NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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AN ANALYSIS OF THE AIRSPEEDS AND NORMAL ACCELERATIONS OF DOUGLAS DC-2 AIRPLANES IN COMMERCIAL TRANSPORT OPERATION

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SUMMARY

Acceleration and airspeed data taken on Douglas DC-2 commercial transport airplanes operated along the east coast of the United States during the period from 1935 to 1940 have been analyzed. The results show the design maximum level-flight speed would be exceeded, on the average, once in about 7.5×10^5 flight miles, and the limit gust load factor would be exceeded, on the average, once in about 1.5×10^8 flight miles. The DC-2 operations indicate that the flight loads were small and the route roughness encountered appears to be small in comparison with the results shown on other routes.

INTRODUCTION

Analyses of acceleration and airspeed data to determine the flight loads of four different types of airplanes operated in commercial transport service have been reported in references 1 to 4. The flight loads were shown to be influenced by such factors as route, season, operating speeds, forecasting and dispatching techniques, and prewar and wartime operations.

This paper summarizes the results of an analysis of V-G records taken on Douglas DC-2 airplanes during the period from June 1935 to December 1940. The operational life is compared with the operational lives of other airplanes flown on different routes during the corresponding period.

SYMBOLS

K gust-alleviation factor

U_e effective gust velocity, feet per second

V_L	design maximum level-flight speed, miles per hour
V_{max}	maximum indicated airspeed on V-G record, miles per hour
V_o	indicated airspeed at which maximum positive or negative acceleration increment occurs on V-G record, miles per hour
V_p	probable airspeed at which maximum acceleration will most likely occur, miles per hour
P_o	probability that maximum acceleration on a record will occur in a given speed range
P_v	probability that maximum indicated airspeed on V-G record will exceed a given value
$P_{\Delta n}$	probability that maximum acceleration increment on V-G record will exceed a given value
τ	average flight time per record, hours
Δn_{max}	maximum positive or negative acceleration increment on V-G record, g units
$\overline{V}_{max}$, $\overline{V}_o$, $\overline{\Delta n}_{max}$	average values of distributions of V_{max}, V_o, and Δn_{max}, respectively
σ_V, σ_o, $\sigma_{\Delta n}$	standard deviations of distributions of V_{max}, V_o, and Δn_{max}, respectively
α_V, α_o, $\alpha_{\Delta n}$	coefficients of skewness of distributions of V_{max}, V_o, and Δn_{max}, respectively

SCOPE OF DATA

Fifty-five V-G records representing a total of 12,141 hours of flight were available for analysis. The records are summarized in table I for the DC-2 airplanes operated by three different airlines referred to herein as airlines D, E, and F on scheduled commercial transport routes during the period from June 1935 to December 1940. Information supplied with the records included installation and removal dates, routes flown, and flight hours per record. Supplementary information was supplied in occasional cases where unusual flight conditions were experienced, but no information was supplied on actual operating weights.

As table I shows, only the 18 V-G records taken on airline D and representing 6615 flight hours within the range of 260 to 560 flight hours per record were used in the statistical analysis. The method of analysis (reference 5) suggests that a minimum of about 15 V-G records representing not less than 2500 flight hours, within a range of about 30 percent of the total variation in flight hours, should be used in the analysis to obtain satisfactory results. The data for the individual airlines given in table I do not exactly meet these requirements. A check analysis was applied to the data from airline D and indicated that departure from the requirement regarding choice of records within a 30-percent range was not important in this case. The records from airline D within the range of 260 to 560 flight hours therefore are considered to be satisfactory for the statistical analysis. All 55 records representing 12,141 flight hours were used, however, to develop a composite flight envelope for all the DC-2 airplane operations.

The airplane characteristics needed for the analysis were obtained from the Civil Aeronautics Administration or were computed in accordance with the design requirements and are as follows:

Gross weight, pounds	18,560
Wing area, square feet	939
Wing span, feet	85
Mean aerodynamic chord, feet	11.0
Slope of lift curve, per radian	4.65
Design maximum level-flight speed, V_L, miles per hour	215
Placard speed, miles per hour	269
Limit gust load factor, g units	3.74
Gust-alleviation factor, K	1.040

The limit gust load factor was computed from the effective gust-load-factor formula of reference 6 by use of an effective gust velocity U_e of 30K feet per second at the maximum level-flight speed V_L. The gust-alleviation factor K, although not required at the time the DC-2 airplane was designed, is included in the present computations to compare the results with those of references 1 to 4. Computed values are based on the design gross weight and on the corresponding gust-alleviation factor K of 1.040. The placard (or never-exceed) speed was computed from information given in reference 7 as $1.25V_L$ or 269 miles per hour. The slope of the lift curve, corrected for aspect ratio, equal to 4.65 per radian was obtained from reference 8.

