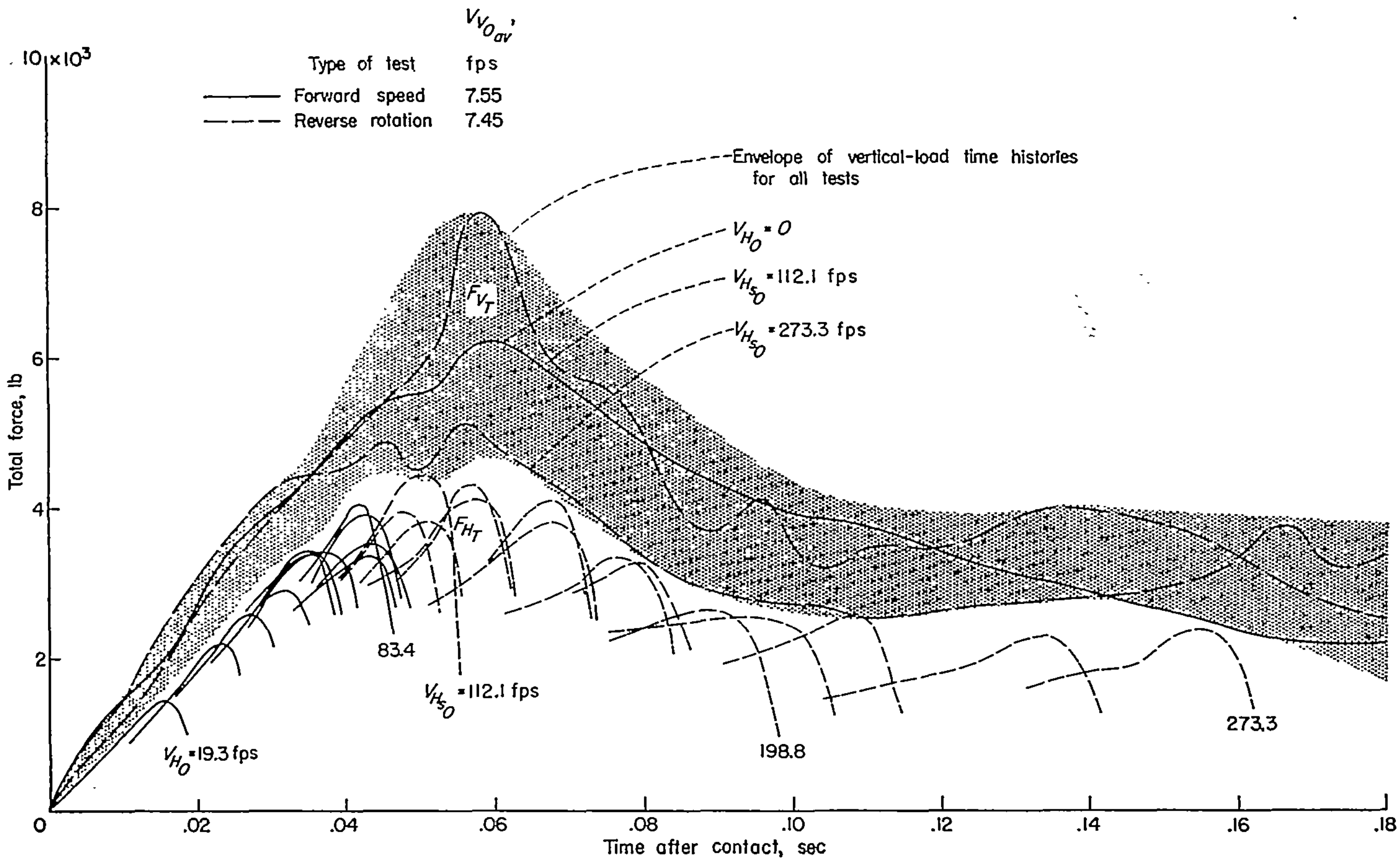


FIGURE 16.—Composite of applied-load time histories in forward-speed tests and forward-speed tests with reverse wheel rotation ($V_{car_{av}}$=86.1 feet per second).

speed impact since the initial slip ratio would be equal to 1.0, which, for the same skidding velocity, would result in greater heating of the tire. Similarly, it would be expected that these differences would also have some effect on the shape of the drag-load time histories and on the time to spin up.

An overall illustrative picture of the load variations in the forward-speed tests and in the forward-speed tests with reverse wheel rotation (complete series of tests) is shown in figure 16. In this figure the shaded area indicates the envelope of the vertical-load time histories for all tests. The boundaries of the drag load are indicated by means of short segments of the drag-load time-history curves in the vicinity of spin-up.

SPIN-UP DROP TESTS

Spin-up drop tests, either in a jig with a single landing gear or with a complete airplane, are widely used in the development and proof testing of landing gears and the airplane structure. In order to evaluate the validity of this method of simulating landing impacts, a series of spin-up drop tests with the carriage fixed was made for comparison with the true forward-speed tests and the forward-speed tests with reverse wheel rotation previously discussed. A few typical time histories of the applied loads and the coefficient of friction from such tests are shown in figure 17. The maximum values of the vertical and drag loads are shown as functions of the simulated horizontal velocity and are compared with the results of the other tests in figure 18. Comparisons of two individual spin-up drop-test time histories with time histories obtained in the other types of tests for corresponding impact conditions are shown in figure 19.

As can be seen from figure 18 and from comparisons of figures 17 and 10, for low simulated horizontal velocities, the applied loads and the coefficients of friction in the spin-up drop tests were higher than in the forward-speed tests. However, for simulated horizontal velocities above about 60 feet per second the loads in the spin-up drop tests were appreciably smaller than in the other types of tests.

In the spin-up drop tests, of course, the slip ratio is infinite throughout the impact, and the angular displacement of the wheel during the skidding process is much larger than in a forward-speed impact. Since, for any given value of the skidding velocity, the rate of introduction of tire-surface area into the ground-contact region is much greater in a spin-up drop test than in a forward-speed impact, the concentration of skidding energy in the tire surface is greatly reduced, so that there is less heating of the tire. This effect tends to make the coefficients of friction for a given skidding velocity in the spin-up drop tests larger than in the forward-speed tests. On the other hand, the spin-up drop tests involve an element which tends to reduce the coefficient of friction; namely, the contamination of the ground beneath the tire by particles of rubber which are removed from the tire by the skidding process and tend to act as a lubricant in the ground-contact area. In an impact with forward speed, this abraded rubber is distributed over an appreciable length along the ground, so that its effect is relatively small. In a drop test, on the other hand, these particles of rubber accumulate in one spot on the ground. For the drop tests at low simulated horizontal velocities this effect is negligible because very little rubber is removed from the tire, since the total amount of work done in skidding is small. With increasing simulated horizontal velocity, however, more and more rubber is removed from the tire and the thickness of the accumulated deposit becomes large enough to cause marked reductions in the coefficient of friction throughout most of the skidding process. At the highest simulated velocities, possibly because the abraded rubber is in a gummy or even molten state, the coefficients of friction, and consequently the drag loads, are reduced to very small values, as can be seen from the time histories in figure 17.

The total accumulation of abraded rubber during a given impact is, of course, greatest at the end of the skidding process. Consequently, at the higher simulated horizontal velocities, the coefficient of friction does not increase as the skidding velocity is reduced, even as the wheel comes to rest, in contrast to the results from the other types of tests where the coefficient of friction increased considerably as the skidding velocity decreased. As a result, in the spin-up drop tests the maximum drag loads for the higher velocities do not occur at the end of the skidding process, as in the other types of tests, but rather at the time of maximum vertical load.

At the lower simulated horizontal velocities, where the effects of the abraded rubber are unimportant, the reduced heating of the tire surface, previously mentioned, results in somewhat higher coefficients of friction in the drop tests than in the forward-speed tests, the greatest differences being in the maximum values of the coefficient of friction. These differences in the maximum values may result from the fact that the nature of the contact between the tire and the ground as the skidding velocity is reduced to zero is different in the two types of tests. In the spin-up drop tests the transition is from a state of skidding to a state of rest; whereas, in the forward-speed tests, the transition is from a state of skidding to a state of rolling. In the drop tests, the maximum value of the coefficient of friction probably corresponds to a condition where the entire area of the tire touching the ground is in a state of adhesive contact. In the forward-speed tests, on the other hand, this condition is never completely reached since, even for the limiting case of a freely rolling tire, local sliding exists over some parts of the contact area. Furthermore, in the case of the rolling tire, the effectiveness of the mechanical interlocking between the tire and the ground in the regions of adhesion is probably reduced somewhat because of inertia and hysteresis effects associated with the deformations of the tire during rolling, which tend to hinder the tire from conforming to the irregularities in the surface of the ground.

