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EVALUATION OF THE REDUCED-MASS METHOD OF REPRESENTING

WING-LIFT EFFECTS IN FREE-FALL DROP

TESTS OF LANDING GEARS

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SUMMARY

The validity of the reduced-mass method of representing wing-lift effects in free-fall drop tests of landing gears has been investigated by means of tests of a small landing gear in the Langley impact basin. The behavior of the landing gear in the reduced-mass drop tests is compared with results obtained in simulated air-borne impacts, in which wing lift forces were mechanically applied to the test specimen during impact, and with the results of free-fall drop tests with full weight.

The reduced-mass drop tests yielded landing-gear load factors and values of the ratio of shock-strut energy to impact energy which were in fairly good agreement with the results of the simulated air-borne impacts. The values of impact period and shock-strut effectiveness were generally lower and the values of strut stroke and mass travel were generally higher in the reduced-mass drop tests than in the simulated air-borne impacts, particularly at the lower vertical velocities.

The free-fall drop tests with full weight produced excessive values of load factor, impact period, strut stroke, mass travel, and impact energy. Values of strut effectiveness, however, were in fairly good agreement with those obtained in the simulated air-borne impacts.

INTRODUCTION

Although the drop test serves as a basic implement in the design and development of airplane landing gears, the significance of such tests has been open to some question in view of the fact that most drop-test machines used in this country do not provide means for simulating the aerodynamic lift forces which sustain an airplane during landing. For many years the effects of wing lift were ignored completely in

landing-gear design and proof testing and free-fall drop tests were carried out by using that part of the total weight of the airplane supported by a given strut. However, the growth in size and the increased landing speeds of modern airplanes have made the weight penalty associated with the landing gear sufficiently great to necessitate consideration of wing-lift effects in landing-gear design. Current airworthiness requirements consequently permit drop tests to be conducted with reduced weight as a simple means of approximating the effects of wing lift during landing. The magnitude of the dropping weight is chosen so that the impact energy in the free-fall drop tests is equal to the energy in an air-borne landing with the same descent velocity. It is generally assumed that, under these conditions, the landing-gear loads, mass travel, and shock-strut effectiveness will be the same in the reduced-mass drop test as in the air-borne impact.

In order to permit an evaluation of the accuracy of the reduced-mass method, tests of a small landing gear have been conducted in the Langley impact basin. The equipment of this facility incorporates mechanical means for applying any desired constant vertical lift force to the test specimen during a landing impact.

For the present investigation several series of tests were made with a small landing gear over a range of vertical velocities. In one group of tests the dropping weight was held constant at 2500 pounds and simulated wing lift forces, covering a range of values between the fully air-borne and free-drop conditions, were mechanically applied to the test specimen during impact. In addition, free-drop tests were made over the same range of vertical velocities with reduced values of weight calculated for each lift condition in accordance with the method prescribed by current airworthiness requirements (references 1 and 2). This paper presents an analysis of the data obtained in these tests and compares the behavior of the landing gear in the simulated air-borne landings, reduced-mass drop tests, and full-weight drop tests.

SYMBOLS AND NOMENCLATURE

d	upper-mass travel from time of ground contact
E	energy, foot-pounds
F	force, pounds
g	gravitational constant, 32.17 feet per second per second
h	height of free drop
K_L	wing lift factor

L   lift force, pounds

n   airplane load factor

n_g landing-gear load factor

p_o fully extended strut air pressure, pounds per square inch

s   strut stroke, feet

t_i impact time; time to reach maximum landing-gear load, seconds

V_{v_o} vertical velocity at initial contact, feet per second

W   weight, pounds

w_c/g effective mass of lift cams, 1.3 slugs

$\ddot{y}$ acceleration, feet per second per second

η effectiveness of shock strut, percent

Subscripts:

e   equivalent

f   free fall

g   landing gear

i   impact

o   oleo or strut

r   reduced-mass drop test

T   total

u   upper mass

max   maximum

Terminology:

    Simulated air-borne impact: An impact in which wing lift is
simulated by the mechanical application of an upward force to the test
specimen.

Reduced-mass drop test: A free-fall drop test with reduced mass which represents an equivalent air-borne impact. The dropping weight in the reduced-mass test is calculated to produce the same impact energy as in the equivalent air-borne impact.

Equivalent air-borne impact: A hypothetical air-borne impact which is represented by a reduced-mass drop test.

APPARATUS

Equipment

The present investigation was conducted in the Langley impact basin (reference 3) and utilized apparatus which had previously been employed in the study of hydrodynamic impact loads on seaplanes. The basic piece of equipment used in the investigation is the impact-basin carriage (fig. 1) which provides means for effecting the controlled descent of the test specimen while the carriage is either stationary or moving horizontally. In the present tests the carriage was held stationary and was used in much the same manner as a conventional landing-gear testing machine.

The carriage is supported by wheels which roll on the upper, lower, and inner surfaces of two horizontal box rails. Relatively thin solid rubber tires are used to minimize deflections under load. Preloading the wheels against the rails with a screw-jack arrangement provides effective vertical and lateral restraint of the carriage. Oscillation of the carriage is limited to very small amplitudes by this arrangement in order to minimize disturbance of the motion of the test specimen and to reduce jarring of the instrumentation located on the carriage.

The motion of the test specimen is restrained by means of a four-bar parallelogram linkage as shown in figure 1. The boom, to which the landing gear is rigidly attached, is a vertical member connected to the carriage by means of two parallel link arms which are pin-jointed at each end. With this arrangement the boom remains vertical throughout its travel and the orientation of the test specimen remains constant during a test. Since the parallelogram linkage results in motion along a circular arc, the travel of the boom is not exactly perpendicular to the horizontal plane of the carriage during the greater part of the descent; however, since the radius of the arc is relatively large compared to the boom travel following ground contact and ground contact can be arranged to occur with the link arms in a horizontal position, the motion of the landing gear relative to the carriage is essentially vertical during the impact process.

In order to simulate mechanically the wing lift forces which support an airplane during landing, the carriage incorporates a pneumatic cylinder and cam system which was designed to apply any desired constant upward force to the boom and test specimen during a landing impact. The lift force is applied to the boom by means of a cable and sheave arrangement which connects the boom to the piston of the pneumatic cylinder in such a manner that the piston is forced to travel against the air pressure in the cylinder as the boom descends. Although the air pressure in the cylinder increases with piston travel, the incorporation of a special cam-shaped sheave in the cable system results in the application of a constant upward force to the boom. The amount of lift force exerted on the boom depends on the air pressure supplied to the cylinder before each test. The vertical lift rod, which can be seen attached to the base of the boom in figures 1 and 2, is one of two such rods which form the lower end connection of the cable system.

The effective weight of the boom and link bars alone is approximately 650 pounds. This weight plus the weight of the test specimen and attachment fittings represents the minimum dropping weight. The dropping weight may be increased, in increments of 50 pounds, to a maximum value of 2500 pounds by means of lead weights fitted around the boom and bolted together. The rotational inertia of the cams incorporated in the lift mechanism increases the effective mass of the boom by 1.3 slugs without, however, increasing the weight of the boom.

The boom may be dropped from 24 different vertical positions corresponding to the number of teeth on the boom rack visible in figure 1. After the desired vertical velocity has been attained during free drop, the predetermined lift force is automatically applied to the boom prior to the instant of contact of the landing gear with the ground. With this arrangement any desired degree of lift, ranging from the free-drop condition up to a maximum value of 2500 pounds, can be applied to the boom and test specimen during a landing impact. Vertical velocities up to approximately 12 feet per second can be attained with the equipment.

Test Specimen

The landing gear tested was originally designed as a main gear for a small single-engine military training airplane of the tail-wheel type, having a gross weight of approximately 5000 pounds. The gear is of conventional cantilever construction and incorporates a standard type of oleo-pneumatic shock absorber. A single leg of the half-fork type connects the shock absorber and the axle. The wheel is fitted with a 27-inch smooth-contour (type I) tire having a nonskid tread.

In order to permit convenient use of the test data obtained in the
present investigation in connection with theoretical studies, the par-
ticular gear tested was somewhat modified in that the metering pin was
removed and the original orifice plate replaced with one having a smaller
orifice diameter. The orifice details and the internal arrangement
of the strut are shown in figure 3. The weight of the landing gear,
including wheel and tire, is 150 pounds. The lower or unsprung weight,
comprising the weight of the wheel, tire, brake assembly, fork
and axle, inner strut cylinder, hydraulic fluid, and instruments, is
131 pounds.

The landing gear is attached to the lower end of the boom by means
of a steel adapter member. In order to minimize eccentric loading of
the boom, the center plane of the wheel was made to coincide with the
plane of symmetry of the boom. With landing gear, adapter fitting, and
instrumentation installed, the minimum dropping weight is approximately
1000 pounds. A view of the landing gear installed on the boom for
testing is shown in figure 2.

Instrumentation

A variety of time-history instrumentation was used during the
tests. A double-impulse type of electromagnetic generator, consisting
of a permanent magnet attached to the boom, which moved with the boom
past a coil fixed to the carriage, was used to determine the vertical
velocity of the landing gear at the instant of ground contact. Vertical
acceleration of the boom was measured by means of an unbonded strain-
gage type of electrical accelerometer having a natural frequency of
85 cycles per second. A low-frequency (16.5 cps) self-recording optical
accelerometer was used as a standby instrument and as a check against
the electrical accelerometer. Another electrical strain-gage accel-
erometer, of 260-cycles-per-second natural frequency, located on the
fork of the landing gear, was used to determine the acceleration of
the unsprung mass. Strut-stroke and tire-deflection measurements were
obtained by means of variable-resistance slide-wire potentiometers.
Values of mass travel were obtained from the sum of the stroke and
tire-deflection measurements. The instant of ground contact was deter-
mined by means of a microswitch, recessed into the ground dynamometer
platform, which closed a circuit as long as the tire was in contact
with the platform.

Except for the self-recording optical accelerometer, all instru-
ments produced an electrical output which was recorded on a 14-channel
oscillograph. The galvanometers were damped to 0.65 critical damping
and had natural frequencies high enough to produce virtually uniform
response up to frequencies commensurate with the measuring instrumenta-
tion. Timing lines at intervals of 1/100 second were produced on the

record paper by means of an electronic timer built into the recorder.
Additional timing pulses, for synchronizing the self-recording accel-
erometer with the oscillograph, were produced at intervals of 1/10 second
by means of a clockwork timer.

The measurements obtained are believed to be accurate within the
following limits:

Lift force, percent . . . . ±10
Upper-mass acceleration, g . . . . ±0.13
Initial vertical velocity, feet per second . . . . ±0.1
Strut stroke, inches . . . . ±0.2
Tire displacement, inches . . . . ±0.2
Mass travel, inches . . . . ±0.3
Time to maximum acceleration, seconds . . . . ±0.003

Typical records, obtained in a simulated air-borne impact and in
a reduced-mass drop test, are reproduced, approximately half size, in
figure 4.

REDUCED-MASS EQUATIONS

In the reduced-mass method of simulating wing lift in drop tests,
the magnitude of the dropping weight is chosen so that the impact energy
in a free-fall drop test is equal to the energy in an air-borne impact
with the same descent velocity.

The impact energy per gear in an air-borne landing is equal to the
sum of the kinetic and potential energies as given by the expression

$$E_i = \frac{W_T V_{v_o}^2}{2g} + W_T\left(1 - K_L\right)d \tag{1}$$

where

E_i impact energy in air-borne landing

W_T total effective weight per gear in air-borne landing

V_{v_o} vertical velocity at ground contact

g gravitational constant

d mass travel in air-borne landing

K_L lift factor $\left(L/W_T\right)$

L lift force

The impact energy in a free-fall drop test is given by

$$E_{i_f} = \frac{W_{T_f} V_{v_o}{}^2}{2g} + W_{T_f} d_f \tag{2}$$

where

E_{i_f} impact energy in free-fall drop test

W_{T_f} total weight in free-fall drop test

d_f mass travel in free-fall drop test

If the energies in the free-fall drop test and air-borne impacts are to be equal, the relationship between the total weights can be obtained by equating formulas (1) and (2). Thus,

$$W_{T_f} = \frac{W_T \left[\dfrac{V_{v_o}{}^2}{2g} + \left(1 - K_L\right)d\right]}{\dfrac{V_{v_o}{}^2}{2g} + d_f} \tag{3}$$

In calculating the reduced weight to be used in representing wing-lift effects it is conventionally assumed that the mass travel will be the same in the air-borne impact as in the free-drop test. The reduced weight for the drop test is then given by

$$W_{T_r} = \frac{W_{T_e} \left[\dfrac{V_{v_o}{}^2}{2g} + \left(1 - K_{L_e}\right)d_r\right]}{\dfrac{V_{v_o}{}^2}{2g} + d_r} \tag{4}$$

where

W_{T_r} total weight used in reduced-mass drop test

d_r mass travel in reduced-mass drop test

W_{T_e} total weight for equivalent air-borne impact represented by
         reduced-mass drop test

K_{L_e} lift factor for equivalent air-borne impact represented by
         reduced-mass drop test

Equation (4) may be written in terms of the equivalent height of free drop, as follows:

$$W_{T_r} = \frac{W_{T_e}\left[h + \left(1 - K_{L_e}\right)d_r\right]}{h + d_r} \tag{5}$$

where h is height of free drop required to attain initial vertical velocity.

Equation (5) corresponds with that given in sections 3.353 and 4b.332 of references 1 and 2, respectively. In order to insure that sufficient energy absorption is represented by the reduced-mass impacts, references 1 and 2 stipulate that the value of d_r used in the computation of W_{T_r} shall not exceed the value actually obtained in the drop tests.

