A STUDY OF PILOTS' EYE MOVEMENTS DURING VISUAL FLIGHT CONDITIONS

By
Thomas M Edwards and Wayne D Howell
Aircraft Division

Technical Development Report No 179

CIVIL AERONAUTICS ADMINISTRATION
TECHNICAL DEVELOPMENT AND
EVALUATION CENTER
INDIANAPOLIS, INDIANA
June 1952

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TABLE OF CONTENTS

Manuscript received April 1952

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SUMMARY

To obtain further substantial information for establishing minimum angles of vision from the cockpit of airplanes, motion picture photographs were taken of pilots' eyes and heads while they performed critical maneuvers with aircraft during daytime visual flight conditions

Boeing 377 Stratocruiser airplanes were used for this study This particular type of aircraft was selected because of its roomy cockpit and because its windshield provides the pilot with greater angles of vision than any other transport type

Three motion picture cameras were used simultaneously Two of these recorded the pilot's eye movements through a system of mirrors, the third photographed the horizon out ahead of the airplane Basic references or fixation points were established for pilot eye positions by selecting definite locations on the windshield and photographing the pilot's eyes while they were fixed on those selected locations while flying

A photographic enlargement of the pilot's eyes was made for each fixation point, and these prints were placed on a large grid which represented the aircraft windshield It was then possible to compare each photographic frame of the film with the print made of each fixation point, and by comparing the pupillary position it was actually possible to select (in degrees) the point toward which the pilot was looking at any particular instant of time

The motion pictures so obtained were analyzed frame by frame to determine which portions of the windshields and windows were being used and how much each section was being used The results are presented in terms of the percentage of frames showing the use of each windshield section Sections are 5° high and 10° wide For presentation, this study is divided into phases of flight taxiing, take-off, climb, turning, approach for landing, and touchdown (the moment at which the plane touches the ground)

Five groups of airline pilots participated as subjects in the tests They were engineering test pilots, flight supervisor pilots, instructor pilots, trainee pilots, and scheduled pilots No outstanding differences were perceived in windshield use by any one pilot, or any group of pilots However, great differences occurred in the vision areas used in the various phases of flight

The areas on the windshield that show high percentages of usage are generally the areas through which the pilot is obtaining visual cues necessary to operate the aircraft and not the areas of the windshield which are used to search the air space for other aircraft. The windshield area used by the pilots during the pilot eye-movement study substantiates, to a considerable extent, the conclusions drawn from an airline pilot questionnaire study previously reported The results of the current study show that transport pilots attempt to search for other aircraft but may be prevented from seeing them because of windshield structure

INTRODUCTION

Growing interest in increased cockpit vision has been shown for some time by the aircraft industry. This interest has been brought about by the general belief of airline pilots that cockpit vision in most present-day transports is not entirely satisfactory Due to the substantial increase in the number of aircraft now using our airports and airways, there is a definite need for increased cockpit vision The operational characteristics of aircraft vary considerably from one type to another, yet all use the same airports

The pilot eye-movement study is one phase of a cockpit vision study that was commenced in 1948 by the Technical Development and Evaluation Center of the Civil Aeronautics Administration at Indianapolis The specific aim of the study was to determine which areas of the windshield and what visual angles the pilots actually use in performing critical flight maneuvers defined as take-off, landing approach, and low altitude turns. These definitions were established by the airline pilots themselves and were taken from a previous study of cockpit visibility, which study was based on an airline pilot questionnaire[1]

TEST PROCEDURE

Since many variables are involved in determining the vision angles which are used

[1]George L Pigman and Thomas M Edwards, "Airline Pilot Questionnaire Study on Cockpit Visibility Problems," Technical Development Report No 123, CAA, Indianapolis, September 1950