Because the coefficients of friction in the spin-up drop tests were so much lower throughout most of the horizontal-velocity range, the drag loads in these tests were considerably smaller than those in the other types of tests for the range of horizontal velocity of practical interest (fig. 18). As a direct consequence of the decreased drag load, the bending deflections of the landing gear were reduced, so that the vertical loads in the drop tests did not exhibit the large increases due to shock-strut friction, which were indicated in both the true

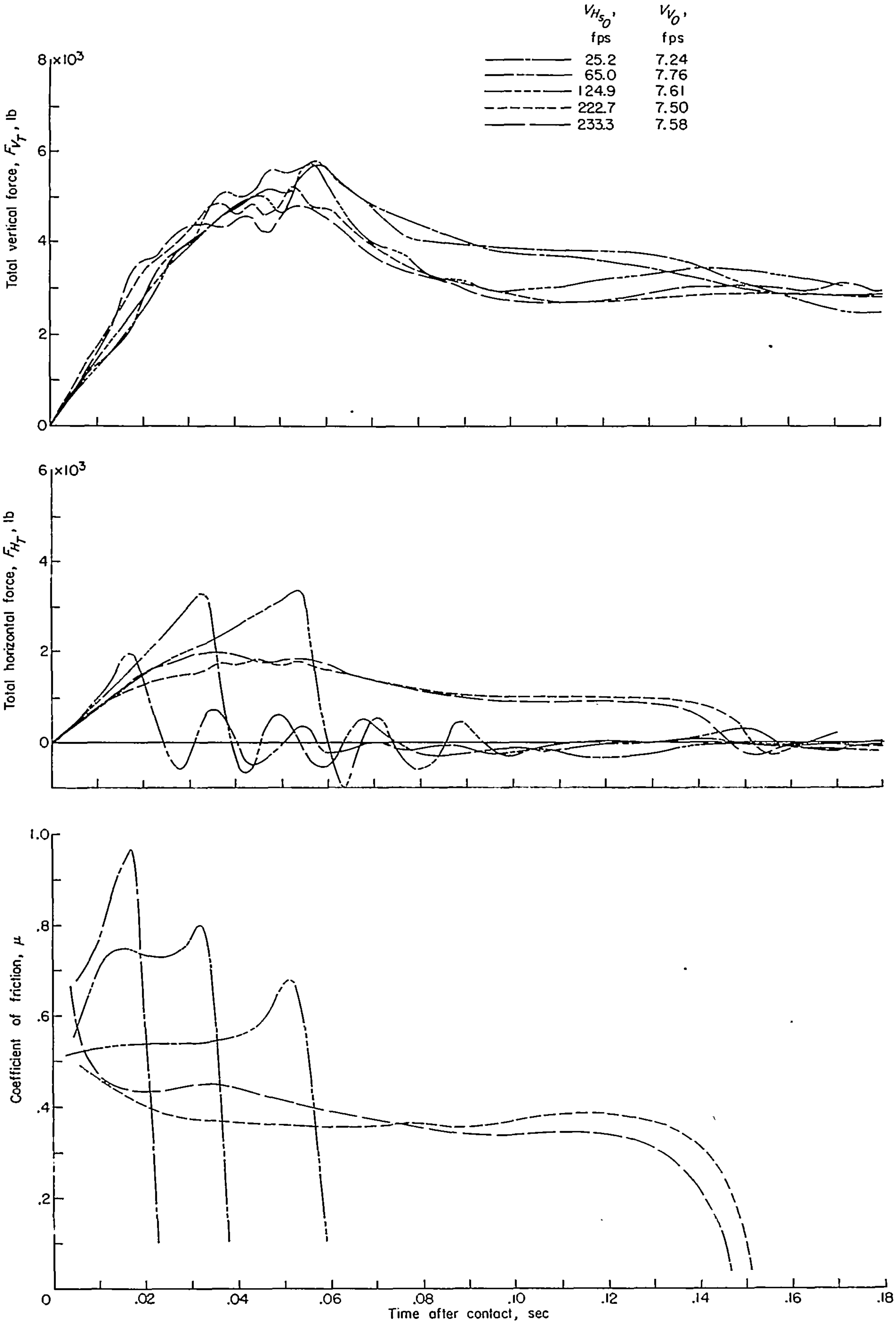


FIGURE 17.—Time histories of applied loads and coefficient of friction in typical spin-up drop tests. $V_{car}=0$; $V_{V_{O_{av}}}=7.54$ feet per second.

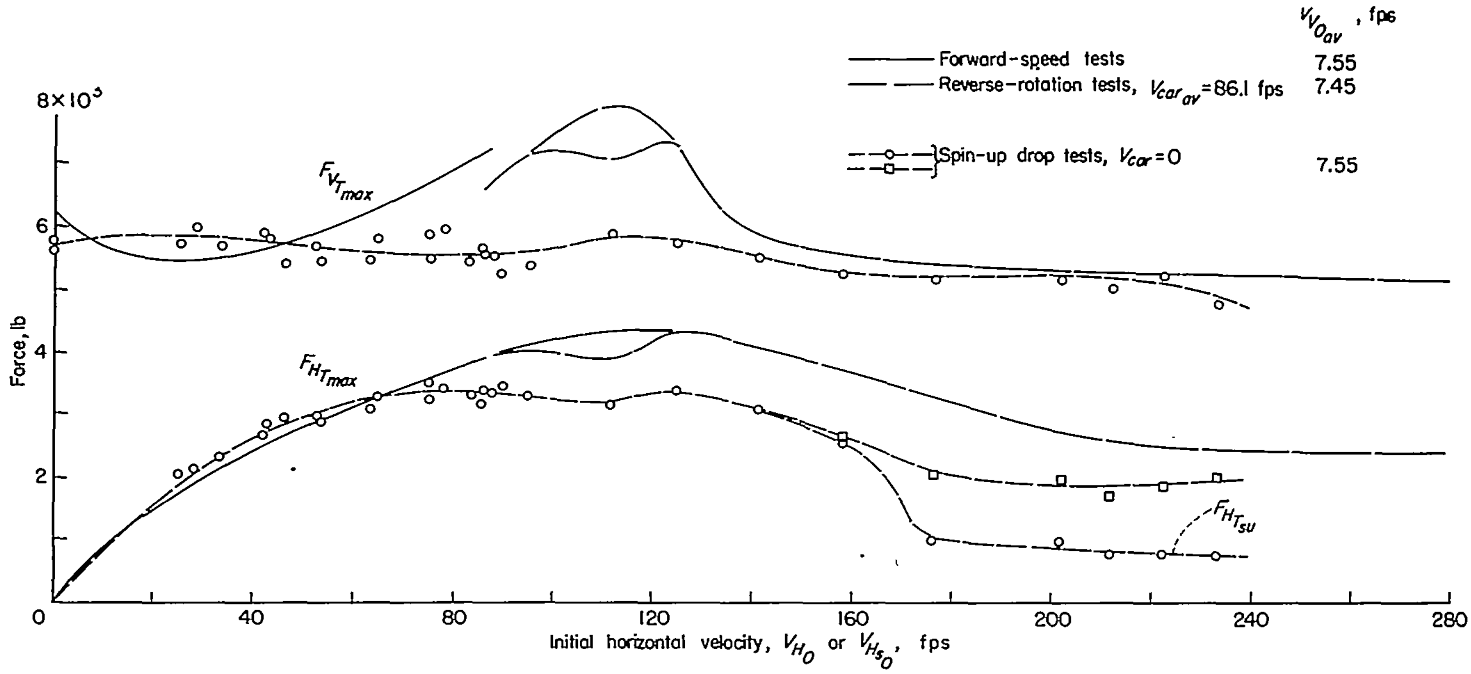


FIGURE 18.—Comparison of maximum applied loads in forward-speed tests, forward-speed tests with reverse rotation, and spin-up drop tests.

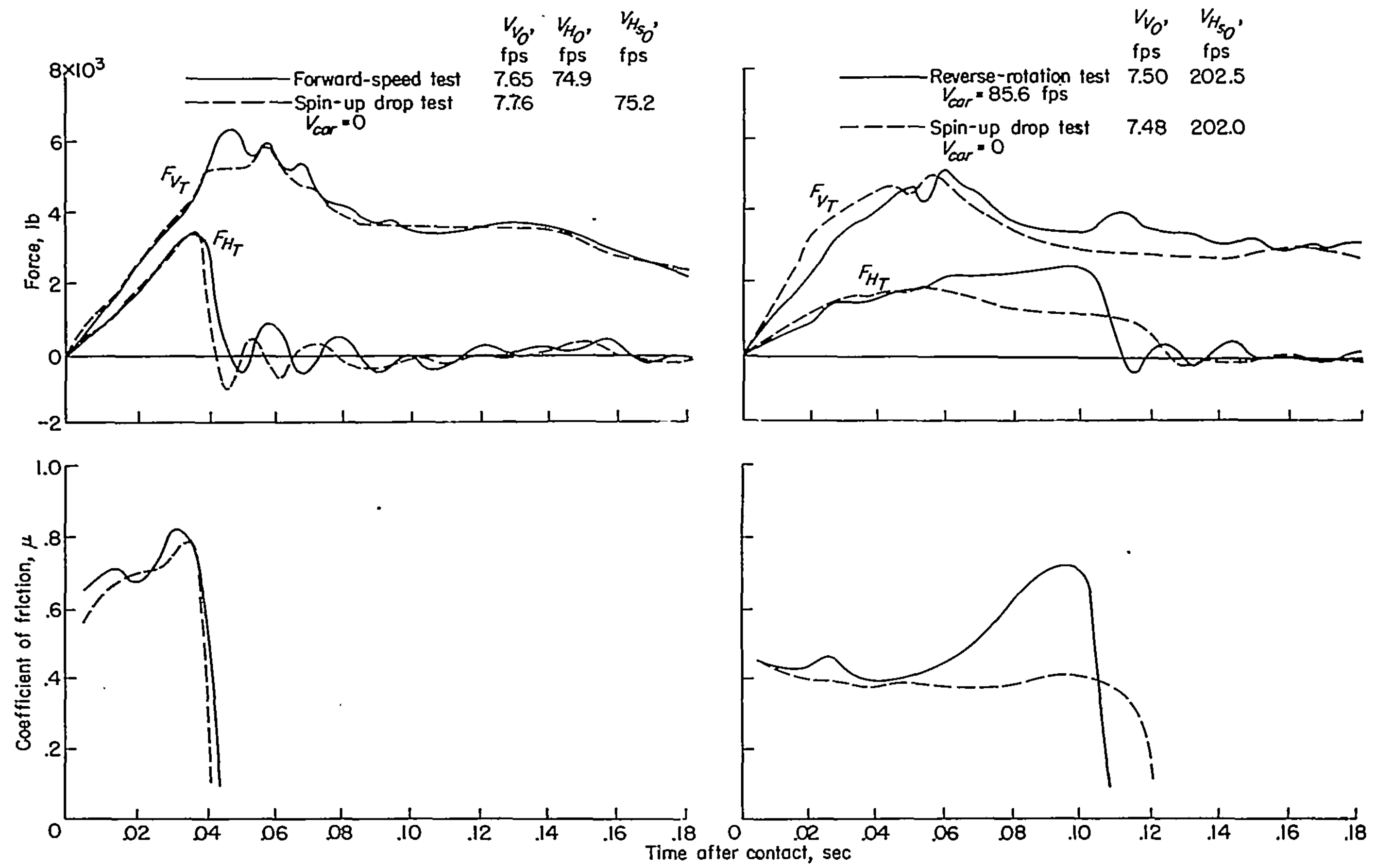


FIGURE 19.—Comparison of time histories of applied loads and coefficients of friction in spin-up drop tests and in corresponding forward-speed tests and forward-speed tests with reverse wheel rotation.

forward-speed tests and the forward-speed tests with reverse wheel rotation. These differences are particularly striking in the range of horizontal velocity where spin-up in the other tests occurs when the vertical load is near its maximum value.

