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OPERATIONAL WEIGHT ESTIMATIONS OF COMMERCIAL JET TRANSPORT AIRCRAFT

By

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SUMMARY

In evaluating current or proposed commercial transport airplanes, there has not been available a ready means to determine weights so as to compare airplanes within this particular class. This paper describes the development of and presents such comparative tools. The major design characteristics of current American jet transport airplanes were collected, and these data were correlated by means of regression analysis to develop weight relationships for these airplanes as functions of their operational requirements. The characteristics for 23 airplanes were assembled and examined in terms of the effects of the number of people carried, the cargo load, and the operating range. These airplane characteristics were correlated for the airplanes as one of three subclasses, namely the small, twin-engine jet transport, the conventional three- and four-engine jets, and the new wide-body jets.

INTRODUCTION

In examining proposed future transport concepts, there has not been available a ready means to compare these aircraft designs with those of current jet transports in terms of aircraft weight, payload carried, and performance. This paper is an extension of earlier unpublished results in which the weights and performance of 66 American transport aircraft ranging from the Douglas DC-3 to the Boeing 747 were examined. In this previous work, it was found that the 66 airplanes could be grouped into five subclasses primarily due to their means of propulsion and secondly due to size. The empty weights and gross weights of the airplanes in each subclass could be correlated by means of graphical and statistical regression analyses methods in terms of the persons carried, still-air range, and the design flight speed. These independent variables were adequate performance variables for the propeller airplanes, but were not very representative for assessing jet-engined transports. Consequently, the jet airplanes were re-examined in terms of better or more representative operating variables.

This paper describes the results of this analysis of jet transports. The designer and operator of transport aircraft are interested in how much payload can be carried a certain distance. To perform this task the airplane has a minimum weight, unloaded, as well as a maximum weight fully loaded and ready to leave the loading dock. These two weight conditions were chosen for this analysis, with the former called "operating empty weight" and the latter designated "maximum ramp weight." These two weights were found to correlate with the number of persons carried, operating range with defined reserves, and cargo load. To improve the correlation, the aircraft were grouped into three subclasses of transports, each representing a nominal size and weight group. These subclasses have been labeled as follows: small jet transports, conventional jet transports, and wide-body transports.

Appendix A lists the aircraft used in the correlations by subclass and summarizes each aircraft's characteristics.

ANALYSIS

Since the parameters used to analyze the jet transports reported herein were evolved from earlier unreported work on transport aircraft, a review of these earlier results is pertinent. In this early work, the characteristics of 66 airplanes were considered to determine which were most apt to characterize a transport airplane's empty or gross weight. Some characteristics analyzed, for example, were: number of passengers; number of persons carried including flight crew and stewardesses; operational parameters such as still air range, cruise speed, and maximum speed; date of first flight; date of "approved type certification" (ATC); type of power plant, total propulsive power, and type of propulsion; body dimensions; cargo load; and total useful load. The dependence of the airplane empty weight and gross weight on operational requirements were first examined visually with linear, semi-log, and log-log graphs. The results of this analysis showed the airplane weights to be primarily a linear function of their independent characteristics.

Another analysis was performed to determine the true independence of the various variables. In making these dependency examinations, it was found that for several variables there was insufficient data to make such a determination, and for some there was difficulty in separating in a consistent manner the desired variables. Four independent variables emerged from this screening process. They were the total persons carried, still air range, cruise speed, and year of approved type certification (ATC). One other important variable, cargo load, was examined; but it did not prove to be amenable to analysis for all 66 airplanes considered.

The characteristics of jet transports are not well defined by the variables of speed nor still air range. First of all, current jet transports cruise at approximately the same Mach number, thus speed is of lesser importance; and secondly, federal regulations require a specified reserve of fuel dependent upon each flight's destination, thus fuel reserves are important. Also of importance is that these jet aircraft have more room, under the passenger floor, to carry cargo. Thus the ability to carry a cargo load as well as passengers has become of greater interest to the airplane designer and user.

With the operating empty weight and maximum ramp weight as the prime aircraft variables, the difference between these two weights is the discretionary load of passengers and/or cargo and fuel. Fuel required is not as operationally descriptive as range, nor did it correlate to the airplane weights as well as range. Thus, persons, range and cargo were found to be the logical independent variables. Yet the number of persons carried is defined by the types of service offered by various airlines, and the range is defined by how much reserve fuel is required. Therefore it was necessary to normalize the passenger load and the operating range for each aircraft considered. Because the greater number of seats of any transport are of economy class it was assumed, for purposes of this study, that the entire airplane was economy class seating with a uniform spacing between rows of seats of 34 inches. Also it was assumed that there was one stewardess for each 30 passengers, and that the flight crew size was that normal for each particular aircraft. To normalize the operating range would be difficult using the FAA rules for fuel reserves. These rules require that the airplane have capability to reach a designated alternate airport, and to be able to loiter over this airport for a given period of time before landing. In general it was found that the required reserves ranged between 15% and 25% of the flight fuel required.

Thus for purposes of this study, it was assumed that the required fuel reserves for all airplanes and ranges would be 20% of each airplane's normal fuel capacity. This assumption does compromise the airplane load carrying capability for short ranges, but for flights with full fuel tanks, the operating ranges as defined for this study are in good agreement with published ranges for these airplanes. One further item in regard to the mix of passenger and cargo load should be noted. In developing data for the effect of cargo load, each aircraft was treated as two vehicles, one being a passenger only vehicle and one being a mixed cargo-passenger vehicle. This changes the weight of fuel which can be carried and consequently the operating ranges for each load condition.

To obtain airplane characteristics, the annual publications of "Jane's All the World's Aircraft" (reference 1) and weekly issues of the magazine, AVIATION WEEK AND SPACE TECHNOLOGY (reference 2), were used extensively. For data on the cargo loads in terms of range, some issues of the magazine, FLIGHT INTERNATIONAL (reference 3), and "D.M.S. Market Intelligence Reports" (reference 4) were found to be helpful.

Statistical regression analysis was used to correlate the independent load and range variables and to develop the airplane weight relations. Linear and non-linear equations were developed for several cases to test which type of equations might yield the better correlations. Linear equations gave the better correlations and thus they were developed for all the cases. Each equation was based on a least squares correlation. In the analysis, each independent variable was introduced separately and the resulting equation was tested for correlation with the given data. The independent variables were introduced in various orders so that a ranking of dominance or importance could be made. One interesting result of these analyses was that the order of importance of the independent variables was not always the same for each subclass of transports. One might anticipate that the number of persons carried would be the major determinant of airplane weight, but for the group consisting of conventional jet transports, the operating range was the more dominant variable (see Tables II, IV, and VI).