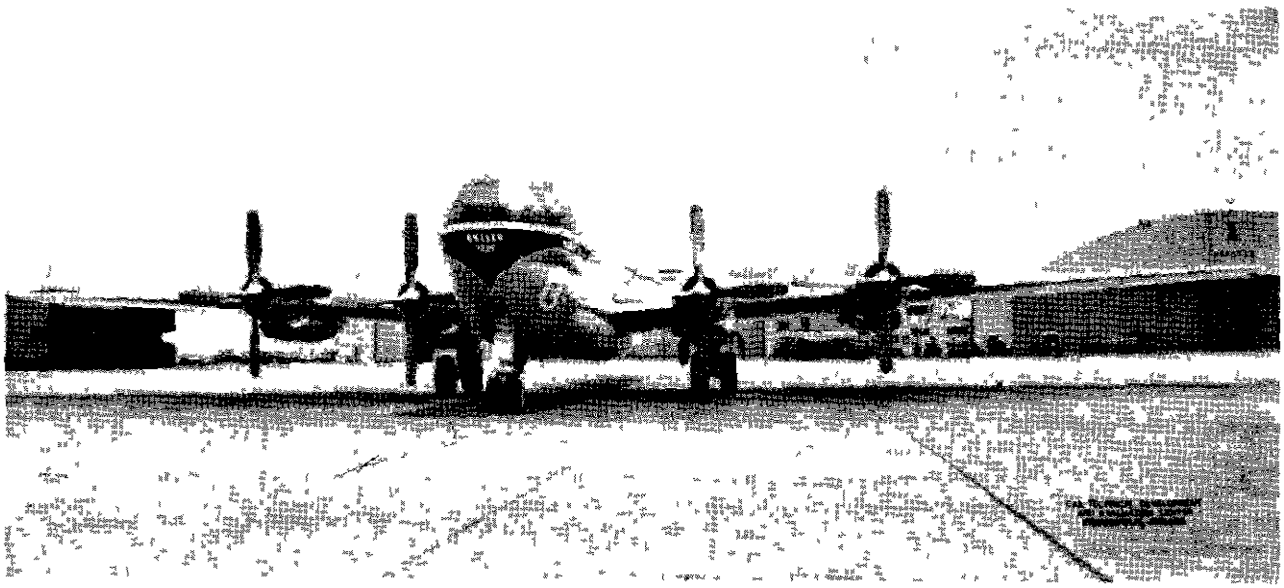

Fig 1 Type of Airplane Used to Obtain Data

by transport pilots, it was not deemed feasible to simulate flight problems in the laboratory The ideal situation would have a pilot sitting at the end of a boom extending forward from the nose of an aircraft with no cockpit enclosure to restrict his vision Since this was not possible, the Boeing 377 Stratocruiser shown in Fig 1 was used as a flying laboratory because it affords a pilot the greatest angular vision of any modern transport

The Department of the Air Force developed a method of recording visual observations made by airplane pilots while conducting flights under instrument conditions[2] This method incorporated the use of a camera and, on the instrument panel, a mirror in which a pilot's eyes were visible. By this means it was possible to determine which instruments a pilot uses, the length of time he actually refers to them, and the relative usage of instruments by pilots.

Discussions were held with the personnel that conducted the Air Force tests to determine the limitations of the method and to discuss a similar application to the cockpit vision problem Though the difficulties of successful analysis were many, the Air Force method still appeared to be the best one for determining the areas toward which pilots look while flying airplanes

[2] Capt Richard E Jones, 1st Lt John L Milton, and Paul M Fitts, Ph D., "Eye Fixations of Aircraft Pilots," Parts II-IV, USAF, Wright-Patterson Air Force Base, Air Materiel Command, 1949-1950

One Cine -Kodak Special and two Bolex H-16 cameras were used for this work These were 16-millimeter cameras driven electrically and operating at eight frames per second, and all three were necessary to obtain complete information. They were mounted on a special stand and installed in the Boeing 377 cockpit See Fig 2. One camera, mounted at the same height as the pilot's eyes, recorded the terrain directly ahead of the pilot This camera recorded airplane attitude and maneuver and provided clues to the object being observed by the pilot The second camera was mounted in such a manner that it recorded the pilot's eyes when visible in the mirror located directly in front of him The mirrors can be seen in Fig 2. An example of the image recorded in the front mirror is shown in Fig 3 The third camera was mounted to record the pilot's eyes when visible in the mirror located to his left, and it thereby photographed his eyes while he was making a left turn During a left turn his eyes were not usually visible in the front mirror The cameras were driven by batteries and were operated simultaneously by one switch No synchronization of the three cameras was possible because of the varying friction clutches in them, however, coordination between cameras was obtained by a flashing light which was mounted in the field of view of each camera A switch permitted control of frequency and duration of the flashes