Figure 19 shows direct comparisons of two typical drop-test time histories with the results of the other types of tests. The figure on the left is for a horizontal velocity of about 75 feet per second and indicates relatively good agreement. The figure on the right, for a horizontal velocity of about 202 feet per second, is typical of the results for the higher horizontal velocities and clearly indicates the greatly reduced drag loads in the drop tests, particularly in the later stages of the skidding process where the accumulation of abraded rubber in the ground-contact region becomes very large.

From the foregoing results it is evident that spin-up drop tests yield unconservative loads for the range of horizontal velocities of practical interest in airplane design. It thus appears that data obtained from such tests should not be used without qualification as a basis for design or for dynamic analyses of landing loads. The foregoing comparisons also indicate why some airplane manufacturers (see, for example, ref. 5) have resorted to the use of artificial ground surfaces in drop tests, such as grids of various types, in order to obtain coefficients of friction high enough to satisfy the ANC–2 ground-loads design requirement of $\mu=0.55$.

VARIATION OF COEFFICIENT OF FRICTION

As was previously indicated in the discussion of the time histories of the applied loads for the three types of tests considered, the coefficient of friction during the wheel spin-up process varied over a wide range of values during any given impact; furthermore, considerably different variations were found under different impact conditions. Some of the factors contributing to the variation of the coefficient of friction, such as the effects of slip ratio, skidding velocity, heating of the tire surface, contamination of the ground-contact area by abraded rubber, and the effects of changes in the vertical load, were briefly discussed. In this section, the variation of the coefficient of friction is considered somewhat more quantitatively; unfortunately, however, because of the nature of the tests, it was not generally possible to separate completely the effects of all the various factors which influence the coefficient of friction.

Effect of skidding velocity.—Figure 20 shows the variations of the coefficient of friction with the instantaneous value of the apparent skidding velocity in several typical impacts for each of the three types of tests considered. These results, of course, include the effects of variations in the slip ratio and in the vertical load during the spin-up process, as well as the effects of tire heating. In these graphs the progress of the spin-up process is from right to left, the highest skidding velocity for each curve corresponding to the value just after initial contact, and zero skidding velocity indicating complete spin-up.

(a) Forward-speed tests:

Figure 20 (a) shows the variation of the coefficient of friction with the apparent skidding velocity in several typical forward-speed impacts. The right-hand extremity of each curve corresponds to a slip ratio of approximately 1.0, the slip ratio in each test decreasing as the skidding velocity is reduced. As can be seen, the coefficient of friction ranged from minimum values of about 0.55 to 0.60, at the beginning of the impacts at the higher forward speeds in this series of tests, to maximum values between about 0.75 and 0.90 at low values of the apparent skidding velocity (just prior to the completion of spin-up), the highest values of the coefficient of friction occurring in the lowest speed impacts.

The fact that the maximum values of the coefficient of friction, which are associated with the interlocking type of contact between the tire and the ground, appear to decrease with increasing forward speed may be due to the inertia and hysteresis effects connected with the rolling deformations of the tire, which tend to hinder the tire from conforming perfectly with the irregularities in the ground and thus tend to reduce the effectiveness of the interlocking bond.

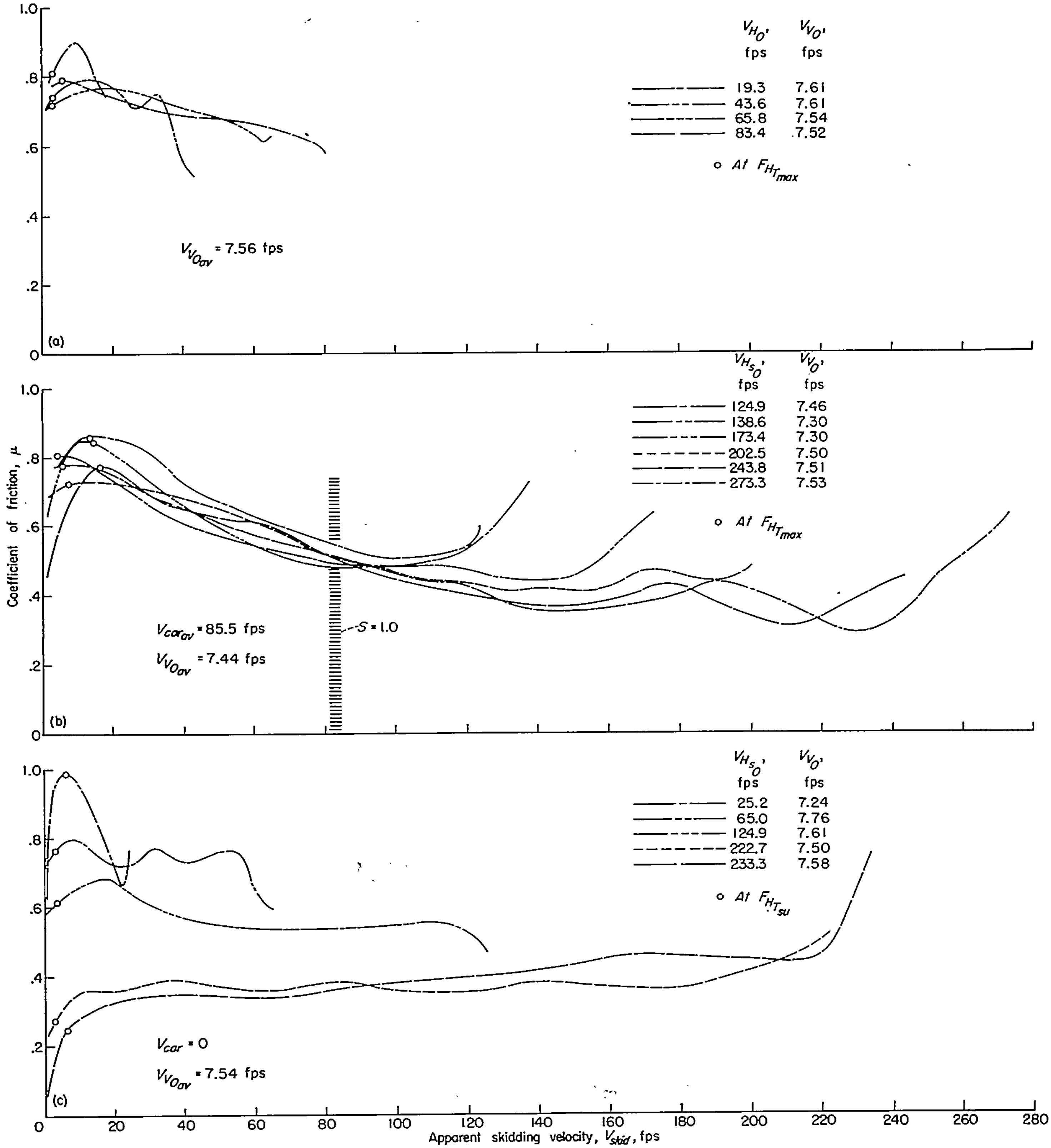
It should be noted that the decrease in the indicated coefficients of friction as the apparent skidding velocity approaches zero is caused by the relaxation of the circumferential distortion of the tire as the spin-up process is completed, which was previously discussed. Because of this relaxation of the strains in the tire the tangential stresses in the ground-contact area, and thus the drag loads, are reduced, so that the indicated values of the coefficient of friction are decreased. These values of the tangential stresses and the indicated coefficients of friction therefore do not correspond to the maximum values which can be maintained by the conditions of contact between the tire and the ground at low skidding velocities; such values should be at least as high as the maximum values (at the "point of impending skidding") shown.

In figure 20 (a) the circular symbols indicate the occurrence of the maximum drag load. Since, in these tests, the vertical load was in the process of increasing when the maximum coefficient of friction was reached, the drag load continued to increase and reached its maximum value after the coefficient of friction had already dropped somewhat from its maximum value.

The curves shown in figure 20 (a) indicate that, in general, the coefficient of friction decreases with increasing skidding velocity, the differences between the individual curves being due primarily to differences in the slip ratios at any given skidding velocity, differences in the heating of the tire running surface which result from the different relationships between the slip ratio and the skidding velocity in the individual tests at the various initial horizontal velocities, and differences in the vertical load at any given skidding velocity. The effects of slip ratio and vertical load is considered further in a subsequent section.

