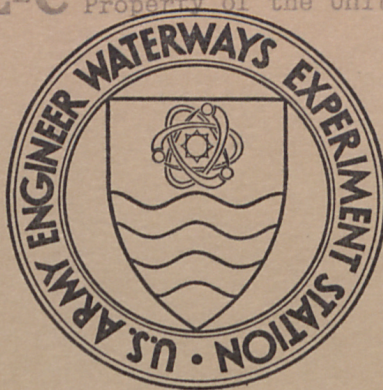


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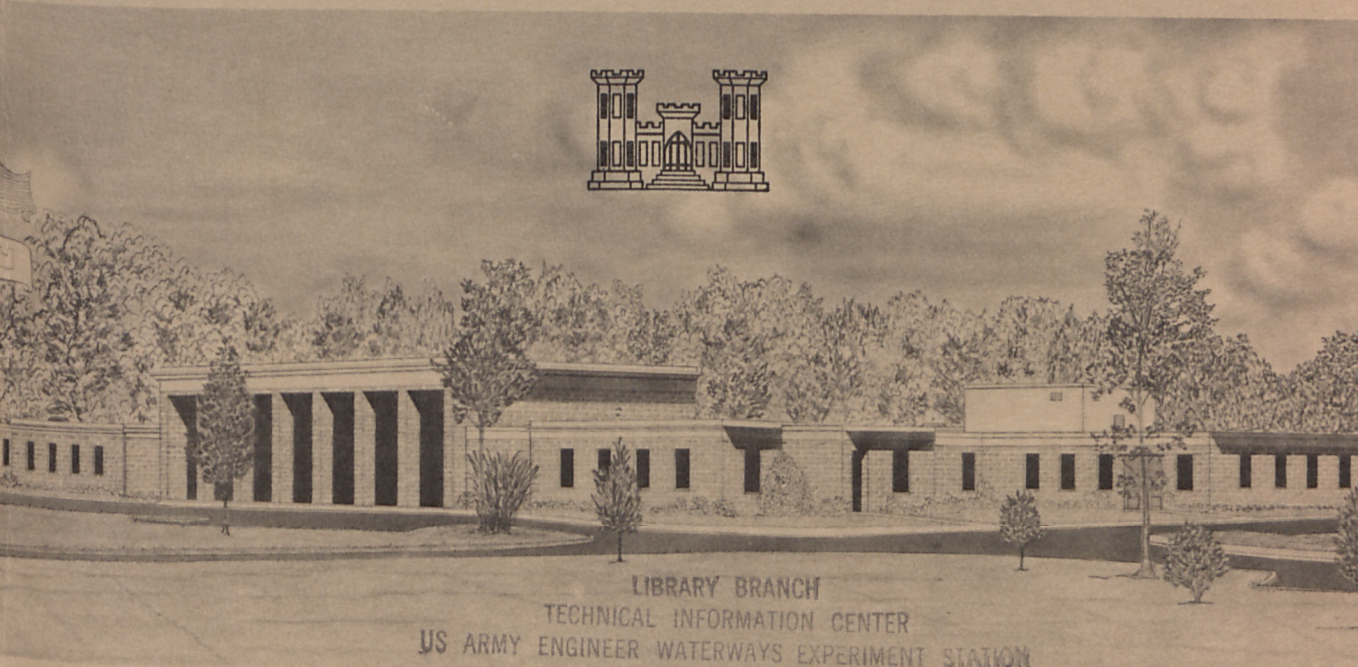


MISCELLANEOUS PAPER S-73-56

LATERAL DISTRIBUTION OF AIRCRAFT TRAFFIC

by

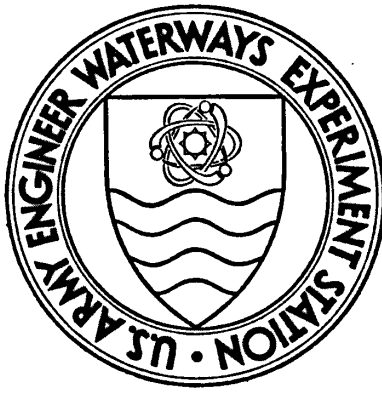
D. N. Brown, O. O. Thompson



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Soils and Pavements Laboratory
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FOREWORD

The study reported herein was sponsored by the U. S. Army Military Engineering Design and Expedient Construction Criteria (MEDECC) Program, Task O2, Work Unit 002, Evaluation of Existing Airfields for C-5A Operations.

This study was conducted under the overall supervision of Messrs. J. P. Sale, R. L. Hutchinson, R. G. Ahlvin, and D. N. Brown, Soils and Pavements Laboratory, U. S. Army Engineer Waterways Experiment Station (WES). The study was conducted by Dr. O. O. Thompson and Mr. D. N. Brown during the period June 1970-July 1971. This report was written by Dr. Thompson and Mr. Brown.

COL Ernest D. Peixotto, CE, was Director of WES during the conduct of this study and preparation of this report. Mr. F. R. Brown was Technical Director.

CONTENTS

	<u>Page</u>
FOREWORD	iii
NOTATION	vii
CONVERSION FACTORS, BRITISH TO METRIC UNITS OF MEASUREMENT	ix
SUMMARY	xi
PART I: INTRODUCTION	1
PART II: THE DEVELOPMENT OF THE CURRENT PASS/COVERAGE RATIO	3
Historical Background	3
Discussion of Operation Levels	16
PART III: DEVELOPMENT OF REVISED TRAFFIC DISTRIBUTION CONCEPTS	18
PART IV: COMPARISON OF METHODS OF DETERMINING PASS/COVERAGE VALUES	30
PART V: CONCLUSIONS AND RECOMMENDATIONS	36
Conclusions	36
Recommendations	36
LITERATURE CITED	38
TABLES 1-5	
PLATES 1-11	

NOTATION

ap	Aircraft passes
A	Area under distribution curve
A_M, A_N	Single tire contact area of main tires and nose tires, respectively (see fig. 8)
B	Total number of cycles (one landing and one takeoff); also, main gear wheel spacing (see fig. 8)
c, c'	Coverages
C_i, C_x C_{xc}, C_z	Maximum ordinates of theoretical normal distribution, GND, cumulative, and SND curves, respectively
D	Center-to-center spacing of nose gear tires (see fig. 8)
gp	Gear passes
GND	General normal distribution
N	Number of wheels in each main landing gear
N_M, N_N	Number of tires per main landing gear and nose gear assembly, respectively (see fig. 8)
p	Wheel passes per inch
p'	Total number of passes for each wheel
p/c	Ratio of aircraft passes to coverages (sometimes expressed as operations per coverage o/c)
$(p/c)_r$	p/c ratio for runways
$(p/c)_t$	p/c ratio for taxiways
P_t, P_w	Passes of aircraft center line and tire center line, respectively
S	Center-to-center wheel spacing
S_m, S_t, S_r	Center-to-center wheel spacing for twin wheels, tandem wheels, and outrigger wheels, respectively
SND	Standard normal distribution
T_w	Tread

u	Mean value in GND
wp	Wheel passes
W	Maximum lateral movement of a point on the center line of an aircraft about the center line (or guideline) on runways and taxiways, respectively, during operation of an aircraft
W_b	Wheel base
W_M, W_N	Width of single-tire contact area for main and nose tires, respectively (see fig. 8)
W_r	Wander on runway
W_t	Width of tire contact area
W_w	Wander width
W_x	Wander on taxiway
W_{75}	Width over which the center line of aircraft traffic is distributed 75 percent of the time
x	Variable in GND
Z	Variable in SND
α_i	Location weighting function
$\sigma, \sigma_i, \sigma_x$	Standard deviations
$\phi(Z)$	Standard normal density function

CONVERSION FACTORS, BRITISH TO METRIC UNITS OF MEASUREMENT

British units of measurement used in this report can be converted to metric units as follows:

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
inches	2.54	centimeters
feet	0.3048	meters
square inches	6.4516	square centimeters
pounds (force) per square inch	0.6894757	newtons per square centimeter

SUMMARY

In the development of pavement design and evaluation criteria for aircraft with complex gear configurations (C-5A, B-747, etc.), it has been revealed that current procedures for relating aircraft operations (passes) to pavement coverages (stress and/or deflection repetitions) are cumbersome and inaccurate.

The procedure for converting aircraft passes to pavement coverages has been reexamined by developing theoretical normal traffic distribution curves and fitting these curves to the limited number of actual traffic distribution curves available for four aircraft (B-47, B-52, KC-97, and KC-135). In this manner, more realistic pass-to-coverage (p/c) ratios have been developed for most currently used military and civil aircraft.

The revised p/c ratios are presented and are recommended for use in pavement design and evaluation criteria. The amount of actual traffic distribution data is recognized to be minimal, and additional data for new generations of aircraft are needed to verify or revise the presented p/c ratios.

LATERAL DISTRIBUTION OF AIRCRAFT TRAFFIC

PART I: INTRODUCTION

1. During the early stages of development of criteria for the design and evaluation of pavements, it became apparent that a method of accounting for repetitions of traffic was needed. To simply count the number of aircraft using an airfield facility is not adequate. The incremental detriment to a pavement caused by a particular wheel of a particular aircraft at a particular location is influenced by many factors. Some of these factors are: (a) number of wheels, (b) wheel configuration, (c) load on each wheel, (d) tire contact pressure, (e) location of aircraft on the pavement, and (f) previous loading history.

2. In an attempt to normalize these various factors so that one number could be obtained to reflect their collective influence on the total system of design and evaluation, the concept of coverages was introduced. As a result of different assumptions and development procedures used in analyzing results of traffic tests, the term "coverage" has different meanings for rigid and flexible pavements. For rigid pavements, coverage is a measure of the number of maximum stress applications that occur within the pavement due to the applied traffic. A coverage occurs when each point in the pavement within the limits of the traffic lane has been subjected to a maximum stress, assuming that the stress is equal under the full tire print. For flexible pavements, coverage is a measure of the number of maximum stress applications that occur on the surface of the pavement due to the applied traffic. A coverage occurs when all points on the pavement surface within the traffic lane have been subjected to one application of maximum stress, assuming that the stress is equal under the full tire print. Thus, for instance, a twin-tandem gear would produce two applications of stress on the surface of a flexible pavement but would produce only one maximum stress application within a rigid pavement if the tandem spacing were small and two maximum stresses if the tandem spacing were large. For

this study, the definition of coverage as applied to flexible pavements was used for the development of aircraft pass per coverage (p/c) ratios. The adjustment for multiple stresses resulting from tandem wheels on rigid pavements was then applied to the developed p/c ratios.

3. Test sections have been used to develop the relationship between load, traffic (coverages), and pavement thickness requirements. Traffic on the test sections is programmed so that successive wheel paths do not overlap and an accurate determination of coverages can be made. It is considered that these test section coverages relate directly to coverages on an airfield facility; however, it is recognized that the p/c ratio used on the test section and that occurring on the actual facility are different. Since the random traffic on an airfield can only be conveniently counted as aircraft passes, the development of the p/c ratio was essential so that test section relationships could be applied to airfield pavement design or evaluation.

4. The background leading to the development and application of the current method for determining the p/c ratios is presented herein, and it is shown that these p/c ratios, especially for aircraft employing complex gears, do not produce distributions that agree well with those developed from actual measurements and observations. Therefore, a new method for determining the p/c ratio was developed and used to compute p/c ratios for most of the currently used military and civil aircraft.

Historical Background

5. In one of the earliest (1942) pavement test sections, Stockton No. 1, accumulations of traffic were simply reported as wheel load repetitions.¹ The moving wheels were programmed so that three nonoverlapping but (theoretically) touching wheel paths were obtained. That is, for every three passes of a wheel, every point on the traffic lane was subjected to the print of a wheel one time (fig. 1).

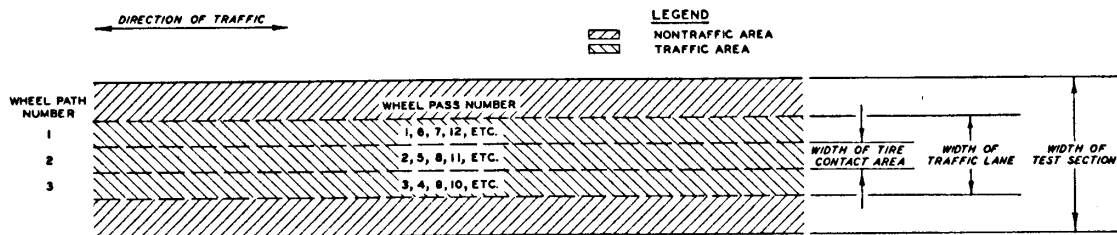


Fig. 1. Typical test section application of nondistributed single-wheel traffic

6. The next significant test section was constructed at Barksdale Field in 1944.² In this study, the pattern of programmed traffic was described in terms of coverages where a coverage was defined as "one pass of the wheel load over each point in the tracking (traffic) lane." Referring to fig. 1, three passes would produce one coverage. In all subsequent test section studies, repetitions of programmed traffic have been recorded in terms of coverages.

7. It is well known that aircraft traffic does not follow such a methodical pattern. Furthermore, it has been proposed, with substantiating evidence, that the sharp discontinuity between the traffic areas and nontraffic areas (fig. 1) causes unrealistic behavior. Test section traffic is now commonly distributed as shown in fig. 2. In this pattern, wheel paths 3 and 4 receive equal amounts of the applied traffic, and the other paths receive less. The maximum number of coverages (occurring in wheel paths 3 and 4) is recorded during testing and at failure. The number of coverages in the other lanes is of no consequence, as these

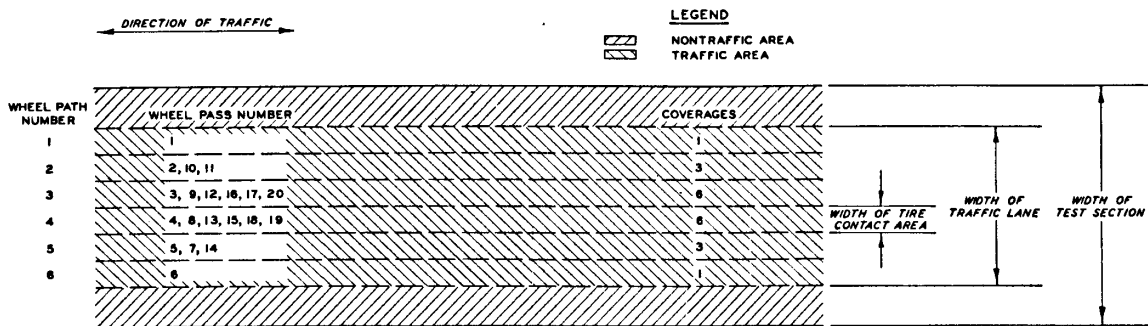


Fig. 2. Typical test section application of distributed single-wheel traffic

repetitions are provided to distribute the traffic and prevent the sharp discontinuity between traffic and nontraffic areas.

8. It is assumed that the coverages to failure are the same for a test section and an airfield facility when both are subjected to the same loadings. In design, therefore, the predicted number of aircraft passes is converted to coverages using the applicable p/c ratio, and the test track coverage versus thickness relations can be applied directly to the airfield facility.

9. The p/c ratio, sometimes called operations per coverage (o/c) ratio, was first described in a letter entitled "Design Curves for Less than Capacity Operations," dated 18 April 1949.³ In this letter, it was pointed out that the conversion from cycles based upon the following assumptions was reasonable:

- a. Each runway is serviced by two taxiways, and a cycle of operation (one landing and one takeoff) applies one pass to each taxiway and two passes to the runway.
- b. Seventy-four percent of all operations on the runway are such that the tire tracks for each gear are uniformly distributed over a 25 ft* width.
- c. Seventy-five percent of all operations on the taxiways are such that the tire tracks for each gear are uniformly distributed over a 12.5 ft width.
- d. All operations at the field are on the same runway.

Using these assumptions, the following relationships were developed:

* A table of factors for converting British units of measurement to metric units is presented on page ix.

$$c(\text{taxiways}) = \frac{0.75BNW_t}{12.5 \times 12} ; \quad c(\text{runways}) = \frac{0.75(2B)NW_t}{25 \times 12}$$

where:

c = coverages

B = total number of cycles of operation

N = number of wheels in each main landing gear*

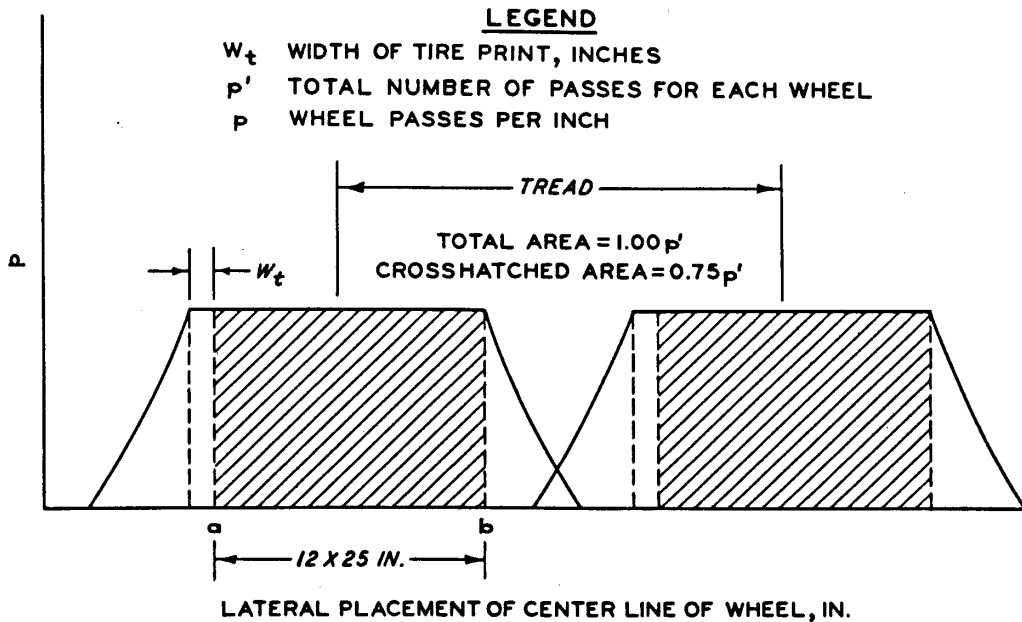
W_t = width of tire print in inches

Based on the assumptions presented above, the number of cycles required to produce one coverage on either a taxiway or a runway is equal to $200/NW_t$.