The purpose of these regression analyses was to develop useful airplane weight relations; thus, any additional discussion of particular regression analyses or of the data correlation does not seem to be warranted. However, to help answer any questions the reader might have, the numerical characteristics utilized, the equations which characterize the airplanes, and a measure of the correlation of the highest order equations are assembled by subclass in Appendix A. For each transport group, weight equations are given for one, two, and three independent variables. The order in which each variable is introduced is an indication of the order of importance of that variable.

RESULTS

Four pairs of weight relations resulted from the analyses of jet transport airplane operating empty and maximum ramp weights. The combined characteristics of the 23 airplanes considered are represented in one pair, and there is one pair of relations for each of the three airplane subclasses. Figures 1 through 8 are graphs which show these relations of airplane weight to the number of persons carried, the operating range in statute miles, and the cargo load.

All Transports

Figures 1 and 2 show the operating empty weight and the maximum ramp weight relations, respectively, for the entire group of 23 jet transports. This pair of figures is typical of the results given for each subclass of transports. For ease of use and understanding, the figure arrangement needs some explanation. Each airplane characteristic is introduced one variable at a time, starting with the persons carried in the upper left-hand graph (refer to Figure 1). If one moves clockwise around the figure, the first approximation for operating empty weight can be determined. The second variable, operating range, is introduced in the upper right-hand quadrant and a better estimate for weight is possible. The third variable, cargo load, is introduced in the lower right-hand quadrant. For further explanation, an example airplane has been delineated on Figure 1. If for example the jet transport is to carry 300 persons, the dotted line indicates the first approximation of its operating empty weight to be 218,000 lbs. For this number of persons carried and for an operating range of 3,000 statute miles, the second quadrant indicates a weight of 216,000 lbs. To complete this example, if this airplane is required to carry 20,000 lbs of cargo with this number of passengers and over the same range, the dotted line indicates this airplane's operating empty weight would be 216,000 lbs. Thus as each independent variable is introduced, a better approximation to the operating empty weight for the particular aircraft is obtainable. The corresponding maximum ramp weights (Figure 2) for this example airplane are: 447,000 lbs, 435,000 lbs, and 435,000 lbs. If a variable is not defined, the weight determined is that corresponding to the mean value(s) for the variable(s) not specified.

On Figures 1 and 2 the mean value weight relations for each of the three subclasses of aircraft are shown. This graphically shows the range of weights which corresponds to each group of transports. These mean value curves give an indication of the range of weights for each group of transports where these general curves of Figures 1 and 2 may be sufficiently accurate for numerous preliminary design determinations. A table in each figure gives the mean value for each independent variable and each transport group.

Relations for aircraft useful load were developed. These load relations were found to give poorer values than if these values were computed from values of operating empty weight and maximum ramp weight obtained from Figures 1 and 2. These same results for the determination of useful load were found to be typical for each subclass of aircraft.

Small Jet Transports

Figures 3 and 4 show the two weight relations for the group of two-engined airplanes which we have labeled "small jet transports." Airplanes in the 737 and DC-9 series comprise this class. The range of values for each of the variables shown on the graphs is approximately the numerical range for these variables for the group of airplanes from which the relations were derived. The mean value of each variable is indicated by the circle symbol on the graph. Figure 3 shows that the small jet transport's operating empty weight is almost wholly dependent upon the persons to be carried, for the variables of range or cargo load have little or no effect upon the empty weight values determined. Figure 4 shows somewhat similar effects, with the effect of range upon the maximum ramp weight being quite small.

The reference airplanes of this group were designed primarily to carry its passengers between 1,000 and 2,000 miles. This limited range requirement makes the changes of weight of fuel required small compared to the effects of people or cargo load.

Conventional Jet Transports

The ordinary three- and four-engined jet transports comprise the "conventional jet transport" group. The weight relations representative of these aircraft are shown in Figures 5 and 6. Since under floor room for cargo comes as a result of providing floor area to seat passengers, the addition to airplane weight to provide cargo storage capability is relatively small.

Wide-Body Transports

This subclass represents the newest type of transport aircraft, the 747, L-1011, and DC-10 series. Figures 7 and 8 show the two weight relations for these aircraft.

CONCLUSIONS

In assembling the characteristics of current commercial jet transport aircraft, it was found that much data was not readily available even though some of these aircraft have been operational for over a decade. For some aircraft there were duplicate data which were not consistent, and thus separate analysis was required to determine what data were the more representative. For all the aircraft, the passenger load was normalized to a single economy class having seat spacing of 34 inches. For all aircraft, it was necessary to define the fuel reserve in a consistent and meaningful manner. When the airplanes were characterized in a consistent manner, it was possible to develop generalized, representative weight characteristics for each of the three subclasses of transport aircraft. These weight relations are sufficiently accurate to satisfy many needs of preliminary design.

REFERENCES

1. "Jane's All the World's Aircraft," B.P.C. Publishing, Ltd., London, England; 1970-71, 1969-70, 1968-69, 1967-68, 1966-67, 1965-66, 1962-63, 1959-60, 1956-57, 1951-52, 1945-46.

2. Aviation Week and Space Technology, McGraw Hill, Inc., New York, New York; March 8, 1971; March 9, 1970; March 10, 1969; March 18, 1968; March 6, 1967; March 7, 1966; March 15, 1965; and March 7, 1960.

3. Flight, International, International Business Press Associates, London, England; November 18, 1971; November 19, 1970; November 20, 1969; November 21, 1968.

4. "D.M.S. Market Intelligence Reports," published by D.M.S., Greenwich, Connecticut, 1971.

APPENDIX A

The characteristics for each airplane used in developing the weight correlations are included in this appendix. These characteristics are in three pairs of tables, with each pair representing one of the three subclasses of jet transport aircraft. The first table of each pair identifies each aircraft and lists its characteristics. Also listed is the percentage correlation of each aircraft's weight with the developed weight equations. The second table of each pair gives the weight equations used for the relations shown in the figures of this report. With each equation there is listed the standard error (S.E.) of the equation indicated weights.