(b) Forward-speed tests with reverse wheel rotation:

Figure 20 (b) shows the variations of the coefficient of friction with the apparent skidding velocity in several typical forward-speed tests with reverse wheel rotation. The right-hand extremities of these curves, of course, correspond to slip ratios greater than 1.0, the highest value being about 3.2 for a simulated horizontal velocity of 273.3 feet per second. The range of skidding velocity where a slip ratio equal to 1.0 occurs is indicated by the shaded band. (This band has a finite width because the carriage horizontal velocities were not exactly the same in all tests.)



(a) Forward-speed tests.
(b) Forward-speed tests with reverse wheel rotation.
(c) Spin-up drop tests.

FIGURE 20.—Variation of coefficient of friction with skidding velocity for typical forward-speed tests, forward-speed tests with reverse wheel rotation, and spin-up drop tests.

It can be seen that in these tests the coefficient of friction starts out at values fairly high as compared with the general trend of the data. As was previously discussed, these relatively high initial values of the coefficient of friction appear to be largely due to the artificially high slip ratios during the first part of the spin-up process, which result in reduced heating of the tire during this period. (Some discussion of the relationship between slip ratio and heating is given in appendix B.) These results suggest that, in the reverse-rotation tests, because of the high slip ratios during the early stages of the skidding process, the transition of the running surface of the tire from its initial cold condition at the instant of contact to the higher temperature representatives of normal spin-up conditions takes place rather slowly. As a result, the coefficient of friction has fairly high values (corresponding to values for cold rubber at high sliding velocities) at the beginning of the skidding process, then gradually decreases as the reverse rotational velocity of the tire and the associated slip ratio are reduced and the energy concentration in the tire surface and, consequently, the temperature are increased. This effect is illustrated schematically in figure 21. In true forward-speed impacts, on the other hand, since the skidding process begins at a slip ratio of 1.0 where the energy concentration in the tire is large, this transition occurs almost instantaneously, and the cold-rubber values of the coefficient of friction are not perceived. As a result, the initial portions of the curves for the reverse-rotation tests appear to have no practical significance as far as true forward-speed impacts are concerned. Nevertheless, the general trend of the curves provides at least an indication of the variation of the coefficient of friction with skidding velocity.

It will be noted from figure 20 (b) that, with the exception of the artificial initial parts of each curve, the basic trend of the data for the entire range of skidding velocity falls within a fairly well defined and relatively narrow band. The band for the complete series of forward-speed tests with reverse wheel rotation, a total of 14 runs covering a range of simulated horizontal velocity from 97 to 273 feet per second, is indicated by the shaded region in figure 21. The basic trend shown, of course, includes the effects of differences in the slip ratio, which in these tests varied directly with the skidding velocity (since the carriage velocity was essentially constant) and, therefore, could not be separated from the effects of the skidding velocity. The spread in the curves within the band (see fig. 20 (b)) appears to be largely due to the effects of differences in the vertical load, which will be discussed later.

The overall trend of the data indicates a variation of the coefficient of friction from low values between 0.25 and 0.40 at an apparent skidding velocity of 260 feet per second to maximum values between 0.70 and 0.85 at an apparent skidding velocity of 17 feet per second. As in the case of the true forward-speed tests previously discussed, the decrease in the indicated values of the coefficient of friction as the apparent skidding velocity approaches zero is due to the relaxation of the tire circumferential distortion and therefore does not represent the variation of the limiting values of the coefficient of friction at low skidding velocities.

(c) Spin-up drop tests:

Figure 20 (c) shows the variation of the coefficient of friction with the skidding velocity for a number of typical spin-up drop tests. As can be seen, these tests yielded very high coefficients of friction when the initial simulated horizontal velocity was low, and very small coefficients of friction, even at low skidding velocities, when the simulated horizontal velocity was large.

The high values at low simulated horizontal velocities were previously attributed to the reduced heating of the tire resulting from the high slip ratios. The particularly high maximum values of the coefficient of friction at low simulated horizontal velocity may be due to the fact that a more perfect interlocking contact between the tire and the ground is possible in the drop tests, where the wheel comes to rest, than in the forward-speed tests, where the wheel comes up to ground rolling speed, as previously discussed. (The indication of a finite skidding velocity corresponding to the maximum value of the coefficient of friction is associated with the circumferential distortion of the tire and does not represent the actual relative velocity between the tire and the ground in this region.)

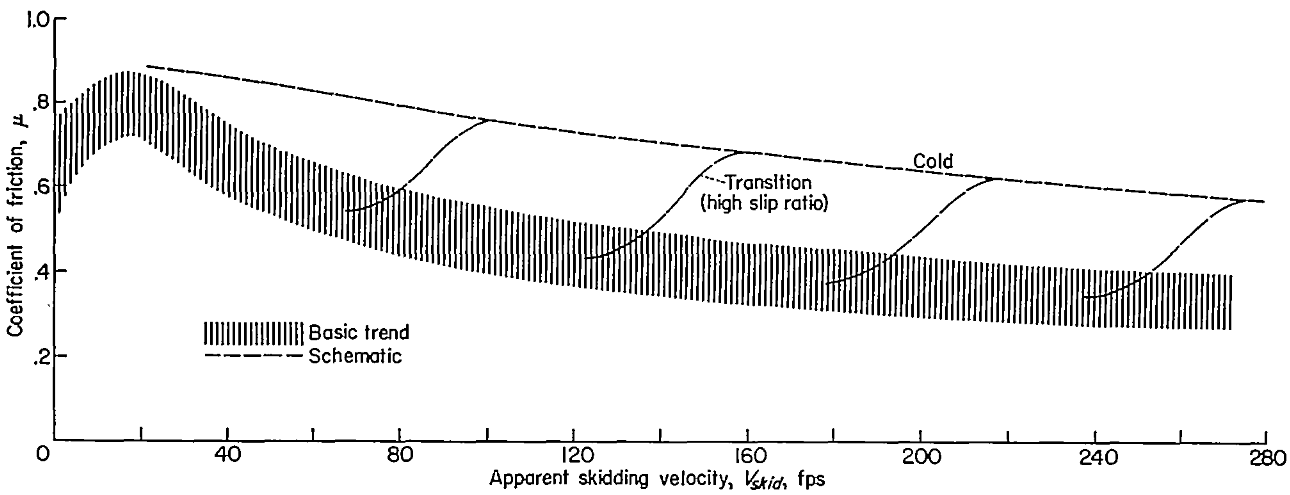


Figure 21.—Schematic representation of variation of coefficient of friction with skidding velocity in forward-speed tests with reverse wheel rotation.

With increasing simulated horizontal velocity, abraded rubber accumulates in the ground-contact region until the deposit becomes large enough to cause marked reductions in the coefficient of friction, also previously discussed. At the higher simulated horizontal velocities, because of the large accumulation of abraded rubber, much of which is in a molten semi-fluid state, the coefficient of friction drops to low values immediately after contact and does not increase as the skidding velocity decreases, even as the wheel comes to rest, so that the entire skidding process takes place at small values of the coefficient of friction. These results are, of course, radically different than those obtained in the other types of tests and are responsible for the much smaller drag loads in the spin-up drop tests at the higher simulated horizontal velocities.

(d) Comparison of coefficients of friction in the three types of tests:

The variations of the coefficient of friction in the three types of tests are compared in figure 22. The band shown for the forward-speed tests with reverse wheel rotation is the same as the basic trend previously presented in figure 21. It can be seen that the values of the coefficient of friction indicated by the basic trend in the reverse-rotation tests appear to be somewhat lower than in the true forward-speed tests. A possible explanation for this result is afforded by the following considerations. In the forward-speed tests with reverse rotation, for the range of skidding velocities greater than the carriage velocity, the slip ratios are greater than 1.0 and increase with skidding velocity up to a maximum value of 3.2 at a skidding velocity of 273 feet per second. Since the slip ratio represents the ratio of an increment in skidding distance to a corresponding increment in ground travel, the concentration of abraded rubber in the ground-contact area increases with increasing slip ratio. As a result, at skidding velocities higher than the carriage velocity in the reverse-rotation tests, the concentration of abraded rubber is somewhat greater than in a true forward-speed test, though smaller than in a spin-up drop test, and the coefficients of friction are therefore somewhat lower than might be expected from true forward-speed tests for the same skidding velocities.

For skidding velocities less than the carriage velocity, the coefficients of friction are also somewhat smaller in the reverse-rotation tests than in the true forward-speed tests, even though the slip ratios in this region are smaller than 1.0. In the reverse-rotation tests the direction of the rotation of the wheel changes when the slip ratio becomes equal to 1.0, so that, for slip ratios less than 1.0, part of the surface of the tire coming into contact with the ground has been in contact with the ground previously, when the slip ratio was greater than 1.0, and is therefore at a higher temperature. In the forward-speed tests, on the other hand, this situation does not exist; since no change in the direction of rotation of the wheel occurs and the wheel does not turn through a full revolution during the spin-up process, the regions of the tire entering the ground-contact area have not been in contact with the ground previously, so that the surface of the tire entering the ground-contact area is cold. When the initial slip ratio in the reverse-rotation tests is only slightly greater than 1.0, however, the angular displacement of the tire prior to reversal of its rotation is small enough that in the very last stages of the skidding process, when the skidding velocity becomes small, cold rubber, which has not previously been in contact with the ground enters the ground-contact area. In these cases, the coefficients of friction are approximately the same as in the forward-speed tests.

Figure 22 also shows, as previously discussed, that spin-up drop tests yield unrealistic values of the coefficient of friction throughout the range of simulated horizontal velocities of practical interest. Because the coefficients of friction are so low, the loads developed in the drop tests are generally unconservative. These results indicate that spin-up drop tests, at least onto a concrete ground surface, are not at all representative of actual landings with forward speed on concrete runways.