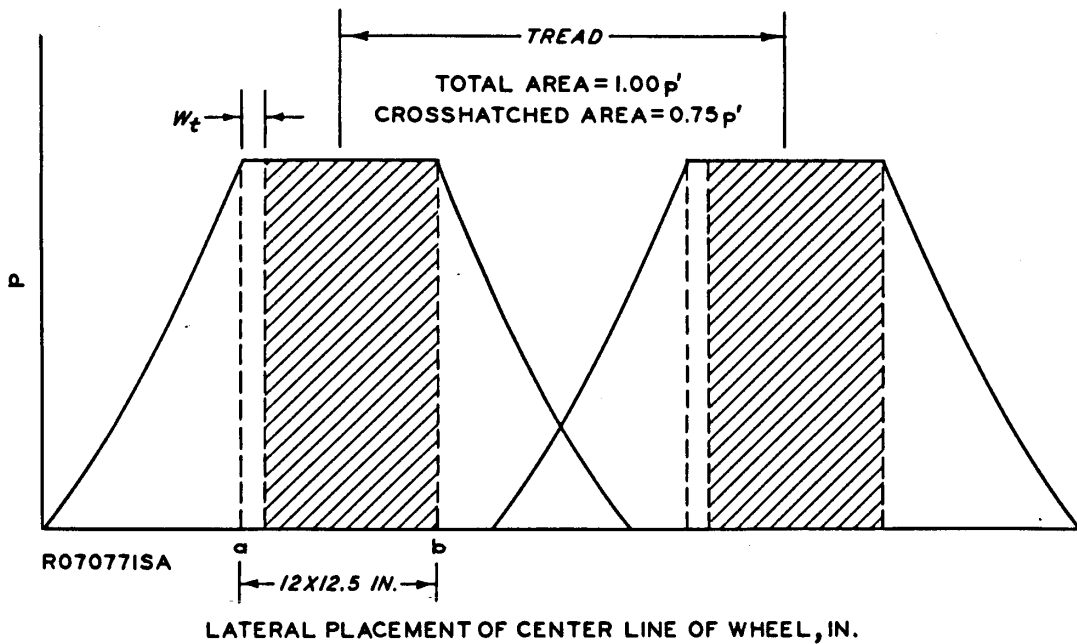
10. The assumed uniform distribution of traffic described above is shown graphically in fig. 3a for runways and fig. 3b for taxiways. The equation for p/c can be determined mathematically as shown in the following paragraphs.

11. Consider an aircraft with single-wheel tricycle gear (see fig. 4). In fig. 3a, one wheel is assumed to be in the zone ab = (12 x 25 in.) 75 percent of the time. If the width of tire print is W_t in., then $(12 \times 25)/W_t$ wheel passes wp will be required to produce one coverage of the width ab. Thus, the average number of wheel passes per inch $P = [(12 \times 25)/W_t][1/(12 \times 25)] = 1/W_t$ (wp/in.). That is, the ordinate after one coverage is $1/W_t$ (wp/in.) and the ordinate after c' coverages is c'/W_t (wp/in.) or the coverages after the total number of passes for each wheel p' is $(c'/W_t) W_t = c'$ (wp). Now, considering both gears, the total number of wheel passes = $2p'$ (wp), but one aircraft pass equals two wheel passes, and the maximum ordinate has not changed. Thus, by definition

* In normal operation, the load on the nose gear wheels is considerably less than that on the main gear wheels, and traffic generated by the nose gear wheels is of minimum consequence; therefore, the nose gear wheels have been consistently ignored in traffic distribution studies. The p/c ratios discussed and presented in this report are not relevant to nose gear wheel traffic.

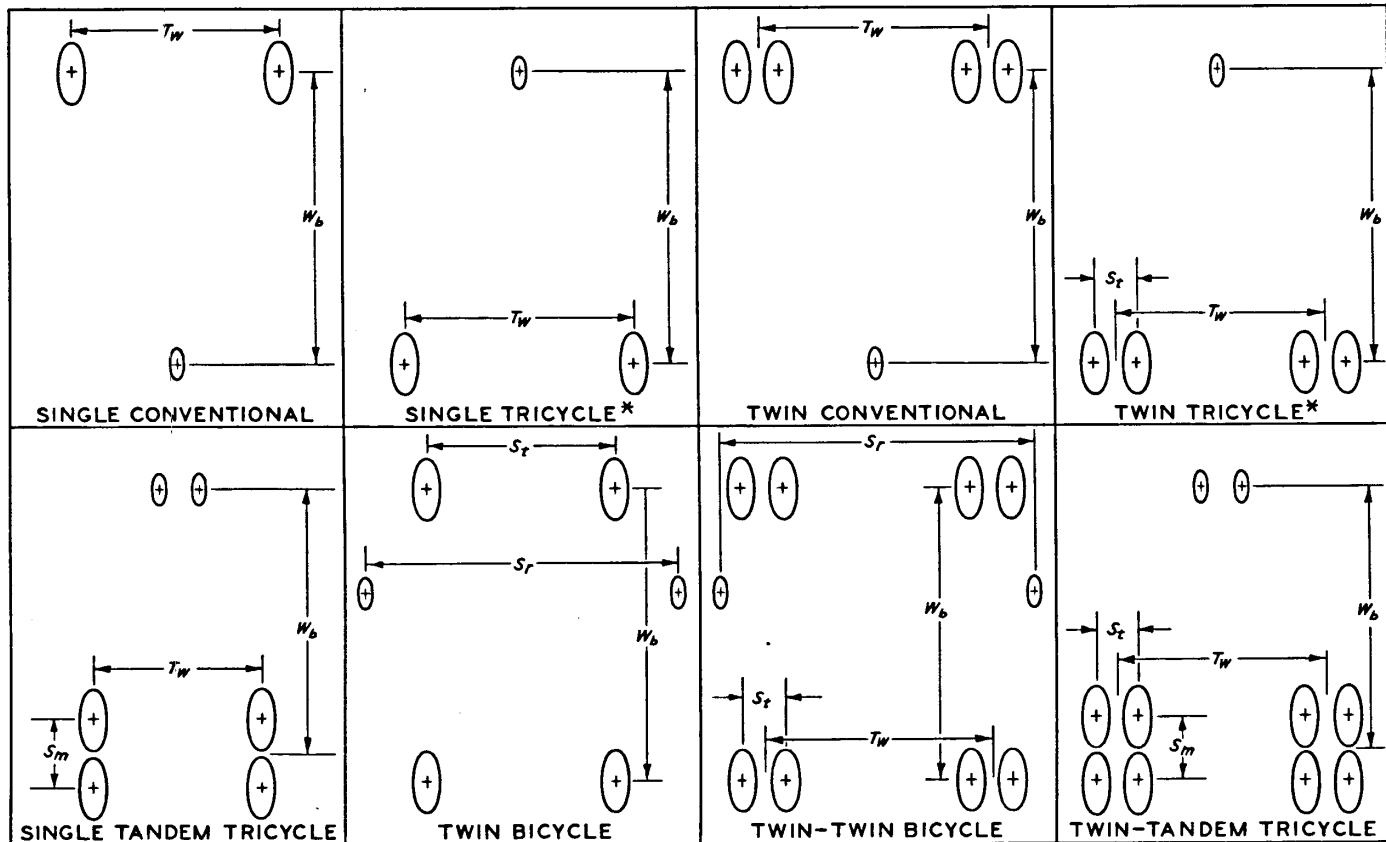


a. RUNWAY



b. TAXIWAY

Fig. 3. Theoretical uniform distribution of aircraft traffic on runways and taxiways



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LEGEND

T_w TREAD
 W_b WHEEL BASE
 S_t TWIN WHEEL SPACING
 S_m TANDEM WHEEL SPACING
 S_r OUTRIGGER WHEEL SPACING

* THE NOSE GEAR ON SOME AIRCRAFT WITH THESE TYPES OF LANDING GEARS CONSISTS OF TWIN WHEELS.

Fig. 4. Wheel configurations for typical aircraft landing gears

$$\begin{aligned} \frac{p}{c} &= \frac{\text{total number of aircraft passes}}{\text{coverages}} \left(\frac{ap}{wp} \right) \\ &= 2p'(wp) \frac{1}{2} \left(\frac{ap}{wp} \right) \left(\frac{w_t}{c'} \right) \frac{1}{w_t} \left(\frac{1}{wp} \right) \\ &= \frac{p'}{c'} \left(\frac{ap}{wp} \right) \end{aligned}$$

However, from fig. 3a:

$$\begin{aligned} 0.75p' &= \left(\frac{c'}{w_t} \right) (12 \times 25) \\ p' &= \frac{c'(12 \times 25)}{(0.75)(w_t)} \end{aligned}$$

Thus

$$\begin{aligned} \frac{p}{c} &= \frac{c'(12 \times 25)}{c'(0.75)(w_t)} \\ &= \frac{12 \times 25}{0.75(w_t)} \left(\frac{ap}{wp} \right) \end{aligned}$$

12. Consider now a bicycle gear with N wheels per gear and neglect the outrigger wheels. The maximum ordinate is now $(c'/NW_t)(wp/in.)$. For one main gear, the total number of wheel passes equals p' and the number of gear passes (gp) equals (p'/N) . For both main gears, the total number of gear passes equals $(2p'/N)(gp)$ but one aircraft pass equals two gear passes and the maximum ordinate has not changed. Thus, as before

$$\begin{aligned} \frac{p}{c} &= \frac{\text{total number of aircraft passes}}{\text{coverages}} \left(\frac{ap}{wp} \right) \\ &= \left(\frac{2p'}{N} \right) (gp) \frac{1}{2} \left(\frac{ap}{wp} \right) \left(\frac{NW_t}{c'} \right) \left(\frac{1}{w_t} \right) \left(\frac{1}{wp} \right) \\ &= \frac{p'}{c'} \left(\frac{ap}{wp} \right) \end{aligned}$$

However, from fig. 3a:

$$\begin{aligned} 0.75p' &= \left(\frac{c'}{NW_t} \right) (12 \times 25) \\ p' &= \frac{c'(12 \times 25)}{0.75(N)(w_t)} \end{aligned}$$

Thus

$$\begin{aligned}\frac{p}{c} &= \frac{c'(12 \times 25)}{c'(0.75)(N)(W_t)} \\ &= \frac{12 \times 25}{0.75(N)(W_t)} \left(\frac{ap}{wp}\right)\end{aligned}$$

This equation is the same as that given previously for runways. Similarly, the equation for taxiways can be developed. Thus, the equations for p/c ratios are written as follows:

$$\left(\frac{p}{c}\right)_t = \frac{12.5 \times 12}{0.75(N)(W_t)} \quad (\text{for taxiways}) \quad (1)$$

$$\left(\frac{p}{c}\right)_r = \frac{25 \times 12}{0.75(N)(W_t)} \quad (\text{for runways}) \quad (2)$$

where p/c denotes aircraft passes/coverage ratio, c has units of wheel passes, N denotes number of wheels of each main gear, and W_t denotes tire width, in.

13. In order to obtain actual traffic distribution data, a count of traffic at four B-47 bases was conducted and reported in 1956.⁴ Of particular interest was the influence of traffic distribution following center-line stripes (traffic guidelines), which had become common and had led to a considerable degree of channelization of traffic. It was reported that 75 percent of the main gear traffic on the straightways of taxiways fell in a lane 7.5 ft wide (see fig. 5). For most takeoffs, the main gear traffic occurred in an area with a width of about 30 ft at runway ends. The data for the reference 4 study were collected for B-47 and KC-97 aircraft.

14. As a result of this study, a letter dated 6 January 1956* was written recommending a revision of coverage criteria for capacity operation. It was suggested that the p/c value for nonchannelized traffic should be five times the value for channelized traffic. This multiplier was selected because:

* U. S. Army Engineer Waterways Experiment Station, CE, "Revised Coverage Criteria," Letter to the Chief of Engineers (ENGER), 6 Jan 1956.

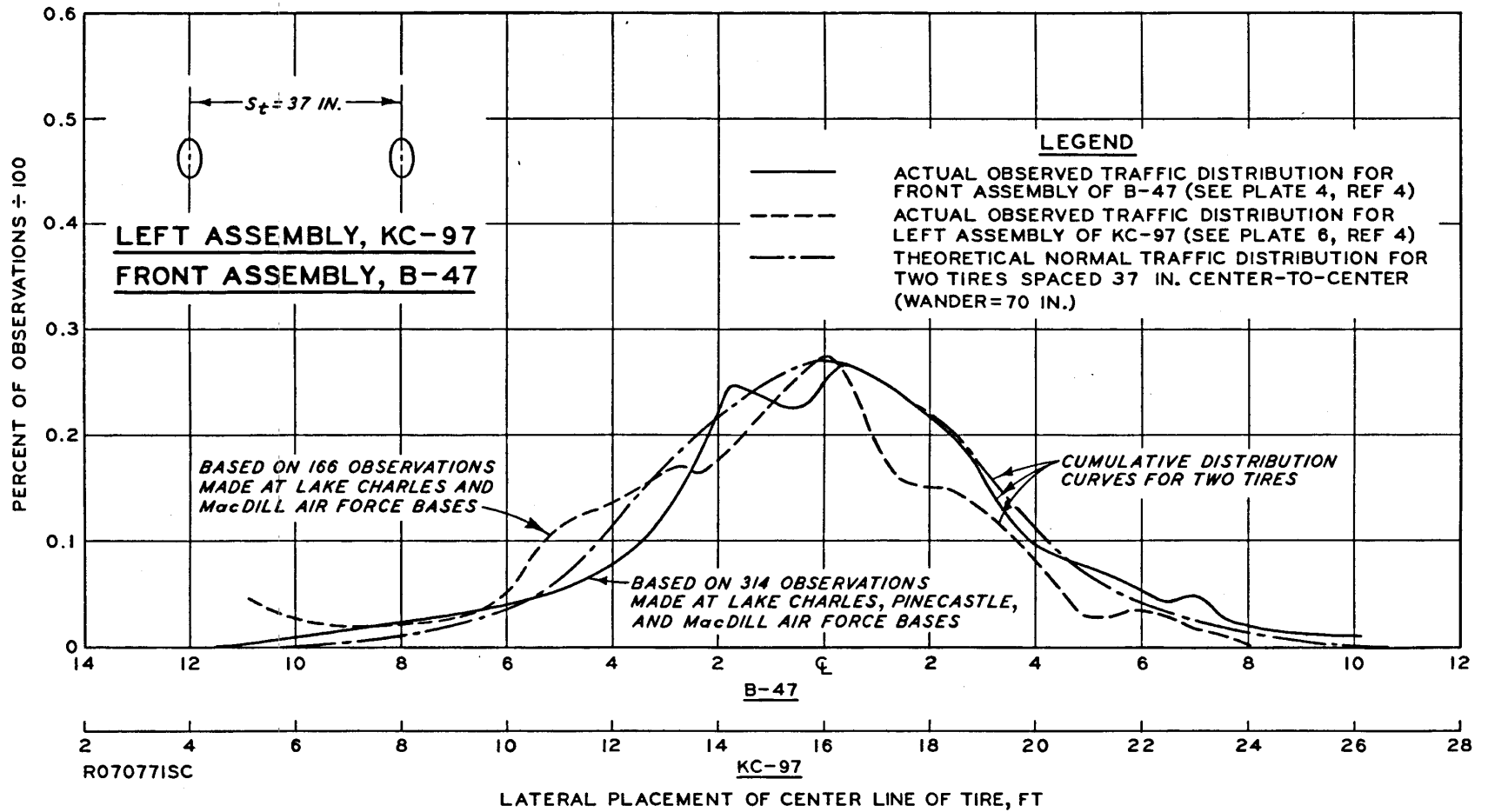


Fig. 5. Distribution of B-47 aircraft traffic along straightways of taxiway

The channelized traffic report shows 75 percent of B-47 traffic on channelized areas to fall within a strip 7.5 ft wide,.... In similar developments for runways (nonchannelized areas) earlier criteria were extended. The early criteria showed 75 percent of traffic in a 50-ft band, which for the 20- to 25-ft-wheel-span aircraft of that time meant a 25- to 30-ft wander width. This was for 150-ft runway widths. With wider runways and newer aircraft sizes, types, and gear configurations, it is considered reasonable to increase this by 30 to 50 percent. This gives a 75 percent tracked width of about 38 ft.

In accordance with this analysis of field data, equations 1 and 2 were revised as follows:

$$\left(\frac{p}{c}\right)_t = \frac{7.5 \times 12}{0.75(N)(W_t)} \quad (\text{for taxiways}) \quad (3)$$

$$\left(\frac{p}{c}\right)_r = \frac{38 \times 12}{0.75(N)(W_t)} \quad (\text{for runways}) \quad (4)$$

Thus, the p/c ratio for the B-47 was calculated as follows:

$$W_t = 14.3 \text{ in.}$$

$$N = 4$$

$$\left(\frac{p}{c}\right)_t = \frac{(7.5)(12)}{(0.75)(4)(14.3)} = 2.10 \text{ for taxiways}$$

$$\left(\frac{p}{c}\right)_r = \frac{(38)(12)}{(0.75)(4)(14.3)} = 10.63 \text{ for runways}$$

15. A second survey⁵ was conducted at seven Air Force bases to record the lateral distribution of B-47, B-52, KC-97, and KC-135 aircraft (see plates 1-8). The conclusions of this study are quoted in part as follows:

It is concluded that: (a) channelized traffic occurs on runways during takeoffs and to a lesser extent during landings; (b) the width in which channelization of B-47 traffic occurs on runways is about three times greater than the width (7.5 ft) in which

it occurs on taxiways; (c) the B-52 tends to use about the same width of runway as of taxiway; (d) due to their gear layout, the KC-135 and KC-97 travel in a slightly wider path than do the B-47 or B-52; and (e) the variation in climatic conditions at the fields investigated did not appear to have any effect on the operational characteristics of the aircraft in relation to takeoffs and landings.