In a landing impact the vertical force imposed by the landing gear on the upper, or sprung, mass is given by the equation

$$F_g = W_u\left(\frac{\ddot{y}_u}{g} + 1\right) - K_L W_T \tag{6}$$

where

F_g landing-gear force imposed on the upper mass

W_u weight of upper mass

$\ddot{y}_u$ acceleration of upper mass

In the case of the impact-basin dropping linkage, the rotational inertia of the cams incorporated in the lift mechanism increases the effective dropping mass by a small amount without, however, increasing the dropping weight. Incorporating this additional inertia reaction

into equation (6) gives

$$F_g = W_u\left(\frac{\ddot{y}_u}{g} + 1\right) - K_L W_T + w_c \frac{\ddot{y}_u}{g} \tag{6a}$$

where w_c/g is the effective inertia of the lift cams.

The landing-gear load factor n_g is defined as the ratio of the maximum load on the landing gear to the weight of the upper mass, or

$$n_g = \frac{F_{g_{max}}}{W_u} = \left(\frac{\ddot{y}_{u_{max}}}{g} + 1\right) - K_L \frac{W_T}{W_u} + \frac{w_c}{W_u}\frac{\ddot{y}_{u_{max}}}{g} \tag{7}$$

The airplane, or upper-mass, load factor n is defined as the ratio of the maximum value of the sum of all the applied forces acting on the airplane or upper mass to the weight of the upper mass, or

$$n = \frac{F_{g_{max}} + L}{W_u} = \left(\frac{\ddot{y}_{u_{max}}}{g} + 1\right) + \frac{w_c}{W_u}\frac{\ddot{y}_{u_{max}}}{g} \tag{8}$$

or

$$n = n_g + K_L \frac{W_T}{W_u} \tag{9}$$

In a free-drop test $K_L = 0$, so that the landing-gear load factor and the airplane load factor are equal.

The reduced-mass method of representing wing lift in free-fall drop tests assumes that, if the weight used in the drop test is calculated in accordance with equation (5), the behavior of the landing-gear, the shock-absorbing effectiveness, and the maximum landing-gear loads will be the same in the drop test as in the equivalent air-borne impact represented by the reduced-mass test. Equating the landing-gear forces for the two types of impacts gives the relationship between the accelerations and load factors in the reduced-mass drop tests and the equivalent air-borne impacts. Thus,

$$n_{g_e} = \frac{W_{u_r}}{W_{u_e}}\left(\frac{\ddot{y}_{u_{r_{max}}}}{g} + 1\right) \tag{10}$$

$$= \frac{W_{u_r}}{W_{u_e}} n_{g_r}$$

and

$$n_e = \frac{W_{u_r}}{W_{u_e}} n_{g_r} + K_{L_e} \frac{W_{T_e}}{W_{u_e}}$$
(11)

where

n_{g_e} landing-gear load factor for equivalent air-borne impact represented by reduced-mass drop test

n_e upper-mass or airplane load factor for equivalent air-borne impact represented by reduced-mass drop test

W_{u_e} weight of upper or sprung mass for equivalent air-borne impact represented by reduced-mass drop test

$\ddot{y}_{u_{r_{max}}}$ maximum acceleration of upper mass measured in reduced-mass drop test

n_{g_r} landing-gear load factor measured in reduced-mass drop test

The foregoing equations provide the relationships between air-borne impacts and free-fall drop tests within the limitations of the assumptions upon which the reduced-mass method is based.

TEST PROCEDURE

The test program was carried out in the Langley impact basin with the modified landing gear previously described. With a total dropping weight of 2500 pounds, a series of impacts was made for each of four wing lift conditions, namely, 0, 50, 75, and 100 percent of the total dropping weight. The vertical velocities at contact ranged between approximately 3 and 12 feet per second. These tests yielded data for the full-weight free-fall drop tests and simulated air-borne impacts and provided a basis for evaluating the results of the reduced-mass drop tests. The dropping weights used in the reduced-mass drop tests were chosen to represent equivalent air-borne impacts with a weight per gear of 2500 pounds and covered the same range of conditions as the simulated air-borne impacts previously described.

In order to calculate the dropping weights for the reduced-mass drop tests, it was first necessary to establish the relationship between weight and mass travel. This relationship was determined experimentally

by means of a preliminary series of free-fall drop tests with dropping
weights of 2500, 2000, 1500, and 1000 pounds at several values of
vertical velocity.

In all tests the tire pressure was maintained at the recommended
value of 32 pounds per square inch. The shock strut was inflated with
sufficient pressure to allow an available strut closure of approximately
$1\frac{1}{8}$ inches in the static position for all dropping weights, in conformity
with the standard operating practice for the landing gear tested.

RESULTS AND DISCUSSION

Requirements of the Reduced-Mass Method

Calculation of dropping weight.- In the reduced-mass method of
drop testing landing gears the value of the weight used depends on the
vertical velocity, the amount of wing lift being represented, and the
mass travel actually attained in the drop test, as shown by equation (4).
For any given vertical velocity, since the mass travel depends on the
dropping weight, it is necessary to establish the relationship between
these two variables for the particular landing gear being tested before
the value of the weight to be used in the drop test can be determined.

As previously noted, preliminary free-fall drop tests were made
with several dropping weights in order to establish the relationship
between weight and mass travel. The results of these preliminary drop
tests are presented in table I and are also shown by the circular
symbols in figure 5. The broken lines in figure 5 represent the varia-
tions of reduced weight with mass travel for the same lift factors as
in the simulated air-borne impacts, as calculated by means of equa-
tion (4) for a total equivalent air-borne weight per gear of 2500 pounds.
These calculated curves show the relationships necessary to satisfy the
equal-energy requirements of the reduced-mass method and apply to any
landing gear. Since the solid lines, which were faired through the
experimental data, are determined by the characteristics of the partic-
ular landing gear being tested, the intersections of the solid and
broken lines determine the dropping weights required to represent equiv-
alent air-borne impacts for the various lift factors considered. For
the reduced-mass drop tests of the present investigation, these values
were approximated as closely as possible with the 50-pound weight
increments available with the impact-basin equipment. Conditions
requiring a dropping weight of less than 1000 pounds could not be inves-
tigated, however, because of the minimum dropping-weight limitations of
the equipment.

The values of weight actually used in the reduced-mass drop tests
are presented in table II and are shown in figure 6 where they are
compared with the values determined by the intersections of the curves
in figure 5. Values of the mass travel obtained in the reduced-mass
drop tests are shown in figure 5 by the square symbols.

Energy requirements.- Before attempting to analyze the reduced-mass
drop-test results, it is necessary to ascertain the extent to which the
requirements of the reduced-mass method have been satisfied by the drop
tests conducted in the present investigation. The primary requirement
of the reduced-mass method is the stipulation that the impact energy in
a free-fall drop test must be equal to the impact energy in the equiv-
alent air-borne impact represented by the reduced-mass drop test.
Table II lists values of the impact energy E_{i_r} determined from the
drop-test results by application of equation (2). Also tabulated are
values of the energy E_{i_e} for the equivalent air-borne impacts as
calculated by application of equation (1).

The extent to which the requirements of the reduced-mass method
have been satisfied by the drop tests can be determined by comparison
of corresponding values of E_{i_r} and E_{i_e} in table II. Examination of
the ratio E_{i_e}/E_{i_r} indicates that the energy conditions were satisfied
within 2 percent in almost all of the reduced-mass drop tests.

Evaluation of Results of Reduced-Mass Drop Tests

The results of the reduced-mass drop tests (table II) are evaluated
by comparisons, in figures 7 to 17, with data obtained in simulated air-
borne impacts (table III) and in free-fall drop tests with the full
weight of 2500 pounds (table I).

Landing-gear load factor.- One of the primary objects in drop
testing a landing gear is the determination of the magnitude of the
loads produced during a landing impact. As a partial evaluation of the
reduced-mass method of drop testing, landing-gear load factors deter-
mined from the reduced-mass drop tests are compared in figure 7 with the
results of simulated air-borne impacts and free-fall drop tests with the
full weight of 2500 pounds.

Figure 7 indicates that the load factors determined from the
reduced-mass drop tests were somewhat greater than those obtained in
the simulated air-borne impacts, except at the lower vertical velocities
where the results of the reduced-mass drop tests were in good agreement
with the data from simulated air-borne impacts. At the higher veloc-
ities, the load factors determined from the reduced-mass drop tests were

up to 12 percent higher than those in the simulated air-borne impacts; this discrepancy increased to as much as 18 percent following the occurrence of tire bottoming.

Reducing the lift factor naturally resulted in increased load factors in both the reduced-mass drop tests and the simulated air-borne impacts. At the lower lift factors, since the differences between the conditions of the simulated air-borne impacts and the reduced-mass drop tests are diminished, improved agreement between the results of these tests might be expected. However, the degree of conservatism of the reduced-mass drop tests for the lower lift factors did not decrease appreciably throughout most of the velocity range. In fact, the agreement at the lower velocities was not quite so good for the lower lift factors as in the case of $K_L = 1$. The discrepancies at the highest velocities, however, were slightly reduced at lower lift factors.

The free-fall drop tests with the full weight produced load factors which were much greater than those obtained in either the reduced-mass drop tests or the simulated air-borne impacts. Throughout most of the velocity range the load factors in the free-fall drop tests were excessive by an amount approximately equal to the lift factor. At the higher velocities subsequent to the occurrence of tire bottoming, however, the load factors in the free-fall drop tests with the full weight exceeded those in the simulated air-borne impacts by as much as three or four times the lift factor.

These results indicate that throughout most of the velocity range the load factors measured in free-fall drop tests with the full weight can be approximately corrected for the effects of wing lift by subtracting the value of the lift factor from the load factors obtained in such tests. At the higher velocities, however, such simple corrections are inadequate to compensate for the greatly excessive loads produced by the early occurrence of tire bottoming in the free-fall drop tests with the full weight.

When tire bottoming occurs, the stiffness of the tire is greatly increased and a marked rise in the rate of shock-strut closure results. Since the shock strut is suddenly forced to absorb energy at a much higher rate, the loads on the landing gear are rapidly increased by tire bottoming. In the case of the simulated air-borne impacts and the reduced-mass drop tests, tire bottoming was delayed to higher impact velocities than in the free-fall drop tests with the full weight which involved much greater impact energies. In these cases, as in the free-fall full-weight tests, tire bottoming was accompanied by an appreciable increase in load.

At the limiting condition of zero vertical velocity, in those cases where the weight was not fully balanced by the lift force, the absorption of the potential energy associated with the settling of the upper mass to its static position was accompanied by load factors somewhat in excess of those corresponding to the unbalanced weight. Since the force resisting the settling is a variable, the maximum force obtained was greater than the average force (equal to the unbalanced weight) required for absorption of the potential energy. Values of the load factor for zero velocity were estimated from other data by means of calculations based on the energy-absorption characteristics of the landing gear.

Impact period.- In the case of large, flexible airplanes, or airplanes with concentrated masses in the wings, the rate of application of the landing-gear reactions becomes an important factor in determining the magnitude of dynamic loads and stresses produced in the structure. The rate of increase of the vertical load also governs the time of occurrence of wheel spin-up in landings with forward speed and determines the maximum values of the drag load produced. Since drop-test results may be used as a basis for the analysis of inertia loads in the airplane structure and drag loads on the landing gear, it is of interest to compare the time required for the maximum vertical load to be attained (impact period) in the reduced-mass drop tests with results for simulated air-borne impacts and free-fall drop tests with the full weight. Such comparisons are shown in figure 8.

These results indicate that the maximum landing-gear loads are attained somewhat more rapidly in the reduced-mass drop tests than in the simulated air-borne impacts. The free-fall drop tests with the full weight require a greater time for the attainment of the maximum load than do either the simulated air-borne impacts or the reduced-mass drop tests. The greatest differences in impact period exist at the lower values of vertical velocity. At velocities of approximately 11 feet per second, on the other hand, no appreciable differences were observed between the impact periods for the three types of tests.

As can be seen from figure 8, the impact period generally decreases as the vertical velocity increases; that is, the most rapid impacts take place at the highest vertical velocities. The greatest variation in impact period with velocity occurs in the free-fall drop tests with the full weight. On the other hand, for a lift factor of 1, there is only a minor variation of impact period with velocity in the simulated air-borne impacts and reduced-mass drop tests. As the lift factor is reduced, however, the periods for the simulated air-borne impacts and reduced-mass drop tests increase and begin to approach the results for the free-fall drop tests with full weight and exhibit the same trend of decreasing impact period with increasing velocity. At the high velocities the impact period appears to be virtually independent of wing

lift and the results of all three types of tests converge to a single
value at a vertical velocity of 11 feet per second.

   Shock-strut effectiveness.- The shock-strut effectiveness (some-
times called "efficiency") is defined as the ratio of the energy
absorbed by the shock strut to the product of the maximum landing-gear
load and the maximum strut stroke attained during an impact, or

$$\eta = \frac{\int_0^{s_{max}} F_g \, ds}{F_{g_{max}} s_{max}} = \frac{E_0}{F_{g_{max}} s_{max}}$$

This quantity is a measure of the extent to which a given combination
of maximum load and stroke has been utilized to absorb the energy of an
impact.

   Figure 9 presents a comparison of values of shock-strut effective-
ness for the three types of impacts under investigation. As can be seen
from the figure, the shock-strut effectiveness in the reduced-mass drop
tests was considerably lower than the results for the simulated air-
borne impacts. At the lower vertical velocities, the reduced-mass drop
tests differed in effectiveness from the simulated air-borne impacts by
as much as 22 percent. However, these differences decreased to 10 per-
cent or less at the higher velocities. The greatest shock-strut effec-
tiveness was attained in the free-fall drop tests with the full weight.
These tests resulted in values of effectiveness which were greater than
those for the simulated air-borne impacts by 5 percent or less, except
at the higher velocities where tire bottoming occurs. As is evident,
the free-fall drop tests with the full weight resulted in values of
strut effectiveness which were more representative of the simulated air-
borne impacts than were the results of the reduced-mass drop tests.

   In general, there was a decrease in shock-strut effectiveness with
an increase in vertical velocity. In addition, tire bottoming at the
higher velocities was in all cases followed by a marked reduction in
effectiveness.