Airplanes and pilots from United Air Lines and Pan American World Airways

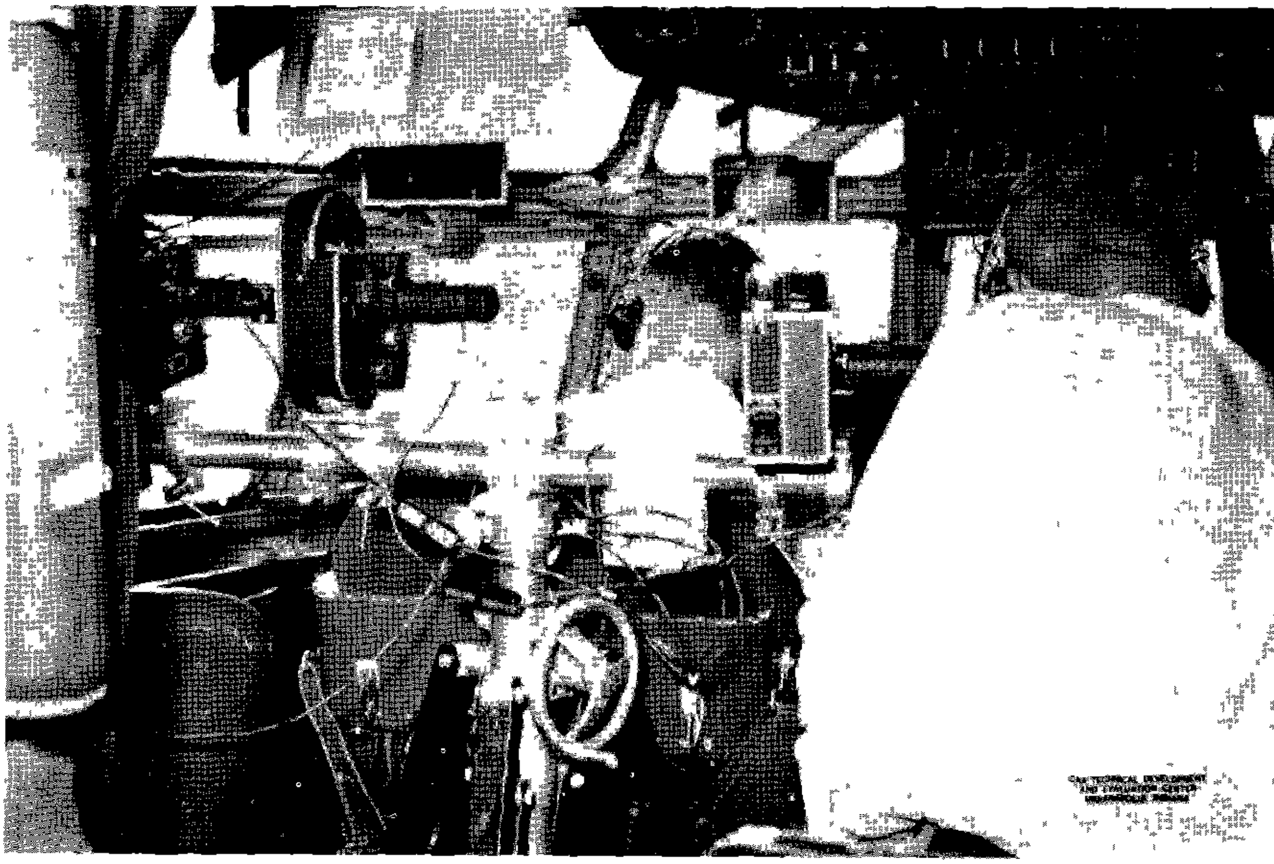

Fig. 2 Cockpit Arrangement Showing Location of Cameras and Mirrors

were used for the pilot eye-movement study It was believed that the visibility requirements could possibly change from one group of pilots to another and that it would be essential to include all groups of airline pilots in this study The tests were therefore conducted at San Francisco, California, where it was possible to obtain pilot eye-movement records of engineering test pilots, flight supervisor pilots, instructor pilots, trainee pilots, and scheduled pilots Eleven different pilots were photographed