16. As a result of the two investigations^{4,5} discussed in paragraphs 13, 14, and 15, the concept of wander was introduced. Under this concept, the width of the traffic lane, in which 75 percent of the traffic falls, is not specified as a constant dimension (7.5 ft for taxiways and 38 ft for runways) but is divided into its components: width of tire contact area W_t , center-to-center wheel spacing S , and wander W , where wander is defined as the maximum lateral movement of a point on the center line of an aircraft about the center line (or guideline) on taxiways or runways during operation of the aircraft. Thus, equations 3 and 4 were rewritten as follows:

$$\left(\frac{p}{c}\right)_t = \frac{W_t + S + W}{0.75(N)(W_t)} \quad (\text{for taxiways}) \quad (5)$$

$$\left(\frac{p}{c}\right)_r = \frac{W_t + S + W}{0.75(N)(W_t)} \quad (\text{for runways}) \quad (6)$$

The B-47 aircraft was used to develop new equations for determining p/c ratios. Specific values for the B-47 landing gear (fig. 6) were used to divide the traffic lane width (numerator of equations 5 and 6) into its components as shown in fig. 7. For the B-47 with a tire width W_t of 14.3 in. and a center-to-center wheel spacing S of 37 in., the wander for taxiways W is 38.7 in.; for runways, W is 404.7 in. These values for wander for the B-47 were rounded off to 40 and 410, respectively, and were used in revisions of equations 5 and 6 as follows:

$$\left(\frac{p}{c}\right)_t = \frac{W_t + S + 40}{0.75(N)(W_t)} \quad (\text{for taxiways}) \quad (7)$$

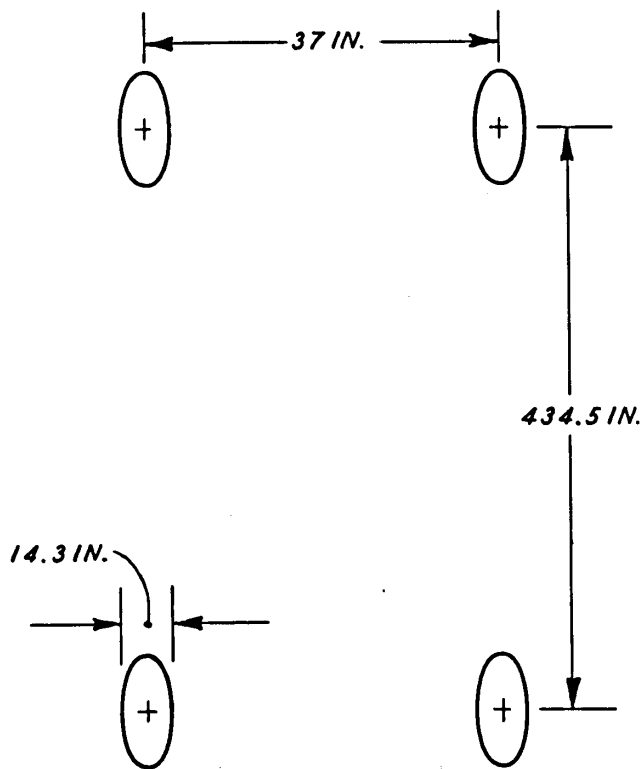
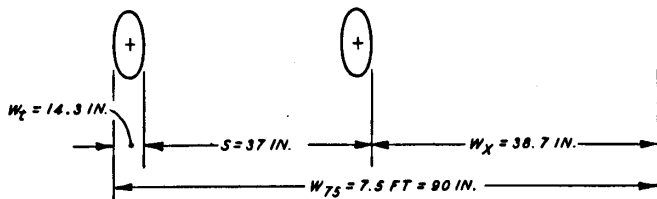
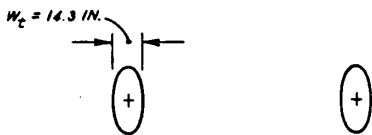


Fig. 6. Twin bicycle gear configuration for B-47 aircraft

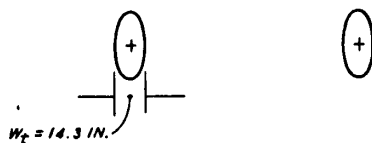
$$\left(\frac{p}{c}\right)_r = \frac{W_t + S + 410}{0.75(N)(W_t)} \quad (\text{for runways}) \quad (8)$$

Comparison of p/c ratios determined through use of equations 7 and 8 with similar ratios based on actual traffic indicated that p/c ratios determined through use of equations 7 and 8 do not agree very well with those determined using actual traffic distribution. Since very little actual traffic distribution data were available for further development, equation 7 was adopted for further use in determining p/c ratios. This equation is currently used to determine p/c ratios for all aircraft for both taxiways and runways.

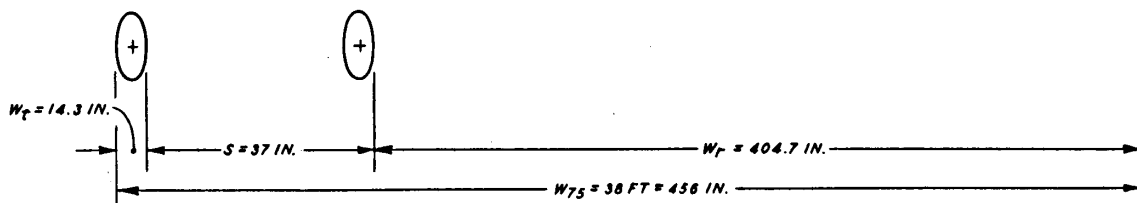
17. In publications prepared by the Air Force Systems Command at Wright-Patterson AFB, Ohio, the U. S. Air Force has proposed several variations of equation 7 for use in determining p/c ratios. The Air Force has concluded that (a) a large percentage of aircraft landings are made at reduced loads and that traffic resulting from landings is of



a. TAXIWAY (CHANNELIZED TRAFFIC)



- LEGEND**
- S CENTER-TO-CENTER WHEEL SPACING, IN.
 - W_t WIDTH OF TIRE, IN.
 - W_x WANDER ON TAXIWAY, IN.
 - W_r WANDER ON RUNWAY, IN.
 - W_{75} WIDTH OF TRAFFIC AREA RECEIVING 75% OF TRAFFIC



b. RUNWAY (NONCHANNELIZED TRAFFIC)

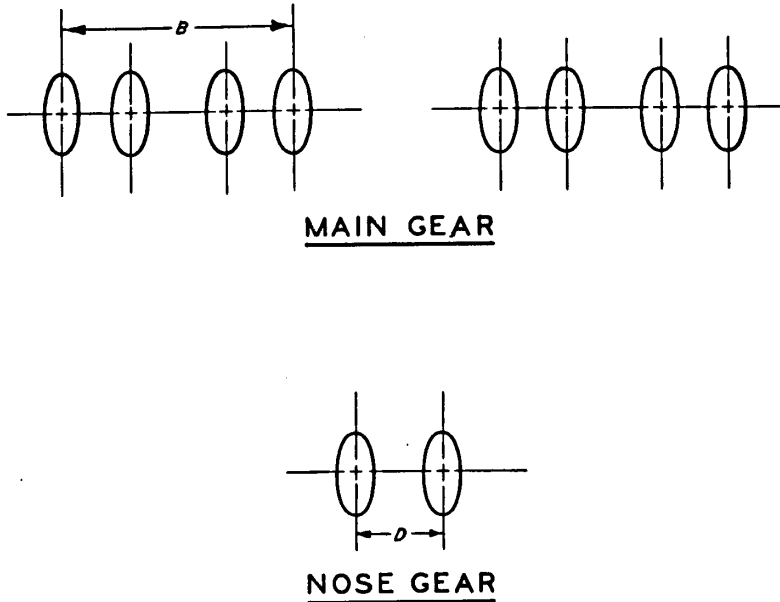
Fig. 7. Traffic lane receiving 75 percent of B-47 aircraft traffic

small consequence, and (b) that wander of a fully loaded aircraft for takeoff is about the same as wander along the taxiway. One Air Force publication⁶ suggests the use of the following equations for determining p/c ratios:

$$\left(\frac{p}{c}\right) = \frac{B + 80 + W_M}{0.75(N_M)(W_M)} \quad (\text{for main gear}) \quad (9)$$

$$\left(\frac{p}{c}\right) = \frac{D + 80 + W_N}{0.75(N_N)(W_N)} \quad (\text{for nose gear}) \quad (10)$$

The terms in these equations are identified in fig. 8. The p/c ratio for a particular aircraft (for taxiway or runway) is the smallest ratio resulting from either of these equations.



$$\text{MAIN ASSEMBLY: } P/C = \frac{B + 80 + W_M}{(0.75)(N_M)(W_M)}$$

$$\text{NOSE ASSEMBLY: } P/C = \frac{D + 80 + W_N}{(0.75)(N_N)(W_N)}$$

- P/C PASSES PER COVERAGE
- N_M NUMBER OF TIRES PER MAIN GEAR
- N_N NUMBER OF TIRES PER NOSE GEAR ASSEMBLY
- W_M WIDTH OF MAIN SINGLE TIRE CONTACT AREA $W_M = 0.878 \sqrt{A_M}$
- W_N WIDTH OF NOSE SINGLE TIRE CONTACT AREA $W_N = 0.878 \sqrt{A_N}$
- A_M SINGLE TIRE CONTACT AREA OF MAIN TIRES
- A_N SINGLE TIRE CONTACT AREA OF NOSE TIRES

Fig. 8. Suggested Air Force method for determining pass-per-coverage ratio (from reference 6)

Discussion of Operation Levels

18. In the past, design and evaluation criteria for pavements were prepared for capacity operation. Capacity operation is defined in the Barksdale report² as:

...the maximum traffic that can possibly operate on an airfield for a period of about 20 years. The daily operations may be assumed as varying from 100 cycles of landings and takeoffs for the very heavy airplanes to 1500 cycles for very lightweight planes.

Subsequently, it became necessary to develop criteria for less than capacity operations such as short-term military operations. Furthermore, at the time that center-line striping became common, the effects of channelization had to be considered. These factors were discussed in the letter, "Revised Coverage Criteria," and the following was presented.

Headquarters, U. S. Air Force has suggested using about 6600 operations per year for B-47 aircraft fields. This suggests the following:

<u>Time Period</u>	<u>Operations</u>	<u>Coverages</u>	
		<u>Channelized</u>	<u>Nonchannelized</u>
2 weeks	254	119	24
6 months	3,300	1,540	304
2 years	13,200	6,160	1,220
10 years	66,000	30,800	6,080

Using these data and attempting to establish reasonable ranges for coverages, operations and evaluation of loads and at the same time incorporating as much existing data as possible, the following has been derived.

<u>Operational Category</u>	<u>Time Period</u>	<u>Coverages</u>		<u>Operations</u>	
		<u>Channelized</u>	<u>Non-channelized</u>	<u>Channelized</u>	<u>Non-channelized</u>
Capacity	5-10 yrs	25,000*	5000*	50,000*	50,000*
Full	1-2 yrs	5,000	1000	10,000	10,000
Minimum	4-6 mos	1,000	200	2,000	2,000
Emergency	2-3 wks	200	40	400	400

* These to be indicated only as "unlimited."

19. The tabulation on the preceding page has been used to define operational categories up to the present. However, these values are no longer realistic because many airfields, both military and civilian, are carrying a considerably greater quantity of traffic. Thus, in the future, design and evaluation curves should be presented in terms of aircraft passes (operations). In this case, the p/c ratios will normally be required only to convert test section traffic in terms of coverages into equivalent aircraft traffic in terms of aircraft passes.

PART III: DEVELOPMENT OF REVISED TRAFFIC
DISTRIBUTION CONCEPTS

20. The discussion in Part II has shown the current stage of development of traffic distribution concepts. Statistical methods have been used to make a more fundamental study, which resulted in the development of improved traffic distribution concepts described in the following paragraphs.

21. A fundamental assumption was made that airfield traffic is normally distributed rather than uniformly distributed as formerly assumed (fig. 3). For a large number of aircraft passes, the statistical representation of the lateral placement of the center line of the aircraft may be as shown in fig. 9. The general shape is assumed to be normal, but the specific shape depends on the standard deviation σ . The specific shape can also be described by prescribing the wander width W , which is defined as that width over which the center line of aircraft traffic is distributed 75 percent of the time. As will be shown later, wander widths of 70 and 140 in., respectively, will be used for taxiways and runways. These values represent the best values obtainable from existing data and are subject to change.

22. The concept of coverage has been revised for this work. It

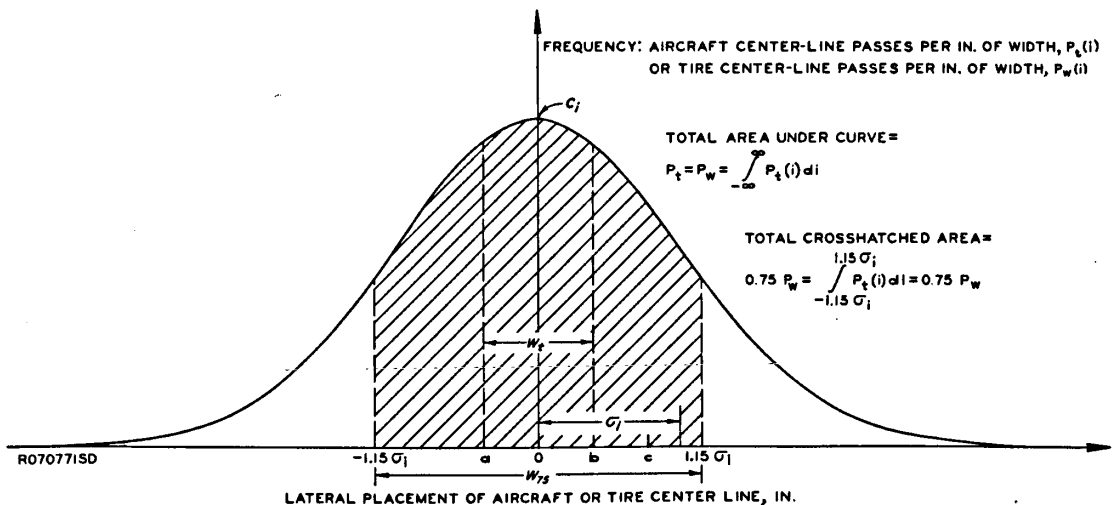


Fig. 9. Theoretical normal distribution of aircraft traffic

was assumed that coverage represents the maximum number of tire prints or partial tire prints applied to the pavement surface at that point where maximum accumulation occurs. Referring to fig. 9, the curve also represents the distribution of the center line of one wheel on the aircraft. Then, when the wheel center line is at $a = -(W_t/2)$, wheel passes accumulate at 0. Similarly, when the wheel center line is between $a = -(W_t/2)$ and $b = +(W_t/2)$ accumulations will occur at 0. By inspection, the maximum number of accumulations will occur at 0 and is equal to:

$$c = \int_{-\frac{W_t}{2}}^{\frac{W_t}{2}} P_t(i) di$$

This is approximately $(C_i)(W_t)$.

23. There is an inherent assumption that the effect of the edge of a tire at 0 is as detrimental as the effect of the center of the tire at 0. This is not necessarily so, and a further refinement would be to use a location weighting function α_i , which would change as the tire center line is moved from the point under consideration (in this case, point 0). The location weighting function would be 1.0 when the center of the tire was directly over the point of maximum accumulations and less than 1.0 as the tire location was moved. Furthermore, it may well be that a tire at location c for example, although not accumulating tire prints at 0, could be contributing detriment at point 0.* Then, the coverages could be defined as:

$$c = \int_{-\infty}^{\infty} [P_t(i)\alpha(i)] di$$

At this time, this refinement will not be considered and the simplified definition $c = (C_i)(W_t)$ will be used.

24. The method can now be extended to an aircraft having many

* Note also that this is even more true at increasing depths, such as at the surface of the subgrade, etc.

wheels. The wheel path patterns, such as in fig. 9, are added graphically, and the coverages for the particular aircraft can be determined. The area (A) under all the distribution curves represents the total number of wheel passes. From this use, the p/c ratio can be determined as described in the following paragraphs.

25. The standard normal distribution (SND) curve is shown in fig. 10. Properties of this curve are tabulated in various publications

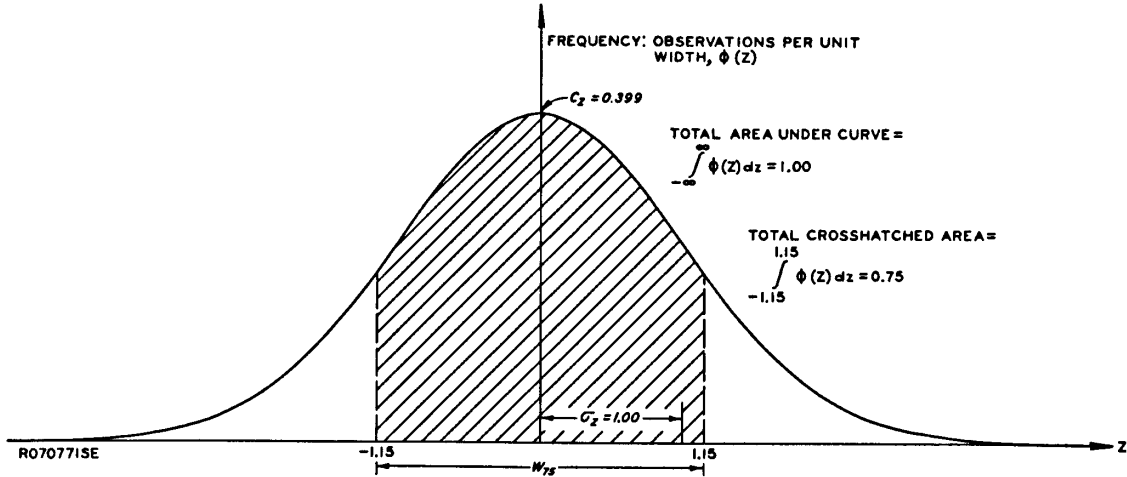


Fig. 10. Standard normal distribution (SND) curve

(for instance, reference 7) and these tabulated values can be used to determine the properties of general normal distributions GND. In the SND,

Standard deviation, $\sigma = 1.0$

Area under the curve, $A = 1.0$

Maximum ordinate, $C_z = 0.399$

and 75 percent of the area under the curve lies between $-1.15 < Z < +1.15$. The GND of aircraft traffic can be related to the SND curve using the substitution

$$Z = \frac{x - u}{\sigma_x}$$

where

Z = a variable in SND

x = a variable in GND

σ_x = standard deviation in GND

u = mean value in GND

The GND is shown in fig. 11 for a wander width W_w of 70 in. Therefore,

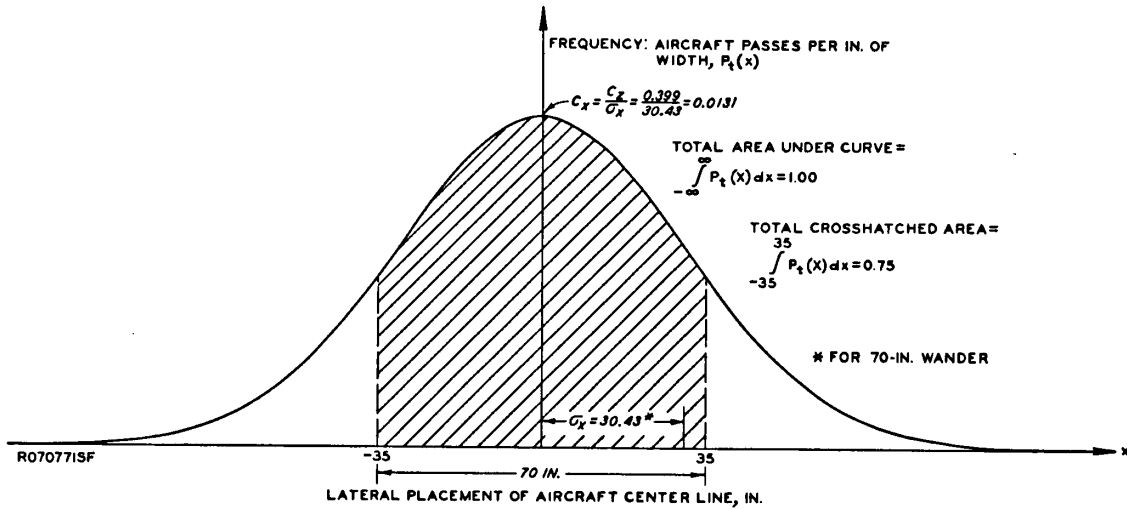


Fig. 11. General distribution (GND) curve for aircraft traffic
75 percent of the wheel paths will be distributed between +35 and -35 in.
Hence, using the above substitution with $u = 0$,

$$1.15 = \frac{35 - 0}{\sigma_x}$$

$$\sigma_x = 30.43$$

Note that as the wander is changed, σ_x changes also and must be recalculated as shown above. Now the SND curve has the equation

$$\phi(z) = \frac{1}{\sqrt{2\pi}} e^{-z^2/2}$$

where $\phi(z)$ = standard normal density function. The GND curve has the equation

$$P_t(x) = \frac{1}{\sigma_x \sqrt{2\pi}} e^{-1/2 (x-u/\sigma_x)^2}$$

which, using the substitution $Z = (x - u)/\sigma$, becomes

$$P_t(x) = \frac{1}{\sigma_x} [\phi(Z)]$$

and

$$C_x = \frac{C_z}{\sigma_x} = \frac{0.399}{30.43} = 0.0131$$

where C_x = the maximum ordinate of GND. Also,

$$\begin{aligned} \text{the area under the GND curve} &= \int_{-\infty}^{\infty} P_t(x) dx \\ &= \int_{-\infty}^{\infty} \frac{1}{\sigma_x} [\phi(Z)] \sigma_x dz \\ &= \int_{-\infty}^{\infty} \phi(Z) dz \\ &= 1.00 \end{aligned}$$