TABLE I - SMALL JET TRANSPORT CHARACTERISTICS

MANUFACTURER	AIRPLANE DESIGNATION	PROPULSION	TOTAL PERSON LOAD (CREW + PASSENGER)	CARGO (lbs)	ECONOMICAL CRUISING RANGE (miles)	OPERATING EMPTY WEIGHT (lbs)	PERCENT CORRELATION EMPTY WEIGHT*	MAXIMUM RAMP WEIGHT (lbs)	PERCENT CORRELATION RAMP WEIGHT*
Boeing	737-100	2-JT8D-7	108	4,900	1,165	56,895	-2.4	104,000	-1.7
"	737-100	2-JT8D-7	108	7,900	885	56,895	-2.3	104,000	-1.6
"	737-200	2-JT8D-7	120	0	1,875	61,020	-3.6	114,000	-1.6
"	737-200	2-JT8D-7	120	10,580	880	61,020	-3.2	114,000	-1.5
"	737-200C	2-JT8D-15	120	0	2,020	59,300	-0.6	116,000	-1.7
"	737-200C	2-JT8D-15	120	12,100	930	59,300	0.1	116,000	-1.0
McDonnell-Douglas	DC-9-10	2-JT8D-1	90	0	1,760	46,160	3.4	91,500	2.3
"	DC-9-10	2-JT8D-1	90	7,440	1,025	46,160	3.6	91,500	2.0
"	DC-9-20	2-JT8D-9	90	5,575	1,760	52,500	-2.0	101,000	-0.6
"	DC-9-20	2-JT8D-9	90	14,075	880	52,500	-1.9	101,000	-1.5
"	DC-9-30	2-JT8D-9	116	4,125	1,560	56,800	2.0	109,000	1.7
"	DC-9-30	2-JT8D-9	116	7,625	1,210	56,800	2.1	109,000	1.5
"	DC-9-40	2-JT8D-11	126	5,875	1,435	59,000	2.8	115,000	1.8
"	DC-9-40	2-JT8D-11	126	11,875	920	59,000	3.0	115,000	2.4
	MEAN		110	6,576	1,308				

$$\text{PERCENT CORRELATION} = \frac{\text{CALCULATED WEIGHT} - \text{ACTUAL WEIGHT}}{\text{ACTUAL WEIGHT}} \times 100$$

*Three variables: persons, cargo, and range.

TABLE II - WEIGHT EQUATIONS FOR SMALL JET TRANSPORTS

Operating Empty Weight (O.E.W.)

O.E.W. = 27,438 + 263 (persons), S.E. = 1,571

O.E.W. = 27,250 + 263 (persons) + 0.031 (cargo), S.E. = 1,634

O.E.W. = 25,529 + 263 (persons) + 0.107 (cargo) + 0.93 (opr. range), S.E. = 1,702

Maximum Ramp Weight, (M.R.W.)

M.R.W. = 44,745 + 567 (persons), S.E. = 3,290

M.R.W. = 43,672 + 567 (persons) + 0.179 (cargo), S.E. = 3,318

M.R.W. = 20,113 + 567 (persons) + 1.215 (cargo) + 12.76 (opr. range), S.E. = 2,158

S.E. = Standard Error

TABLE III - CONVENTIONAL JET TRANSPORT CHARACTERISTICS

MANUFACTURER	AIRPLANE DESIGNATION	PROPULSION	TOTAL PERSON LOAD (CREW + PASSENGER)	CARGO (lbs)	ECONOMICAL CRUISING RANGE (miles)	OPERATING EMPTY WEIGHT (lbs)	PERCENT CORRELATION EMPTY WEIGHT*	MAXIMUM RAMP WEIGHT (lbs)	PERCENT CORRELATION RAMP WEIGHT*
Boeing	707-320B/C	4-JT3D-7	199	0	5,035	147,800	-4.9	336,000	-2.8
"	707-320B/C	4-JT3D-7	199	8,455	4,640	147,800	-5.1	336,000	-2.5
"	727-100C	3-JT8D-7	130	0	2,480	87,000	-1.9	161,000	-0.5
"	727-100C	3-JT8D-7	130	4,140	2,185	87,000	-3.2	161,000	-2.7
"	727-100C	3-JT8D-7	130	1,915	2,500	88,000	-1.8	170,000	-3.2
"	727-100C	3-JT8D-7	130	10,265	1,980	88,000	-3.5	170,000	-5.7
"	727-200	3-JT8D-7	177	0	1,685	95,000	3.2	170,000	3.9
"	727-200	3-JT8D-7	177	4,890	1,395	95,000	2.4	170,000	2.7
"	727-200ADV	3-JT8D-15	177	2,200	2,185	99,500	4.4	191,000	4.6
"	727-200ADV	3-JT8D-15	177	6,050	1,975	99,500	4.0	191,000	4.2
McDonnell-Douglas	DC-8-61	4-JT3D-3B	258	0	3,335	152,000	-1.6	328,000	-2.3
"	DC-8-61	4-JT3D-3B	258	21,600	2,430	152,000	-1.3	328,000	-0.6
"	DC-8-62	4-JT3D-7	199	0	5,595	141,900	2.9	338,000	3.0
"	DC-8-62	4-JT3D-7	199	8,585	5,195	141,900	2.8	338,000	3.2
"	DC-8-62	4-JT3D-7	199	7,395	5,380	143,255	2.7	353,000	0.2
"	DC-8-62	4-JT3D-7	199	12,995	5,120	143,255	2.6	353,000	0.4
"	DC-8-63	4-JT3D-7	258	0	4,175	158,740	-0.6	358,000	-1.5
"	DC-8-63	4-JT3D-7	258	20,860	3,340	158,740	-0.1	358,000	0.4
	MEAN		192	6,075	3,368				

*Three variables: persons, cargo, and range.

TABLE IV - WEIGHT EQUATIONS FOR CONVENTIONAL JET TRANSPORTS

Operating Empty Weight (O.E.W.)

O.E.W. = 11,969 + 582 (persons), S.E. = 14,109

O.E.W. = 2,714 + 463 (persons) + 9.51 (opr. range), S.E. = 5,035

O.E.W. = 4,350 + 436 (persons) + 9.82 (opr. range) + 0.432 (cargo), S.E. = 4,256

Maximum Ramp Weight (M.R.W.)

M.R.W. = 98,727 + 50.02 (opr. range), S.E. = 49,547

M.R.W. = -71,262 + 36.98 (opr. range) + 1,115 (persons), S.E. = 14,613

M.R.W. = -64,181 + 38.29 (opr. range) + 996 (persons) + 1.869 (cargo), S.E. = 7,690

TABLE V - WIDE BODY JET TRANSPORT CHARACTERISTICS

MANUFACTURER	AIRPLANE DESIGNATION	PROPULSION	TOTAL PERSON LOAD (CREW + PASSENGER)	CARGO (lbs)	ECONOMICAL CRUISING RANGE (miles)	OPERATING EMPTY WEIGHT (lbs)	PERCENT CORRELATION EMPTY WEIGHT*	MAXIMUM RAMP WEIGHT (lbs)	PERCENT CORRELATION RAMP WEIGHT*
Boeing	747	4-JT9D-3A	465	0	4,950	357,810	-1.0	713,000	0.7
"	747	4-JT9D-3A	465	77,090	2,670	357,810	-1.1	713,000	0.3
"	747A	4-JT9D-3A	465	0	5,385	358,685	1.3	738,000	1.9
"	747A	4-JT9D-3A	465	76,215	3,155	358,685	1.4	738,000	1.8
"	747B	4-JT9D-7	465	0	5,455	367,755	-0.7	778,000	-2.7
"	747B	4-JT9D-7	465	67,145	3,585	367,755	-0.1	778,000	-1.8
Lockheed	L-1011-1	3-RB211-22	337	0	2,945	234,275	-0.9	428,000	-1.1
"	L-1011-1	3-RB211-22	337	18,025	2,340	234,275	-1.6	428,000	-2.6
McDonnell-Douglas	DC-10-10	3-CF6-6D	344	0	3,155	234,665	2.7	433,000	3.2
"	DC-10-10	3-CF6-6D	344	32,685	2,085	234,665	1.7	433,000	1.1
"	DC-10-20-UG	3-JT9D-25W	323	0	4,740	268,175	-2.2	558,000	-1.9
"	DC-10-20-UG	3-JT9D-25W	323	36,275	3,630	268,175	-2.6	558,000	-2.7
"	DC-10-30-UG	3-CF6-50C	323	0	5,070	264,091	2.0	558,000	2.7
"	DC-10-30-UG	3-CF6-50C	323	40,360	3,820	264,091	1.5	558,000	1.6
	MEAN		389	24,843	3,785				

*Three variables: persons, cargo, and range.