The V-G records were evaluated without attempting to distinguish between accelerations caused by gusts and by maneuvers. All large accelerations at speeds above 100 miles per hour are assumed to be due to gusts because experience indicates that most of the large loads imposed during normal transport operations are caused by gusts.

ANALYSIS

The method of analysis is given in reference 5. Five values were read from each V-G record; namely, the maximum positive and maximum negative acceleration increments Δn_{max}, the corresponding speeds of maximum acceleration occurrence V_o, and the maximum speeds flown V_{max}, together with the flight miles per record, obtained by multiplying the average time per record by an assumed average cruising speed of $0.8V_L$. These values constitute the flight-load data needed for the statistical computation. The distribution of positive and negative acceleration increments measured from the 1 g line is essentially symmetrical, and the maximum values were therefore sorted and tabulated without regard to sign.

In order to compare results from different sets of data, some measure is required to determine whether indicated differences in the probabilities of exceeding the larger values of acceleration or gust velocity are significant. Based on experience, a criterion of engineering concern has been used (references 1 to 4) which states that significant differences between probabilities are considered to exist if they differ by more than a ratio of 5:1. The 5:1 ratio is used herein as a level of engineering concern in connection with the spread of flight miles required to exceed the limit gust load factor and to exceed a fixed effective gust velocity at the probable speed of gust encounter.

PRECISION

The precision of the V-G recorder and the limitations of the method of analysis employed are discussed in reference 1. The inherent instrument errors are assumed not to exceed ±0.2g for acceleration and 3 percent of the maximum airspeed range of the instrument.

Since reference 5 indicates that satisfactory results may be obtained with a minimum of about 15 records representing not less than about 2500 flight hours, the 18 records representing 6615 flight hours used in the present analysis would seem to be adequate with respect to size of the sample of data.

RESULTS

The statistical parameters of the distributions of V_{max}, Δn_{max}, and V_o are given at the bottom of table II; namely, the average values indicated by a bar over the symbol, the standard deviation σ, which is a measure of the dispersion of the distribution from the average value, and the coefficient of skewness α, which is a measure of the deviation from symmetry of the distribution. Pearson type III probability curves (reference 9), which are assumed to be reasonable representations of V-G data, were computed from the statistical parameters. The Pearson probability curves were transformed to curves of average flight miles required to exceed given values of speed and acceleration increment by multiplying $1/P_V$ and $1/P_{\Delta n}$ by the factor $0.8V_L\tau$, where $\tau = 367.5$ hours. Figures 1 and 2 present the transformed curves together with the cumulative V-G data. From these curves and the probability P_o that maximum acceleration on a record will occur in any given speed range, the flight envelopes of figure 3 were derived to show the average flight miles required to exceed stated values of acceleration and speed.

Figure 4 compares results for the DC-2 airplane at values of the limit gust load factor and fixed effective gust velocity with corresponding results obtained for the airplanes reported in references 1 to 4. The ratios of the probable speed in rough air to the design maximum level-flight speed V_p/V_L are also given in figure 4. Flight miles are plotted in the figure on a logarithmic scale.

The frequency distributions (defined in reference 5) of accelerations and speeds in table II and the results derived from the statistical analysis shown in figures 1 to 4 do not include data from two unusual V-G records. These records have not been included because, insofar as normal transport operations are concerned, the unusually large accelerations and airspeeds of such records may be expected to occur, on the average, at very infrequent intervals. Therefore, the inclusion of such records in a limited sample of data, as used herein to describe average conditions, would give a distorted picture. These unusual records, however, have been considered as part of the over-all picture. The first of these records was taken on a DC-2 airplane of airline D during flight through a severe thunderstorm between Richmond, Va. and Washington, D. C. The meteorological and flight conditions existing at the time during which the storm was encountered are described in reference 10. The accelerations recorded are much larger than those indicated on any other V-G record taken on the DC-2 airplanes. The other V-G record was obtained on a DC-2 airplane of airline E and exhibits the highest airspeed (248 mph) recorded on any V-G record of a DC-2 airplane. No information was obtained relative to flight conditions for this record. These two records are included in dashed outline in figure 3 which shows the composite V-G record prepared from all the available V-G records given in table I for comparison with the predicted flight envelopes.