   Variations in the wing lift factor resulted in relatively small
changes in shock-strut effectiveness for the simulated air-borne impacts.
The effectiveness in the reduced-mass drop tests, however, increased
appreciably as the lift factor was reduced. In the reduced-mass drop
tests representing the fully air-borne condition, the unusually low
values of effectiveness apparently resulted from the relatively small
dropping weights necessary to satisfy the energy requirements of these
tests. The increased weights used in the reduced-mass drop tests repre-
senting partial-lift conditions, on the other hand, resulted in high

values of effectiveness which begin to approach more closely those
obtained in the simulated air-borne impacts and free-fall drop tests
with the full weight. These results indicate that the magnitude of the
dropping weight has an appreciable effect on shock-strut effectiveness,
whereas the value of the applied wing lift force has only a minor effect.

Strut stroke.- In figure 10 the maximum values of strut stroke for
the reduced-mass drop tests are compared with the results obtained in
the simulated air-borne impacts and in the free-fall drop tests with
the full weight. As might be expected, the largest values of stroke
were attained in the drop tests with the full weight, whereas the
smallest values of stroke were attained in the simulated air-borne
impacts. The reduced-mass drop tests resulted in values of stroke
approximately halfway between those of the other two tests.

The greatest differences in the values of stroke attained in the
different types of tests occurred at the lower vertical velocities. In
this region, because the potential energy associated with the unbalanced
weight represents a fairly large portion of the total impact energy,
the free-fall drop tests resulted in values of stroke very much greater
than those attained in the simulated air-borne impacts. For example,
at a vertical velocity of 4 feet per second, the values of stroke
attained in the free-fall drop tests with the full weight and in the
reduced-mass impacts for $K_L = 1$ were, respectively, approximately
3 inches and $1\frac{1}{2}$ inches greater than those for the simulated air-borne
impacts with full wing lift. At the higher vertical velocities, how-
ever, where the potential energy is a relatively small part of the total
impact energy, the differences in stroke were less pronounced. At the
maximum vertical velocity of 11 feet per second, the impact energy was
sufficiently great to require the use of almost all of the available
stroke in all cases.

There was, of course, a general increase in stroke with vertical
velocity. The greatest variation was obtained in the simulated air-
borne impacts, whereas a less-marked variation of stroke with velocity
was obtained in the reduced-mass drop tests. In the case of the free-
fall drop tests with the full weight, because of the relatively large
amount of potential energy, almost all of the available stroke was used
even at the lower velocities. Thus, in these tests, there was relatively
little increase of stroke with velocity.

As might be expected, reductions in wing lift factor resulted in
an increase in stroke in both the simulated air-borne impacts and
reduced-mass drop tests, particularly at the lower values of vertical
velocity. In the simulated air-borne impacts this increase in stroke
was due to the increased potential energy associated with that part of

the total weight not balanced by the lift force. In the case of the
reduced-mass drop tests, the increase in stroke was due to the increased
weight necessary to satisfy the energy requirements of the reduced-lift
conditions.

As a result of the pronounced increase in stroke at the lower
velocities, which accompanied a decrease in lift factor, the reduced-
lift cases resulted in a smaller variation of stroke with vertical
velocity. For $K_L = 0.50$, the values of stroke attained in the reduced-
mass drop tests and the simulated air-borne impacts begin to approach
the results of the free-fall drop tests with the full weight.

In order to illustrate more clearly the marked effects of lift
factor on strut stroke, a composite plot of the trends previously dis-
cussed is shown in figure 11, which includes both simulated air-borne
and drop-test results. The curves were extrapolated to zero vertical
velocity by calculating the stroke required to produce absorption of
the potential energy by the air compression alone. In these calcula-
tions it was assumed that, because of the low rates of strut closure,
energy absorption by hydraulic resistance would be negligible.

It can be seen from figure 11 that the magnitudes of the wing lift
force and the initial vertical velocity had marked effects on the values
of stroke attained in the simulated air-borne impacts. In comparison,
the strokes attained in the reduced-mass drop tests were much greater
and were affected to a much smaller extent by variations in lift factor
and/or vertical velocity.

The excessive strokes, in conjunction with the conservative load
factors which were obtained in the reduced-mass drop tests, indicate
the relatively low effectiveness of energy absorption by the shock strut
previously noted for these tests.

Upper-mass travel.- In calculating the effective weight for the
reduced-mass drop tests, since the maximum values of upper-mass travel
for the equivalent air-borne impacts are usually not known, it is
assumed in the derivation of equation (4) that the mass travel is the
same in the air-borne impact as in the drop test. In order to evaluate
this assumption, figure 12 presents a comparison of values of upper-mass
travel for the reduced-mass drop tests with similar results for the
simulated air-borne impacts and free-fall drop tests with full weight.

At the higher vertical velocities the values of mass travel
attained in the simulated air-borne impacts were slightly greater than
those in the reduced-mass drop tests. At the lower velocities, how-
ever, the reduced-mass drop tests, which produced the larger strokes,

resulted in considerably greater values of mass travel than were
attained in the simulated air-borne impacts.

As might be expected, the mass travel, like the strut stroke, was
appreciably greater in the free-fall drop tests with the full weight
than in the simulated air-borne impacts or in the reduced-mass drop
tests. The greatest differences occurred at the lower values of ver-
tical velocity. In this region the trend of the data is similar to
that exhibited by the strut stroke as a result of the fact that the stroke
comprises the greater part of the mass travel since the tire deflection
associated with the relatively small loads at the lower velocities is
also correspondingly small.

There was a large increase in mass travel with an increase in
vertical velocity. The simulated air-borne impacts resulted in a
greater variation of mass travel with velocity than did any of the free-
fall drop tests.

Figure 13 illustrates the marked effects of wing lift factor on
the upper-mass travel. As in the case of the strut-stroke variations,
reductions in wing lift factor were accompanied by an appreciable
increase in mass travel for both the simulated air-borne impacts and
reduced-mass drop tests. This result was particularly pronounced in
the case of the simulated air-borne impacts at the low velocities
primarily because of the large variations in stroke which, as previ-
ously noted, accompanied differences in potential energy associated
with the unbalanced weight.

Energy.- Figure 14 presents a comparison of the impact energy and
shock-strut energy for the simulated air-borne impacts, reduced-mass
drop tests, and free-fall drop tests with the full weight.

For partial-wing-lift conditions, because the mass travel in the
reduced-mass drop tests was not the same as in the simulated air-borne
impacts, the impact energy in the two types of tests differed slightly.
It was previously noted that the values of mass travel in the reduced-
mass drop tests were high at the low velocities and somewhat low at
the high velocities, in comparison to those in the simulated air-borne
impacts. For values of lift factor less than one, therefore, the
assumption of equal values of mass travel in calculating the weights
for the reduced-mass drop tests (equation (4)) resulted in drop tests
having somewhat excess energy at the low velocities and slightly insuf-
ficient energy at the high velocities compared to the simulated air-
borne impacts, as may be seen from figure 15. These differences in
energy are, however, only a small percentage of the total energy through-
out the upper part of the velocity range where the potential energy is
a relatively small fraction of the total impact energy. In the case

of $K_L = 1$, of course, since there is no potential energy, the mass travel in the simulated air-borne impacts has no significance and the application of equation (4) results in reduced-mass drop tests which necessarily satisfy the energy requirements for the fully air-borne condition exactly.

Because of the large potential energy in the free-fall drop tests with the full weight, the impact energy in these tests greatly exceeded the energy in the other tests. The greatest differences in energy between the tests with $K_L = 0$ and $K_L = 1$ occurred at the high velocities where the largest values of mass travel were obtained. As a result of the increase in mass travel which accompanied a reduction in lift factor in the simulated air-borne impacts, the impact energy in these tests increased somewhat nonlinearly with decreasing values of K_L, particularly at the low velocities.

A comparison of the energy absorbed by the shock strut in the different types of tests is shown in figure 16. It was previously noted that the reduced-mass drop tests produced excessive values of stroke at low vertical velocities and excessive loads at high velocities in comparison with the simulated air-borne impacts. As a result, the amount of energy absorbed by the shock strut was generally somewhat greater in the drop tests than in the simulated air-borne impacts, notwithstanding the reduced shock-strut effectiveness in the drop tests. For the case of $K_L = 1$, however, the amount of energy absorbed by the shock strut at the lower velocities in these tests was slightly greater than the strut energy absorption in the reduced-mass drop tests.

The relationship between shock-strut energy and impact energy is shown in figure 17. In general, the values of the ratio of strut energy to impact energy differed by only a relatively small amount in the three types of tests. Except for the simulated air-borne impacts for the case of $K_L = 1$, there was only a minor variation in the energy ratio with velocity, the shock strut absorbing between 75 and 85 percent of the total impact energy. Similarly, the value of the wing lift factor appeared to have very little effect on the energy ratio. In general this ratio was somewhat greater for the reduced-mass drop tests than for the simulated air-borne impacts. For the simulated fully air-borne impacts ($K_L = 1$) the increased energy absorption of the strut at low velocities resulted in a marked increase in the energy ratio in this region, the shock strut absorbing almost all the impact energy at vertical velocities approaching zero.

SUMMARY OF RESULTS

In order to permit an evaluation of the reduced-mass method of representing wing-lift effects in free-fall drop tests of landing gears, the results of such tests have been compared with data obtained in simulated air-borne impacts and in free-fall drop tests with the full dropping weight. These comparison indicate that:

1. Landing-gear load factors determined from the reduced-mass drop tests were in fairly good agreement with data obtained in the simulated air-borne impacts throughout most of the vertical-velocity range. At the higher velocities, however, the reduced-mass drop tests yielded load factors up to 12 percent higher than those in the simulated air-borne impacts; this discrepancy increased to as much as 18 percent following the occurrence of tire bottoming.

2. Throughout most of the velocity range, the free-fall drop tests with the full weight resulted in load factors which were greater than those obtained in the simulated air-borne impacts by an amount approximately equal to the lift factor. Except for tests at the extremities of the velocity range, the load factors from the drop tests with the full weight can be approximately corrected for the effects of wing lift by subtracting the lift factor from the load factors obtained. At the higher velocities, however, such simple corrections are inadequate to compensate for the greatly excessive loads following the early occurrence of tire bottoming in the free-fall drop tests with the full weight, which exceeded the load factors in the simulated air-borne impacts by as much as three or four times the lift factor.

3. The time required for the maximum load to be attained was somewhat smaller in the reduced-mass drop tests than in the simulated air-borne impacts. The free-fall drop tests with the full weight required a greater time for the attainment of the maximum load than did either of the other two types of tests. These differences in time were most pronounced at low vertical velocities and became very small at high velocities. In general, the time to reach maximum load decreased with increasing velocity and increased with decreasing lift factor.

4. The shock-strut effectiveness in the reduced-mass drop tests was considerably lower than in the simulated air-borne impacts, particularly at the lower vertical velocities where differences in strut effectiveness as great as 22 percent were found. However, these differences decreased to 10 percent or less at the higher velocities. The effectiveness in the free-fall drop tests with the full weight, however, was approximately 5 percent greater than in the simulated air-borne impacts and more closely approximated the results of the simulated air-borne impacts than did the reduced-mass drop tests. In general, there

was a decrease in effectiveness with an increase in vertical velocity. Whenever tire bottoming occurred at high vertical velocities, a marked reduction in strut effectiveness resulted.

5. The largest values of strut stroke and upper-mass travel were attained in the free-fall drop tests with the full weight, whereas the smallest displacements were attained in the simulated air-borne impacts. The displacements in the reduced-mass drop tests were approximately halfway between the results for the other two types of tests. The greatest differences in displacement between the various tests occurred at the low velocities. At the high velocities the displacements were in fairly good agreement. The greatest increase in the displacements with vertical velocity occurred in the simulated air-borne impacts for a lift factor $K_L = 1$. Reductions in lift factor were accompanied by increased displacements at the lower velocities which resulted in a smaller variation of displacement with velocity.

6. The assumption that the mass travel in air-borne impacts is the same as in reduced-mass drop tests, which was used in calculating the weights for the latter tests, resulted in reduced-mass drop tests which, for partial-lift conditions, had somewhat excessive energy at low vertical velocities and very slightly insufficient energy at the high velocities, in comparison with the simulated air-borne impacts. The impact energy in the free-fall drop tests with the full weight was, of course, greatly in excess of the energy in any of the other tests.

7. The energy absorbed by the shock strut was generally somewhat greater in the reduced-mass drop tests than in the simulated air-borne impacts. The greatest strut energy absorption naturally occurred in the free-fall drop tests with the full weight. In general, the values of the ratio of strut energy to impact energy differed by only a relatively small amount in the three types of tests. Except for the simulated air-borne impacts for $K_L = 1$, there was only a minor variation in the energy ratio with velocity or lift factor. In most cases the strut absorbed between 75 and 85 percent of the total energy. In the case of the simulated air-borne impacts for $K_L = 1$, there was a marked increase in the ratio of strut energy to impact energy with a decrease in velocity. At the lowest velocities for this case the strut absorbed almost all the impact energy.

CONCLUDING REMARKS

The foregoing summary of results obtained in the present investigation indicates that the reduced-mass method of drop testing landing gears, although yielding somewhat conservative results, in general more closely

approximates the results of air-borne impacts and is an appreciable improvement over the former very conservative practice of using the full weight in free-fall drop tests. However, when a more exact representation of the time history of the landing-gear behavior is required, as in tests in which drag loads are simulated by the method of wheel spin-up or in tests which are used as a basis for dynamic analyses of flexible structures, it may be necessary to simulate wing lift by mechanical means rather than by the reduced-mass method of free-fall drop testing.

Langley Aeronautical Laboratory
    National Advisory Committee for Aeronautics
        Langley Field, Va., March 29, 1951

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    Restricted Purpose Categories. Pt. 3 of Civil Air Regulations,
    Civil Aero. Board, U. S. Dept. Commerce, Nov. 1, 1949.

2. Anon.: Airplane Airworthiness - Transport Categories. Pt. 4b of
    Civil Air Regulations, Civil Aero. Board, U. S. Dept. Commerce,
    July 20, 1950.

3. Batterson, Sidney A.: The NACA Impact Basin and Water Landing Tests
    of a Float Model at Various Velocities and Weights. NACA Rep. 795,
    1944.