UG - upper galley

TABLE VI - WEIGHT EQUATIONS FOR WIDE BODY JET TRANSPORTS

Operating Empty Weight (O.E.W.)

O.E.W. = -15,870 + 807 (persons), S.E. = 19,153

O.E.W. = -37,796 + 760 (persons) + 10.65 (opr. range), S.E. = 15,394

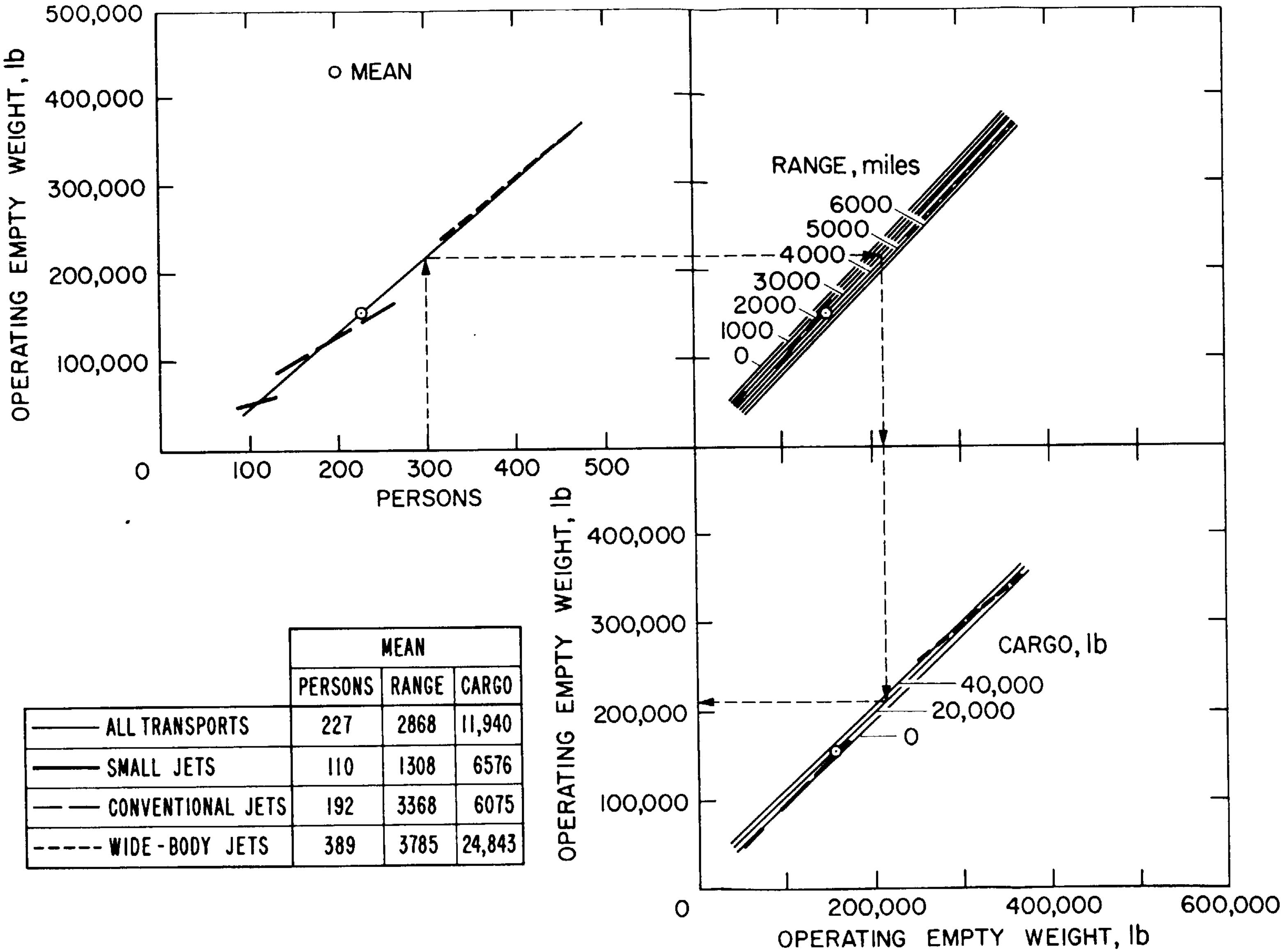
O.E.W. = -38,760 + 615 (persons) + 21.62 (opr. range) + 0.633 (cargo), S.E. = 5,342

Maximum Ramp Weight (M.R.W.)