DISCUSSION

Figure 1 indicates that the flight miles required for the DC-2 airplane to exceed the maximum level-flight speed V_L is, on the average, once in about 7.5×10^5 flight miles, while the chance of exceeding the placard speed is decidely remote. Examination of figure 2, which presents the flight loads of the airplane, shows that the limit gust load factor will be exceeded, on the average, once in about 1.5×10^8 flight miles. These limiting values represent an appreciable extrapolation of the curves and confidence in the results may be questionable. The amount of data used, however, satisfies the requirements for analysis and the clustering of the data at low values appears to indicate that the limiting values given are of the right order.

Examination of figure 3 shows good agreement between the composite V-G record, indicated in solid outline, and the predicted flight envelope computed for an equivalent number of flight miles. Although the unusual V-G records shown in figure 3 in dashed outline were not used in the analysis, it is of interest to determine roughly the number of flight miles required to establish a flight envelope to include these records. The envelope was arbitrarily selected so that the maximum positive acceleration peak would fall within the envelope by an amount about equal to the amount the maximum negative acceleration peak would extend beyond the envelope. As shown in figure 3, the computed flight envelope based on average conditions represents 10^9 flight miles of operation. The flight envelope predicts that, on the average, in the stated number of flight miles the maximum value of airspeed will be exceeded once and that one positive and one negative acceleration increment will exceed the envelope with equal probability of being experienced at any airspeed. Thus, unusual accelerations and speeds such as those mentioned can be expected to occur, on the average, only once in a rather large number of flight miles.

The flight loads of the DC-2 airplanes (fig. 4), as indicated by the average flight miles required to exceed the limit gust load factor, show differences from the loads obtained with the other airplanes which range from a negligible difference with the DC-3 airplanes of airline C (reference 2) to a difference of about 12:1 with the M-130 airplanes (reference 3). Relative to the results shown by the whole group, the DC-2 airplanes appear to have been operated in a conservative manner, since the flight miles required to exceed the limit gust load factor are large in comparison with results shown for most other airplanes.

On the basis of flight miles required to exceed the acceleration increment due to an effective gust velocity of 37.5K feet per second at the most probable speed of gust encounter V_p, the effect of operating speed is removed and the roughnesses of the several routes are compared. In this respect, figure 4 indicates that differences in roughness for the route flown by the DC-2 airplanes are within the 5:1 ratio in comparison with the roughness of most of the other routes analyzed. The exceptions are the transcontinental operations of airline B with DC-3 airplanes and trans-Pacific operations of the M-130, both of which differ from the DC-2 operations by about 10:1. For the operations of DC-2 airplanes along the east coast of the United States, however, the results indicate that route roughness is small in comparison with most of the other routes, as shown by the large number of flight miles required to exceed the effective gust velocity of 37.5K feet per second.

CONCLUDING REMARKS

The analysis of acceleration and airspeed data taken on DC-2 airplanes during operations along the east coast of the United States indicates the design maximum level-flight speed would be exceeded, on the average, once in about 7.5×10^5 flight miles, and the limit gust load factor would be exceeded, on the average, once in about 1.5×10^8 flight miles. The DC-2 airplane flight loads were small in comparison with most of the other operations analyzed. For the DC-2 operations over the east coast route, the route roughness encountered appears to be small in comparison with the roughness indicated by the results for most of the other routes analyzed.