26. The theoretical normal distribution can now be applied to real aircraft. Consider, for example, an aircraft with single-wheel tricycle gear (fig. 12). Plotting the theoretical distribution of each wheel and superimposing the patterns, the distribution of fig. 12 is obtained. Graphical addition of these curves does not result in an increase in the value of the maximum ordinate C_x . Therefore, the total area under the curves equals two wheel passes or one aircraft pass, and the maximum coverages equal $(C_x)(W_t)$. Thus

$$\frac{p}{c} = \frac{1}{(C_x)(W_t)} \left(\frac{ap}{wp} \right) \quad (11)$$

27. As the wheel spacing S becomes smaller, a pattern such as that shown in fig. 13 is obtained. In this case, a graphical addition

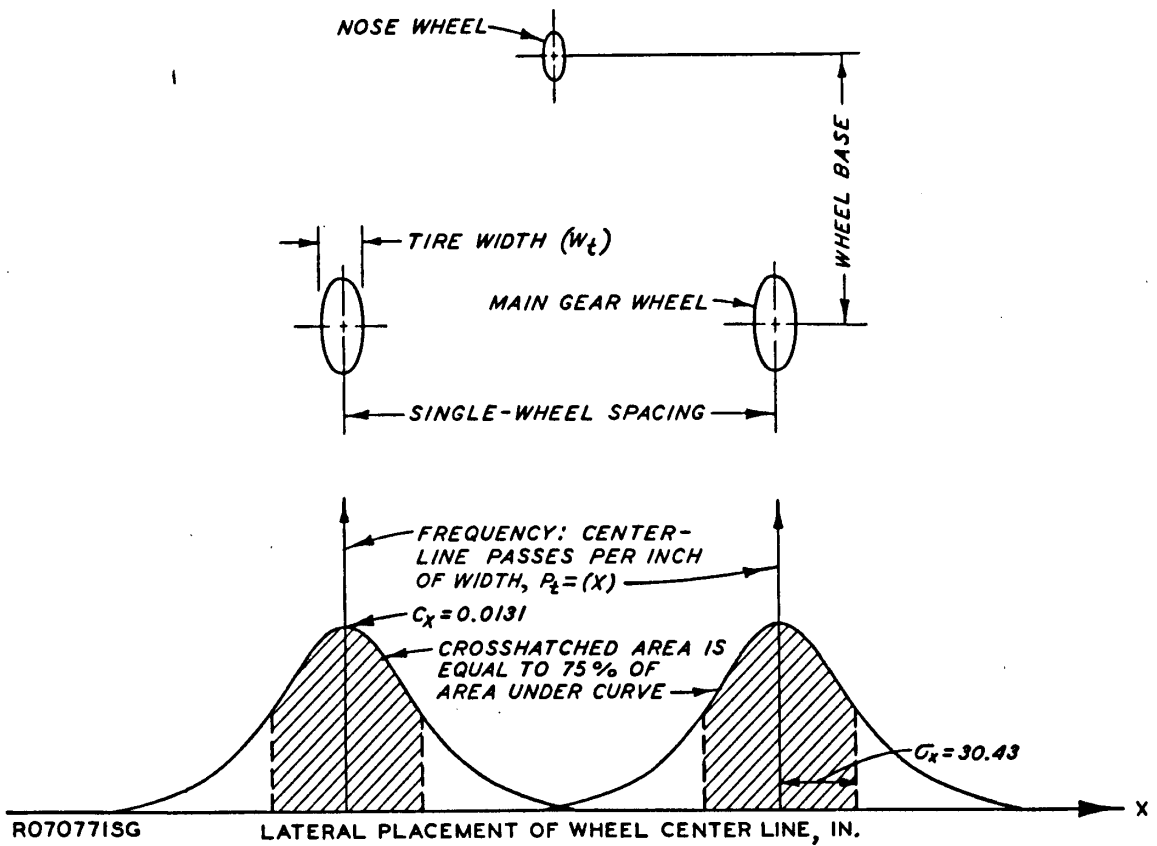


Fig. 12. General normal distribution for nonoverlapping wheels for the tricycle landing gear shown above

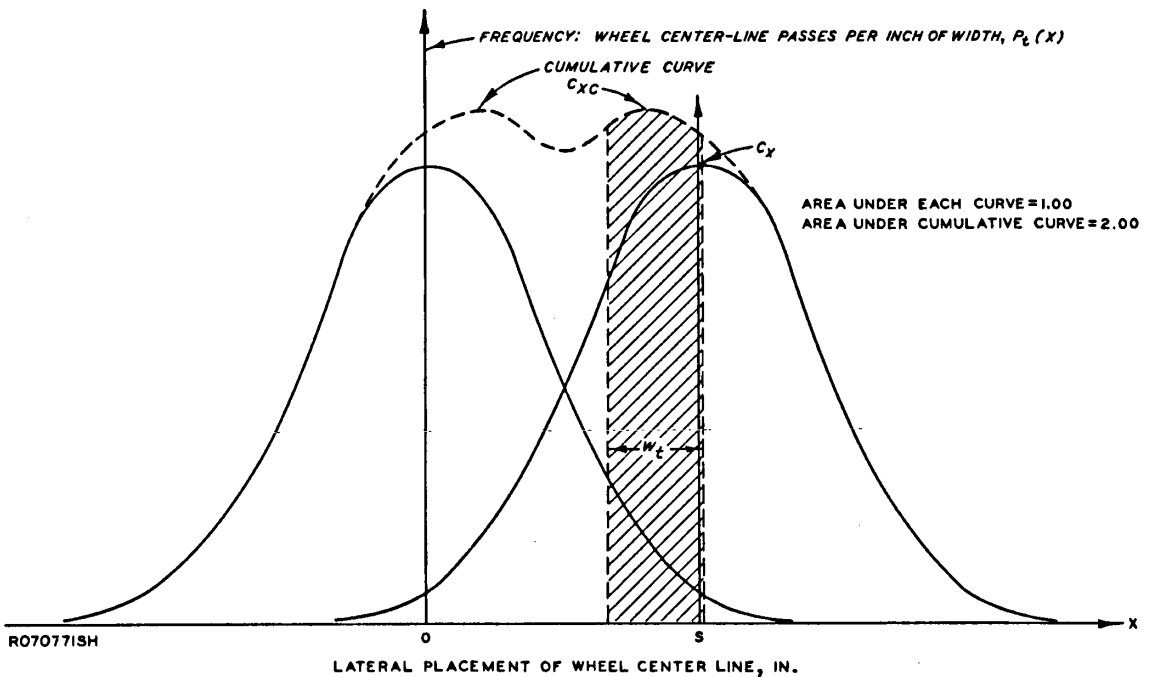


Fig. 13. General normal distribution curve for overlapping single wheel

of the overlapping wheel path patterns gives the cumulative curve. The area under the curve equals two wheel passes or one aircraft pass as before. Now, however, the maximum coverage is the maximum area under the cumulative curve within a width of W_t . This value will not necessarily occur under one wheel but must be determined in both magnitude and location. The maximum area may be as shown by the crosshatched area in fig. 13. Such a refinement is not considered warranted, and, for simplicity, the value $(C_{xc})(W_t)$ is taken as coverages. C_{xc} must be obtained graphically. The determination of C_{xc} could easily be programmed to be determined using a computer, but this has not been done since this determination need be made only one time for each aircraft. Thus

$$\frac{p}{c} = \frac{1}{(C_{xc})(W_t)} \left(\frac{ap}{wp} \right) \quad (12)$$

28. As an aid in determining the maximum ordinate C_{xc} on cumulative traffic distribution curves for two wheels, fig. 14 was drawn.

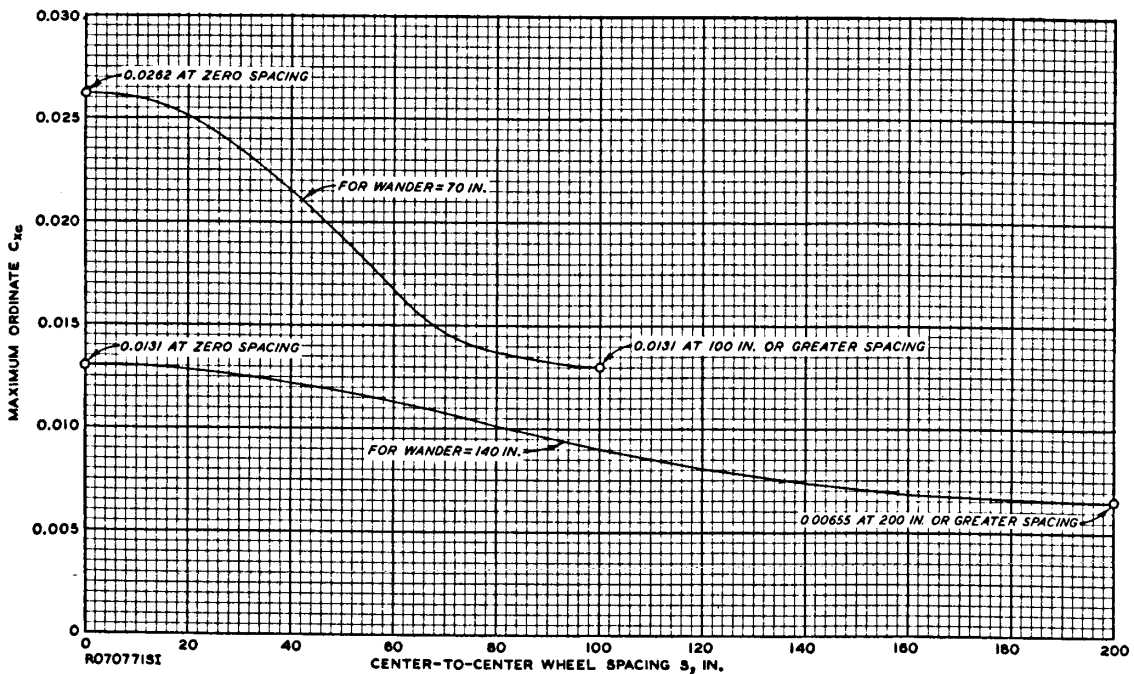


Fig. 14. Maximum ordinate on cumulative traffic distribution curve for two wheels versus wheel spacing

This figure shows C_{xc} versus wheel spacing for wander widths of 70 and 140 in. For a wander of 70 in., $C_{xc} = C_x = 0.0131$ when the wheel spacing is greater than 100 in. (nonoverlapping wheel paths). When the wheel spacing is zero, $C_{xc} = 2C_x = 0.0262$ (tandem assembly). When the wheel spacing is greater than zero and less than 100 in., C_{xc} can be read from fig. 14. For a wander of 140 in., $C_{xc} = C_x = 0.00655$ when the wheel spacing is greater than 200 in. (nonoverlapping wheel paths). When the wheel spacing is zero, $C_{xc} = 2C_x = 0.0131$ (tandem assembly). When the wheel spacing is greater than zero and less than 200 in., C_{xc} can be read from fig. 14. Fig. 14 is applicable to the following gear configurations (see wheel configuration diagrams in fig. 4) without exception: single conventional, single tricycle, single-tandem tricycle,* and twin bicycle; and to the following gear configurations when the tread minus the twin-wheel spacing is greater than 100 in. (for 70-in. wander) or 200 in. (for 140-in. wander): twin conventional, twin tricycle, and twin-tandem tricycle.* In all other instances (when the tread minus the single-wheel spacing is less than indicated above) and for other gear configurations, it is necessary to determine C_{xc} graphically as shown for the C-5A in fig. 15.

29. The versatility of this method is demonstrated with the determination of p/c values for the C-5A and Boeing 747 landing gear wheel configurations as shown below for a wander of 70 in.

- a. The C-5A gear configuration is shown in fig. 16. The theoretical normal traffic distribution curves for the wheel groups A or B and A plus B or B plus D are shown in fig. 15. By inspection, it can be seen that the maximum ordinate for group A plus group C (or group B plus group D) is the maximum ordinate for the assembly. Thus

$$C_{xc} = 0.086 \left(\frac{wp}{in.} \right)$$

For the main gear assembly, the total number of wheel

* Note that for these gear configurations, values of C_{xc} can be read directly from fig. 14 for use in calculating p/c ratios for aircraft operating on rigid pavements. These same values of C_{xc} are doubled for use in calculating p/c ratios for aircraft operating on flexible pavements and landing-mat-surfaced and unsurfaced airfields.

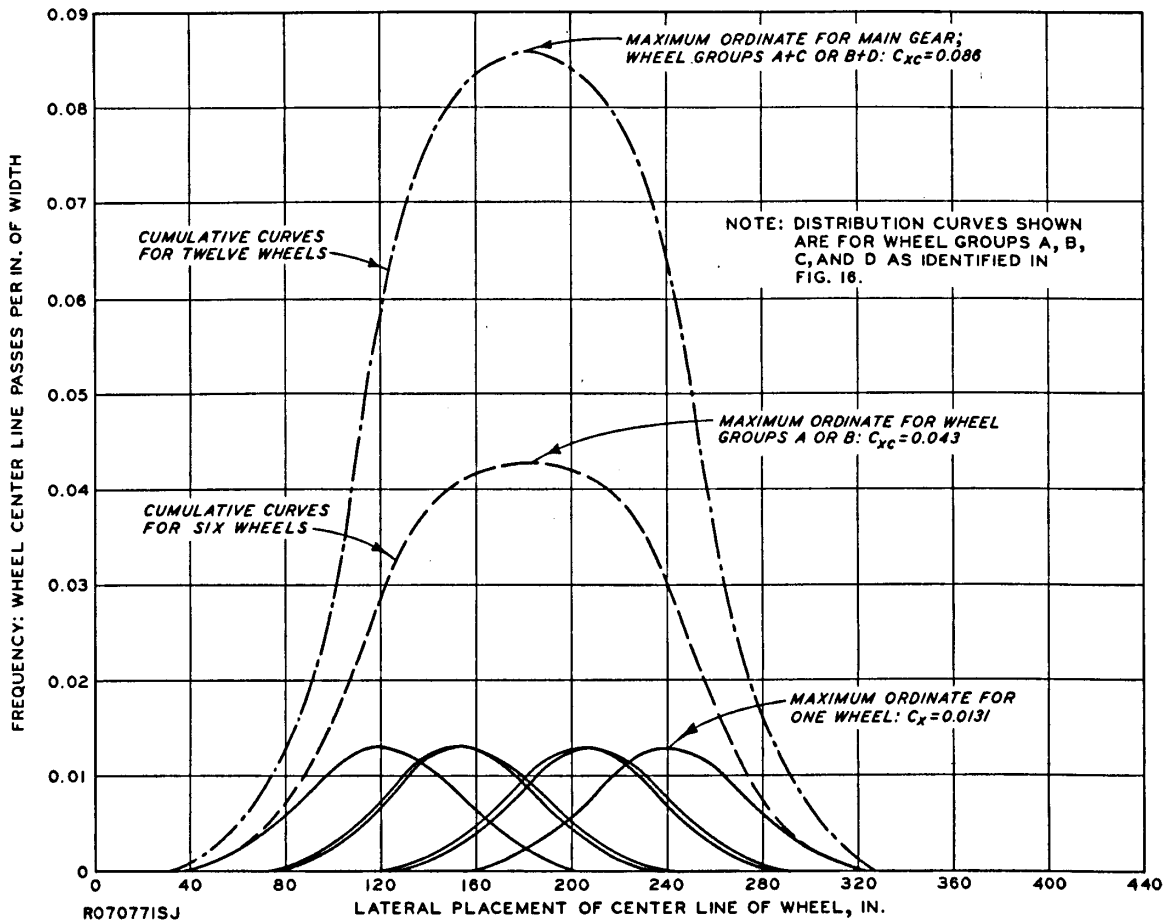


Fig. 15. Theoretical normal distribution for main gear of C-5A, wander = 70 in.

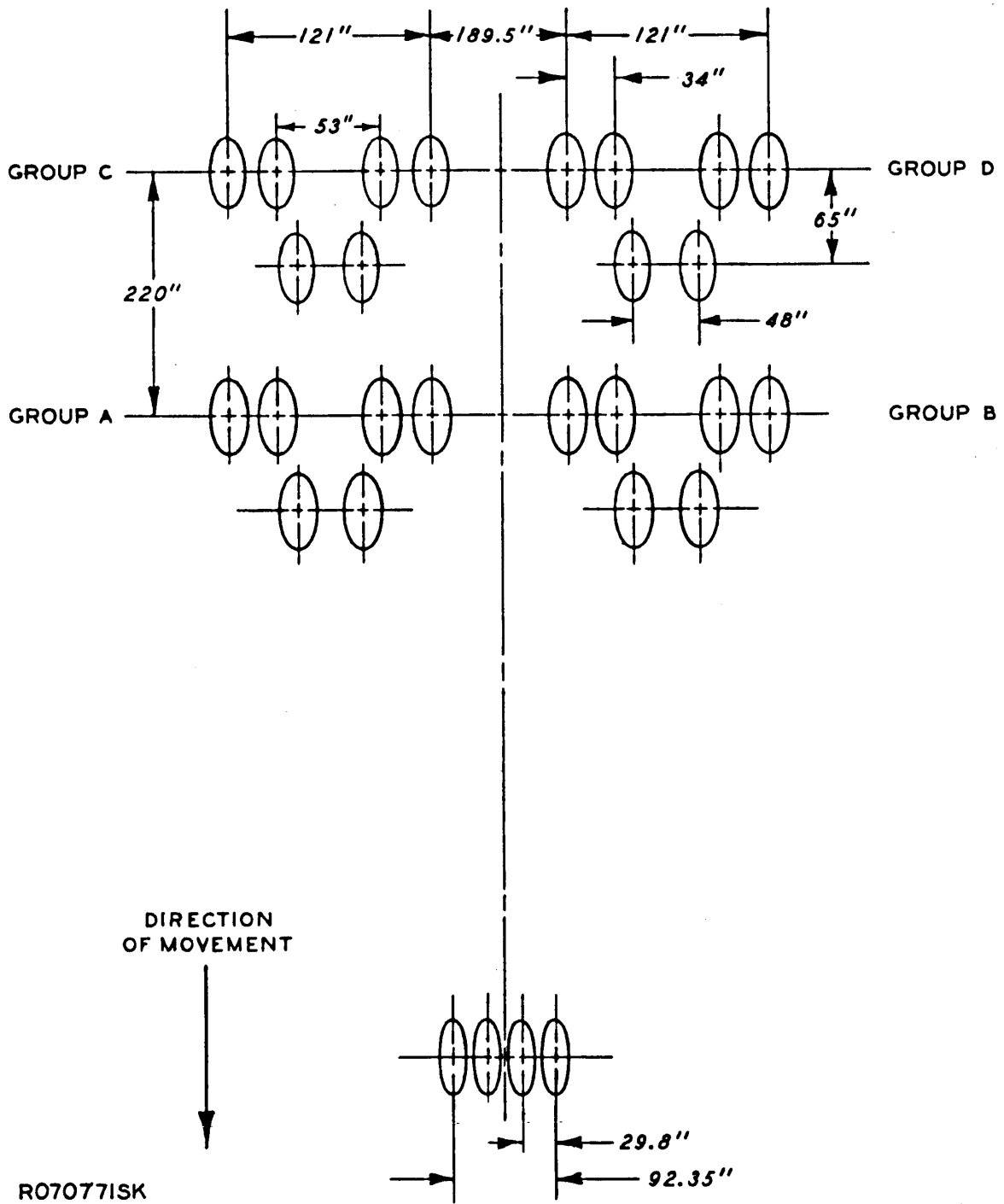
passes is 24. However, 24 wheel passes equal 1 aircraft pass. Thus,

$$\begin{aligned} \frac{p}{c} &= \frac{1}{24} \left(\frac{ap}{wp} \right) \frac{24(wp)}{1} \frac{1}{(0.086)(w_t)} \left(\frac{\text{in.}}{wp} \right) \left(\frac{1}{\text{in.}} \right) \\ &= \frac{1}{(0.086)(w_t)} \left(\frac{ap}{wp} \right) \end{aligned}$$

or, as before,

$$\frac{p}{c} = \frac{1}{(C_{xc})(w_t)} \left(\frac{ap}{wp} \right) \quad (12 \text{ bis})$$

b. The Boeing 747 wheel configuration is shown in fig. 17.