Several preliminary flights in the Boeing 377 were necessary to perfect procedure, equipment, and sequence of operations Coordination of the three cameras was attempted on a frame-by-frame basis by using auxiliary mirrors and a motor-driven Veeder-Root counter, however, severe vibration was encountered, and the arrangement was not usable Aperture settings were a constant problem, since the exposure varied on all three cameras because of the different subject material being recorded and because of the varying light conditions A considerable number of test flights were conducted at sunrise, and the low angle of the sun created a problem Low altitude left turns off the San Francisco airport were impractical due to prevailing winds and terrain roughness, however, several low altitude turns were made over the bay especially for the tests

Tests were conducted during engineering test flights, pilot training flights, standard test flights, and one scheduled flight A separate reel of film was used for each flight, and each reel included fixation photographs These were obtained as follows Before commencing the flight, the pilot was asked to stare at certain fixation points in the aircraft cockpit These points are shown in Fig 4 and are listed in Table I While the pilot's eyes and head were fixed on each of these known spots, the cameras made a photographic record of his eyes

After the fixation point records were made, the airplane was taxied out for take-off The cameras were started and operated for a limited time while taxiing the airplane The cameras were started again as the pilot swung onto the runway for take-off As the

Fig 3 Sample Pilot Eye Movement, 16-Millimeter Film Strip

throttles were opened, the synchronizing light was flashed once The light was flashed twice when the wheels left the ground Three flashes were made when the airplane reached a 400-foot altitude after take-off Four flashes indicated the airplane was making a low altitude turn The first flash of the series indicated the execution of the maneuver The cameras were then shut off until the airplane was about to complete the flight and was at a 1,000-foot altitude on the approach for landing Arrival at this point was indicated by flashing the light five times. Six flashes were made when the 200-foot altitude was reached on the approach for landing Seven flashes indicated that the airplane had touched the ground Pictures were also taken during the landing roll and taxi phase

ANALYSIS OF FILMS

A contract for analyzing the photographic records was let to Antioch College in Yellow Springs, Ohio Two copies of each

TABLE I

LOCATION OF FIXATION POINT PRINTS BY DEGREES

Print Number	Horizontal Location (Degrees)	Vertical Location (Degrees)
1	115 L (Left)	3 D (Down)
2	95 L	30 U (Up)
3	88 L	3 D
4	67 L	12 U
5	67 L	23 D
6	47 L	3 D
7	29 L	12 U
8	33 L	35 D
9	14 L	3 D
10	2 R (Right)	10 U
11	0	13 D
12	12 R	1 D
13	33 R	0
14	10 R	22 D
15	10 R	25 U

Above angles measured with respect to pilots' line of vision while looking straight ahead and at the horizon with aircraft in taxiing position See 0° angle reference point marked on Fig 4

film were supplied to expedite two independent analyses of each film Enlargements of the fixation photographs were also supplied and were placed on a grid, as shown in Fig 5 These locations corresponded to the fixation spots shown in Fig 4 and listed in Table I

The fixation grid was mounted at one end of a room that was specially arranged to facilitate the analysis of the eye-movement films A plan of the film reading room is shown in Fig 6 The purpose of this arrangement was to obtain a maximum visibility of the projected eye-motion films and the fixation photographs In order to accomplish this, sources of light were highly localized with most of the room in near darkness There were no windows, and the walls and ceiling were painted black The fixation grid was lighted by fluorescent tubes shielded by black cloth Two projection set-ups were provided to expedite the duplicate analyses of each film Each projection was focused into a black projection box with a white screen at its end A red overhead light provided sufficient illumination for recording the results With this arrangement, the two analysts were able to see the fixation