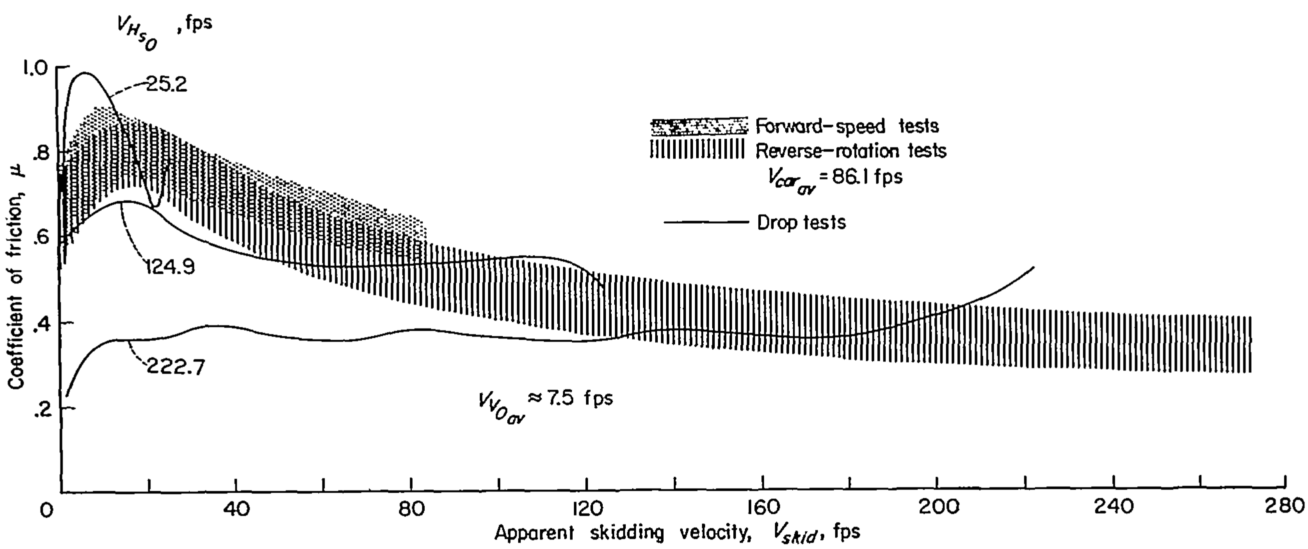
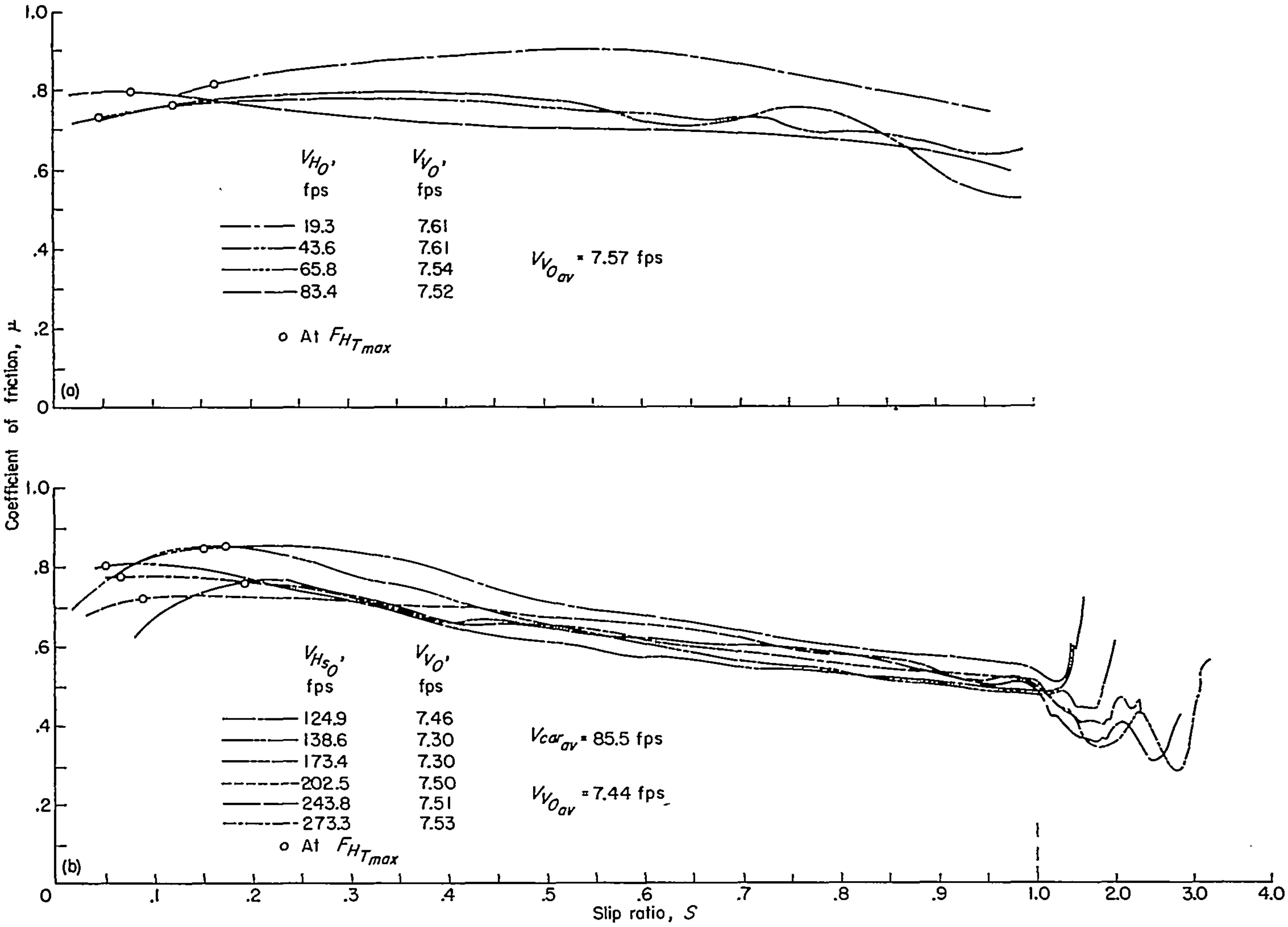


FIGURE 22.—Comparison of variations of coefficient of friction with skidding velocity in forward-speed tests, forward-speed tests with reverse wheel rotation, and spin-up drop tests.



(a) Forward-speed tests.
(b) Forward-speed tests with reverse wheel rotation.

FIGURE 23.—Variation of coefficient of friction with slip ratio in typical forward-speed tests and forward-speed tests with reverse wheel rotation.

Effect of slip ratio.—Figures 23 (a) and 23 (b) show the variations of the coefficient of friction with the slip ratio in the forward-speed tests and the forward-speed tests with reverse wheel rotation, respectively. These results, of course, include the effects of variations in the skidding velocity and in the vertical load, as well as the effects of tire heating.

In the forward-speed tests (fig. 23(a)) the slip ratio is equal to 1.0 at the instant of initial contact, the skidding velocity at this instant being equal to the forward speed. The instantaneous skidding velocity, of course, decreases as the slip ratio becomes smaller during the spin-up process. The main interpretation which can be drawn from this figure is that, for any given slip ratio, there is a general decrease in the coefficient of friction with increasing skidding velocity, the largest effect of variations in the skidding velocity appearing at low skidding velocities. The limitations of the data prevent separating the effects of skidding velocity and vertical load from those due to variations in the slip ratio.

The coefficients of friction in the forward-speed tests with reverse wheel rotation are plotted against slip ratio in figure 23(b), the scale for slip ratios greater than 1.0 being compressed. Since the actual horizontal velocities were approximately the same in all tests, the slip ratios are directly proportional to the skidding velocities and these effects can again not be separated. This figure is therefore essentially the same as figure 20(b). Since, for any given slip ratio, the skidding velocity is the same for all tests, the vertical spread of the curves must be due to some other variable factor such as the vertical load. This effect is considered next.

Effect of vertical load.—As previously noted, in the forward-speed tests with reverse rotation, since the horizontal velocities were essentially the same for all tests, differences in the coefficient of friction at any given slip ratio or skidding velocity must be due to some other variable factors, such as the instantaneous vertical load. These differences in the vertical load appear because the time at which a given skidding velocity or slip ratio is reached in any particular test is a variable depending on the magnitude of the initial simulated horizontal velocity.

Some indication of the effect of the vertical load on the coefficient of friction is given in figure 24 where the coefficients of friction at slip ratios of 1.0 and 0.15, corresponding to skidding velocities of about 84 and 13 feet per second, respectively, are plotted against the vertical load at the same

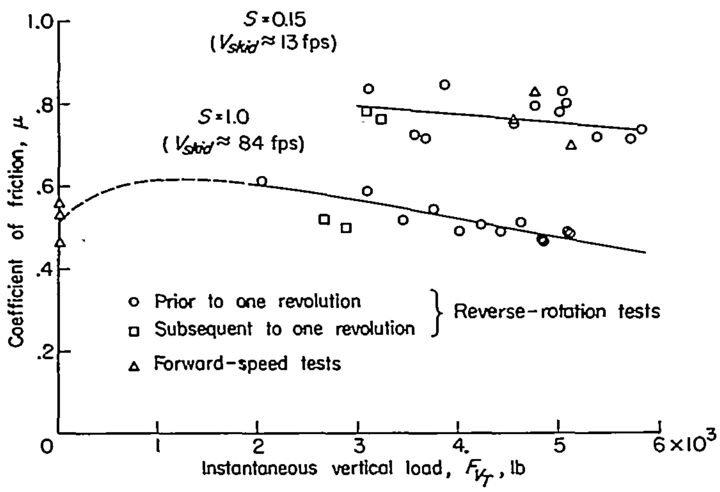


FIGURE 24.—Effect of vertical load on coefficient of friction.

instant. The data shown were obtained from the complete series of forward-speed tests with reverse wheel rotation. Also shown are corresponding test points from three true forward-speed tests at approximately the same carriage velocity as in the reverse-rotation tests. The test points for a slip ratio of 1.0 generally exhibit relatively little scatter. Most of the test points in figure 24 correspond to a time when the tire had rotated through only a fraction of a revolution. The square symbols represent test points which occur shortly after the tire has completed one full revolution; that these values of the coefficient of friction are somewhat lower than the general trend of the data for a slip ratio of 1.0 may be due to the higher temperature of the surface of the tire remaining from its previous passage through the ground-contact area. This effect is not evident for the slip ratio of 0.15, possibly because a greater time has been available to permit cooling of the part of the tire in contact with the ground when this slip ratio occurs.