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Fig. 16. C-5A gear configuration

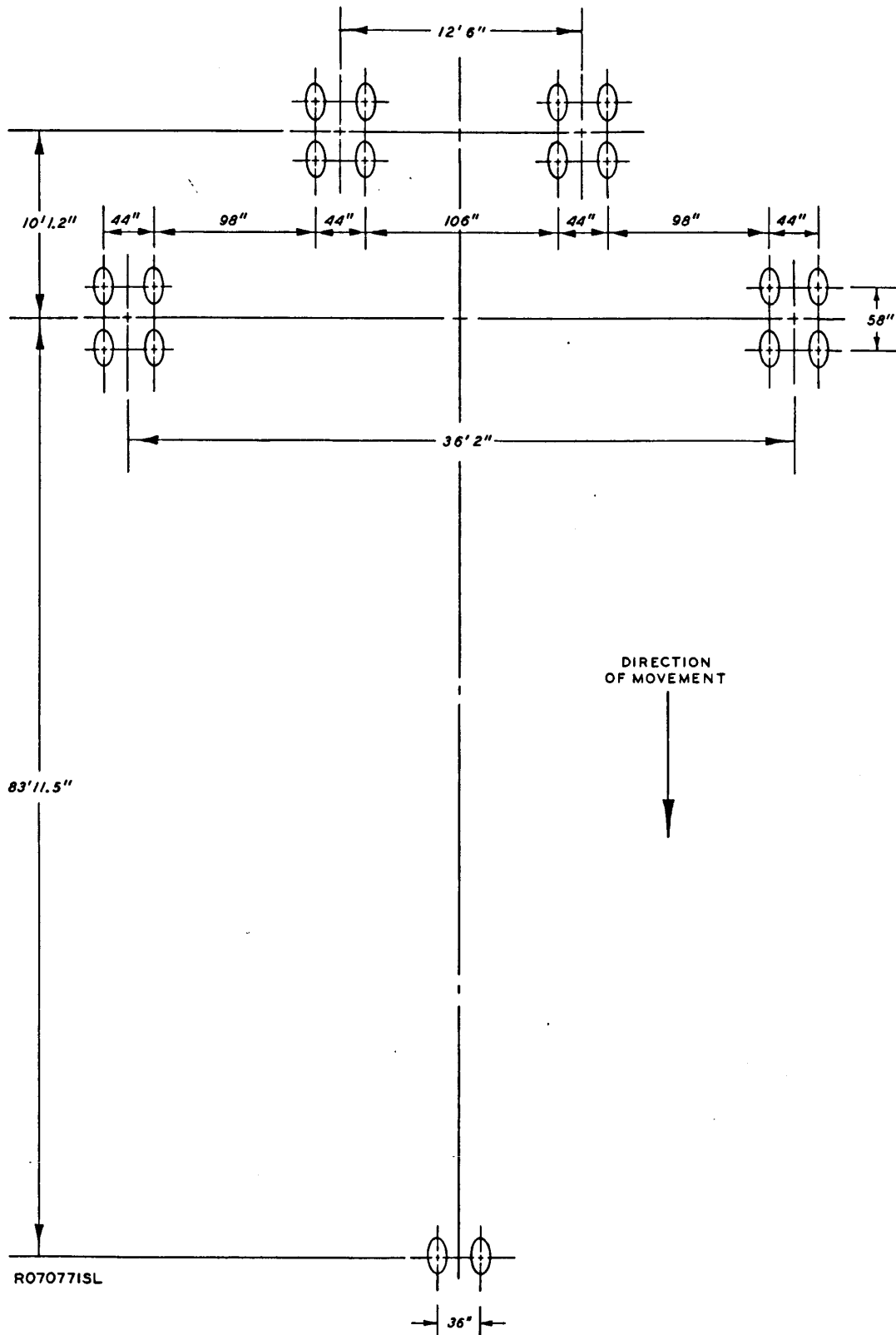


Fig. 17. Boeing 747 gear configuration

The theoretical normal traffic distribution curve for one-half the main gear is shown in fig. 18. The maximum ordinate on this curve is 0.042 resulting from one of the four twin-tandem assemblies. Thus, by inspection it can be seen that the maximum ordinate for the 747 assembly will be that resulting from one twin-tandem assembly where:

$$C_{xc} = 0.042$$

This value could have been estimated, with reasonable accuracy, through use of fig. 14 since the minimum spacing between twin-tandem assemblies is approximately 100 in. For the main gear assembly, the total number of wheel passes is 16; however, 16 wheel passes equal 1 aircraft pass. Thus,

$$\frac{p}{c} = \frac{1}{16} \left(\frac{ap}{wp} \right) 16 (wp) \frac{1}{(0.042)(W_t)} \left(\frac{\text{in.}}{wp} \right) (\text{in.})$$

$$\frac{p}{c} = \frac{1}{(0.042)(W_t)} \left(\frac{ap}{wp} \right)$$

and, as before,

$$\frac{p}{c} = \frac{1}{(C_{xc})(W_t)} \left(\frac{ap}{wp} \right) \quad (12 \text{ bis})$$

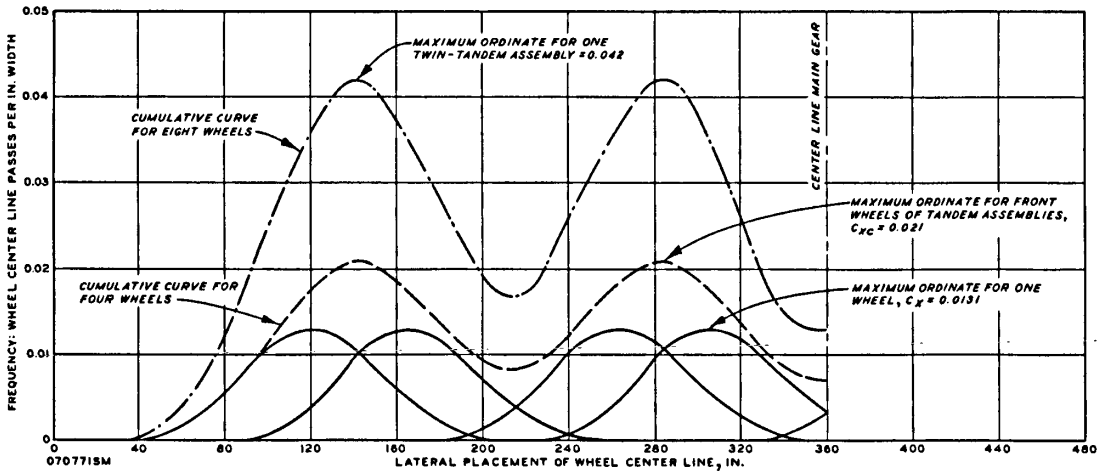


Fig. 18. Theoretical normal distribution for main gear of Boeing 747, wander = 70 in.

PART IV: COMPARISON OF METHODS OF DETERMINING
PASS/COVERAGE VALUES

30. In Part II, the current method for determining p/c ratios is presented (equation 7); in Part III, a theoretical method for determining p/c ratios is presented (equations 11 and 12). In this part, values obtained using the two methods are compared for common aircraft in service in 1971. Both military and civilian aircraft are included.

31. A listing of the relevant dimensions of current aircraft is given in table 1. In many cases, a particular aircraft has been produced in various models with slightly different dimensions from those listed. However, the values in table 1 are considered representative since small changes in physical dimensions are of no significant consequence. The diagrams in figs. 4, 16, and 17 depict the types of gear configurations considered in table 1.

32. In Part II, reference is made to studies in which actual traffic distribution patterns were developed from an analysis of field traffic distribution data obtained from observations of the operation of specific aircraft at several locations along taxiways and runways at various Air Force bases.^{4,5} These traffic distribution patterns for B-47, KC-97, B-52, and KC-135 aircraft are shown in graphic form as traffic distribution curves (solid lines) in fig. 5 and plates 1-11. These data represent the total information presently available relative to actual lateral traffic distribution of aircraft operating on airfield pavements at military installations.

33. Theoretical normal traffic distribution curves (dashed lines) are also shown in fig. 5 and plates 1-11 for all aircraft considered and at all locations where actual traffic distribution data were available. These traffic distribution curves are based on computed values calculated in such a manner that the maximum ordinate on each theoretical traffic distribution curve is equal or approximately equal to the maximum ordinate on each actual traffic distribution curve. The theoretical wander used in each case is given in table 2.

34. The comparison of actual and theoretical normal traffic

distribution curves along straightways of taxiways shown for the B-47 and KC-97 in fig. 5 indicates that a theoretical wander of 70 in. is representative of observed traffic distribution along straightways of taxiways. Similar comparisons, shown in plates 1-3, for taxiway curves indicate that a variable theoretical wander (32-95 in.) is required to represent observed traffic distribution along taxiway curves. Since the Corps of Engineers has been designing pavements along both straightways and curves on taxiways for the same traffic distribution pattern for many years and no indication has ever been noted that the service life of pavements along taxiway curves has been materially different from that of pavements along straightways on taxiways, a theoretical wander of 70 in. has been selected for use in this study as the best value for representation of actual observed traffic distribution along taxiways.

35. The comparisons of actual observed and theoretical traffic distribution curves for the B-47, KC-97, B-52, and KC-135 aircraft along runways, shown in plates 4-11, indicate that the theoretical wander required to represent actual traffic distribution varies with type of aircraft and location of aircraft along the runway. This observation is in agreement with service behavior records for airfield pavements. Calculated values for the theoretical wander required to best represent actual traffic distribution, shown in table 2, are presented in graphic form in fig. 19. This plot shows the variation in theoretical wander along runways for the B-47, KC-97, B-52, and KC-135 aircraft. It is not considered practical at the present time to attempt to design runway pavements for continuously changing traffic distribution patterns, as indicated by the solid curves in fig. 19; therefore, on the basis of the data shown in fig. 19, a theoretical wander of 70 in. has been selected as the best value for representation of actual traffic distribution along the first 1000 ft at each end of a runway, and a theoretical wander of 140 in. has been selected as the best value for representation of actual traffic distribution along the interior portions of runways, as indicated by the dashed lines in fig. 19. The Corps of Engineers has recognized that traffic distribution patterns vary along taxiways and runways and have zoned their pavements for thickness design on the

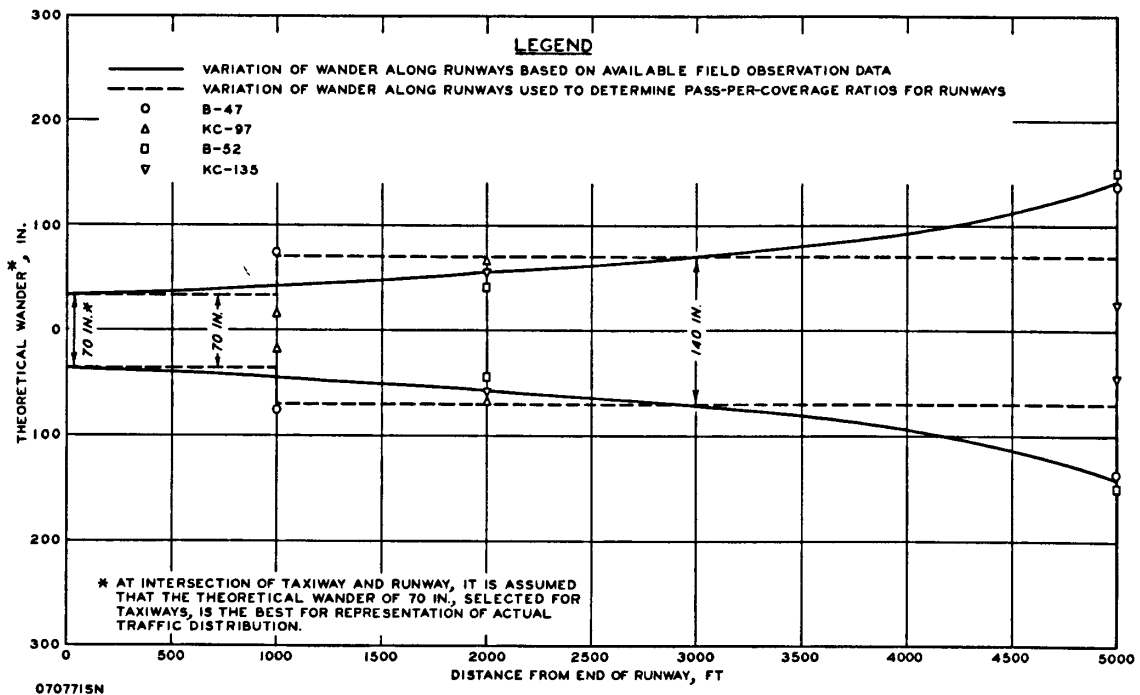


Fig. 19. Variation in theoretical wander along runways

basis of variable traffic distribution.⁹

36. Pass-per-coverage ratios have been calculated using equations 7 and 12 for uniform, theoretical, and actual traffic distribution. These p/c ratios are shown in columns 4, 5, and 6 of table 3. Values shown in column 4 were calculated through use of equation 7 using a 40-in. wander in accordance with current practice. Values shown in column 5 were calculated through use of equation 12 using a wander of 70 in. for taxiways and 140 in. for runways as proposed herein. Values shown in column 6 were calculated through use of equation 12 using the theoretical wander values shown in table 2. The relation between p/c ratios based on uniform and actual traffic distribution is shown in column 7 of table 3. As can be seen, p/c ratios based on uniform traffic distribution do not agree very well with p/c ratios based on actual traffic distribution. The implication of this observation is significant. For instance, using the B-47, the current basic design of 5000 coverages represents 10,650 (2.13 x 5000) aircraft passes for uniform traffic distribution, but 5000 coverages represent from 7750 (1.55 x 5000)

to 26,300 (5.26 x 5000) aircraft passes for actual traffic distribution. Whereas it is currently assumed that pavements designed for 5000 coverages will sustain 10,650 aircraft passes before accumulation of the critical coverages (5000), it appears that, in fact, based on actual observed traffic distribution, the critical number of coverages is accumulated after 7750 or 26,300 aircraft passes, depending on the location or the airfield. Similar calculations for other aircraft will show comparable variations.

37. The reason for a wide variation between p/c ratios based on uniform and actual traffic distribution is shown in fig. 20, where the actual and theoretical normal traffic distribution curves determined through use of equation 12 for a B-47 on straightways of taxiways have been superimposed on a uniform traffic distribution diagram determined through use of equation 7 for a B-47 on straightways of taxiways. Assuming the following dimensions for the B-47:

$$W_t = 14.3 \text{ in.} = 1.19 \text{ ft}$$

$$W = 40 \text{ in.} = 3.33 \text{ ft}$$

$$S_t = 37 \text{ in.} = 3.08 \text{ ft}$$

$$\text{Width of traffic lane} = 7.60 \text{ ft}$$

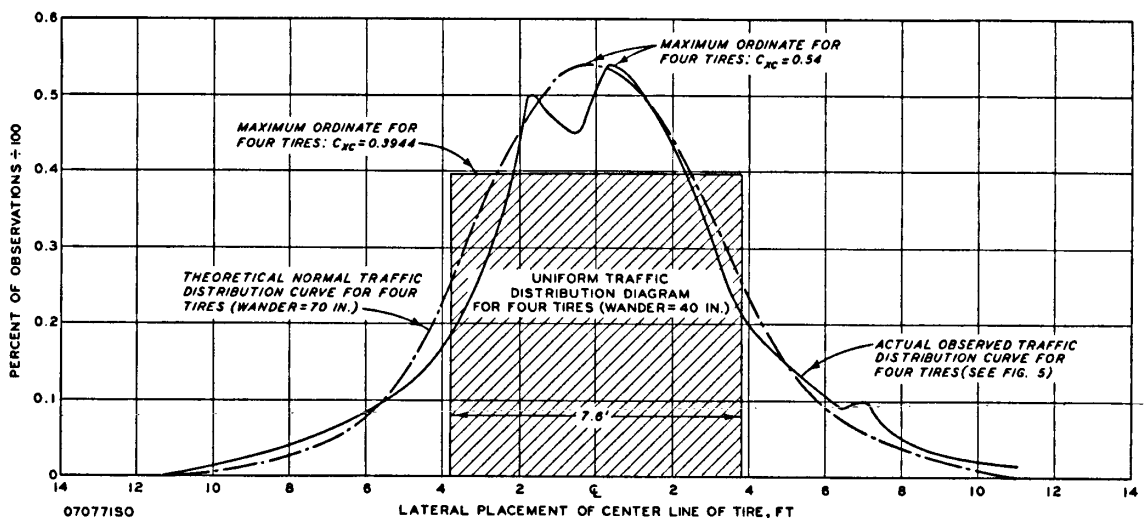


Fig. 20. Comparative plots of uniform, theoretical normal, and actual traffic distribution along straightways of taxiways for B-47 aircraft

According to equation 7:

$$\left(\frac{p}{c}\right)_t = \frac{W_t + S_t + 40}{0.75(N)(W_t)}$$

Therefore,

$$\left(\frac{p}{c}\right)_t = \frac{1.19 + 3.08 + 3.33}{(0.75)(4)(1.19)} = 2.13$$

For the B-47, one aircraft pass generates four wheel passes. Thus, the area within the uniform traffic distribution diagram is equal to 4 units, and the area within this diagram representing 75 percent of the traffic is equal to 3 units. Therefore, the uniform traffic distribution diagram for the B-47 can be represented by a rectangular diagram with a width (abscissa) of 7.6 ft and a height (ordinate) of:

$$\frac{3.00}{7.6} \left(\frac{wp}{ft}\right) = 0.3944 \left(\frac{wp}{ft}\right)$$

as shown in fig. 20. Using equation 12 and applying it to the uniform traffic distribution diagram shown:

$$\frac{p}{c} = \frac{1}{(C_{xc})(W_t)} \quad (12 \text{ bis})$$

where

$$C_{xc} = 0.3944 \left(\frac{wp}{ft}\right)$$

$$W_t = 1.19 \text{ ft}$$

$$\frac{p}{c} = \frac{1}{(0.3944)(1.19)} = 2.13 \text{ as before.}$$

Using equation 12 and applying it to the actual traffic distribution curve shown in fig. 20:

$$C_{xc} = 0.54 \left(\frac{wp}{ft}\right)$$

$$W_t = 1.19 \text{ ft}$$

$$\frac{p}{c} = \frac{1}{(0.54)(1.19)} = 1.55$$

and the ratio between p/c ratios for uniform and actual traffic distribution is:

$$\frac{2.13}{1.55} = 1.37$$

38. Similar calculations may be made to show the variation in p/c ratios based on theoretical normal and actual traffic distribution patterns. Results of these calculations are shown in column 8 of table 3. Examination of resulting relations between p/c ratios based on theoretical and actual traffic distribution patterns shows that considerably better agreement exists between these p/c ratios than between p/c ratios for uniform and actual traffic distribution except in two instances, KC-97 aircraft 1000 ft from the runway end and KC-135 5000 ft from the runway end. It is inconceivable that the KC-97 or the KC-135 will consistently operate within the narrow limits indicated by the actual traffic distribution shown for these aircraft in plates 6 and 11. If these actual traffic distribution curves are not considered, then the p/c ratios based on theoretical normal traffic distribution are in better agreement with the p/c ratios based on actual traffic distribution than p/c ratios based on uniform traffic distribution. It is on this basis that it is suggested that the basis for determining p/c ratios be changed from uniform traffic distribution, as presently used, to theoretical normal traffic distribution. Adoption of procedures discussed herein, based on theoretical normal traffic distribution for a wander of 70 in. on taxiways and 140 in. on runways, will provide improved procedures for calculating p/c ratios representative of actual traffic distribution.