TABLE I

LANDING-GEAR PERFORMANCE IN FREE-DROP TESTS

$$\left[K_L = 0\right]$$

W_T (lb)	V_{v_o} (fps)	p_o (lb/sq in.)	d (in.)	s (in.)	n_g	E_i (ft-lb)	E_o (ft-lb)	E_o/E_i	η (percent)	t_i (sec)
2500	2.15	43.5	9.72	6.86	1.48	2205	1710	0.776	85.3	0.354
	3.66		9.83	6.92	1.77	2568	2009	.782	83.1	.126
	4.69		9.79	6.92	2.15	2894	2298	.794	78.3	.116
	6.29		9.99	6.97	2.72	3619	2885	.797	77.1	.103
	8.11		10.63	7.12	3.60	4770	3777	.792	74.6	.093
	10.88		11.50	7.17	6.54	6995	5528	.790	59.7	.073
2000	2.15	34.3	8.96							
	3.66		8.76							
	4.69		8.65							
	6.29		8.69							
	8.11		9.36							
	10.88		10.24							
1500	2.15	25.1	7.91							
	3.66		8.26							
	4.69		8.07							
	6.29		8.07							
	8.11		8.22							
	10.88		9.01							
1000	2.15	16.0	6.90							
	3.66		6.91							
	4.69		7.03							
	6.29		7.30							
	8.11		7.31							
	10.88		7.35							

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TABLE II

LANDING-GEAR PERFORMANCE IN REDUCED-MASS DROP TESTS

$$\left[W_{T_e} = 2500 \text{ lb}\right]$$

K_{L_e}	V_{v_o} (fps)	W_{T_r} (lb)	p_o (lb/sq in.)	d_r (in.)	s_r (in.)	E_{i_r} (ft-lb)	E_{i_e} (ft-lb)	E_{i_e}/E_{i_r}	n_{g_r}	n_{g_e}	E_{o_r} (ft-lb)	E_{o_i}/E_{i_r}	η_r (percent)	t_{i_r} (sec)
1.00	4.69	1000	16.0	6.78	5.66	907	855	0.942	3.18	1.17	737	0.813	56.6	0.073
	6.29	1250	20.5	7.26	6.01	1525	1537	1.008	3.78	1.79	1248	.818	58.9	.075
	8.11	1500	25.1	8.18	6.48	2556	2556	1.000	4.52	2.61	2087	.817	62.5	.075
	10.88	1750	29.7	9.51	6.99	4607	4600	.999	6.75	4.61	3772	.819	59.3	.073
.75	4.69	1300	21.5	7.34	5.87	1240	1237	.998	2.77	1.37	1026	.827	64.8	.078
	6.29	1550	26.1	8.00	6.30	1977	1950	.986	3.41	2.04	1655	.837	65.1	.079
	8.11	1700	28.8	8.48	6.59	2939	2997	1.020	4.21	2.79	2360	.803	65.1	.077
	10.88	1900	32.5	9.91	7.03	5065	5116	1.010	6.90	5.15	4060	.802	56.8	.071
.50	4.69	1650	27.9	8.07	6.34	1674	1695	1.013	2.48	1.59	1382	.826	69.4	.090
	6.29	1800	30.6	8.54	6.66	2388	2430	1.017	3.15	2.22	2012	.843	69.0	.085
	8.11	1950	33.4	9.09	6.92	3471	3503	1.009	3.93	3.02	2870	.827	69.6	.083
	10.88	2050	35.2	10.22	7.04	5518	5664	1.027	6.52	5.28	4378	.793	59.6	.074

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TABLE III

LANDING-GEAR PERFORMANCE IN SIMULATED AIR-BORNE IMPACTS

$$\left[W_T = 2500 \text{ lb;} \atop p_o = 43.5 \text{ lb/sq in.} \right]$$

K_L	V_{v_o} (fps)	n_g	d (in.)	s (in.)	E_i (ft-lb)	E_o (ft-lb)	$\dfrac{E_o}{E_i}$	η (percent)	t_i (sec)
1.00	3.37	0.78	4.44	3.41	441	409	0.927	78.0	0.080
	4.35	1.12	5.40	4.16	735	689	.937	74.9	.087
	5.29	1.37	6.18	4.72	1087	952	.876	74.4	.081
	6.64	1.87	7.27	5.43	1713	1437	.839	71.6	.082
	8.29	2.65	8.50	5.95	2670	2207	.827	70.8	.080
	11.00	3.99	10.22	6.56	4702	3510	.746	68.0	.073
.75	4.54	1.25	6.03	4.71	1150	907	.789	78.2	.090
	5.35	1.54	6.80	5.20	1466	1197	.817	75.6	.090
	6.06	1.81	7.41	5.62	1813	1491	.822	74.4	.092
	7.37	2.33	8.30	6.12	2543	2051	.807	72.8	.087
	8.92	2.98	9.47	6.59	3585	2795	.780	72.0	.087
	11.41	5.05	10.60	7.15	5611	4335	.773	60.8	.072
.50	5.35	1.76	7.82	5.92	1927	1558	.809	75.8	.097
	6.06	2.05	8.21	6.17	2296	1902	.828	76.2	.097
	6.78	2.29	8.70	6.37	2692	2110	.784	73.1	.095
	7.91	2.79	9.32	6.63	3402	2718	.799	74.5	.087
	9.04	3.28	10.11	6.80	4228	3239	.766	73.5	.084
	9.87	3.95	10.38	7.00	4866	3715	.763	68.0	.082
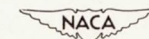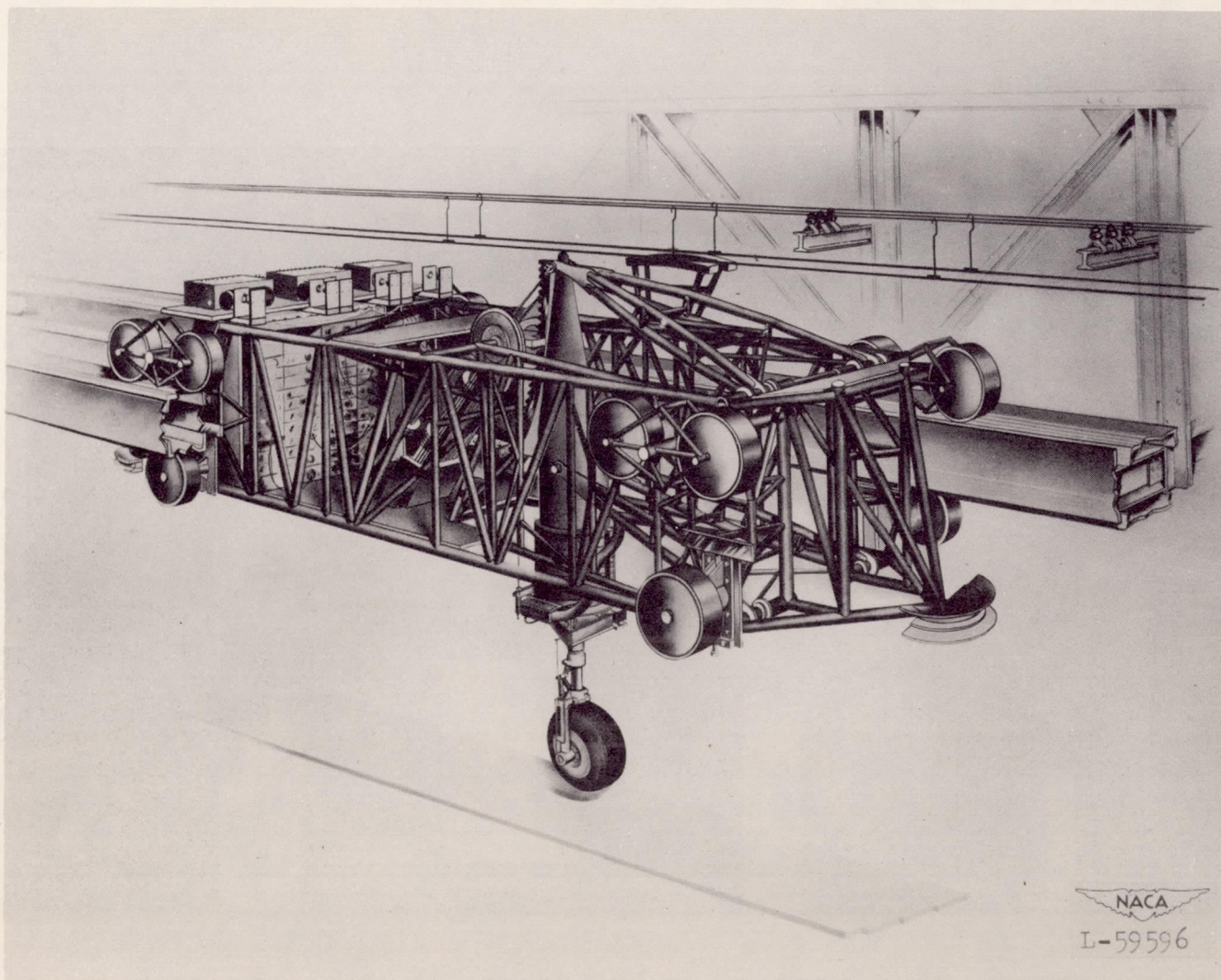
Figure 1.- View of Langley impact-basin carriage adapted for landing-
gear tests.
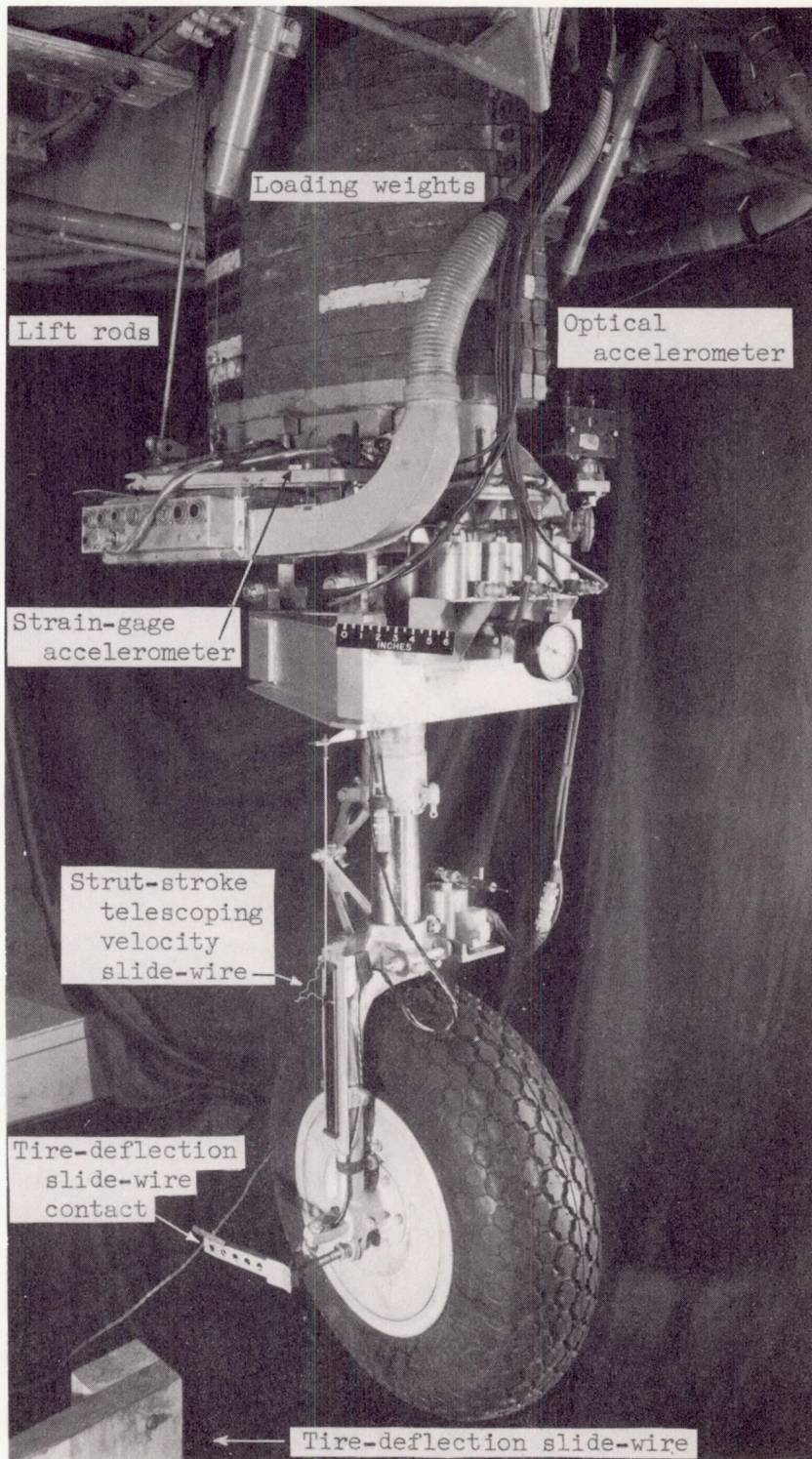
Figure 2.- View of landing gear and instrumentation.