Langley Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va., September 22, 1948

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TABLE I

SUMMARY OF V-G RECORDS AVAILABLE AND USED IN THE ANALYSIS

		Records available		Records used in analysis		
Airline	Routes flown	Number of records	Total flight hours	Number of records	Total flight hours	Average flight hours per record, τ
D	Miami, Florida to Boston, Mass.	28	9,981	18	6615	367.5
E	Newark, N. J. to Los Angeles, Cal.	11	1,507	None	----	-----
F	Santiago, Chile to Buenos Aires, Arg.	16	653	None	----	-----
Total		55	12,141	18	6615	367.5

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TABLE II

FREQUENCY DISTRIBUTIONS AND STATISTICAL PARAMETERS

OF V_{max}, Δn_{max}, AND V_o

V_{max}		Δn_{max}		V_o	
Velocity (mph)	Frequency	Acceleration increment (g units)	Frequency	Velocity (mph)	Frequency
195 to 199	3	0.60 to 0.69	1	110 to 119	2
200 to 204	3	.70 to .79	4	120 to 129	2
205 to 209	10	.80 to .89	4	130 to 139	3
210 to 214	1	.90 to .99	4	140 to 149	2
215 to 219	0	1.00 to 1.09	3	150 to 159	3
220 to 224	1	1.10 to 1.19	4	160 to 169	8
		1.20 to 1.29	2	170 to 179	10
		1.30 to 1.39	4	180 to 189	6
		1.40 to 1.49	2		
		1.50 to 1.59	1		
		1.60 to 1.69	2		
		1.70 to 1.79	2		
		1.80 to 1.89	1		
		1.90 to 1.99	2		
Total	18	Total	36	Total	36
$\overline{V}_{max}$	206.10	$\overline{\Delta n}_{max}$	1.21	$\overline{V}_o$	161.70
σ_v	5.70	$\sigma_{\Delta n}$	0.37	σ_o	20.40
α_v	0.79	$\alpha_{\Delta n}$	0.47	α_o	-0.90