M.R.W. = -89,278 + 1,775 (persons), S.E. = 67,794

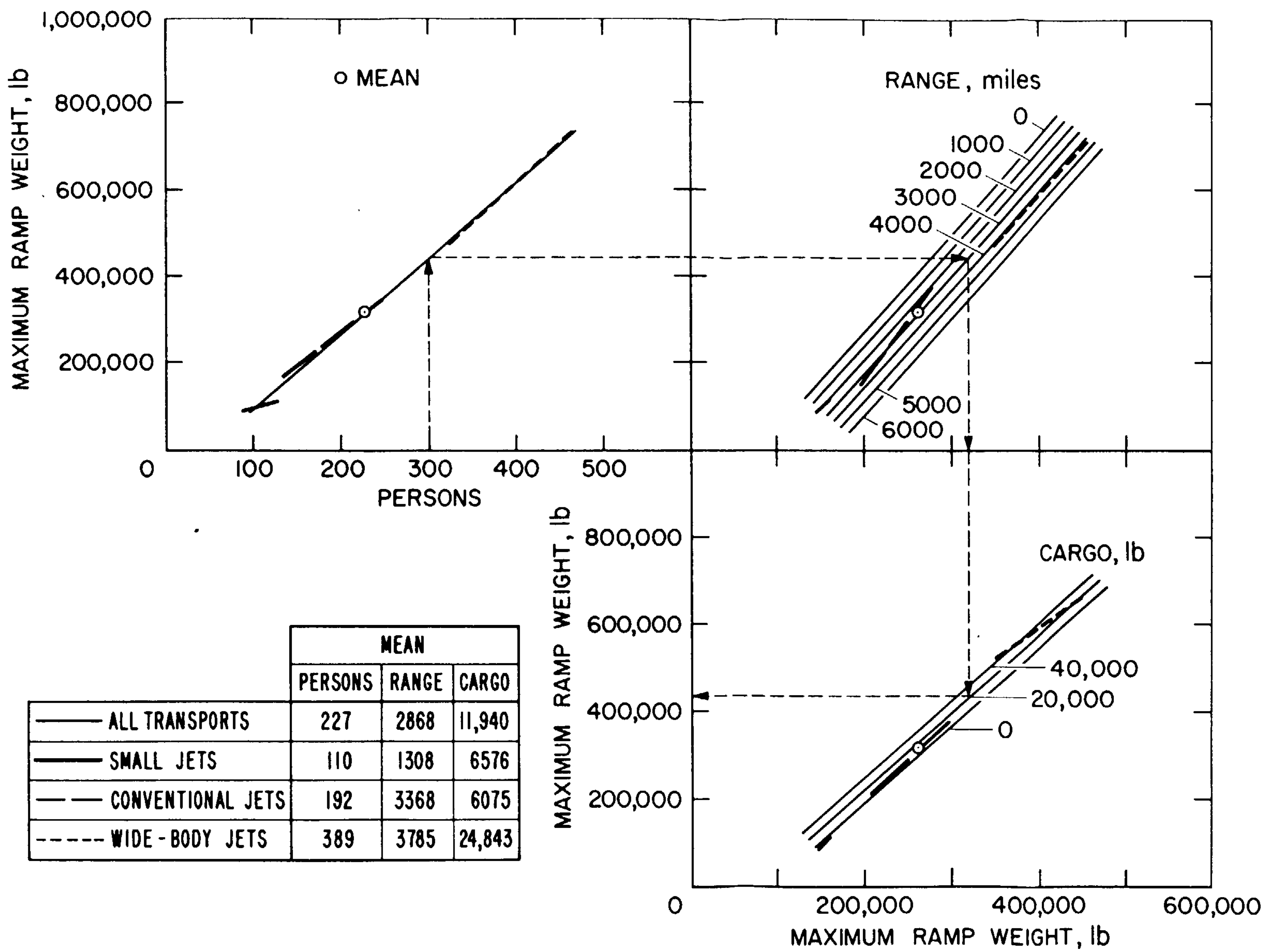
M.R.W. = -168,542 + 1,604 (persons) + 38.49 (opr. range), S.E. = 53,670

M.R.W. = -171,990 + 1,086 (persons) + 77.72 (opr. range) + 2.264 (cargo), S.E. = 14,247



	MEAN		
	PERSONS	RANGE	CARGO
——— ALL TRANSPORTS	227	2868	11,940
——— SMALL JETS	110	1308	6576
— — CONVENTIONAL JETS	192	3368	6075
- - - - - WIDE-BODY JETS	389	3785	24,843

Figure 1.- Operating Empty Weight Relations for All Jet Transport Aircraft.



	MEAN		
	PERSONS	RANGE	CARGO
——— ALL TRANSPORTS	227	2868	11,940
━━━ SMALL JETS	110	1308	6576
— — CONVENTIONAL JETS	192	3368	6075
- - - - - WIDE-BODY JETS	389	3785	24,843

Figure 2.- Maximum Ramp Weight Relations for All Jet Transport Aircraft.

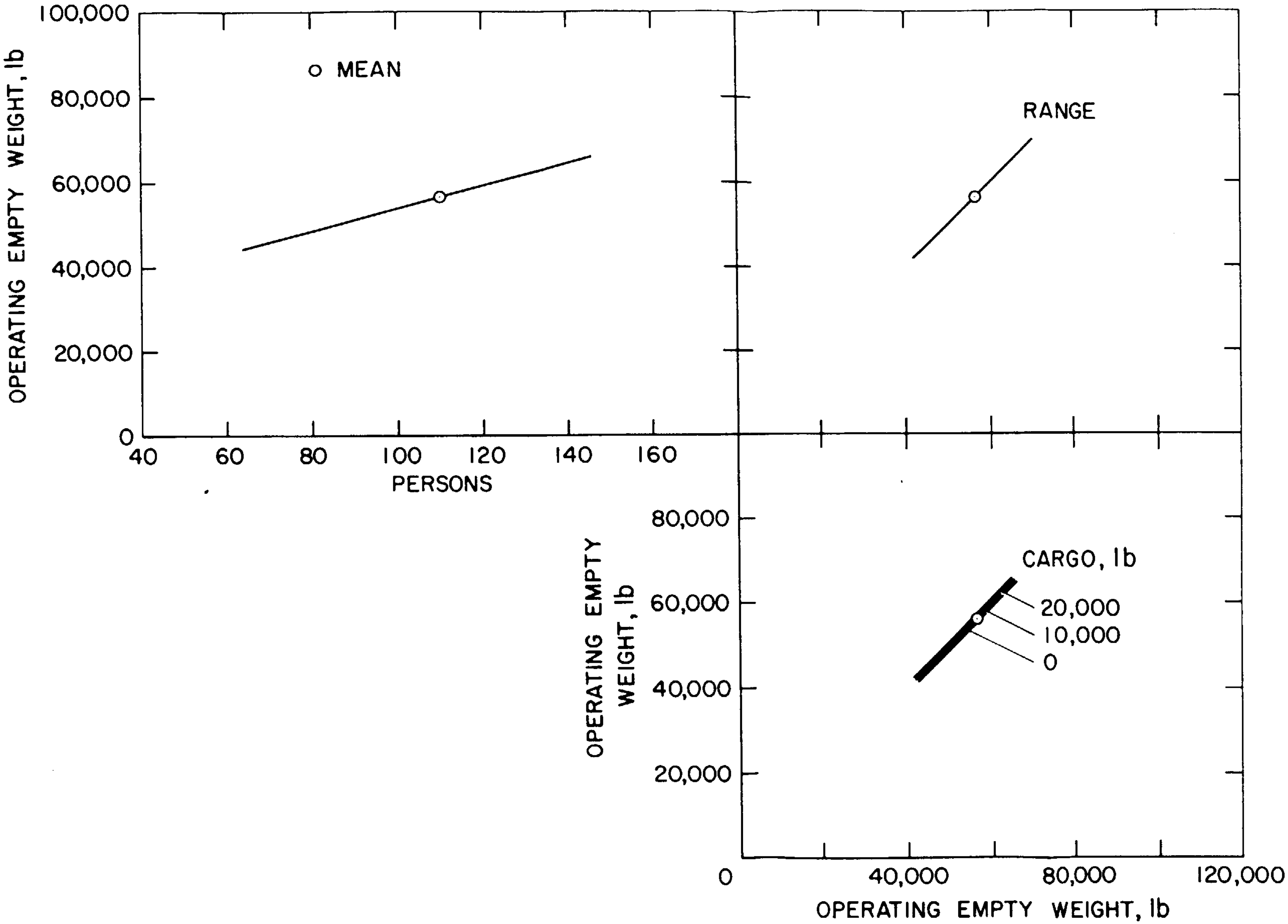


Figure 3.- Operating Empty Weight Relations for Small Jet Transports.