Boom

Lift cable

Attachment
fitting

Orifice details
(Dimensions in inches)

.320

.250   .250 R

2.936
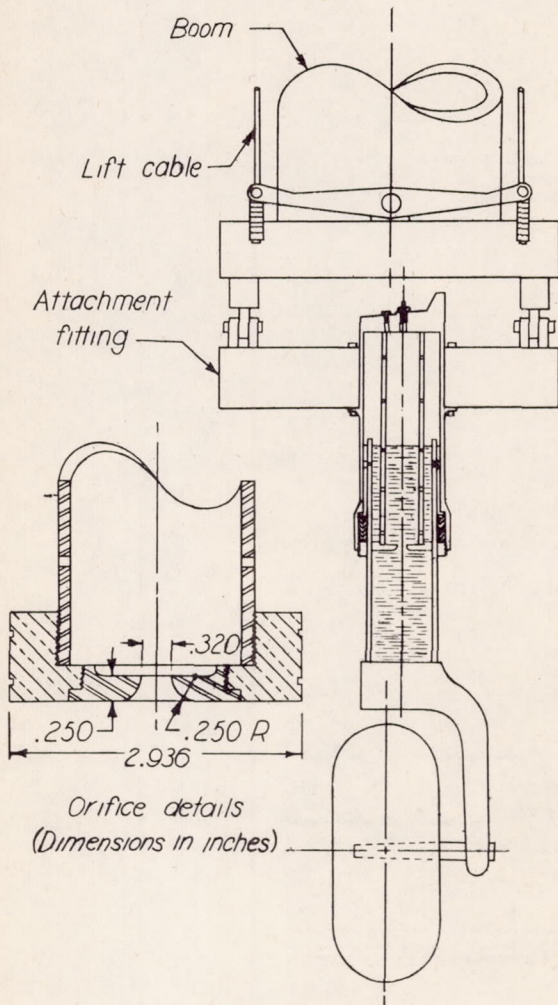
LANDING-GEAR SPECIFICATIONS

Air-supporting area, sq in. 8.30
Oil-supporting area, sq in. 6.78
Air volume - extended, cu in. . . . 61.26

Stroke, maximum, in. . . . . $7\frac{3}{8}$

Static extension, in. . . . . $1\frac{1}{8}$

Fluid specification AN-VV-O-336B
Fluid volume, cu in.   123
Strut inclination to vertical,
  deg   0
Tire diameter, in.   27
Tire type . . . . Smooth contour (type I),
                        nonskid tread
Tire pressure, psi   32
Landing-gear weight, lb   150
Unsprung weight, lb   131

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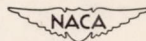
Figure 3.- Landing gear tested in Langley impact basin.
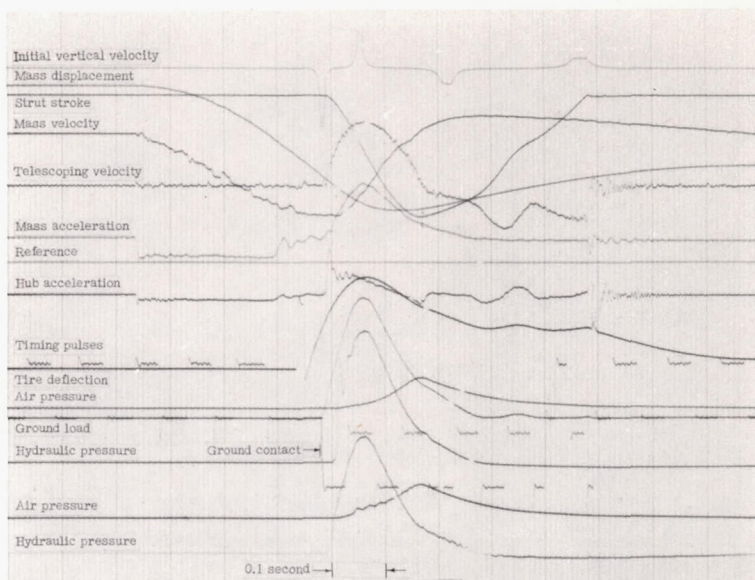
(a)   Simulated air-borne impact. W_T = 2500 pounds;
V_{v_o} = 8.29 feet per second; K_L = 1.00.
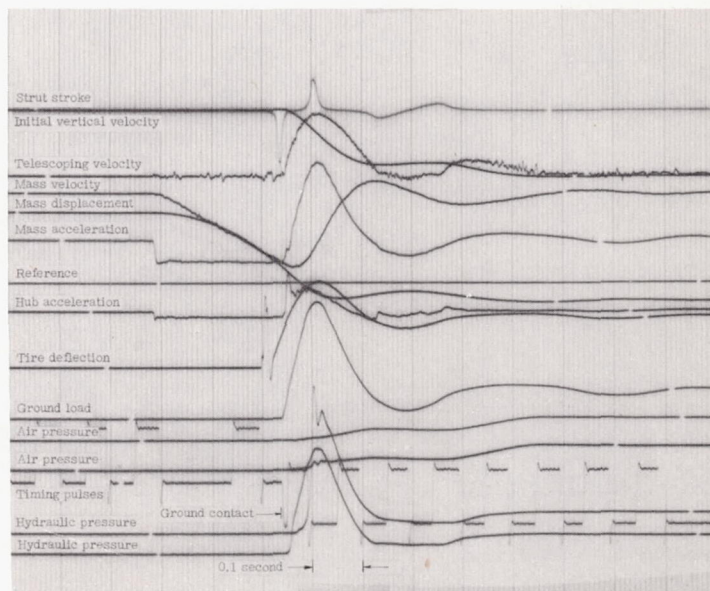
(b)   Reduced-mass drop test. W_{T_e} = 2500 pounds; W_{T_r} = 1500 pounds;
V_{v_o} = 8.11 feet per second; K_{L_e} = 1.00.
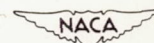
Figure 4.- Typical records of simulated air-borne impacts and reduced-mass
drop tests (half size).
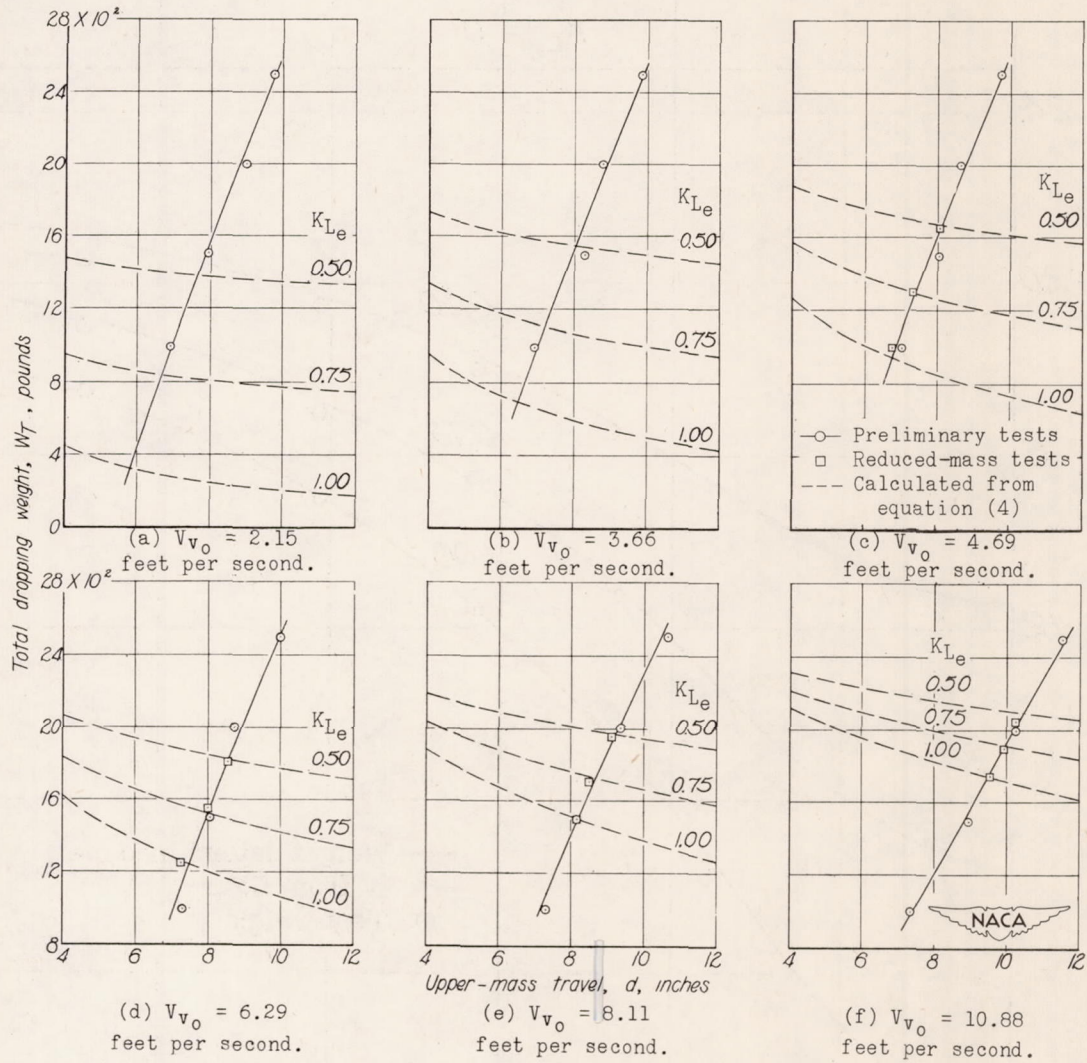
Figure 5.- Variation of mass travel with weight in free-fall drop tests.
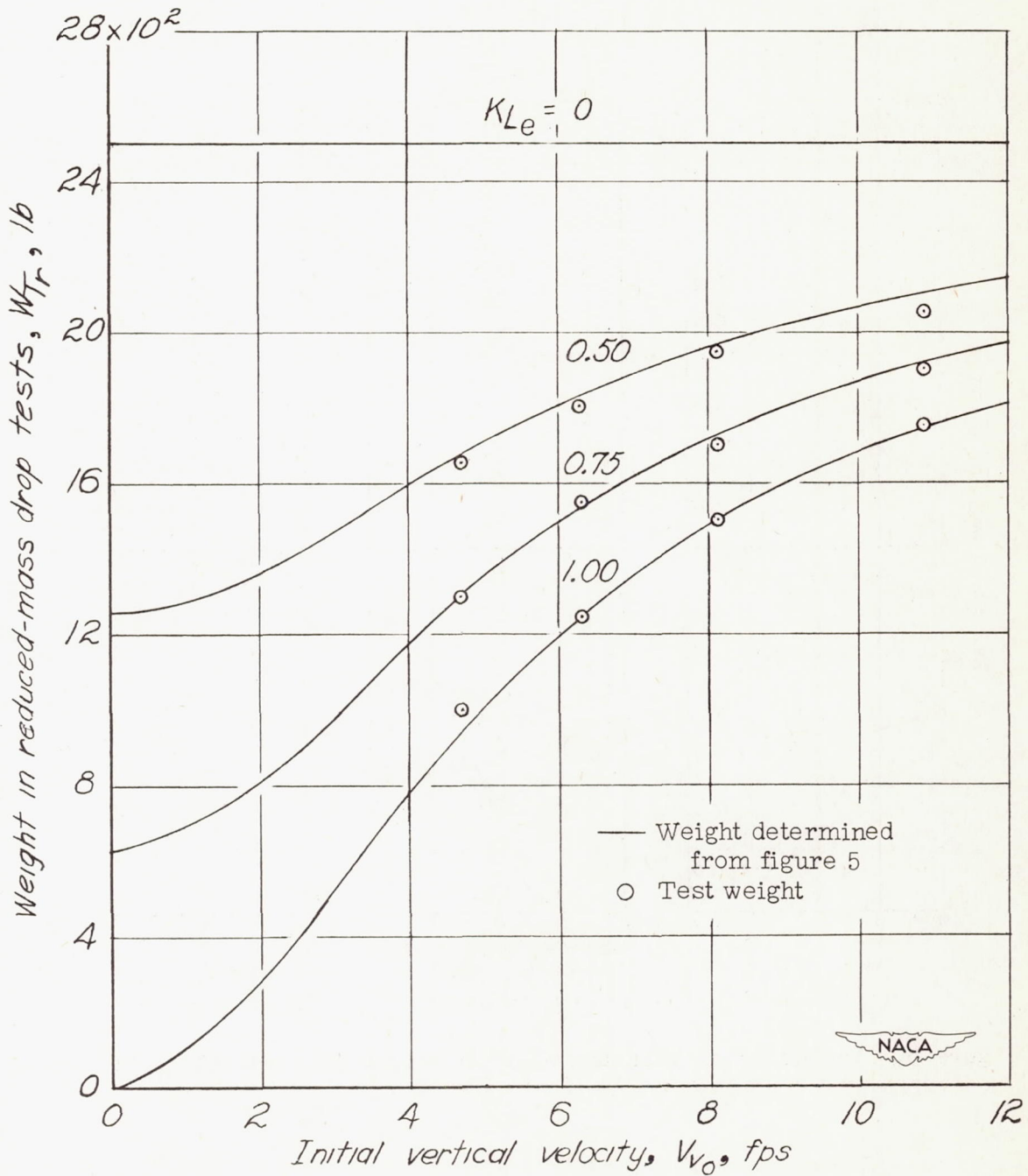
Figure 6.- Variation of weight in reduced-mass drop tests with vertical velocity.
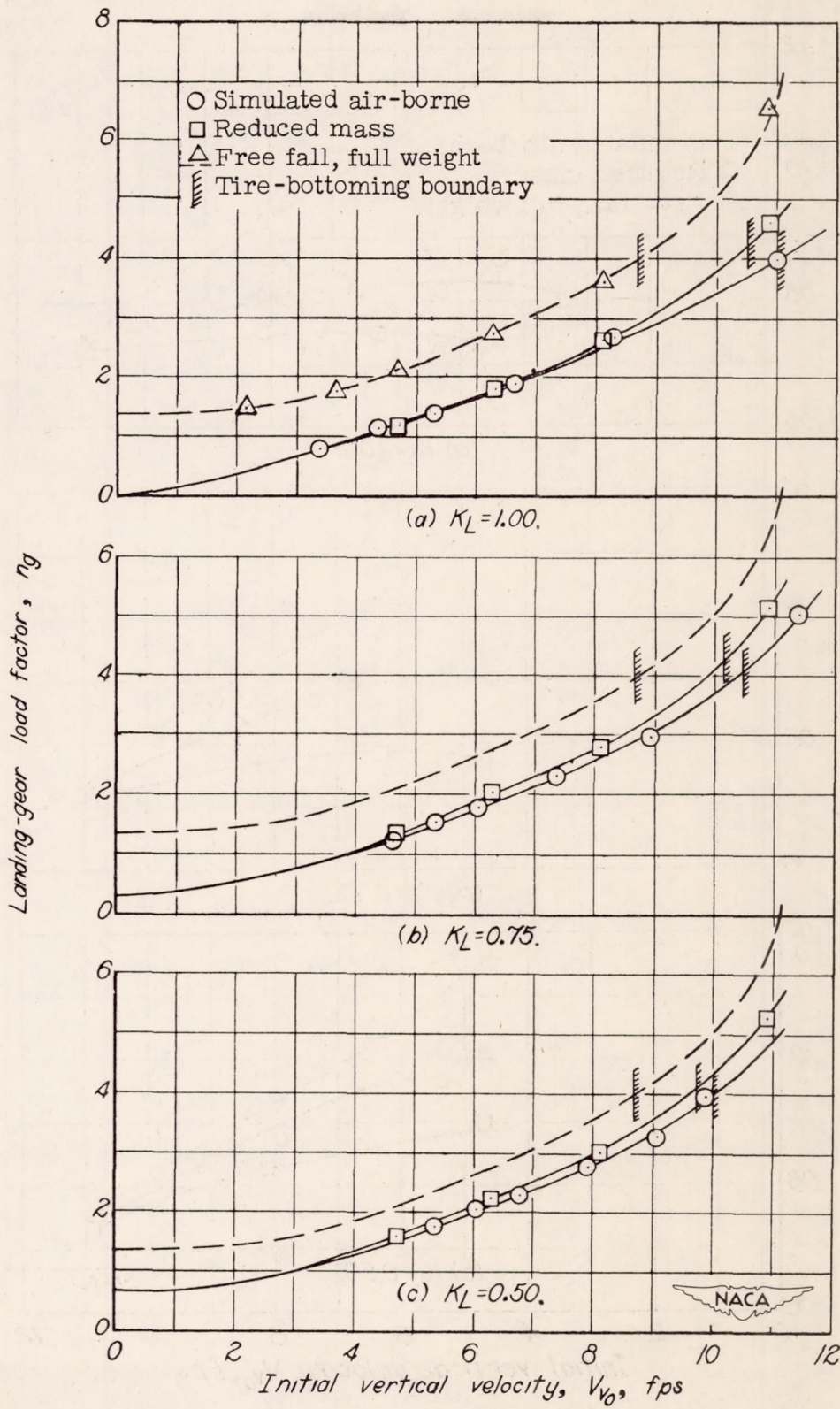
Figure 7.- Variation of landing-gear load factor with vertical velocity.