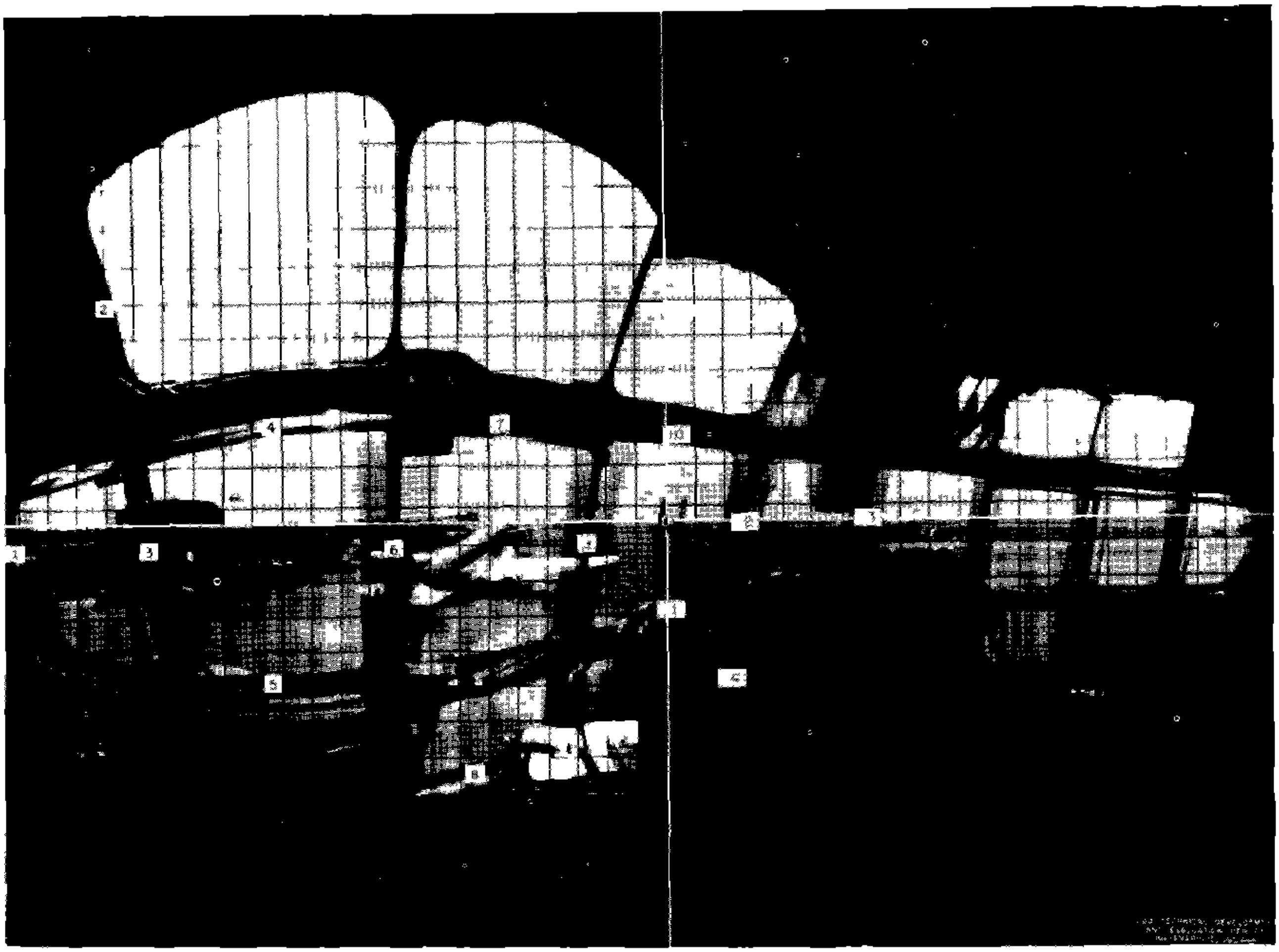

Fig. 4 Fixation Points in Position on Windshield

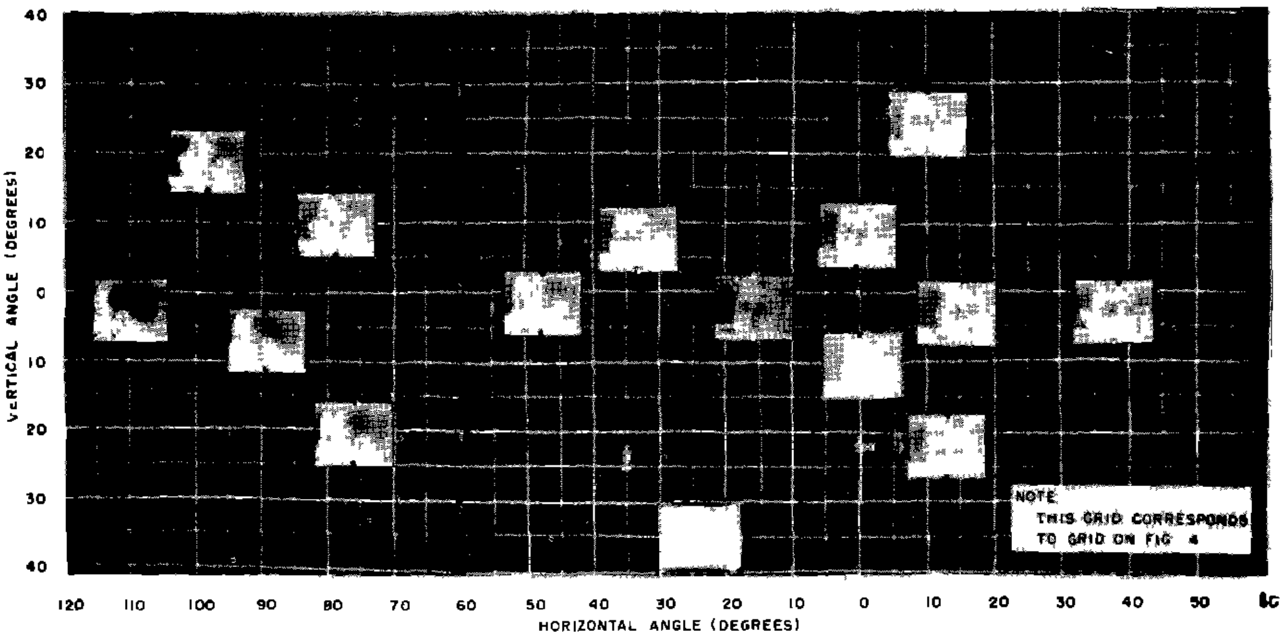