The overall trend of the data in figure 24 indicates that the coefficient of friction generally decreases appreciably with increasing vertical load, the data for a slip ratio of 1.0 suggesting that the coefficient of friction reaches a maximum value at a finite vertical load, in the neighborhood of 1,000 pounds in these tests. A similar decrease in the coefficient of friction with vertical load is indicated, though not so clearly because of the greater scatter, by the data for a slip ratio of 0.15. The effect of the vertical load on the coefficient of friction appears to be more pronounced at high slip ratios, where full skidding exists, than at very small slip ratios, where an appreciable part of the ground-contact region is in a state of interlocking or adhesive contact. The general level of the coefficient of friction was, of course, considerably higher in the interlocking-contact region, as was discussed previously.

EFFECTS OF PREROTATION

Although prerotation of the landing wheels of an airplane before impact to decrease the relative velocity between the tire and the ground has often been suggested as a means for reducing spin-up drag loads, one of the main reasons that prerotation has not come into wider use is a general belief that the reductions in drag load would be very small unless the prerotation speed is matched almost exactly with the ground-rolling speed, a requirement which may be rather difficult to achieve in practice. In order to obtain quantitative information regarding the effects of prerotation on wheel spin-up drag loads, a series of forward-speed tests with varying degrees of prerotation was included in the overall investigation of applied ground loads. All tests were made at a carriage horizontal velocity of about 85 feet per second.

Figure 25 shows the manner in which different amounts of prerotation, ranging from no prerotation up to 94 percent, or almost complete prerotation, affect the applied loads on the landing gear for impacts at a vertical velocity of about 9.4 feet per second. (The percentage prerotation is based on the ratio of the peripheral velocity of the undeflected tire at the instant of contact to the horizontal velocity at contact.) These results show that, as would be expected, increasing the

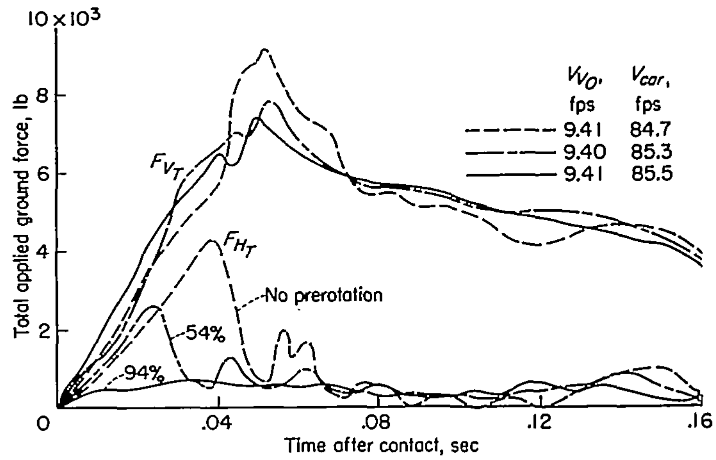


FIGURE 25.—Effect of prerotation on time histories of applied loads. $V_{car_{av}}$=85.2 feet per second.

amount of prerotation decreases the time to spin up and reduces the maximum drag load, with a consequent reduction in the vertical load. The influence of the drag load on the vertical load was similar to that discussed previously in connection with the other tests.

In figure 26, the maximum vertical loads and the maximum drag loads from tests at three vertical velocities are plotted against the percentage prerotation. The ratios of the maximum loads with prerotation to the maximum loads without prerotation are shown in figure 27. The effect of prerotation in reducing the drag load is evident. It can also be seen that prerotation produced a larger percentage reduction in drag load at the higher vertical velocities, where the need for reduction is greatest.

In figure 26 it will be noted that the drag load is not equal to exactly zero at 100-percent prerotation, even though the peripheral velocity of the undeflected tire at the instant of contact is equal to the horizontal ground speed. The reason for this result is that the rolling radius of the wheel becomes smaller as the tire compresses under the vertical load during the impact; consequently, the angular velocity of the wheel must increase if the peripheral velocity of the tire is to remain equal to the horizontal velocity. To produce the necessary angular acceleration of the wheel requires a finite drag force,

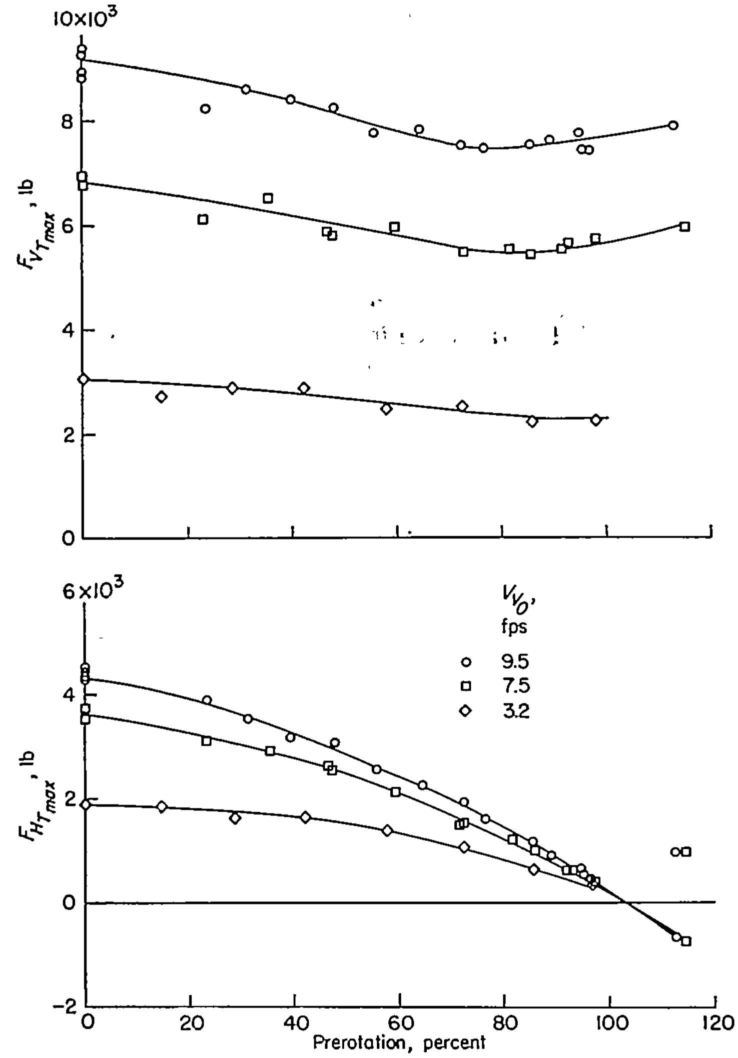


FIGURE 26.—Effect of prerotation on maximum applied loads. $V_{car_{av}}$=84.5 feet per second.

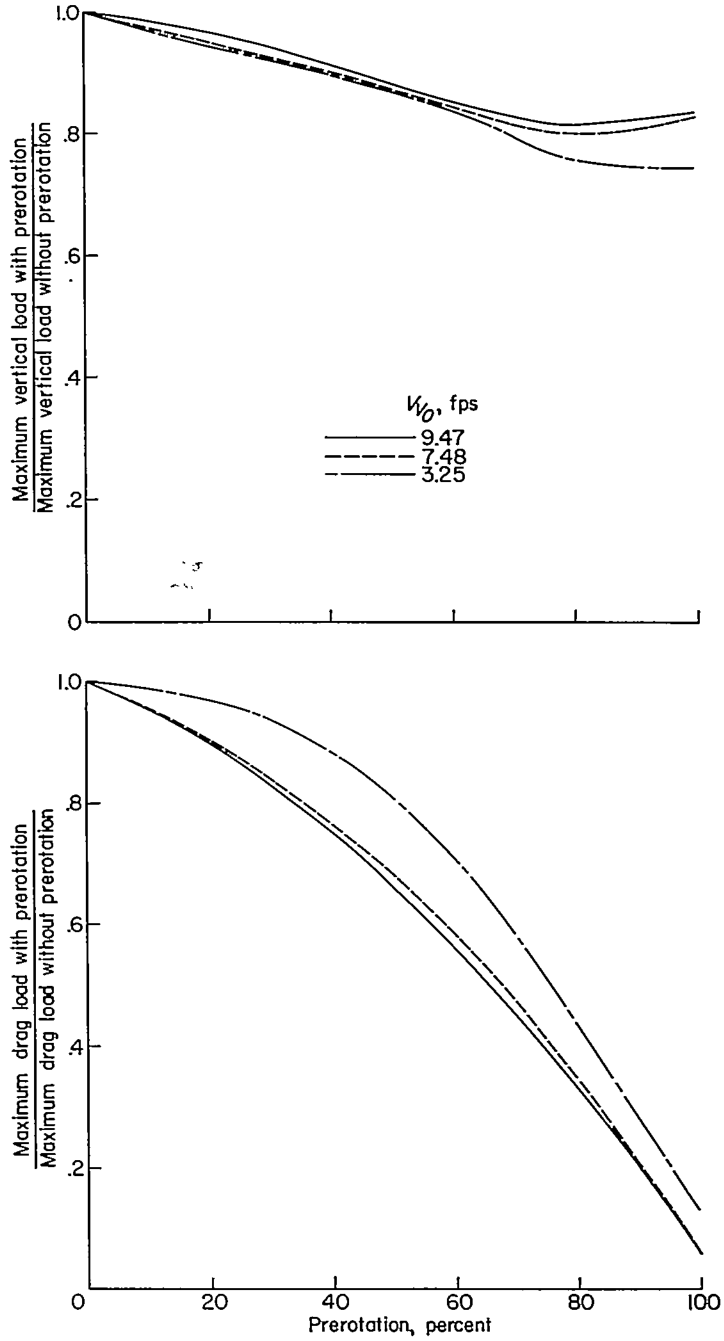


Figure 27.—Ratios of maximum applied loads with prerotation to maximum applied loads without prerotation, as functions of percentage prerotation. $V_{car_{av}}$=84.5 feet per second.

as is indicated by the curves for 100-percent prerotation. On the other hand, a slight amount of excessive prerotation initially produces a small negative drag load, followed by a positive drag load which arises for the same reason as at 100-percent prerotation. (See, for example, data for 115-percent prerotation in fig. 26.) Because of this variation in rolling radius, it appears impossible to obtain exactly zero drag load throughout an impact.