(a) $K_L = 1.00$.

(b) $K_L = 0.75$.

(c) $K_L = 0.50$.
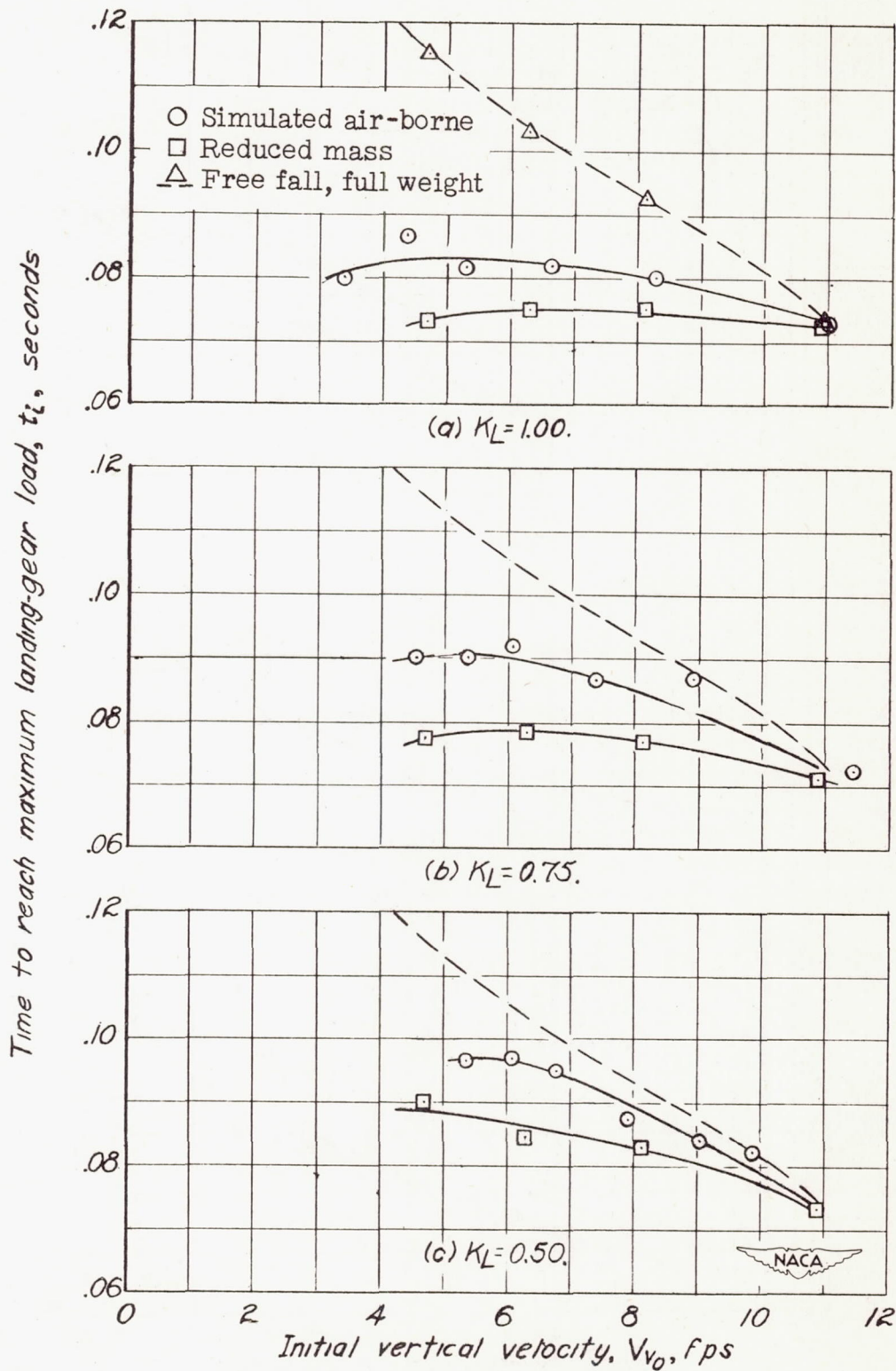
Figure 8.- Variation of time to reach maximum landing-gear load with vertical velocity.
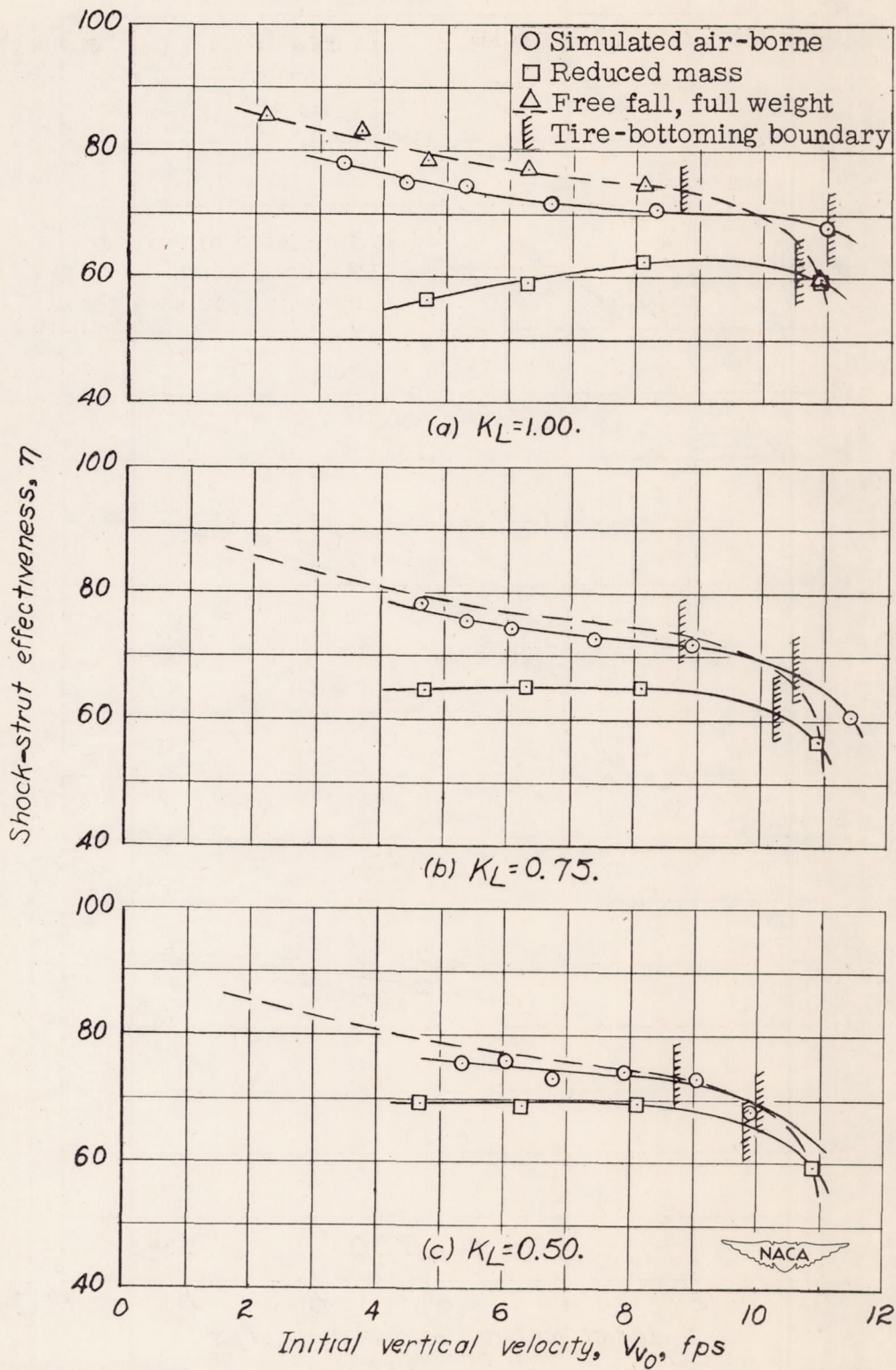
Figure 9.- Variation of shock-strut effectiveness with vertical velocity.
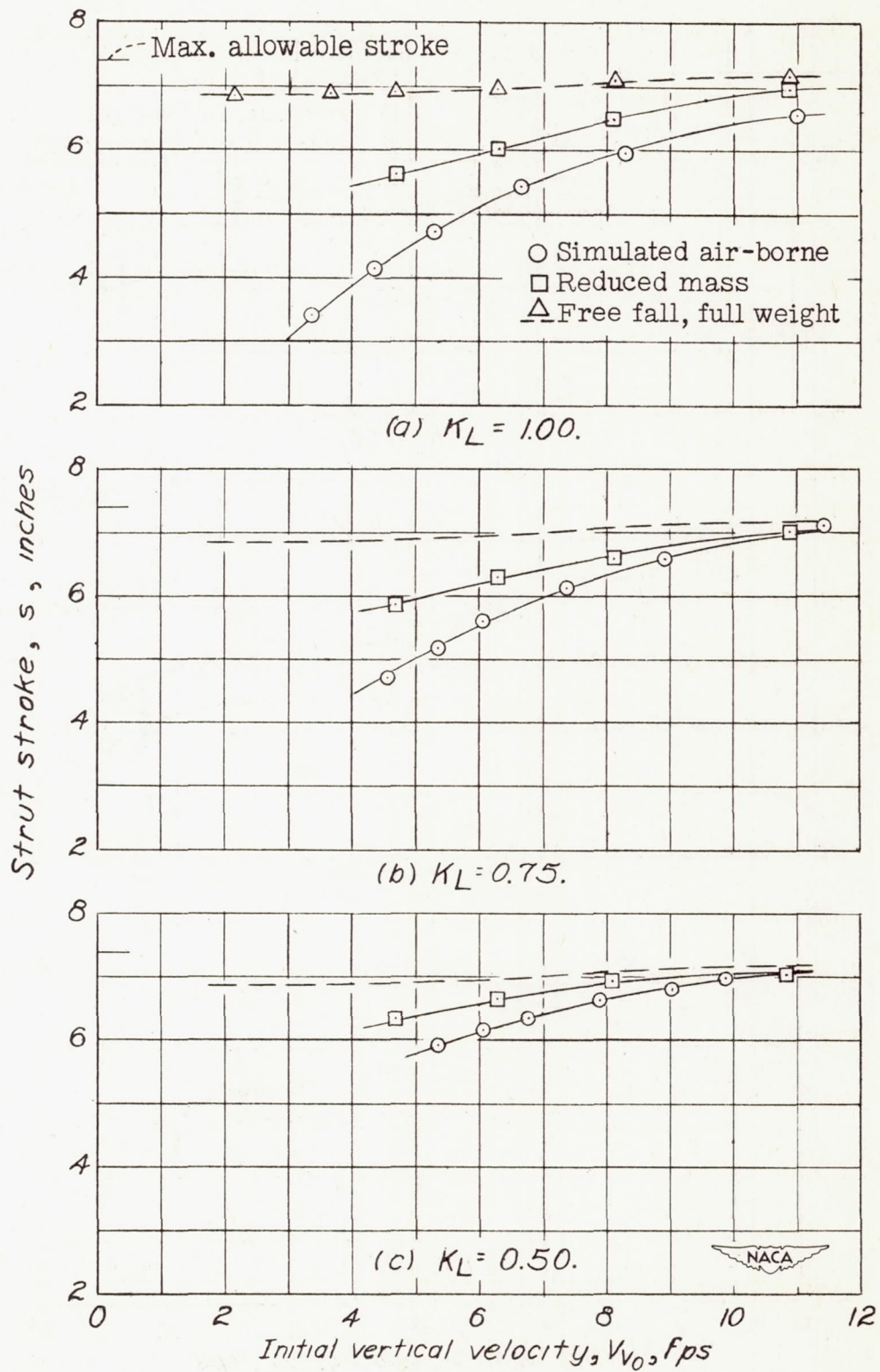
Figure 10.- Variation of strut stroke with vertical velocity.
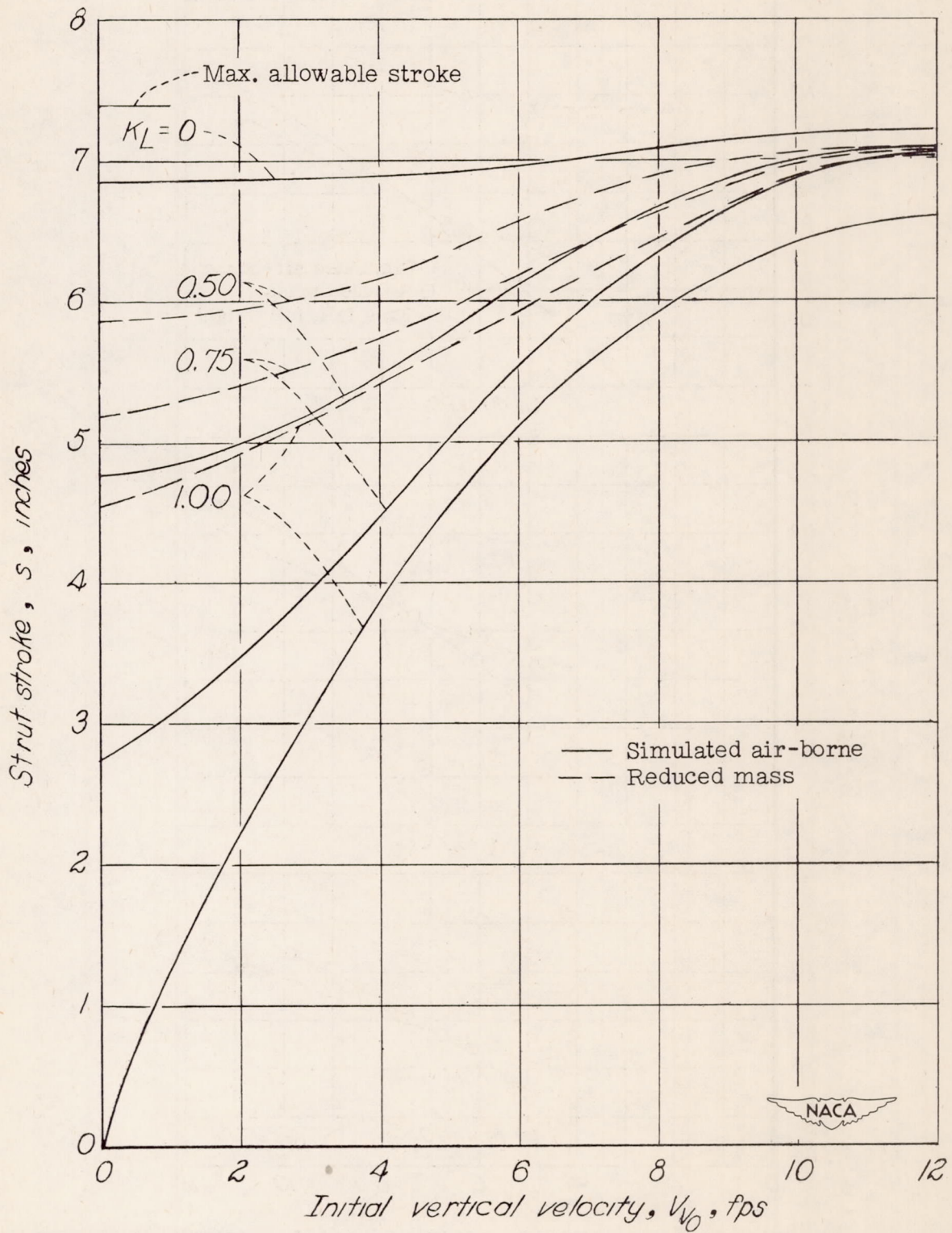
Figure 11.- Effect of wing lift on shock-strut stroke in simulated air-borne
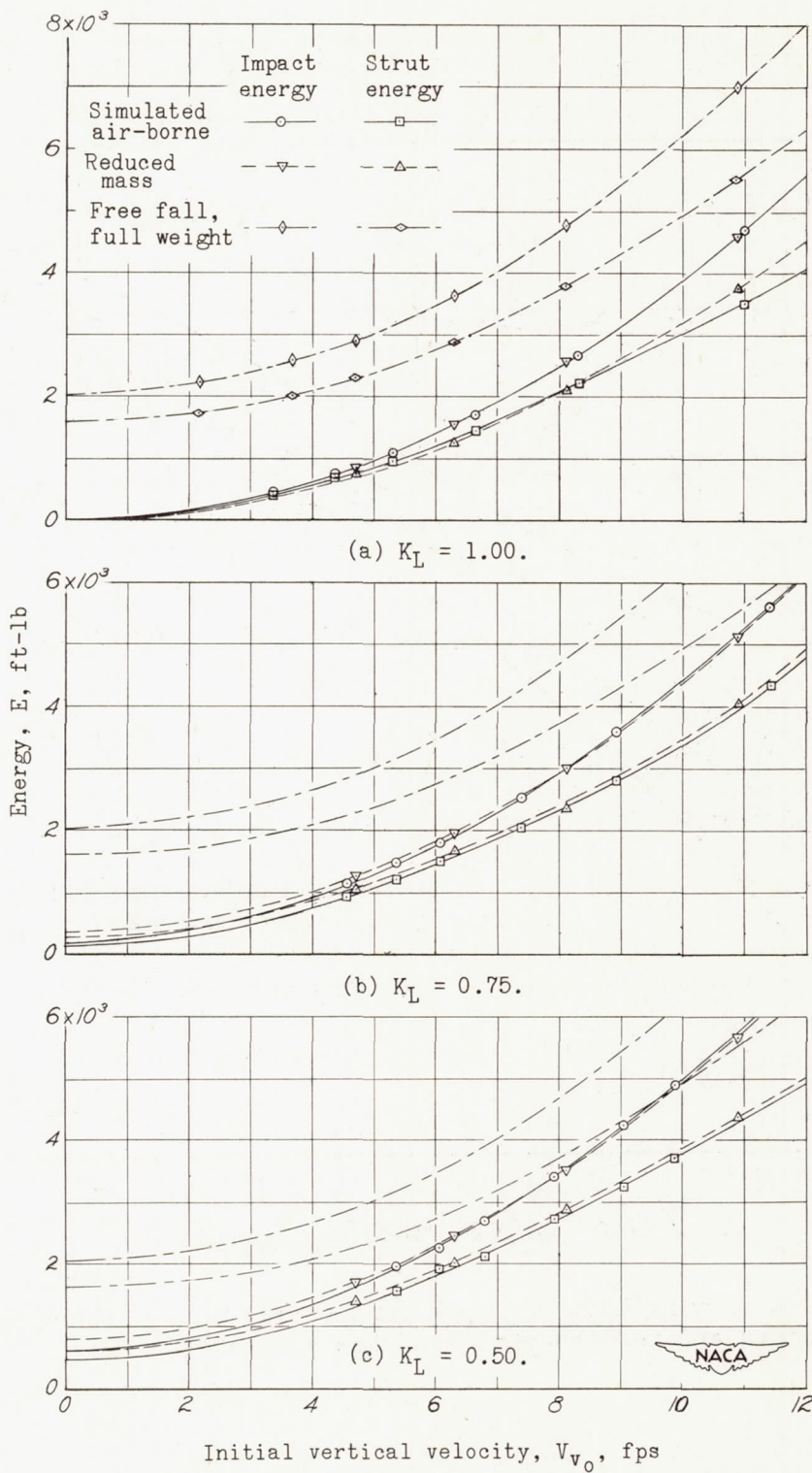impacts and reduced-mass drop tests (see fig. 10).