Fig 5 Fixation Point Photographs in Position on Grid

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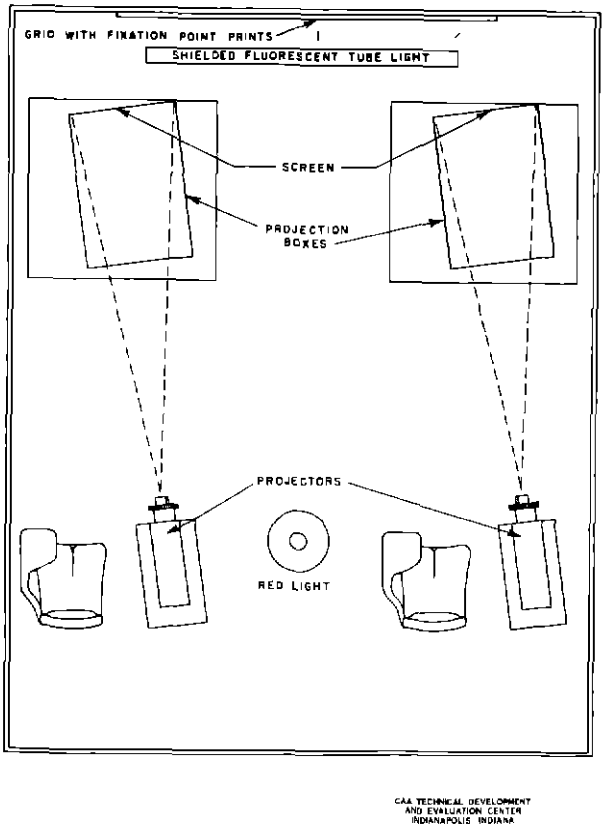