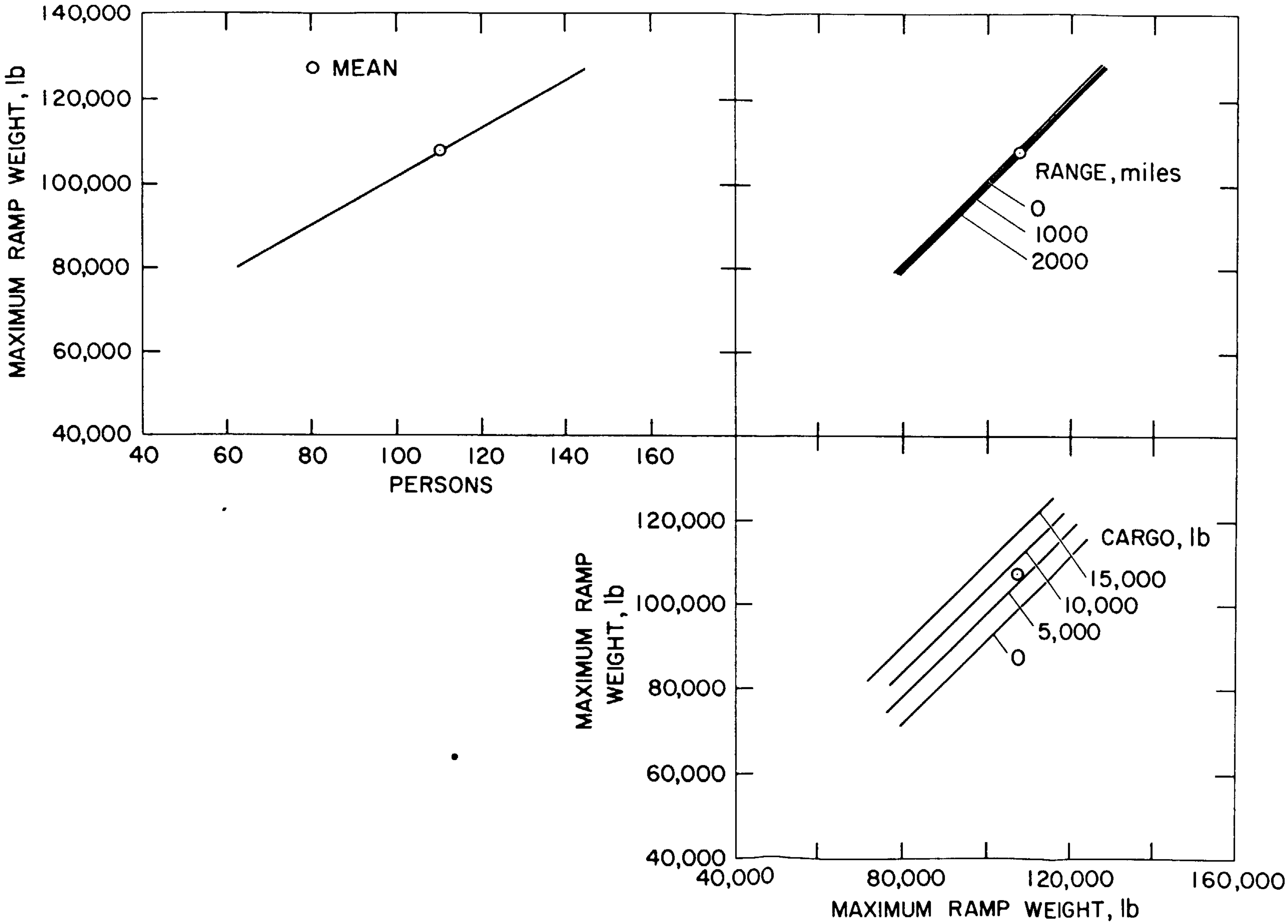


Figure 4.- Maximum Ramp Weight Relations for Small Jet Transports.