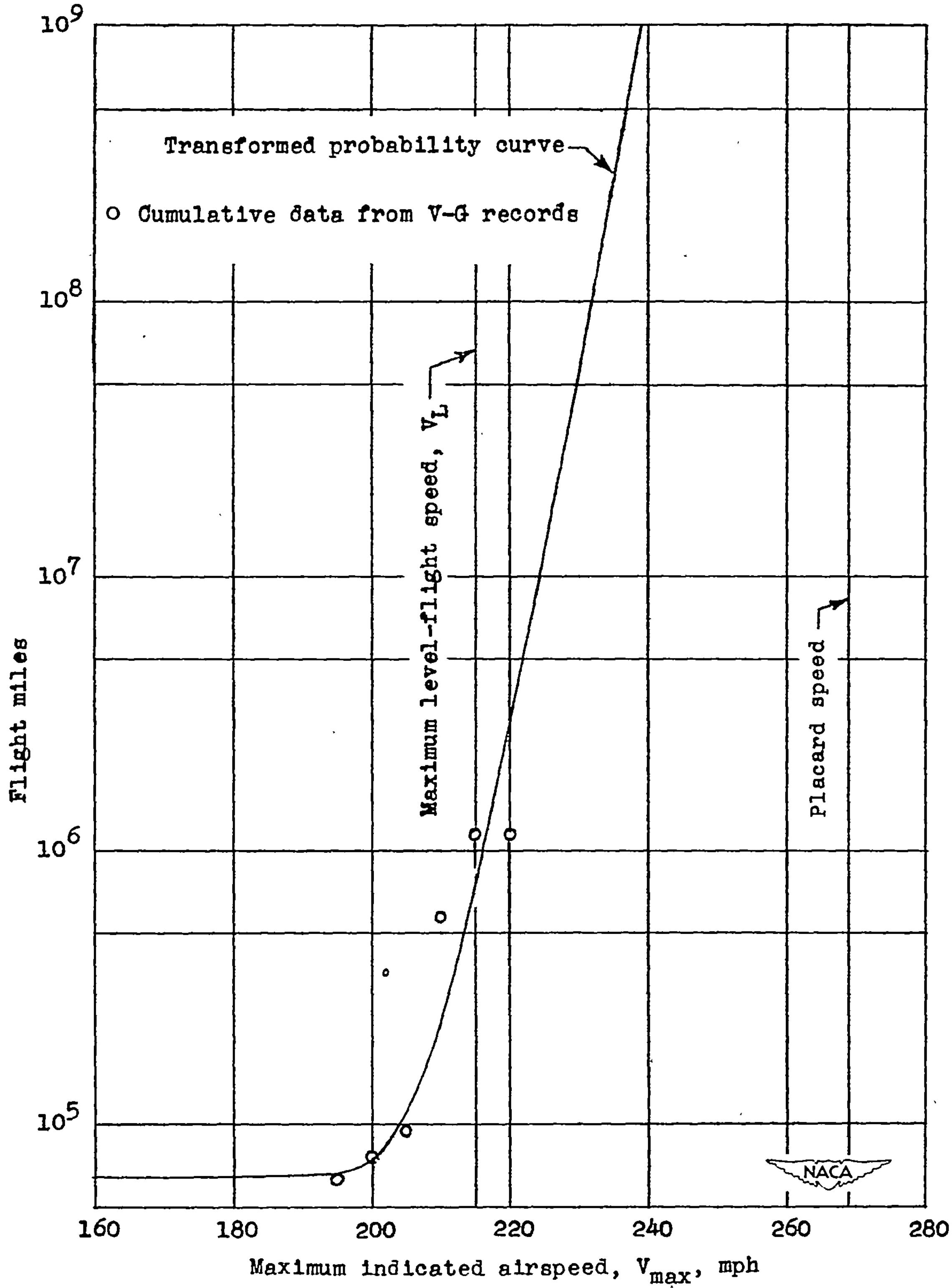

Figure 1.- Average flight miles required to exceed a given value of airspeed.