With regard to the practical usefulness of prerotation, it should be noted that in many cases there may be no particular need to reduce the spin-up drag load to levels below those established by other design loading conditions, since the landing gear must be strong enough to withstand these other loads. For example, the design requirement for braked rolling amounts to 2,400 pounds for the configuration tested. As can be seen from figure 26, for the horizontal velocity of these tests and a vertical velocity of 9.5 feet per second, the drag load can be reduced from about 4,400 pounds to 2,400 pounds (a 45-percent reduction) by use of a prerotation of 60 percent. This result indicates that, for the range of conditions covered in these tests, partial prerotation can be employed to produce useful reductions in the spin-up drag load.

Figures 26 and 27 also show the effect of prerotation on the maximum vertical loads. It can be seen that increasing the percentage prerotation also leads to a reduction in vertical load, through reduction of the bending moments acting on the landing gear, as previously discussed. In these tests the minimum vertical load occurred at a prerotation of about 80 to 85 percent, where the minimum strut bending response occurred at the time of maximum vertical load.

It is of interest to compare the results of the prerotation tests with those obtained for the same initial skidding velocity of the tire in forward-speed tests without prerotation. In the forward-speed tests without prerotation, of course, the initial skidding velocity is the same as the horizontal velocity at contact. In figure 28 the maximum values of the drag

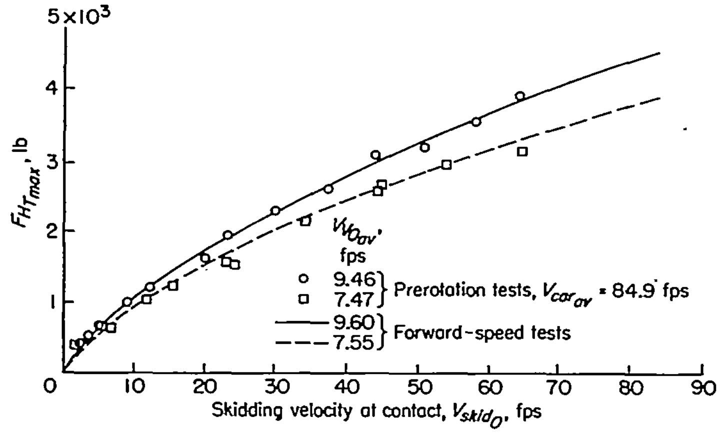


FIGURE 28.—Comparison of maximum drag loads in prerotation tests and forward-speed tests for equal initial skidding velocities.

load in both types of tests are plotted against the initial skidding velocity. The maximum drag loads with prerotation are seen to agree closely with the curves for the forward-speed tests without prerotation. It thus appears that the effect of prerotation on the maximum drag load is essentially the same as the effect of reducing the forward speed.

Comparisons of the time histories of the drag load for tests with prerotation and without prerotation are shown in figure 29 for several selected intial skidding velocities and a vertical velocity of about 9.5 feet per second. As can be seen, for tests with approximately the same initial skidding velocity, the time histories are similar; however, the tests with prerotation indicate a slightly longer time to spin up.

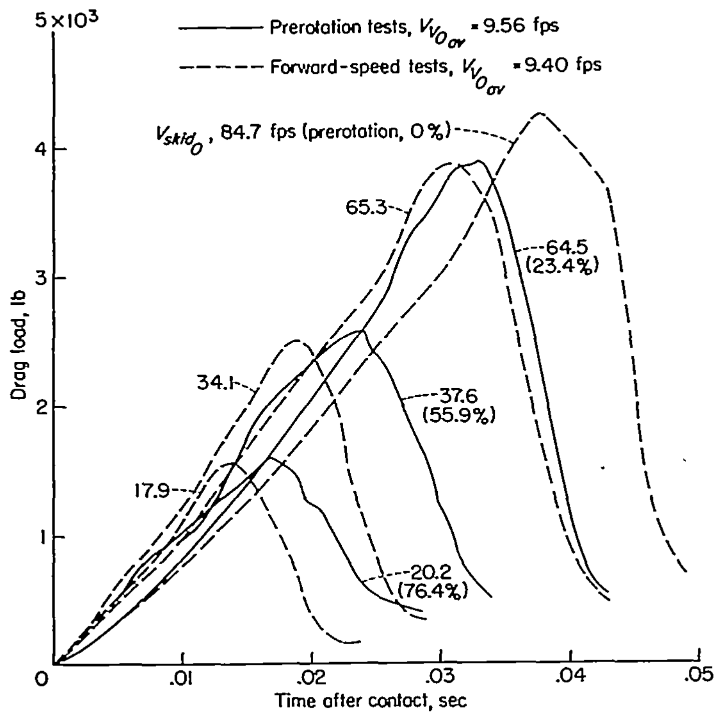


FIGURE 29.—Comparisons of drag-load time histories in prerotation tests and forward-speed tests for several initial skidding velocities. V_{car} in prerotation tests, approximately 85 feet per second.

The same type of agreement was found for impacts at a vertical velocity of 7.5 feet per second.

In evaluating the effects of prerotation, a word of caution is necessary. The results for the forward-speed tests with and without reverse rotation in figure 15 show that the maximum drag load first increases with increasing forward speed (initial skidding velocity), reaches a peak at about 120 feet per second, then decreases with further increase in velocity. In the prerotation tests of the present investigation the carriage horizontal velocity was about 85 feet per second, well below the value for peak drag load, so that any reduction in skidding velocity obtained by prerotation, even a small amount of prerotation, caused a decrease in the drag load. On the other hand, for horizontal velocities above 120 feet per second, an insufficient amount of prerotation may actually cause an increase in drag load if the skidding velocity at contact is reduced to values in the vicinity of the peak drag load. For example, at a horizontal velocity of 200 feet per second, figure 15 indicates a maximum drag load of about 2,700 pounds. In order to reduce the maximum drag load below this level, the relative skidding velocity would have to be reduced to less than 50 feet per second, that is, by a prerotation of 75 percent or more. Any lesser amount of prerotation would actually cause the drag load to be increased. This possibility should always be considered in the design of prerotation devices when the horizontal velocity is higher than that at which the peak drag load occurs, and care should be taken to insure that sufficient prerotation is produced to yield a relative velocity small enough actually to cause a reduction in drag load. This restriction, however, still provides considerable latitude in matching the forward speed. On the other hand, for very high forward speeds, the maximum spin-up drag load may be of the same order as, or even less than, the drag load caused by other design conditions, so that the practical advantages of prerotation would be greatly reduced. Even in such cases, however, prerotation might still be useful as a means of reducing dynamic stresses and consequent fatigue problems in the landing gear and other parts of the airplane structure.

From the results of the many tests which were made in the basic study of wheel spin-up drag loads, certain inferences may be drawn regarding the probable effects of prerotation on tire wear. It would seem that prerotation should greatly decrease tire wear. On the other hand, no appreciable amount of tire wear was evident in the impact-basin tests, even though the program involved some 450 simulated landings without prerotation, covering a range of vertical velocities up to 9.6 feet per second and initial skidding velocities up to 273 feet per second. The tires on an airplane having the same type of landing gear were worn out, however, in a substantially smaller number of landings under much less severe impact conditions. Since the only source of tire wear in the impact-basin tests is the wheel spin-up process, the much larger rate of wear in the flight landings appears to be due to sources other than wheel spin-up, perhaps braking and turning conditions. From these considerations it would appear that prerotation should have little effect on tire life.

CONCLUDING REMARKS

A study has been made of the applied loads and the coefficient of friction in impacts of a small landing gear under controlled conditions on a concrete landing strip in the Langley impact basin. The basic investigation included three major phases: forward-speed tests at horizontal velocities up to approximately 86 feet per second, forward-speed tests with reverse wheel rotation to simulate horizontal velocities up to about 273 feet per second, and spin-up drop tests for comparison with the other tests. In addition to the basic investigation, supplementary tests were made to evaluate the drag-load alleviating effects of prerotating the wheel before impact so as to reduce the relative velocity between the tire and the ground.

In the presentation of the results an attempt has been made to interpret the experimental data so as to obtain some insight into the physical phenomena involved in the wheel spin-up process. From this study it appears that the conditions of contact between the tire and the ground, and consequently the magnitude of the coefficient of friction, vary greatly during the course of an impact and with different impact conditions. The coefficient of friction appears to be appreciably influenced by a number of factors, including the instantaneous skidding velocity, the slip ratio, the vertical load, the effects of tire heating produced by the skidding process, and the effects of contamination of the ground surface by abraded rubber. Some quantitative indications of these effects were obtained from the experimental data but the nature of the tests did not permit complete separation of all individual effects.