39. In accordance with the suggestion made above, p/c ratios have been computed for various aircraft now operating at both civilian and military airfields. These p/c ratios for taxiways (wander = 70 in.) and runways (wander = 140 in.) are given in tables 4 and 5.

PART V: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

40. Two conclusions can be drawn from this study. First, and most important, it is unmistakably clear that considerably more field traffic data are required, particularly with reference to current aircraft, before any further progress can be made in the development of p/c ratios that are truly representative of actual traffic distribution patterns. Secondly, adoption of the theoretical normal traffic distribution curves as a basis for development of p/c ratios will provide an improved and more realistic procedure for determining p/c ratios that will, in general, be more representative of actual traffic distribution than similar ratios based on uniform traffic distribution.

Recommendations

41. It is recommended that the p/c ratios given in tables 4 and 5 be adopted for use in converting test section traffic in terms of coverages into equivalent aircraft traffic in terms of aircraft passes until such time as additional field traffic data become available for further studies.

42. Investigations should be made that will provide information on the influence of factors such as the random placement of traffic across the width of a runway or taxiway, the variation of load intensity and contact pressure of the tires of a multiple-wheel gear, and the variation of loading conditions of the main and nose gears of an aircraft. The following studies are recommended.

- a. Airfield surveys to determine the actual lateral and longitudinal distribution of traffic for all types of aircraft.
- b. Studies to determine the percentage of operations for each type of aircraft expected to operate on a pavement for design or the percentage of operations for each type of aircraft that has been on a pavement for evaluation. Then the traffic could be accumulated graphically.

- c. Studies to determine the detrimental effects of a wheel at various distances from the point of maximum accumulation of repetitions and then develop a location weighting function α_i to be applied to traffic repetitions.

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Table 1
Typical Aircraft Landing Gear Characteristics

Type Landing Gear and Aircraft	Tire Inflation Pressure lb/in. ²	Tire Contact Area in. ²	Tire Width W _t in.	Wheel Base W _b in.	Tread T _w in.	Twin Wheel Spacing S _t in.	Tandem Wheel Spacing S _m in.	
<u>Civilian Aircraft*</u>								
Twin tricycle								
Boeing 727-00	170	236	13.5	639	225	34		
Boeing 723-200	130	170	13.5	448	206	34		
DC-9-30	145	168	11.5	638	197	25		
Twin-tandem tricycle								
Boeing 707-100	180	236	13.5	628	265	34	56	
DC-8-10	155	228	13.5	692	250	30	55	
DC-10-10, 20	176	276	15.0	868.5	420	54	64	
Convair 880	150	152	11.0	637	226	22.5	45	
Multiple-wheel tricycle								
Boeing 747	200	208	12.9	← See fig. 17 →				
<u>Military Aircraft*</u>								
Single tricycle								
A-7D	280	62	6.9	188	114			
A-26A	70	262	14.2	161	233			
B-57B	152	182	11.8	171	188			
C-123K	92	275	14.6	288	151			
F-104G	208	63	6.9	181	106			
F-4E	265	102	8.9	279	215			
F-111A	150	313	15.5	288	120			
Twin tricycle								
C-7A	115	272	14.4	251	277	20		
C-8A	38	218	12.9	335	336	23		
C-54G	77	250	13.8	329	296	28		
KC-97	183	227	13.2	437	342	37		
C-124C	79	640	22.1	357	410	44		
C-140A	205	43	5.7	248	148	14.5		
Single-tandem tricycle								
C-130	80	400	17.5	388	172		60	
HC-130H	115	364	16.7	388	172		60	
Twin bicycle								
B-47	195	267	14.3	531	436	37		
Twin-twin bicycle								
B-52	248	267	14.3	597	99	37		
Twin-tandem tricycle								
C-135A	130	261	14.2	548	265	36	60	
KC-135A	155	230	13.3	548	265	36	60	
C-141A	180	208	12.6	636	210	32.5	48	
Multiple-wheel tricycle								
C-5A	105	285	15.1	← See fig. 16 →				

* Values shown for civilian aircraft were obtained from manufacturer of particular aircraft. Practically all values shown for military aircraft were obtained from reference 8.

Table 2

Theoretical Wander Used in Computing
Data for Theoretical Normal Traffic
Distribution Curves

<u>Aircraft</u>	<u>Facility</u>	<u>Location</u>	<u>Theoretical Wander, in.*</u>
B-47	Taxiway	Straightways	70
		Curves	32, 95
	Runway	1000 ft from end	150
		5000 ft from end	275
KC-97	Taxiway	Straightways	70
		Curves	65
	Runway	1000 ft from end	37
		2000 ft from end	136
B-52	Runway	2000 ft from end	87.5
		5000 ft from end	300
KC-135	Runway	2000 ft from end	115
		5000 ft from end	90

* Wander for theoretical normal traffic distribution based on actual observed traffic distribution as shown in fig. 5 and plates 1-11.

Table 3
Pass-Per-Coverage Ratios for Various Wander Widths

(1) Aircraft	(2) Facility	(3) Location	(4) (5) (6) Pass-Per-Coverage Ratio			(7) (8) Comparison of Pass-Per-Coverage Ratios	
			Uniform Traffic Distribution*	Theoretical Normal Traffic Distribution**	Actual Traffic Distribution†	Ratio of Uniform-to- Actual Traffic Distribution	Ratio of Theoretical Normal-to- Actual Traffic Distribution
B-47	Taxiway	Straightways and curves	2.13	1.57	1.55	1.37	1.00
	Runway	1000 ft from end (takeoff)	2.13	2.85	3.09	0.69	0.92
		5000 ft from end (landing)	2.13	2.85	5.26	0.41	0.54
KC-97	Taxiway	Straightways and curves	4.56	3.40	3.31	1.38	1.03
	Runway	1000 ft from end (takeoff)	4.56	6.15	2.67	1.70	2.30
		2000 ft from end (landing)	4.56	6.15	6.06	0.75	1.02
B-52	Runway	2000 ft from end (takeoff)	2.25	2.00	1.87	1.20	1.07
		5000 ft from end (landing)	2.25	2.00	3.24	0.69	0.62
KC-135	Runway	2000 ft from end (takeoff)	2.24	3.03	2.51	0.89	1.21
		5000 ft from end (landing)	2.24	3.03	2.01	1.11	1.51

* Calculated using equation 7 with values based on 40-in. wander (current procedure).

** Calculated using equation 12 with values based on 70-in. wander for taxiways and 140-in. wander for runways (proposed procedure).

† Calculated using equation 12 with values based on wander values given in table 2.

Table 4
Pass-Per-Coverage Ratios for Various Aircraft
on Taxiways and Runway Ends*

(1)	(2)	(3)	(4)	(5)	(6)	(7)
Aircraft	Twin Wheel Spacing S_t in.	Tire Width W_t in.	No. of Main Gear Wheels in Traffic Lane N^{**}	$\frac{p}{c} = \frac{W_t + S + 40 \text{ in.}^{**}}{(0.75)(N)(W_t)}$ Equation 7	C_x or C_{xc}^\dagger	$\frac{p}{c} = \frac{1}{(C_x \text{ or } C_{xc})(W_t)}$ Equation 11 or 12
Boeing 727-00	34	13.5	2	4.32	0.0228	3.25
Boeing 723-200	34	13.5	2	4.32	0.0228	3.25
DC-9-30	25	11.5	2	4.43	0.0243	3.58
Boeing 707-100	34	13.5	4	2.16	0.0456	1.62††
DC-8-10	30	13.5	4	2.06	0.0472	1.57††
DC-10-10	54	15.0	4	2.42	0.0366	1.82††
Convair 880	22.5	11.0	4	2.23	0.0494	1.84††
Boeing 747	#	12.9	16	2.69	0.0420	1.85††
A-7D	114##	6.9	1	9.06	0.0131	11.10
A-26A	233##	14.2	1	5.09	0.0131	5.37
B-57B	188##	11.8	1	5.85	0.0131	6.47
C-123K	151##	14.6	1	4.99	0.0131	5.23
F-104G	106##	6.9	1	9.06	0.0131	11.10
F-4E	215##	8.9	1	7.33	0.0131	8.58
F-111A	120##	15.5	2	4.77	0.0131	4.92
C-7A	20	14.4	2	3.44	0.0250	2.78
C-8A	23	12.9	2	3.92	0.0245	3.16
C-54G	28	13.8	2	3.95	0.0238	3.05
KC-97	37	13.2	2	4.56	0.0222	3.41
C-124C	44	22.1	2	3.20	0.0207	2.19
C-140A	14.5	5.7	2	7.04	0.0256	6.85
C-130	172##	18.3	2	2.19	0.0262	2.09††
HC-130H	172##	16.7	2	2.26	0.0262	2.29††
B-47	37	14.3	4	2.13	0.0444	1.57
B-52	37	13.4	8	2.25	0.0458	1.63
C-135A	36	13.3	4	2.24	0.0448	1.68††
KC-135A	36	13.3	4	2.24	0.0448	1.68††
C-141A	32.5	12.6	4	2.25	0.0462	1.72††
C-5A	#	14.3	12	1.30	0.0860	0.81††

* For wander = 70 in.; 1000 ft at end of each runway.

** Ignoring nose wheels.

† Values for C_x or C_{xc} read from fig. 14 or determined by graphical procedure discussed in paragraphs 26-28.

†† Pass-per-coverage ratios for rigid pavement for these aircraft are equal to twice the value shown (see paragraph 2).

See figs. 16 or 17.

Twin wheel spacing for single wheel and single-tandem wheel landing gear is equal to the tread.

Table 5

Pass-Per-Coverage Ratios for Various Aircraft
on Interior Portion of Runways*

(1)	(2)	(3)	(4)	(5)	(6)	(7)
Aircraft	Twin Wheel Spacing S_t in.	Tire Width W_t in.	No. of Main Gear Wheels in Traffic Lane N^{**}	$\frac{p}{c} = \frac{W_t + S + 40 \text{ in.}^{**}}{(0.75)(N)(W_t)}$ Equation 7	C_x or C_{xc}^\dagger	$\frac{p}{c} = \frac{1}{(C_x \text{ or } C_{xc})(W_t)}$ Equation 11 or 12
Boeing 727-00	34	13.5	2	4.32	0.0124	6.00
Boeing 723-200	34	13.5	2	4.32	0.0124	6.00
DC-9-30	25	11.5	2	4.43	0.0126	6.90
Boeing 707-100	34	13.5	8	2.16	0.0248	3.00††
DC-8-10	30	13.5	8	2.06	0.0250	2.96††
DC-10-10	54	15.0	8	2.42	0.0230	2.90††
Convair 880	22.5	11.0	8	2.23	0.0254	3.58††
Boeing 747	‡	12.9	16	2.69	0.028	2.77††
A-7D	114‡‡	6.9	1	9.06	0.0066	22.00
A-26A	233‡‡	14.2	1	5.09	0.0066	10.70
B-57B	188‡‡	11.8	1	5.85	0.0066	12.83
C-123K	151‡‡	14.6	1	4.99	0.0066	10.38
F-104G	106‡‡	6.9	1	9.06	0.0066	22.00
F-4E	215‡‡	8.9	1	7.33	0.0066	17.00
F-111A	120‡‡	15.5	2	4.77	0.0066	9.80
C-7A	20	14.4	2	3.44	0.0128	5.42
C-8A	23	12.9	2	3.92	0.0127	6.10
C-54G	28	13.8	2	3.95	0.0126	5.75
KC-97	37	13.2	2	4.56	0.0124	6.11
C-124C	44	22.1	2	3.20	0.0120	3.77
C-140A	14.5	5.7	2	7.04	0.0136	12.89
C-130	172‡‡	17.5	4	2.19	0.01325	4.05††
HC-130H	172‡‡	16.7	4	2.26	0.01325	4.44††
B-47	37	14.3	4	2.13	0.0248	2.81
B-52	37	13.4	8	2.25	0.0374	2.00
C-135A	36	13.3	8	2.24	0.0248	3.03††
KC-135A	36	13.3	8	2.24	0.0248	3.03††
C-141A	32.5	12.6	8	2.25	0.025	3.17††
C-5A	‡	14.3	24	1.30	0.0636	1.10††

* For wander = 140 in.

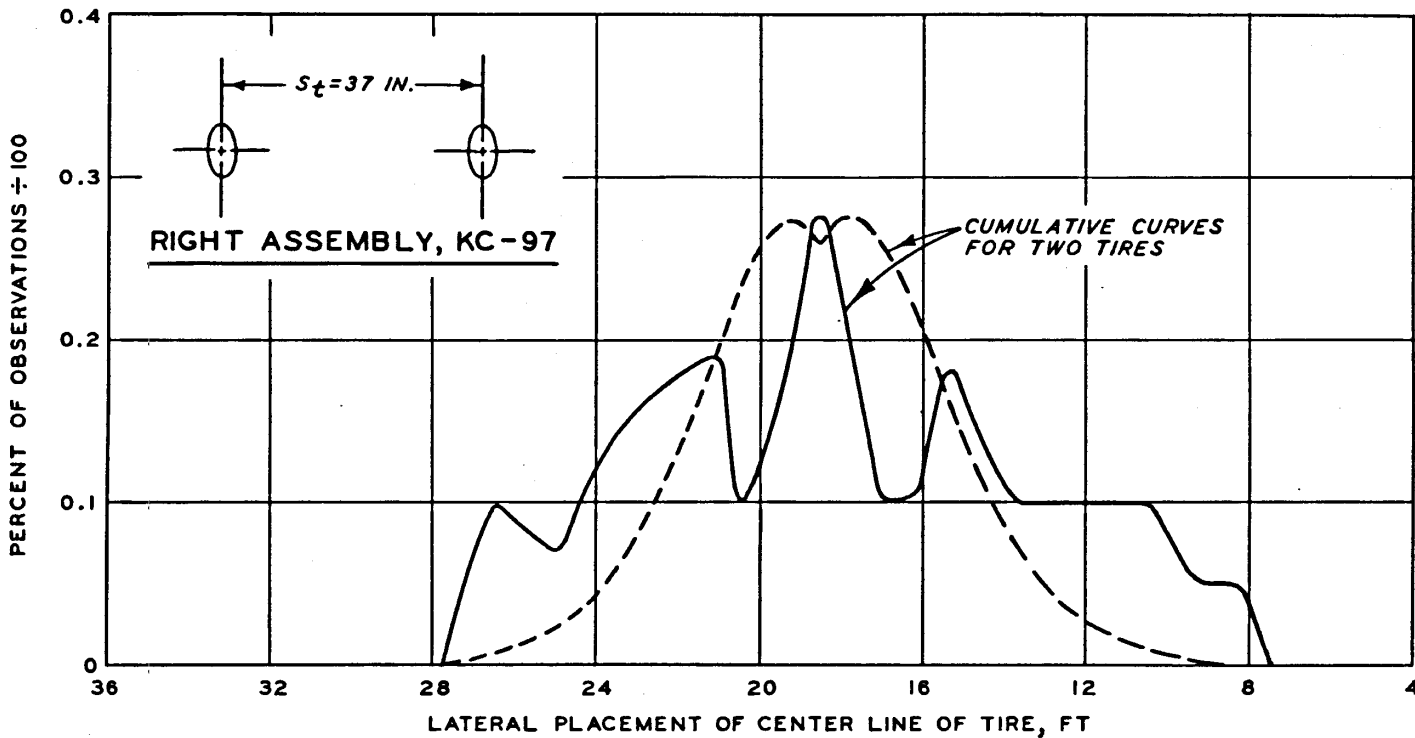
** Ignoring nose wheels.

† Values for C_x and C_{xc} read from fig. 14 or determined by graphical procedure discussed in paragraphs 26-28.

†† Pass-per-coverage ratios for rigid pavement for these aircraft are equal to twice the values shown (see paragraph 2).

‡ See figs. 16 or 17.

‡‡ Twin wheel spacing for single-wheel and single-tandem-wheel gear is equal to the tread.