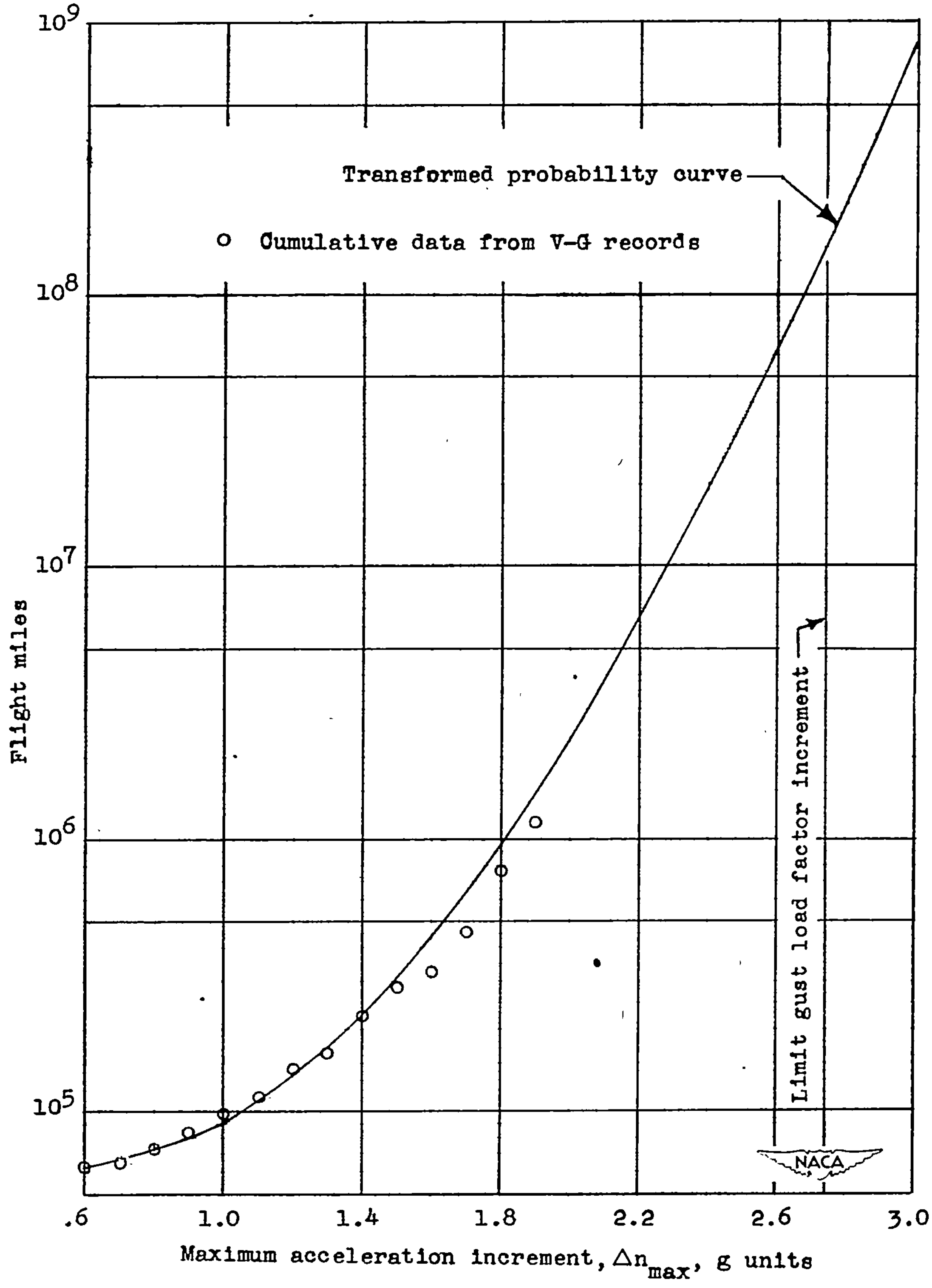

Figure 2.- Average flight miles required to exceed a given acceleration increment.