From the study of the effects of wheel prerotation, it appears that this means may be used to obtain appreciable reductions in the maximum drag loads; however, at very high forward speeds, because the spin-up drag loads may be of the same order as, or even less than, the drag loads caused by other design conditions, the practical advantages of prerotation could be greatly reduced.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *August 18, 1955.*

APPENDIX A

DEFINITIONS

The purpose of this appendix is to present briefly some of the equations used in calculating the relative motions between the wheel and the ground from the measured data.

ROLLING RADIUS

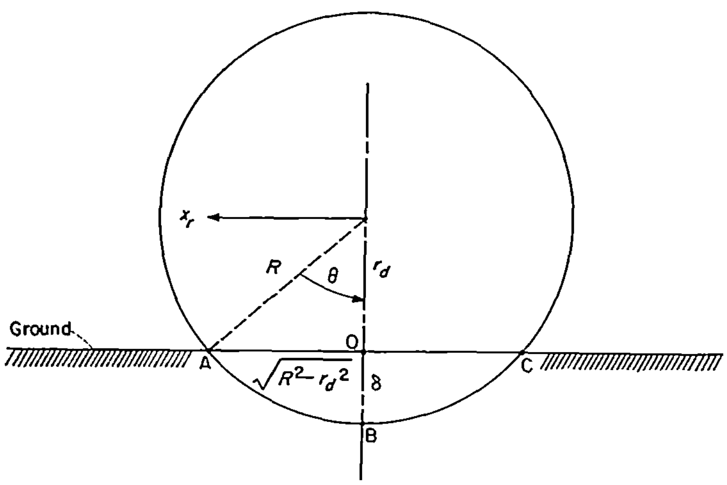
By analogy with the rolling of a rigid wheel, the effective radius for the free rolling of a deformable wheel is defined by the equation

$$x_r = r_e \theta \tag{A1}$$

where

- x_r horizontal translation of the axle in rolling
- θ angular displacement of wheel
- r_e rolling radius

An estimate of the rolling radius may be obtained by means of a simple geometrical argument, along the same lines as that used by R. C. Whitbread and described in reference 6. The adjacent sketch represents a rolling wheel of free radius R, deflected by an amount δ=OB; the deflected



Sketch (a).

radius is r_d. Assume that the arc ABC has been compressed so that the mean footprint length is equal to the chord AOC. Assume, also, that no sliding between the tire and the ground occurs in rolling. Thus, for an angular displacement

$$\theta = \sin^{-1}\frac{\sqrt{R^2 - r_d^2}}{R}$$

as shown, the axle will be displaced horizontally by an amount

$$x_r = \text{OA}$$
$$= \sqrt{R^2 - r_d^2}$$

With the foregoing substitutions, equation (A1) gives the following expression for the rolling radius:

$$r_e = \frac{R\sqrt{1-\frac{r_d^2}{R^2}}}{\sin^{-1}\sqrt{1-\frac{r_d^2}{R^2}}} \tag{A2}$$

It can be readily shown that the right-hand member of equation (A2) is very closely approximated by the linear function $\frac{2R+r_d}{3}$ for the practical range of tire deflection, so that

$$r_e \approx \frac{2R+r_d}{3} \tag{A3}$$

or, since $r_d = R - \delta$,

$$r_e \approx R - \frac{\delta}{3} \tag{A3a}$$

where δ is the tire deflection.

Equation (A3a) appears to be substantiated fairly well by experimental data. (See ref. 6.)

APPARENT SKIDDING VELOCITY

If skidding exists, the horizontal displacement of the axle x_{axle} is not equal to the horizontal displacement x_r in free rolling. The apparent skidding distance x_{skid} is the difference between the actual translation of the axle and the translation in free rolling, for the same angular displacement of the wheel. Thus,

$$x_{skid} = x_{axle} - x_r$$
$$= x_{axle} - r_e\theta \tag{A4}$$

Differentiating with respect to time gives the following expression for the apparent skidding velocity:

$$V_{skid} = V_{axle} - r_e\dot{\theta} \tag{A5}$$

where

$$V_{skid} = \dot{x}_{skid}$$
$$V_{axle} = \dot{x}_{axle}$$

SLIP RATIO

The slip ratio is normally defined as the ratio of the change in the angular velocity of a wheel, under the application of torque, to the angular velocity of a freely rolling wheel at the same axle velocity; that is,

$$S = \frac{\dot{\theta}_f - \dot{\theta}}{\dot{\theta}_f} \tag{A6}$$

where

- $\dot{\theta}$ angular velocity of wheel under torque
- $\dot{\theta}_f$ angular velocity of freely rolling wheel

Multiplying numerator and denominator in equation (A6) by r_e and noting that $r_e\dot{\theta}_f = V_{axle}$ gives

$$S = \frac{V_{axle} - r_e\dot{\theta}}{V_{axle}}$$
$$= \frac{V_{skid}}{V_{axle}} \tag{A7}$$

APPENDIX B

TIRE HEATING

A rough evaluation of the factors which influence the heating of the tire during the skidding process may be obtained from the following elementary considerations. Assume that the tire is a good insulator, so that the heat produced by the skidding remains on the surface of the tire; the temperature rise of the surface will then be directly proportional to the concentration of skidding energy per unit of tire surface area. For simplicity assume that F_{V_T}, μ, and r_e are constant; also, assume line contact between the tire and the ground (rigid tire). Consider the work done in skidding and the area of the tire in contact with the ground during an increment in time Δt, during which the tire rotates through an angle $\Delta\theta$ and the axle is displaced horizontally through a distance Δx_{axle}; the skidding distance during this interval is given by (see eq. (A4))

$$\Delta x_{skid} = \Delta x_{axle} - r_e \Delta\theta \qquad \text{(B1)}$$

The work done in skidding is

$$\Delta W = F_{H_T} \Delta x_{skid}$$
$$= \mu F_{V_T} \Delta x_{skid}$$

The amount of tire surface making contact with the ground is

$$\Delta A = \frac{\Delta\theta}{|\Delta\theta|} w r_e \Delta\theta$$

where w is the width of the tire contact area. $\left(\text{The factor } \frac{\Delta\theta}{|\Delta\theta|} \text{ is introduced to insure that } \Delta A \text{ is positive regardless of the direction of rotation.}\right)$

The ratio of the incremental work to the incremental area is, therefore,

$$\frac{\Delta W}{\Delta A} = \frac{|\Delta\theta|}{\Delta\theta} \frac{\mu F_{V_T}}{w} \frac{\Delta x_{skid}}{r_e \Delta\theta}$$

Dividing numerator and denominator of the right-hand side by Δt and passing to the limit gives the intensity of the skidding energy in the tire surface area making contact with the ground:

$$\epsilon = \frac{dW}{dA} = \frac{|\dot\theta|}{\dot\theta} \frac{\mu F_{V_T}}{w} \frac{V_{skid}}{r_e \dot\theta}$$

From the definitions of V_{skid} and S (eqs. (A5) and (A7)) it follows that

$$\epsilon = \frac{|\dot\theta|}{\dot\theta} \frac{\mu F_{V_T}}{w} \frac{S}{1-S} \qquad \text{(B2)}$$

where, for

$$S<1, \dot\theta>0$$
$$S>1, \dot\theta<0$$

so that ϵ is always positive.

Equation (B2) indicates, in first approximation, how the energy concentration in the tire surface varies. It is immediately evident that, everything else being equal, the greatest energy concentration occurs at $S=1$, the values at the extremes of the range of S being

$$\epsilon_{(S=0)} = 0$$
$$\epsilon_{(S=\infty)} = \frac{\mu F_{V_T}}{w}$$

Since the coefficient of friction decreases with increasing tire-surface temperature, that is, decreases with increasing skidding energy per unit surface area, this simplified argument indicates that, all other factors being the same, the coefficient of friction should reach its minimum value at a slip ratio $S=1$ and increase as S becomes either less than or greater than 1. It also appears that the coefficient of friction should decrease with increasing values of $\frac{F_{V_T}}{w}$. These observations, of course, refer only to the effects of heating.

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TABLE I.—CHARACTERISTICS OF TEST INSTRUMENTATION

Quantity measured	Instrument natural frequency, cps	Galvanometer natural frequency, cps	Estimated total maximum error
Axle normal force, F_{N_a}	[a]220	800	±90 lb
Axle axial force, F_{A_a}	[a]403	800	±240 lb
Axle normal acceleration, inner, $a_{N_{a_i}}$	800	800	±0. 8g
Axle normal acceleration, outer, $a_{N_{a_o}}$	800	800	±0. 5g
Axle axial acceleration, a_{A_a}	140	150	±0. 4g
Ground vertical force, F_{V_g}	[b]275	800	±150 lb
Ground horizontal force, F_{H_g}	[b]100+	800	±230 lb
Ground vertical acceleration, a_{V_g}	520	800	±0. 2g
Ground horizontal acceleration, a_{H_g}	530	800	±0. 2g
Wheel angular displacement, θ	------------	1, 650	±1°
Wheel angular velocity, $\dot{\theta}$	------------	800	±1. 5 percent
Upper mass displacement, z_u	Flat response to 20 cps	500	±0. 2 inch
Shock-strut axial stroke, s	Flat response to 20 cps	100	±0. 15 inch
Tire displacement (fixed installation)	Flat response to 20 cps	100	±0. 15 inch
Vertical velocity at contact, V_{V_O}	1, 000+	800	±0. 1 fps
Lift force	------------	100	±2 percent
Carriage horizontal displacement	------------	1, 650	±0. 1 ft
Oscillograph timing	------------	-----	±1 percent

[a] With wheel assembly attached.
[b] With ground platform attached.