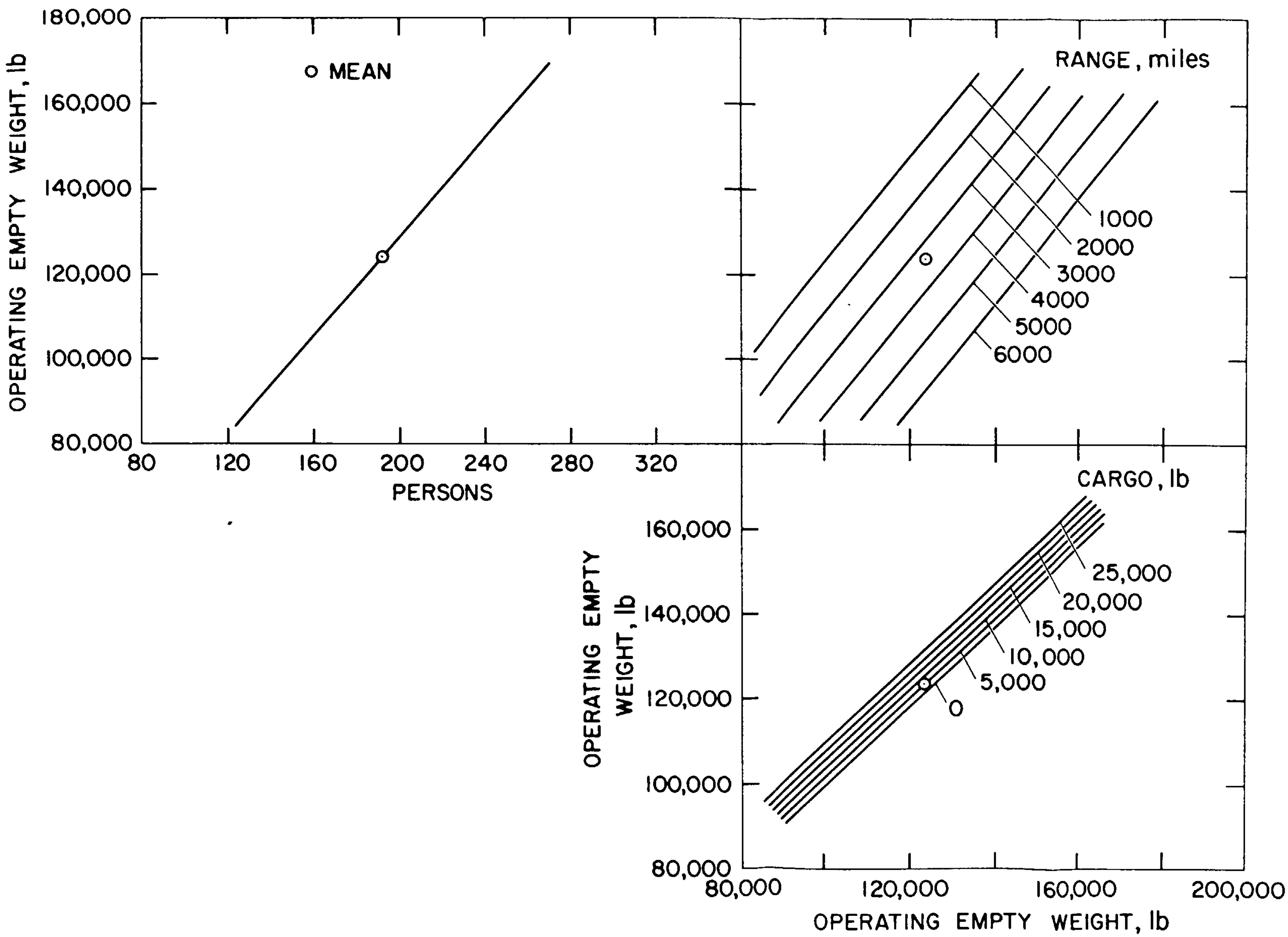


Figure 5.- Operating Empty Weight Relations for Conventional Jet Transports.

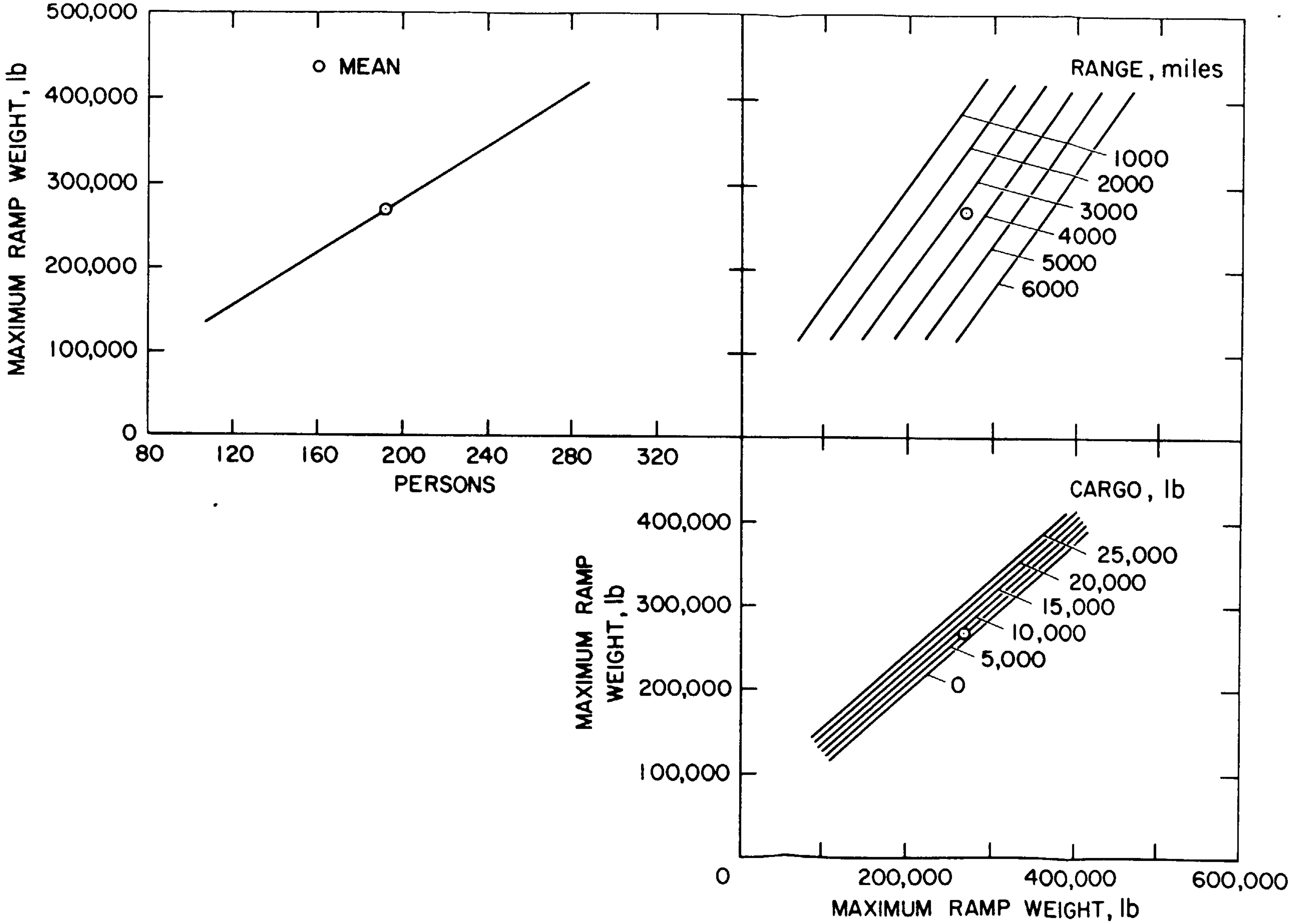
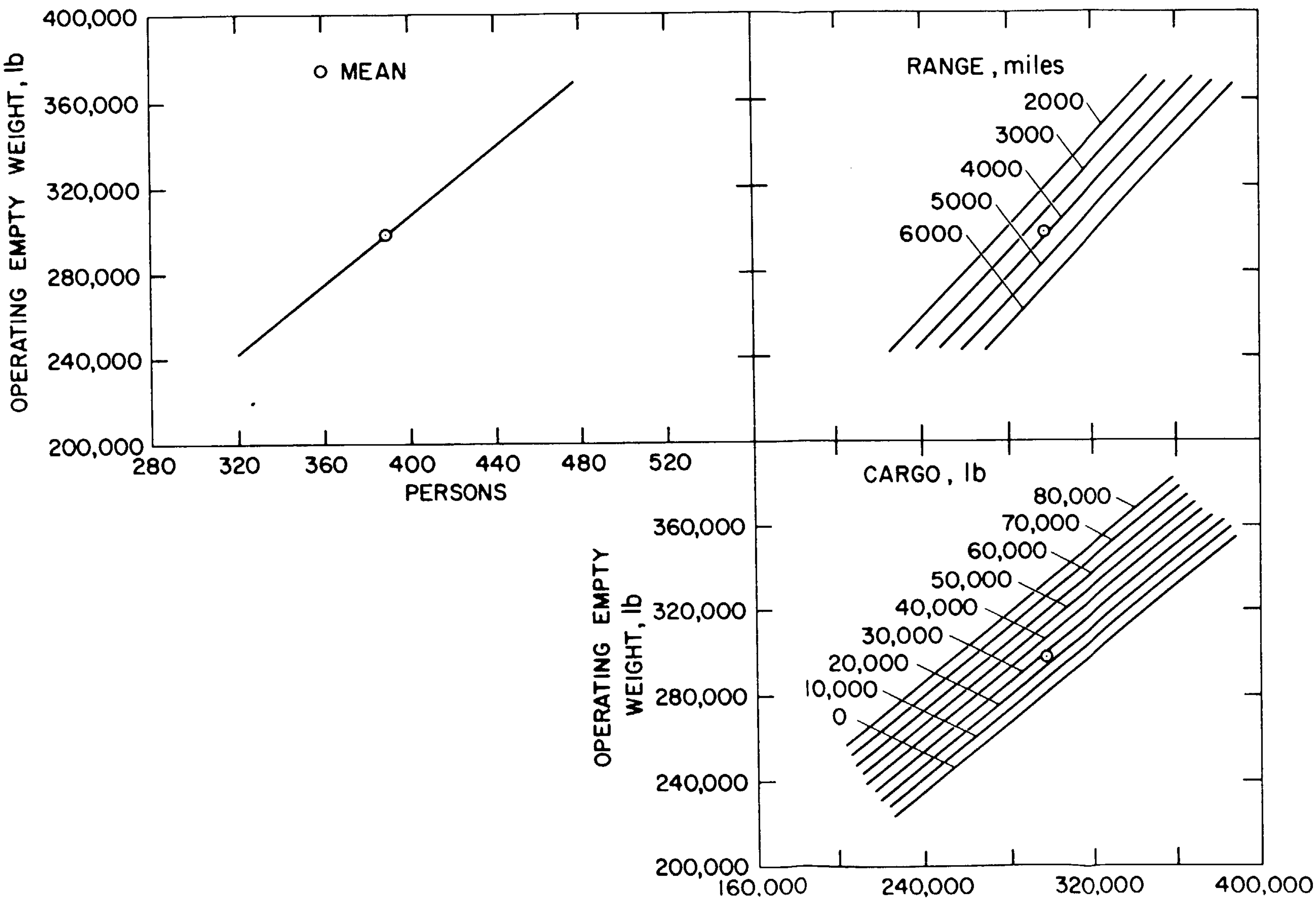