(a) $K_L = 1.00$.

(b) $K_L = 0.75$.

(c) $K_L = 0.50$.

○ Simulated air-borne
□ Reduced mass
△ Free fall, full weight

Upper-mass travel, d, inches

Initial vertical velocity, V_{V_0}, fps
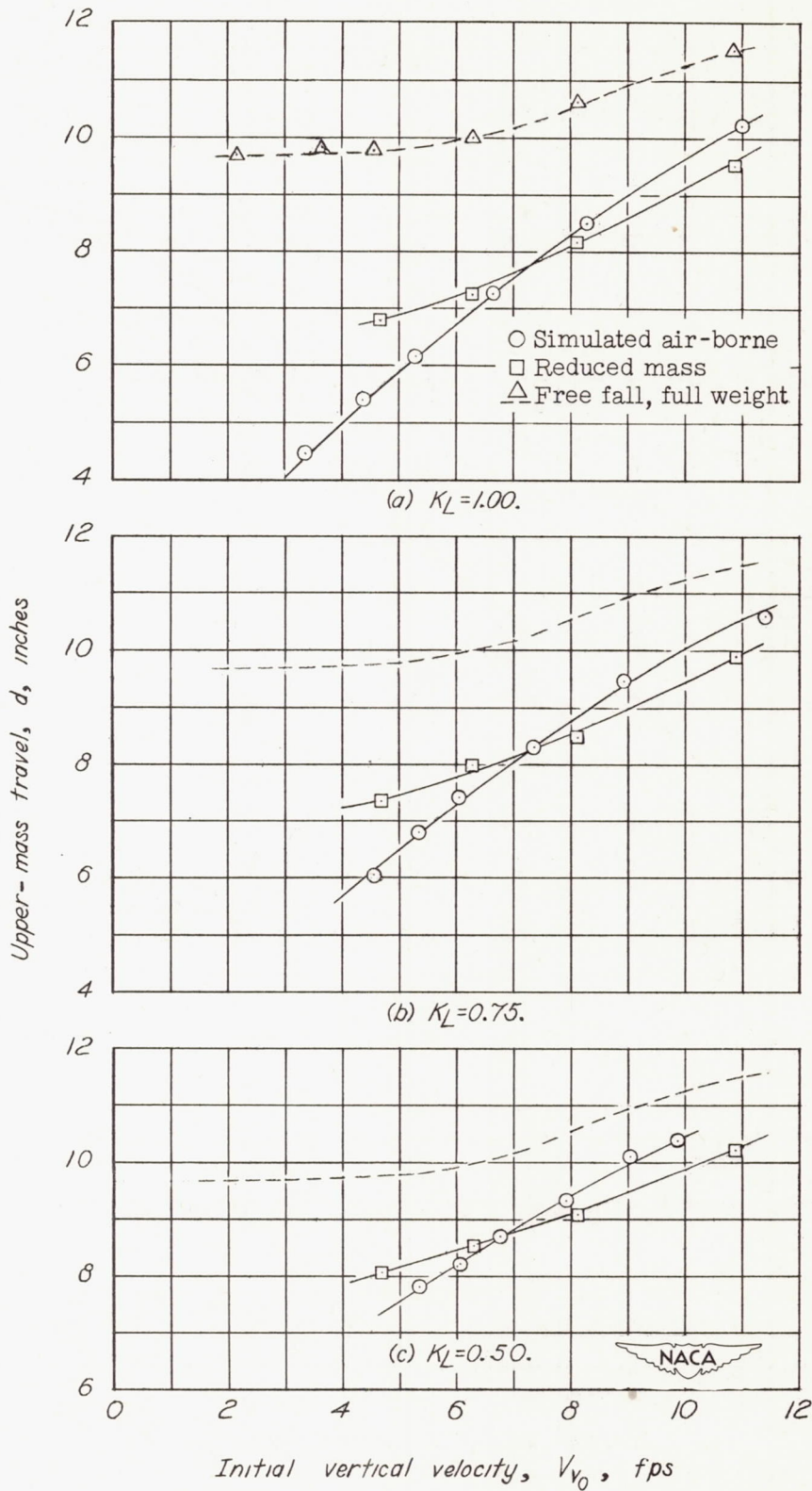
Figure 12.- Variation of upper-mass travel with vertical velocity.
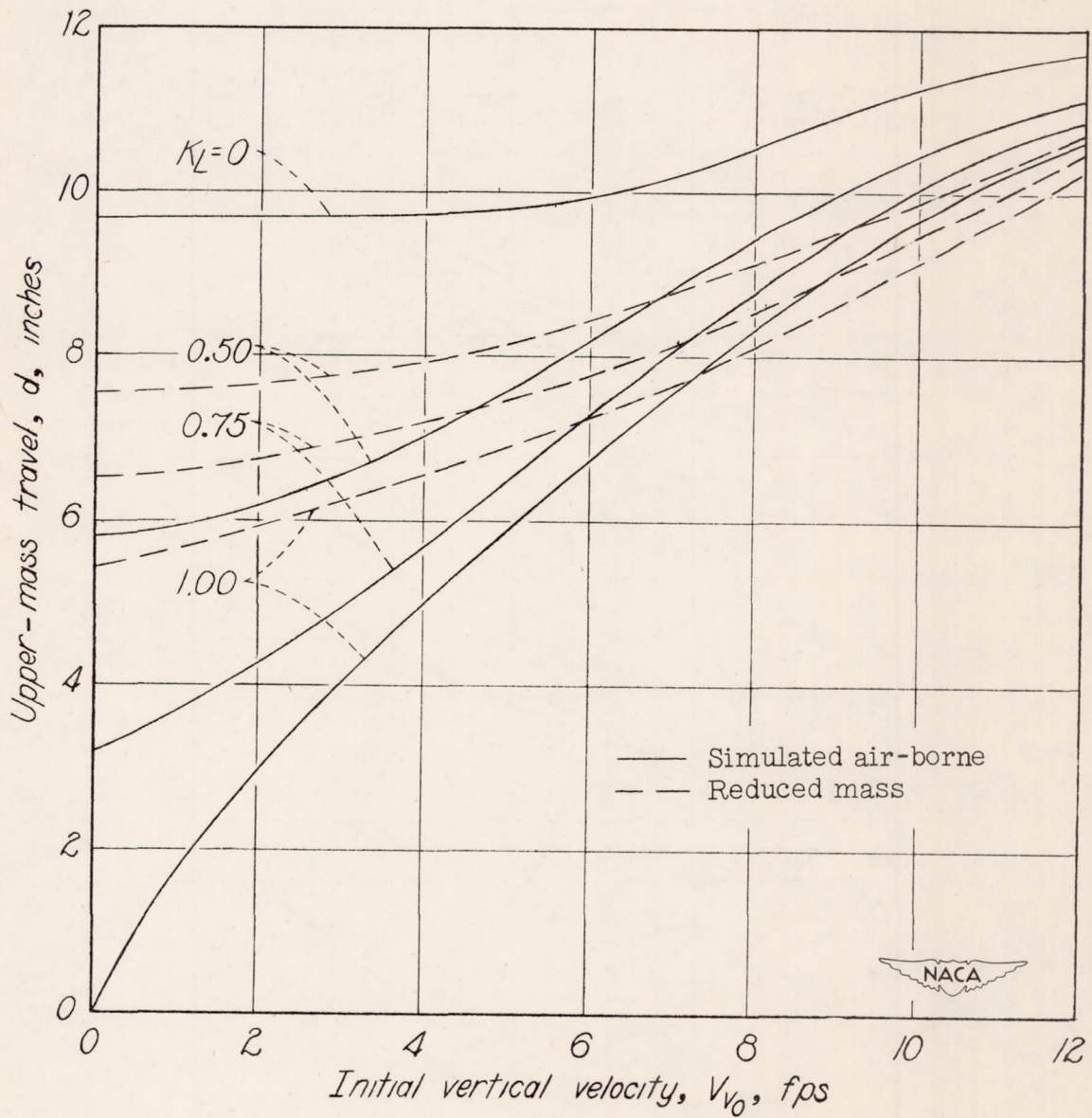
Figure 13.- Effect of wing lift on upper-mass travel in simulated air-borne impacts and reduced-mass drop tests (see fig. 12).