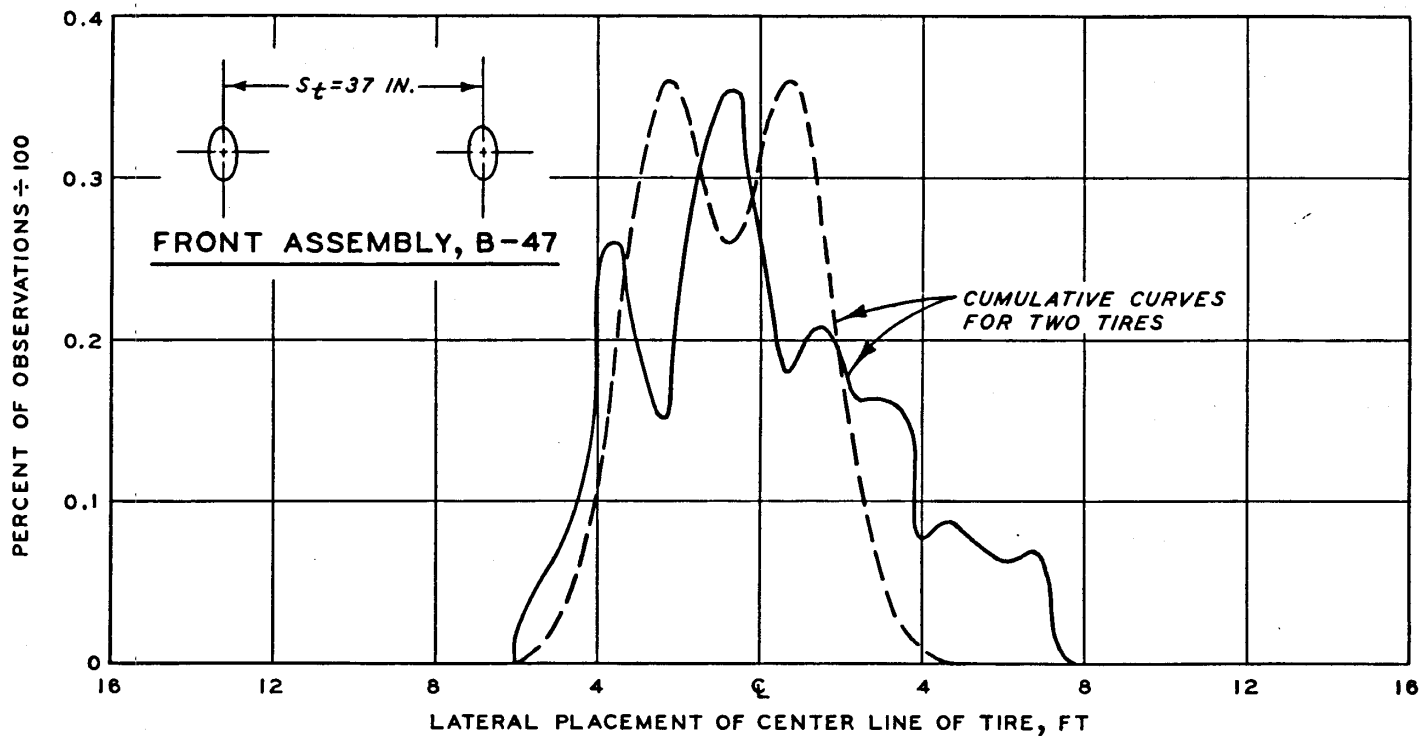


LEGEND

- ACTUAL OBSERVED TRAFFIC DISTRIBUTION FOR RIGHT ASSEMBLY OF KC-97 AIRCRAFT AT POSITION 3, LINE 4, MacDILL AIR FORCE BASE (SEE PLATES 3 AND 7, REF 4)
- - - THEORETICAL NORMAL TRAFFIC DISTRIBUTION FOR RIGHT ASSEMBLY OF KC-97 AIRCRAFT (WANDER=65 IN.)

NOTE: ACTUAL OBSERVED TRAFFIC DISTRIBUTION IS BASED ON 21 OBSERVATIONS.

DISTRIBUTION OF KC-97 AIRCRAFT TRAFFIC ON TAXIWAY CURVES

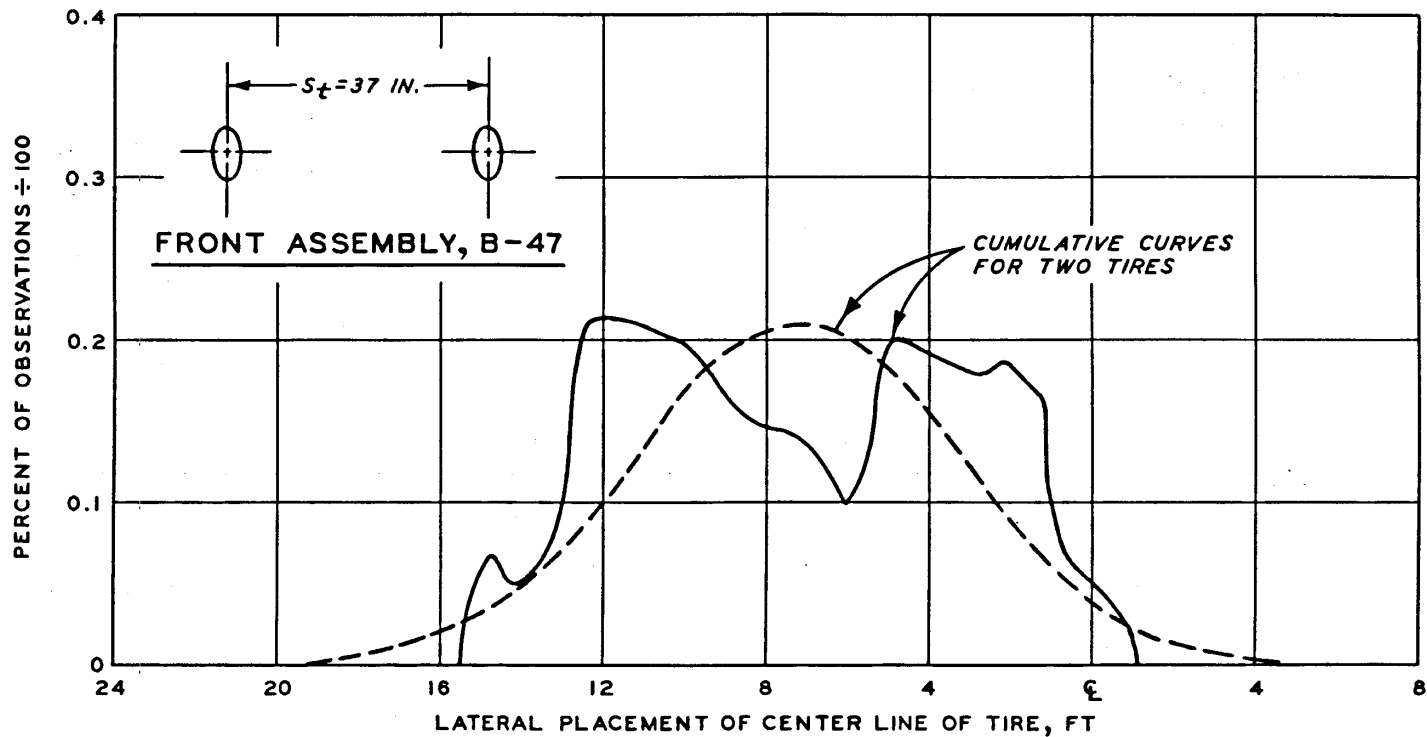


LEGEND

- ACTUAL OBSERVED TRAFFIC DISTRIBUTION FOR FRONT ASSEMBLY OF B-47 AIRCRAFT AT POSITION 1, LINE 3, LAKE CHARLES AIR FORCE BASE (SEE PLATES 1 AND 5, REF 4)
- - - THEORETICAL NORMAL TRAFFIC DISTRIBUTION FOR FRONT ASSEMBLY OF B-47 AIRCRAFT (WANDER=32 IN.)

NOTE: ACTUAL OBSERVED TRAFFIC DISTRIBUTION IS BASED ON 61 OBSERVATIONS.

**DISTRIBUTION OF B-47
AIRCRAFT TRAFFIC
ON TAXIWAY CURVES
(WANDER=32 IN.)**

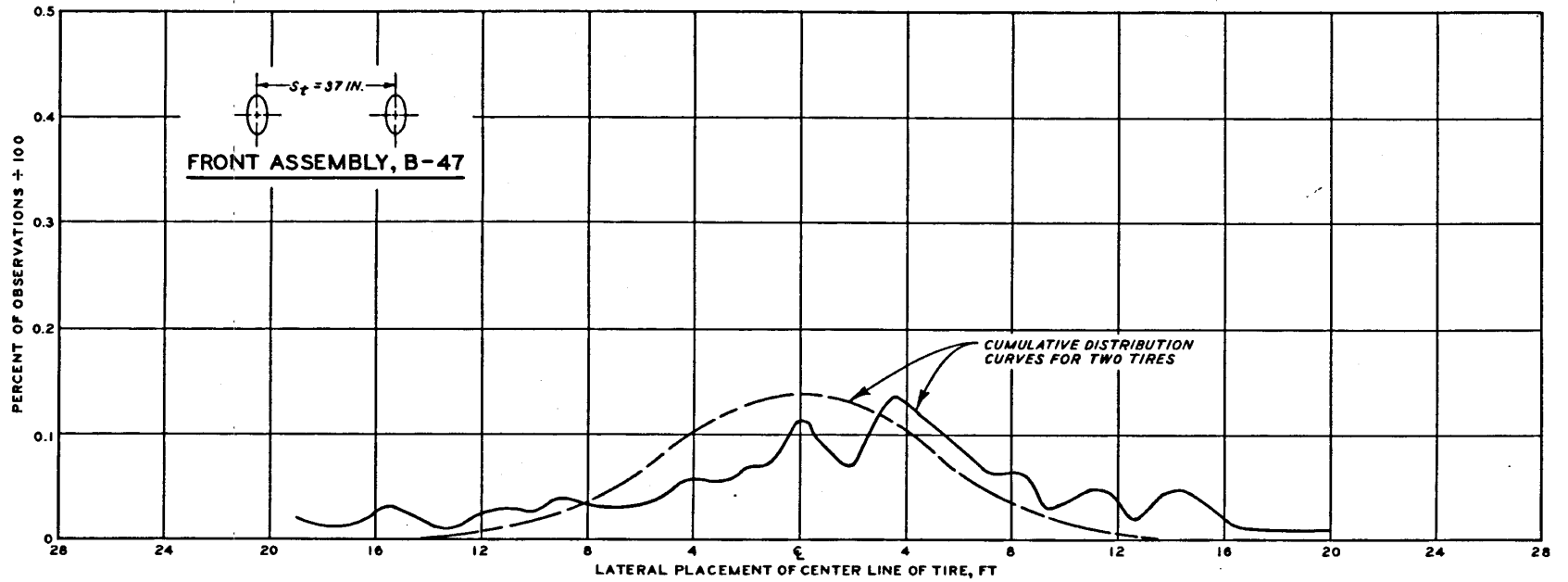


LEGEND

- ACTUAL OBSERVED TRAFFIC DISTRIBUTION FOR FRONT ASSEMBLY OF B-47 AIRCRAFT AT POSITION 3, LINE 4, MacDILL AIR FORCE BASE (SEE PLATES 3 AND 5, REF 4)
- - - THEORETICAL NORMAL TRAFFIC DISTRIBUTION FOR FRONT ASSEMBLY OF B-47 AIRCRAFT (WANDER=95 IN.)

NOTE: ACTUAL OBSERVED TRAFFIC DISTRIBUTION IS BASED ON 21 OBSERVATIONS.

**DISTRIBUTION OF B-47
AIRCRAFT TRAFFIC
ON TAXIWAY CURVES
(WANDER= 95 IN.)**

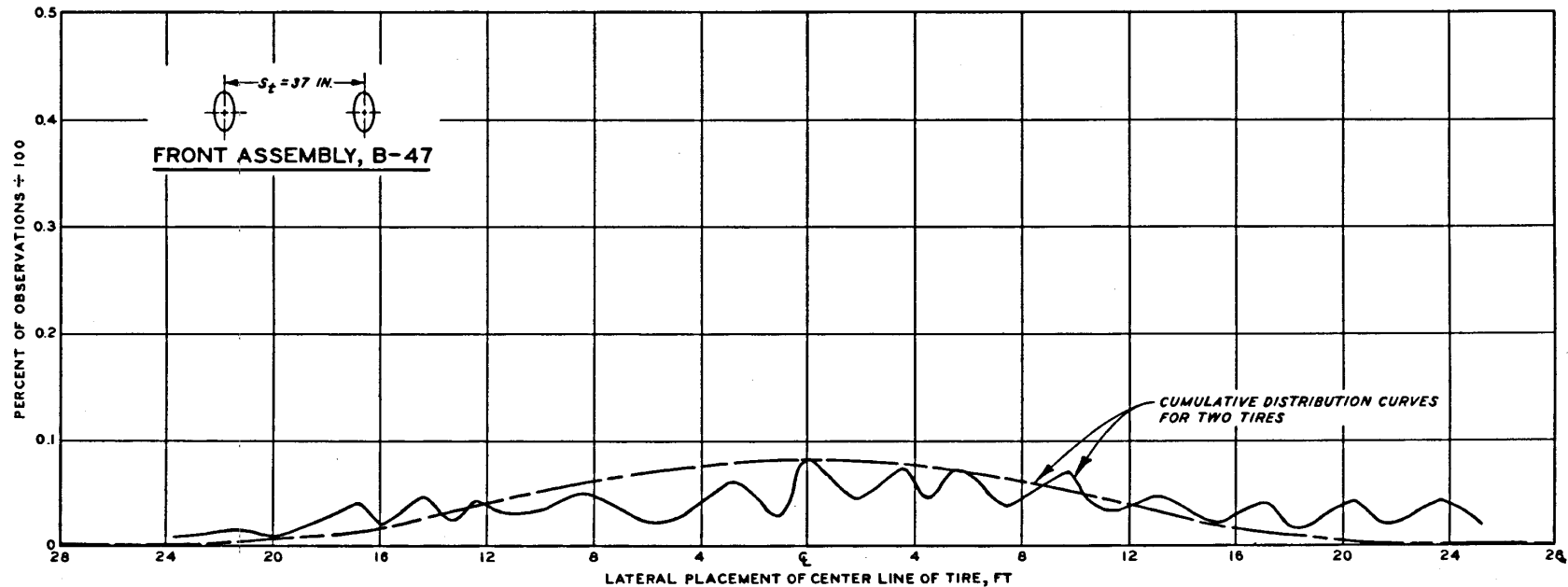


LEGEND

- ACTUAL OBSERVED TRAFFIC DISTRIBUTION FOR FRONT ASSEMBLY OF B-47 (SEE PLATE 2, REF 5)
- THEORETICAL NORMAL TRAFFIC DISTRIBUTION FOR FRONT ASSEMBLY OF B-47 (WANDER = 150 IN.)

NOTE: ACTUAL OBSERVED TRAFFIC DISTRIBUTION CURVE IS BASED ON 253 OBSERVATIONS MADE AT DYESS, ALTUS, HOMESTEAD, AND McCOY AIR FORCE BASES.

**DISTRIBUTION OF B-47
AIRCRAFT TAKEOFF TRAFFIC
ALONG RUNWAYS
1000 FT FROM RUNWAY END**

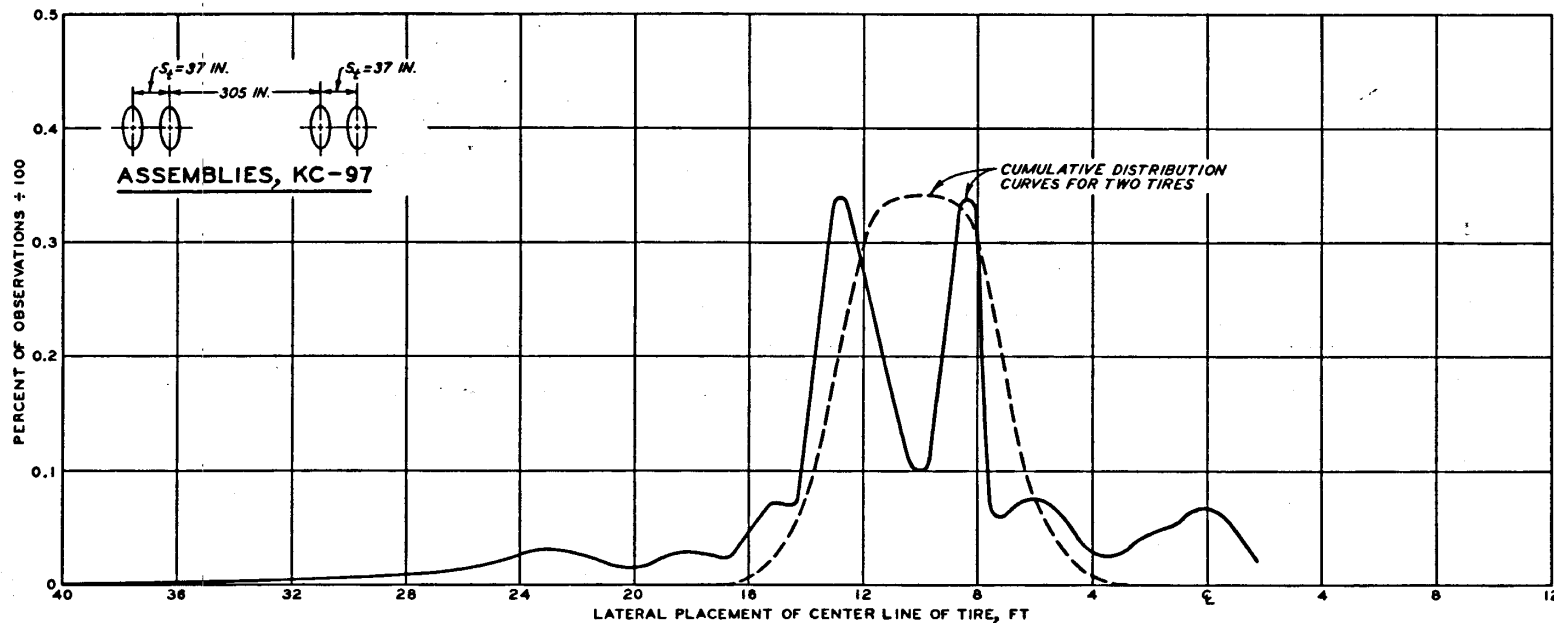


LEGEND

- ACTUAL OBSERVED TRAFFIC DISTRIBUTION FOR FRONT ASSEMBLY OF B-47 (SEE PLATE 2, REF 5)
- - - - - THEORETICAL NORMAL TRAFFIC DISTRIBUTION FOR FRONT ASSEMBLY OF B-47 (WANDER= 275 IN.)

NOTE: ACTUAL OBSERVED TRAFFIC DISTRIBUTION CURVE IS BASED ON 309 OBSERVATIONS MADE AT DYESS, ALTUS, HOMESTEAD, AND MCCOY AIR FORCE BASES.