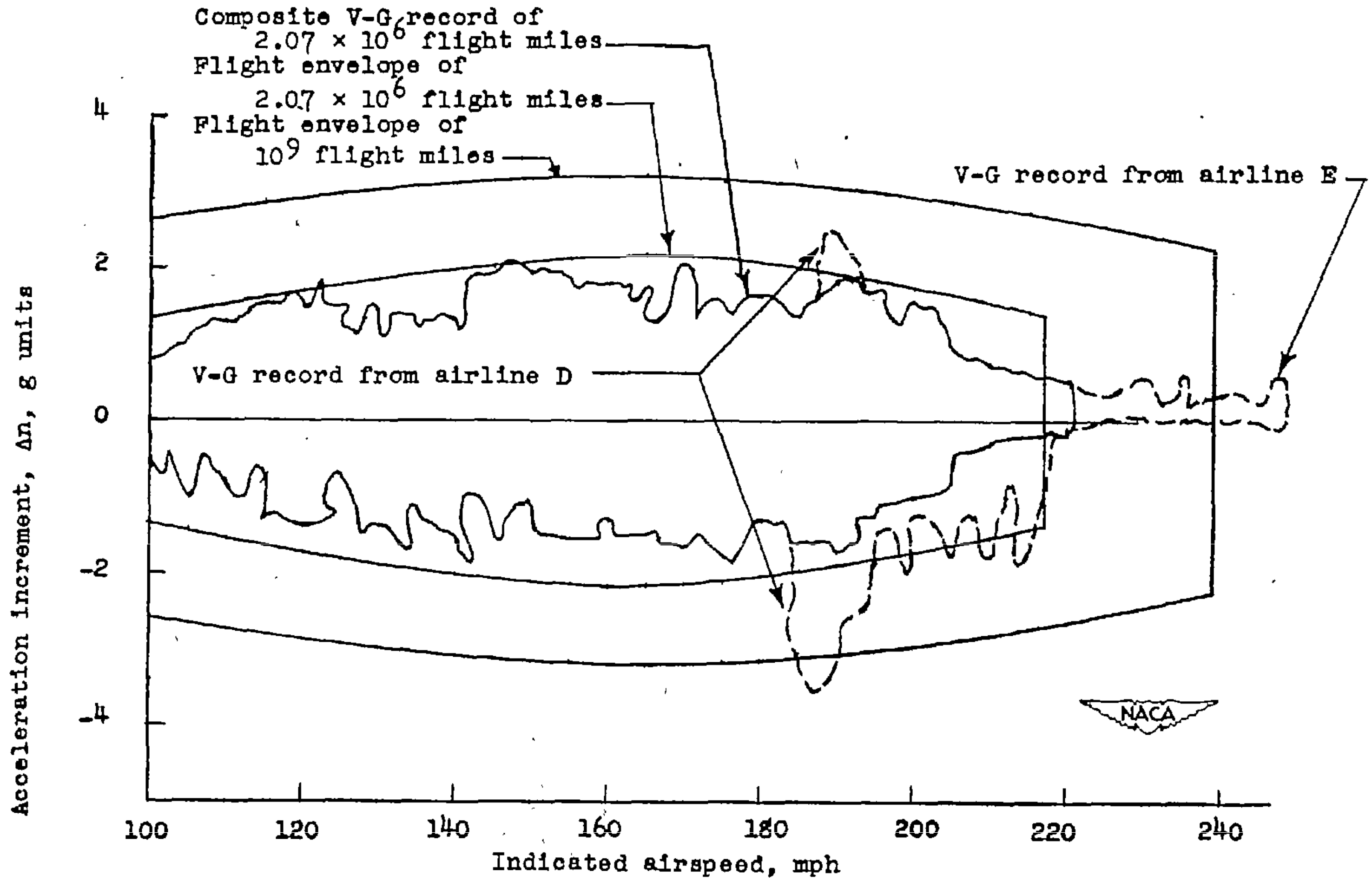

Figure 3.- Comparison of computed flight envelopes with the composite V-G record of Douglas DC-2 airplanes.

Airplane	Airline	Reference	Route	V_p/V_L
DC-3	A	2	Trans-continental U.S.A.	0.83
DC-3	B	2	Trans-continental U.S.A.	.81
DC-3	C	2	Trans-continental U.S.A.	.69
S-307	-	1	Caribbean	.63
M-130	-	3	Trans-Pacific	.79
S-42A	-	4	Caribbean and South America	.76
DC-2	D	-	East Coast of U.S.A.	.75

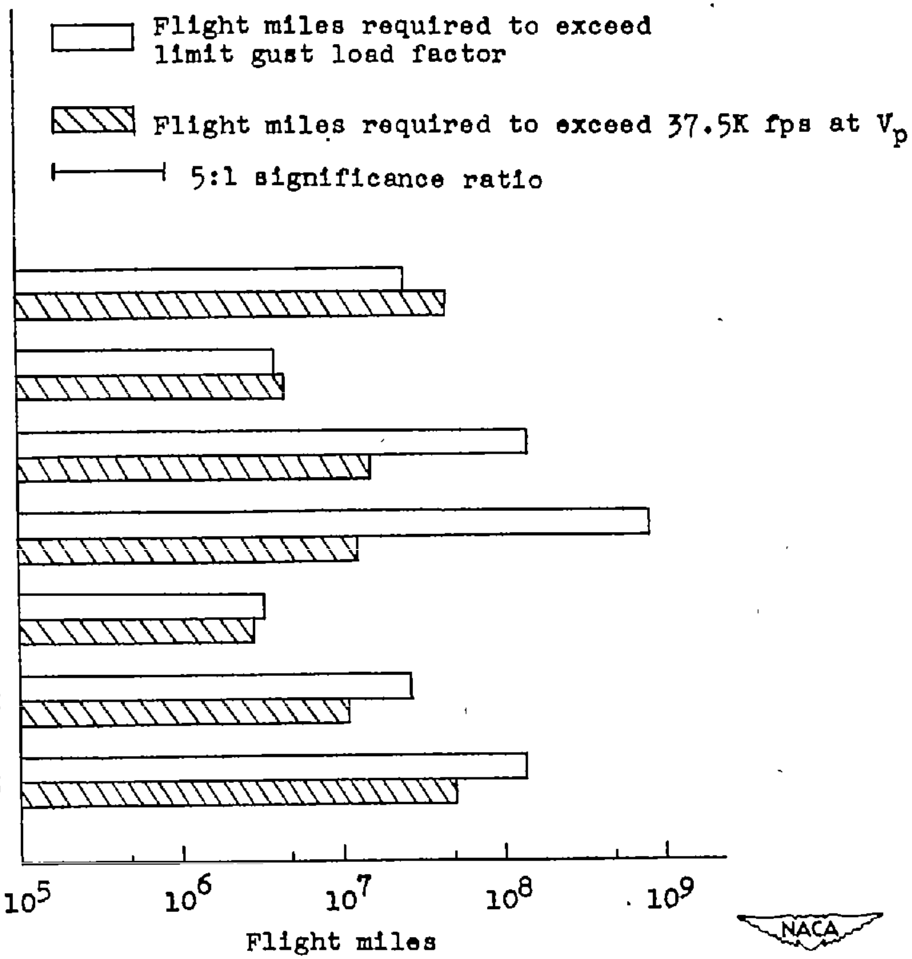

Figure 4.- Comparison of average flight miles required to exceed limit gust load factor and to exceed fixed effective gust velocity at probable speed V_p of gust encounter.