Figure 6.- Maximum Ramp Weight Relations for Conventional Jet Transports.



OPERATING EMPTY WEIGHT, lb
400,000
360,000
320,000
280,000
240,000
200,000
MEAN
280
320
360
400
440
480
520
PERSONS
RANGE, miles
2000
3000
4000
5000
6000
CARGO, lb
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
OPERATING EMPTY WEIGHT, lb
360,000
320,000
280,000
240,000
200,000
160,000
240,000
320,000
400,000

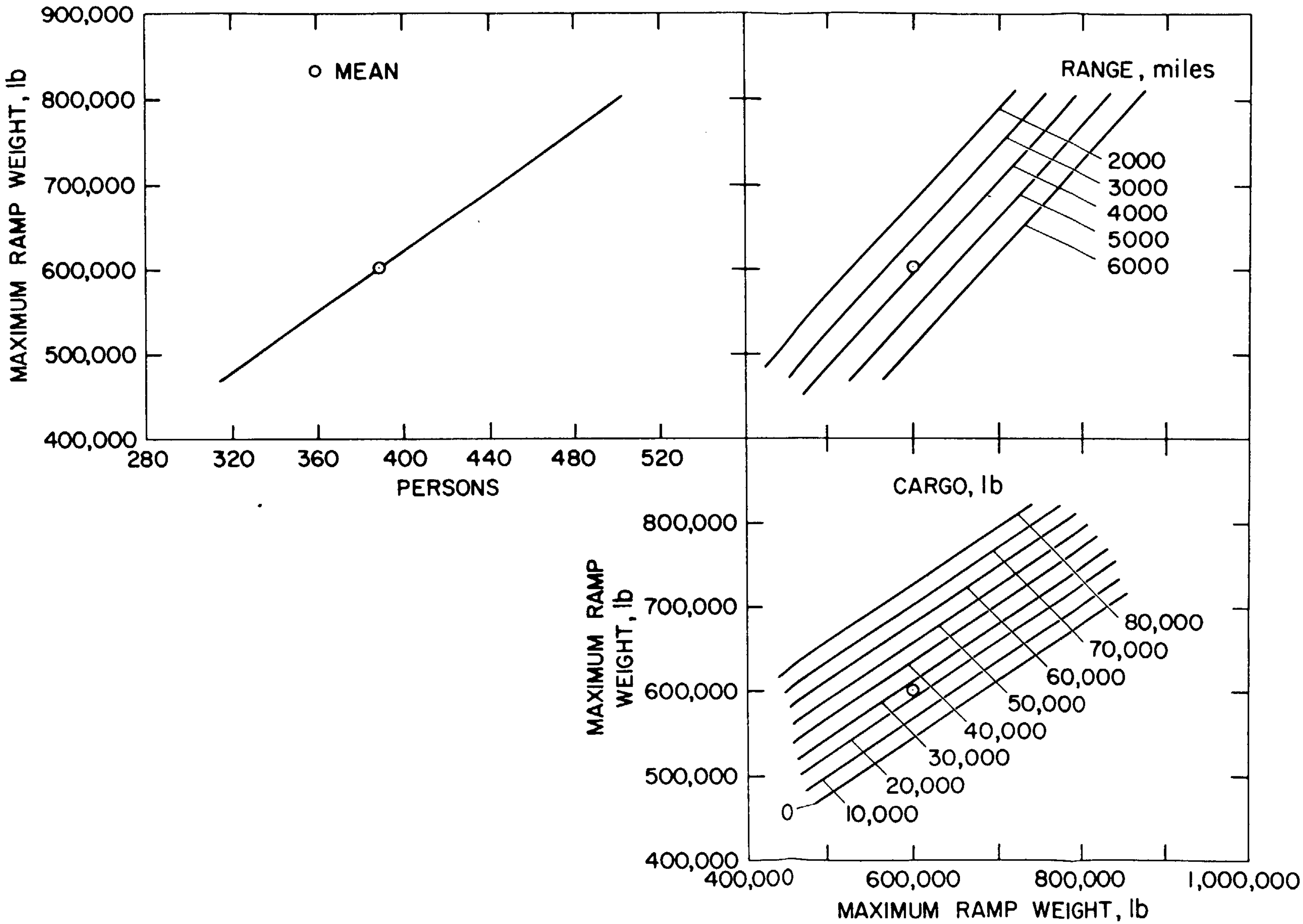


Figure 8.- Maximum Ramp Weight Relations for Wide-Body Jet Transports.