DISTRIBUTION OF B-47
AIRCRAFT LANDING TRAFFIC
ALONG RUNWAYS
5000 FT FROM RUNWAY END

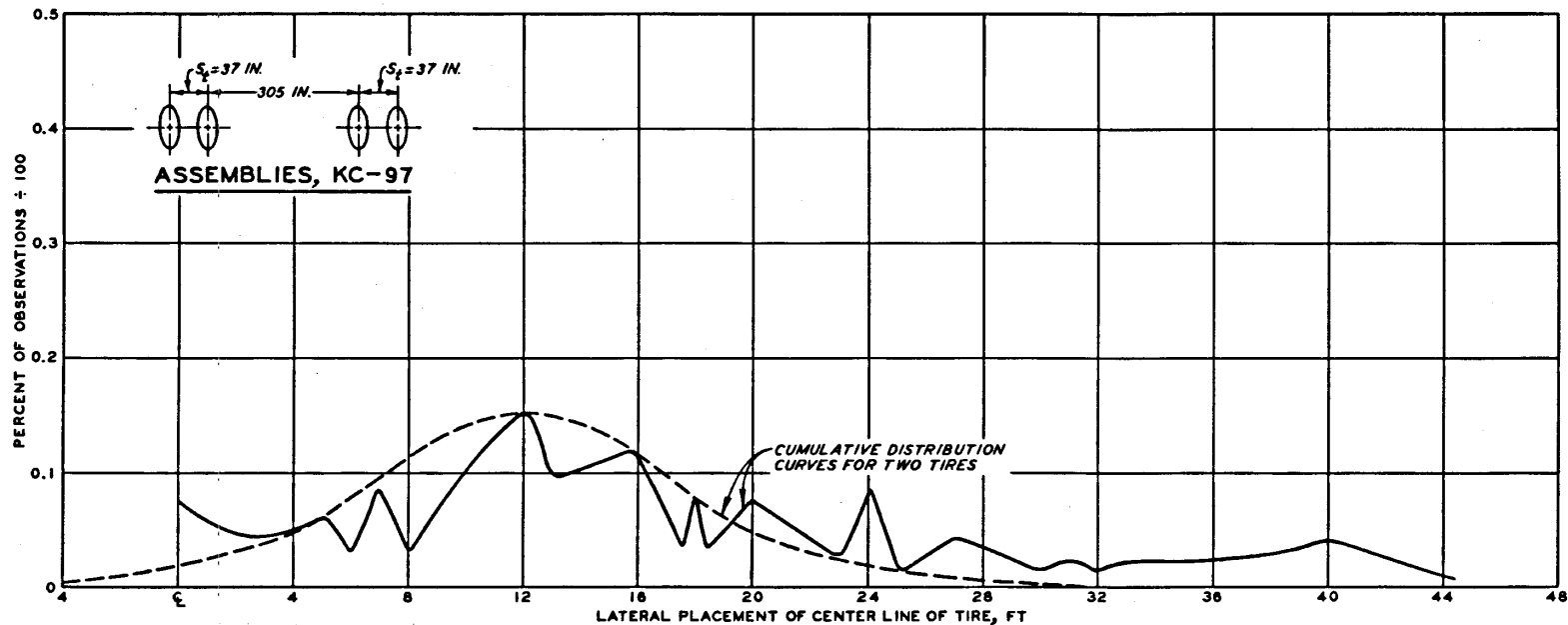


LEGEND

- ACTUAL OBSERVED TRAFFIC DISTRIBUTION FOR LEFT ASSEMBLY OF KC-97 (SEE PLATE 5, REF 5)
- - - THEORETICAL NORMAL TRAFFIC DISTRIBUTION FOR LEFT ASSEMBLY OF KC-97 (WANDER=37 IN.)

NOTE: ACTUAL OBSERVED TRAFFIC DISTRIBUTION CURVE IS BASED ON 113 OBSERVATIONS MADE AT DYESS, ALTUS, HOMESTEAD, McCOY, LORING, AND MacDILL AIR FORCE BASES.

**DISTRIBUTION OF KC-97
AIRCRAFT TAKEOFF TRAFFIC
ALONG RUNWAYS
1000 FT FROM RUNWAY END**

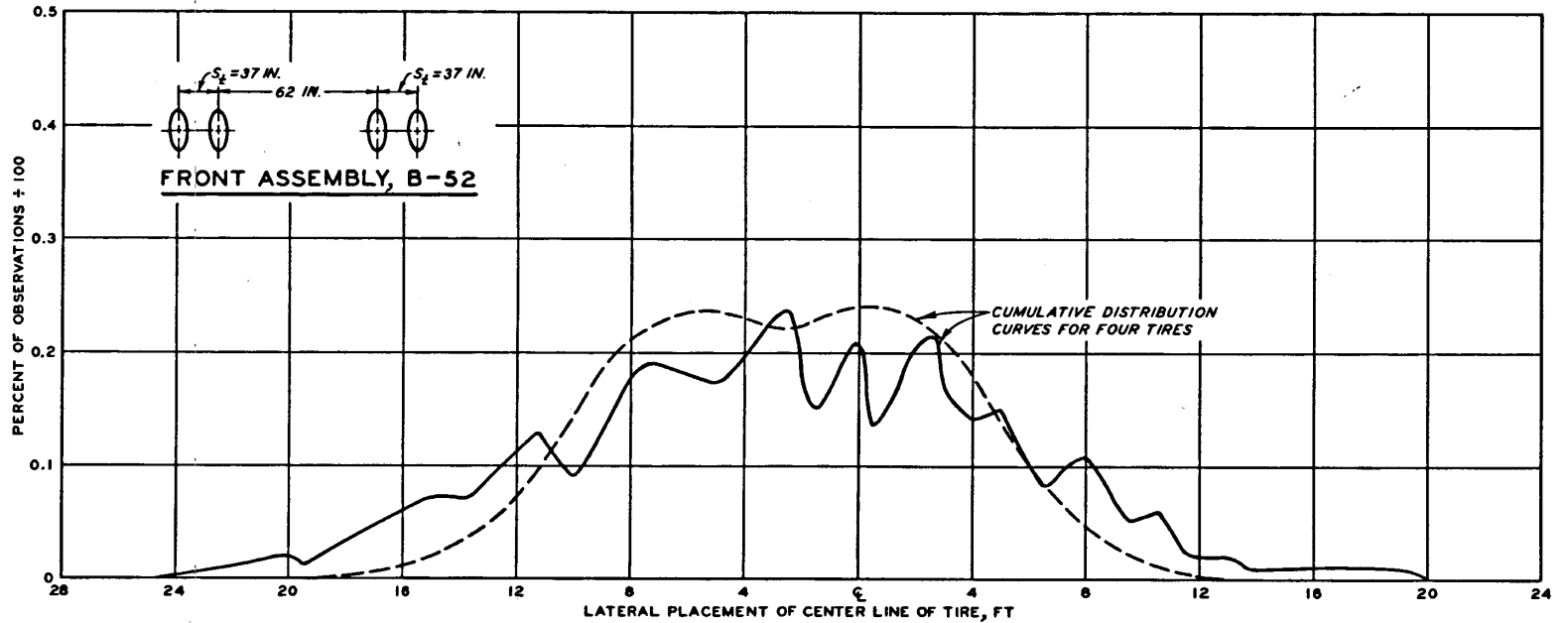


LEGEND

- ACTUAL OBSERVED TRAFFIC DISTRIBUTION FOR LEFT ASSEMBLY OF KC-97 (SEE PLATE 5, REF 5)
- - - THEORETICAL NORMAL TRAFFIC DISTRIBUTION FOR LEFT ASSEMBLY OF KC-97 (WANDER=138 IN.)

NOTE: ACTUAL OBSERVED TRAFFIC DISTRIBUTION CURVE IS BASED ON 95 OBSERVATIONS MADE AT DYESS, ALTUS, HOMESTEAD, McCOY, LORING, AND MacDILL AIR FORCE BASES.

**DISTRIBUTION OF KC-97
AIRCRAFT LANDING TRAFFIC
ALONG RUNWAYS
2000 FT FROM RUNWAY END**

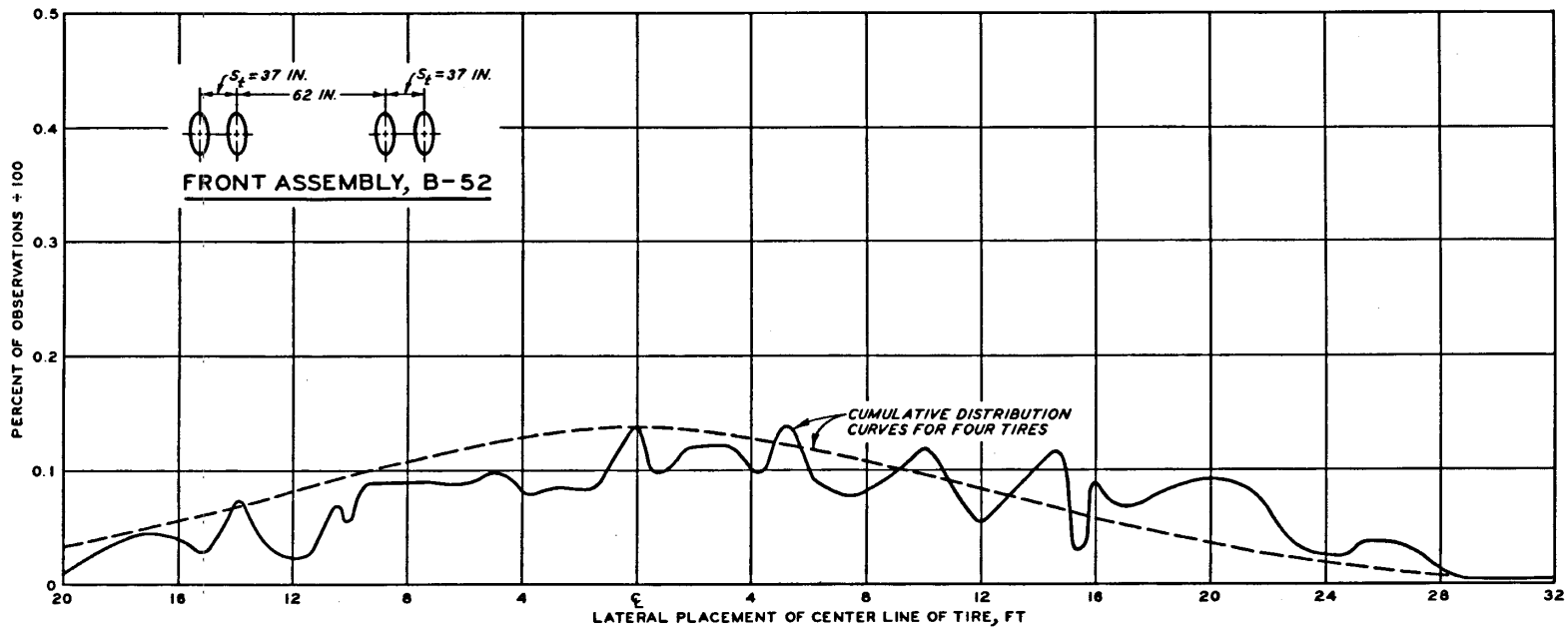


LEGEND

- ACTUAL OBSERVED TRAFFIC DISTRIBUTION FOR FRONT ASSEMBLY OF B-52 (SEE PLATE 3, REF 5)
- - - THEORETICAL NORMAL TRAFFIC DISTRIBUTION FOR FRONT ASSEMBLY OF B-52 (WANDEER=87.5 IN.)

NOTE: ACTUAL OBSERVED TRAFFIC DISTRIBUTION CURVE IS BASED ON 100 OBSERVATIONS MADE AT LORING AND CASTLE AIR FORCE BASES.

**DISTRIBUTION OF B-52
AIRCRAFT TAKEOFF TRAFFIC
ALONG RUNWAYS
2000 FT FROM RUNWAY END**

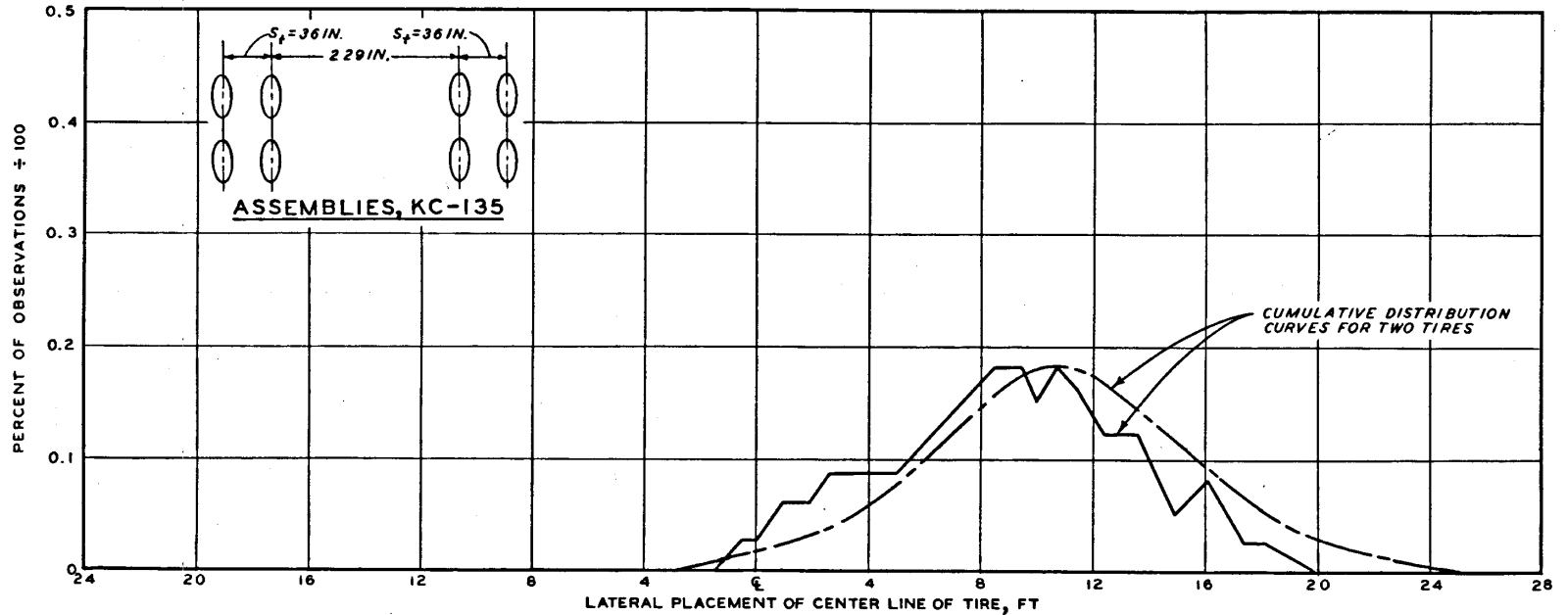


LEGEND

- ACTUAL OBSERVED TRAFFIC DISTRIBUTION FOR FRONT ASSEMBLY OF B-52 (SEE PLATE 3, REF 5)
- - - THEORETICAL NORMAL TRAFFIC DISTRIBUTION FOR FRONT ASSEMBLY OF B-52 (WANDER=300 IN.)

NOTE: ACTUAL OBSERVED TRAFFIC DISTRIBUTION CURVE IS BASED ON 110 OBSERVATIONS MADE AT LORING AND CASTLE AIR FORCE BASES.

**DISTRIBUTION OF B-52
AIRCRAFT LANDING TRAFFIC
ALONG RUNWAYS
5000 FT FROM RUNWAY END**



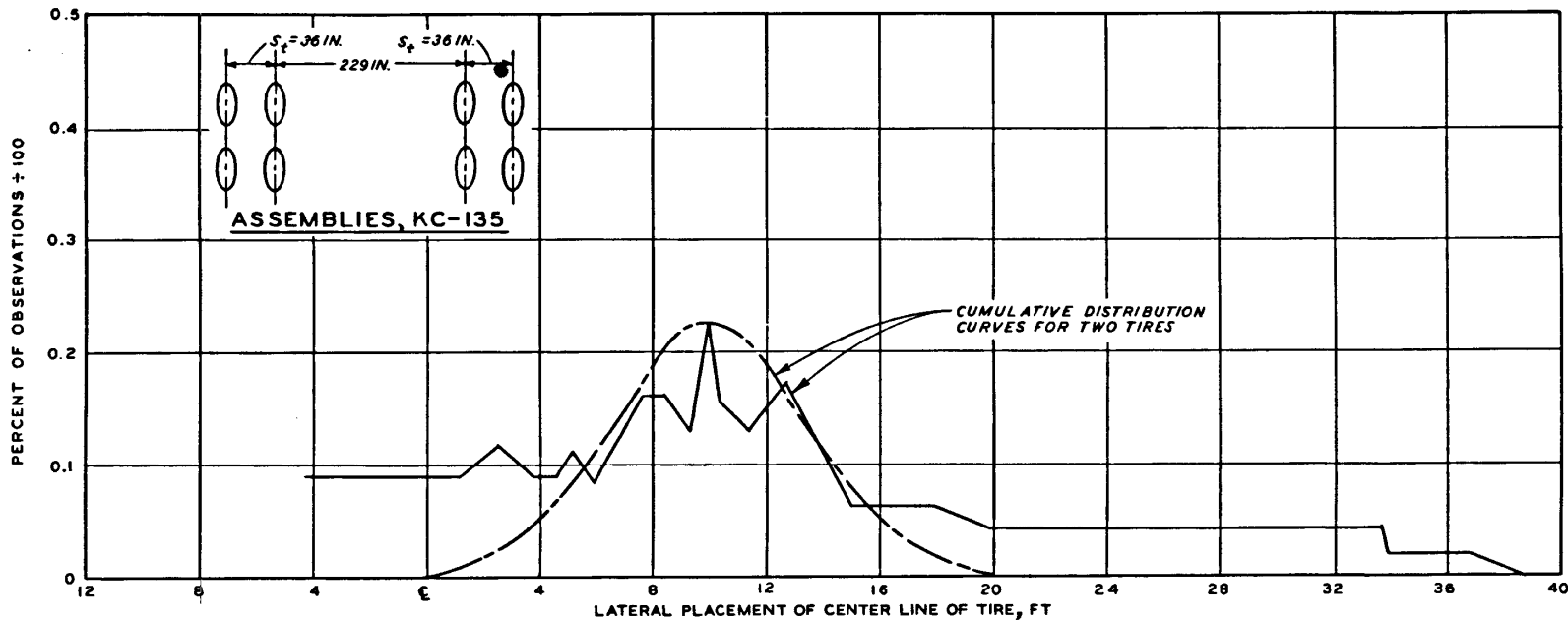
LEGEND

- ACTUAL OBSERVED TRAFFIC DISTRIBUTION FOR ONE-HALF RIGHT ASSEMBLY OF KC-135 (SEE PLATE 4, REF 5)
- - - THEORETICAL NORMAL TRAFFIC DISTRIBUTION FOR ONE-HALF RIGHT ASSEMBLY OF KC-135 (WANDER = 115 IN.)

NOTE: ACTUAL OBSERVED TRAFFIC DISTRIBUTION CURVE IS BASED ON 44 OBSERVATIONS MADE AT CASTLE AIR FORCE BASE.

**DISTRIBUTION OF KC-135
AIRCRAFT TAKEOFF TRAFFIC
ALONG RUNWAYS**

2000 FT FROM RUNWAY END



LEGEND

- ACTUAL OBSERVED TRAFFIC DISTRIBUTION FOR ONE-HALF RIGHT ASSEMBLY OF KC-135 (SEE PLATE 4, REF 5)
- - - THEORETICAL NORMAL TRAFFIC DISTRIBUTION FOR ONE-HALF RIGHT ASSEMBLY OF KC-135 (WANDER = 90 IN.)

NOTE: ACTUAL OBSERVED TRAFFIC DISTRIBUTION CURVE IS BASED ON 49 OBSERVATIONS MADE AT CASTLE AIR FORCE BASE.

**DISTRIBUTION OF KC-135
AIRCRAFT LANDING TRAFFIC
ALONG RUNWAYS**

5000 FT FROM RUNWAY END

Unclassified

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13. ABSTRACT In the development of pavement design and evaluation criteria for aircraft with complex gear configurations (C-5A, B-747, etc.), it has been revealed that current procedures for relating aircraft operations (passes) to pavement coverages (stress and/or deflection repetitions) are cumbersome and inaccurate. The procedure for converting aircraft passes to pavement coverages has been reexamined by developing theoretical normal traffic distribution curves and fitting these curves to the limited number of actual traffic distribution curves available for four aircraft (B-47, B-52, KC-97, and KC-135). In this manner, more realistic pass-to-coverage (p/c) ratios have been developed for most currently used military and civil aircraft. The revised p/c ratios are presented and are recommended for use in pavement design and evaluation criteria. The amount of actual traffic distribution data is recognized to be minimal, and additional data for new generations of aircraft are needed to verify or revise the presented p/c ratios.		

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