(a) $K_L = 1.00$.

(b) $K_L = 0.75$.

(c) $K_L = 0.50$.

Initial vertical velocity, V_{v_0}, fps

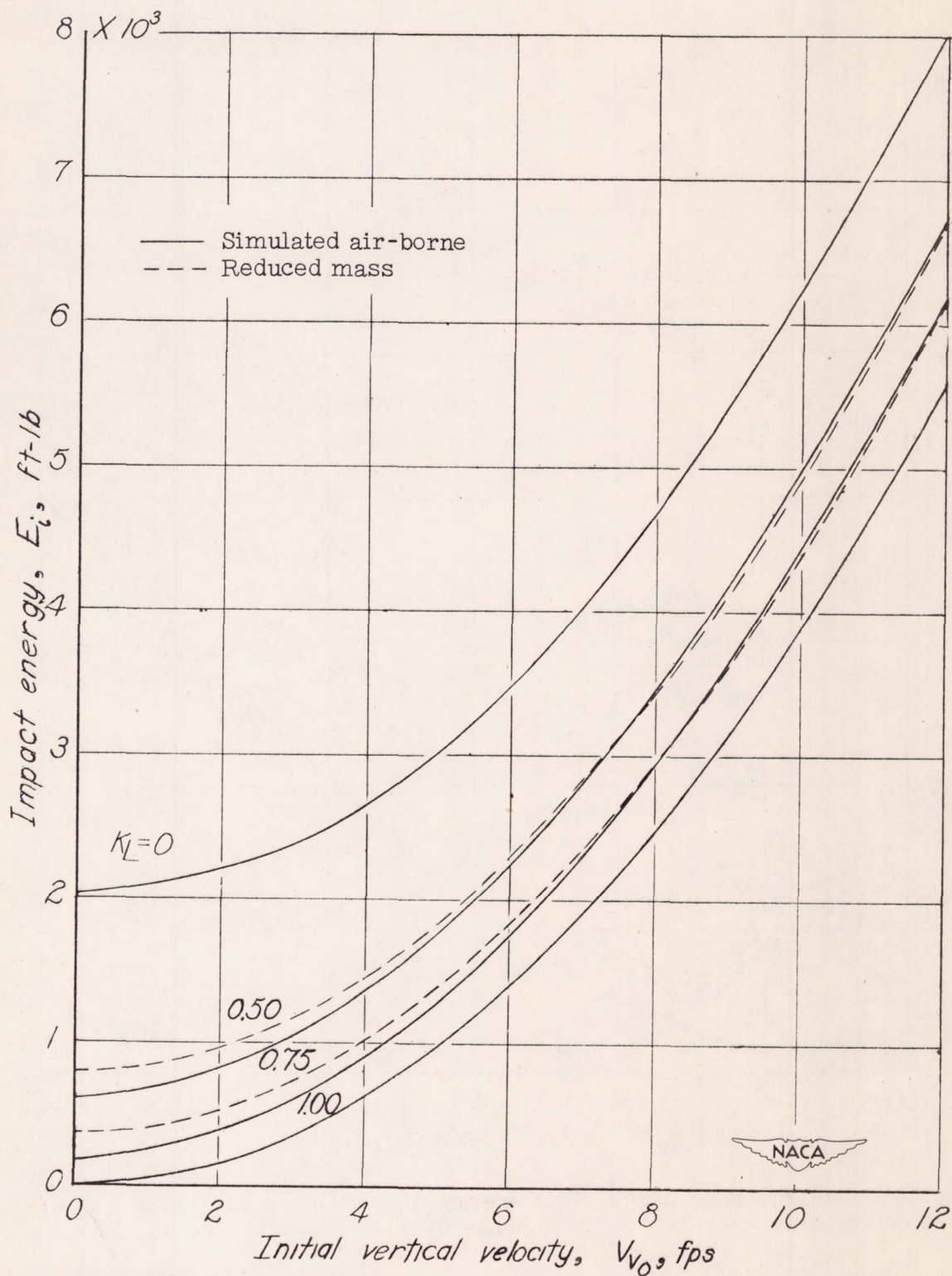Figure 14.- Variation of impact energy and shock-strut energy with
vertical velocity.

Figure 15.- Comparison of impact energy in simulated air-borne impacts and reduced-mass drop tests for a range of lift factors (see fig. 14).
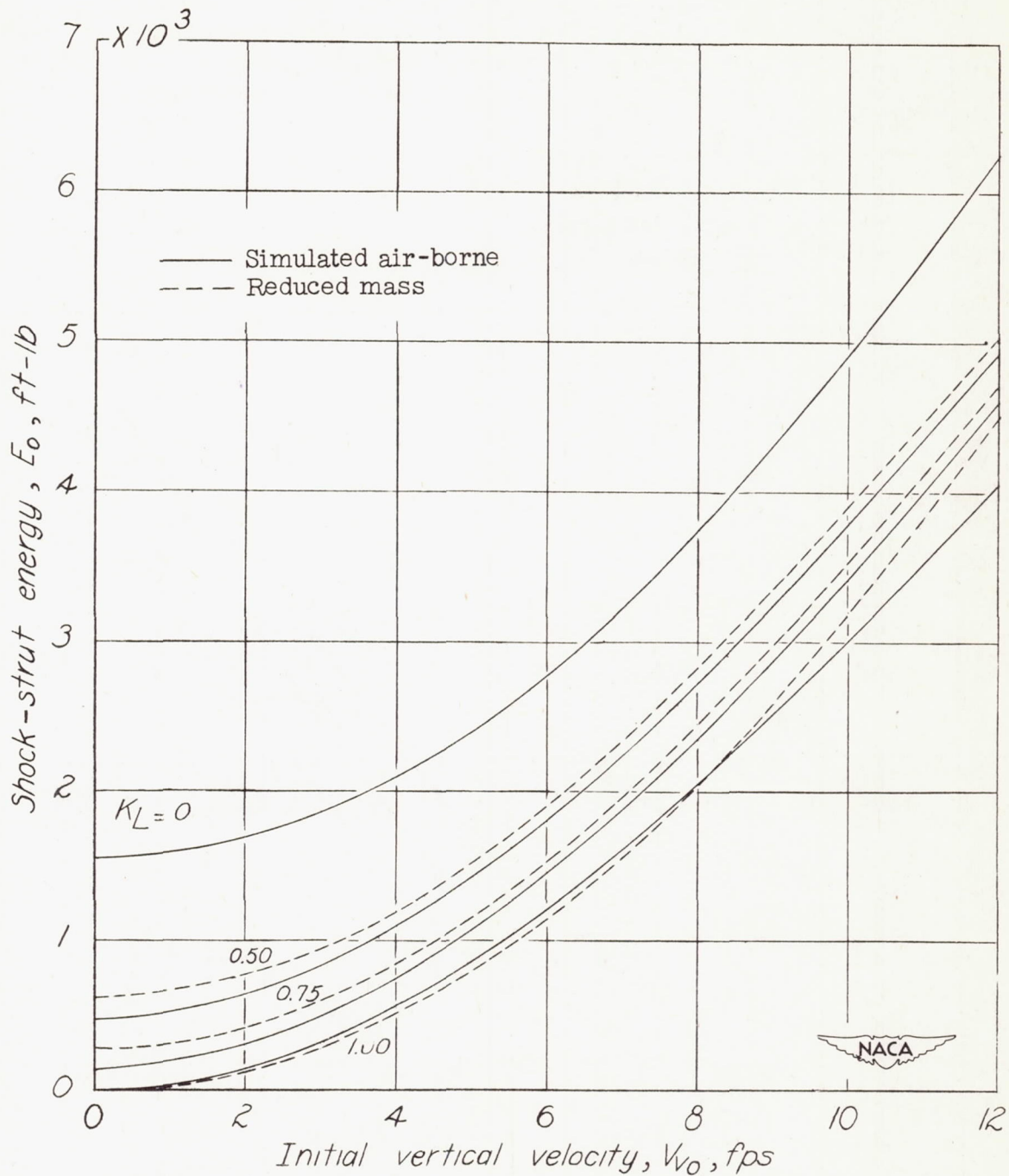
Figure 16.- Comparison of shock-strut energy in simulated air-borne impacts and reduced-mass drop tests for a range of lift factors (see fig. 14).
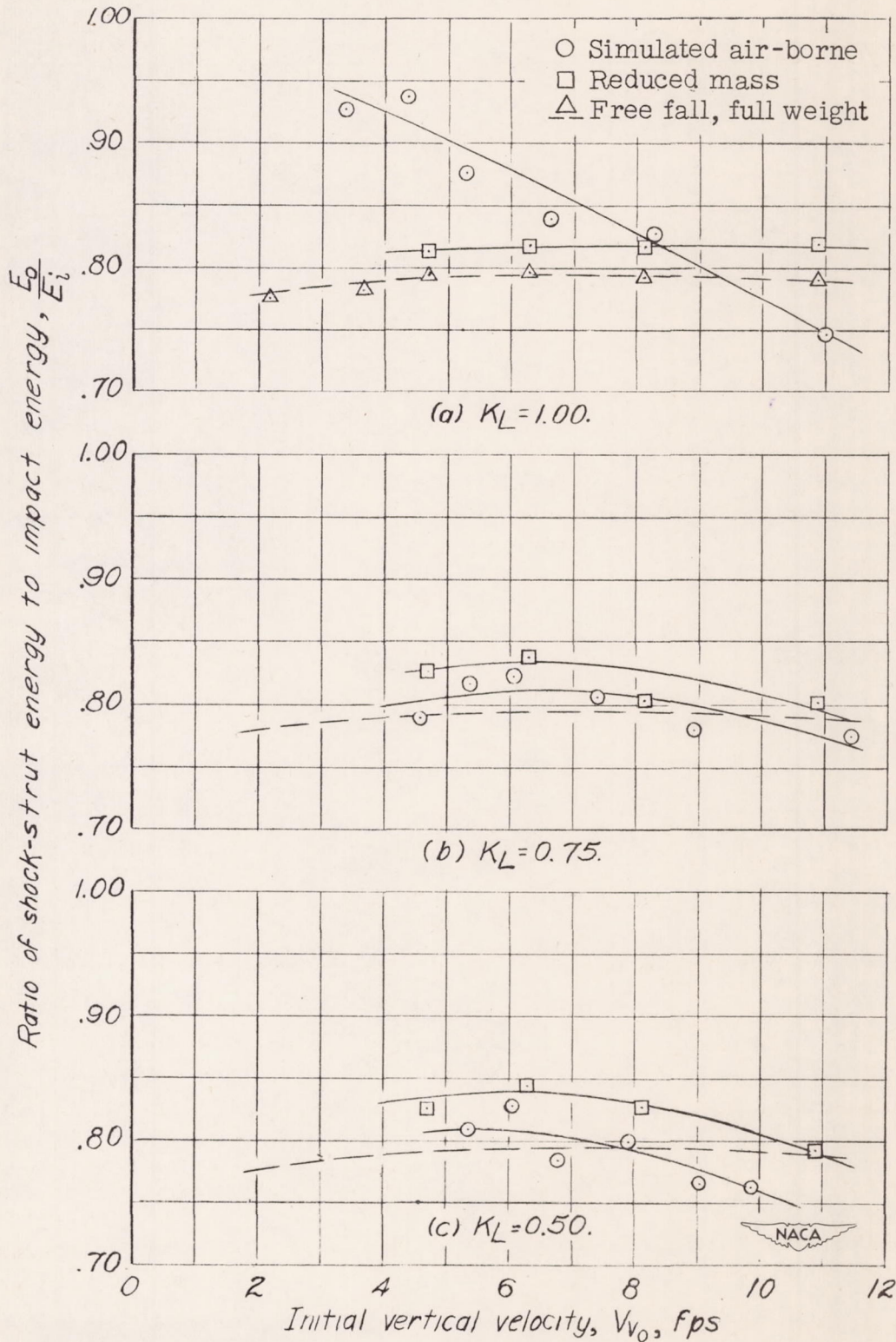
Figure 17.- Variation of the ratio of shock-strut energy to impact energy
with vertical velocity.