Fig 6 Plan of Film Reading Room for Analysis of Eye-Movement Films

photographs clearly and to compare them with clear, bright projections of the eye-movement films

The eye movements of eleven airline pilots were analyzed by two advanced psychology students under the immediate direction of a psychologist The majority of the films showed the pilots' eyes reflected from the front mirror Films involving the side mirror were used in only a few cases when the pilots' eyes were not visible in the front mirror The groups of airline pilots and the phases of flight involved are listed in Table II.

When the fixation photographs were developed, it was found that on two of the reels the photographs were unusable It was therefore necessary to compare the eye-movement pictures on those reels with fixation photographs from other reels. However, when the fixation photographs on the remaining nine reels were compared for any one fixation point, it was found that the possible errors involved were within the acceptable limits of accuracy for the intended purpose of this study

Working independently, each analyst compared each photographic frame with the fixation point prints and made a judgment of its location An attempt at absolute analysis was made, for example, the analysts wrote '26° Left, 13° Up" rather than merely indicating a range of angles There were various categories into which photographic frames might fall For example

a Correct Independent readings by two analysts were in reasonable agreement

b Blink The pilot clearly closed his eyes for a few photographic frames

c. Blur The film was rendered unusable due to vibration in the aircraft or movement of a pilot's eyes

d Eyes Not Visible Only the top of the pilot's head, or his chin, or hand in front of his face was visible, and there was not sufficient evidence for making any estimate of the position of the eyes

e Approximations When a pilot's eyes were not visible but the position of his head clearly indicated the direction of his gaze, each analyst made the best estimate he could and marked it as approximate However, a

TABLE II

GROUPS OF PILOTS PARTICIPATING IN VARIOUS PHASES OF FLIGHT

Type of Airline Pilot	Phases of Flight
Engineering Test Pilot	Take-off and landing
Flight Supervisor Pilot	Take-off and landing
Instructor Pilot	Take-off and landing
Trainee Pilot	Take-off and climb
Trainee Pilot	Descent and landing
Trainee Pilot	Take-off and climb
Trainee Pilot	Descent and landing
Trainee Pilot	Take-off and landing
Trainee Pilot	Take-off and landing
Scheduled Pilot	Normal flight and landing
Scheduled Pilot	Take-off, climb, descent, and landing

photographic frame might be approximated in one direction but read exactly in the other

After both analysts had completed viewing a film, their duplicate readings were compared. Those photographic frames on which the analysts agreed to within 10° in the horizontal dimension and to within 5° in the vertical dimension were marked correct Those photographic frames on which they did not agree within these limits were marked incorrect in the dimension in which they disagreed Approximations were not compared, however, spot checks were made on the approximations, and their agreement was almost as good as readings on the photographic frames that were read accurately

After the comparison had been made, photographic frames marked incorrect were reread independently by both analysts. The second readings were accepted as correct, regardless of their agreement or lack of it It might have been desirable to require 100 per cent agreement for the rereadings This was actually tried, but it appeared, on careful consideration, to be better to have two careful rereadings without forced agreement Honest disagreement continued to occur in some cases, and, if agreement had been forced, there would have been some doubt as to the adequacy of compromise values

It should be emphasized that throughout the entire analysis the two analysts worked independently They sat in the same room but worked at different rates and were seldom reading the same photographic frame at the same time. They did not at any time discuss with each other their judgments of any photographic frame, and in rereading they continued to work independently Whatever agreement exists between their readings exists therefore because they were able to read accurately enough to agree within the established limits, in spite of difficulties, rather than because discussion and consultation enabled them to reach a joint decision

Table III is a numerical résumé of the photographic eye-movement data For each pilot it lists the number of frames obtained on the original films, the number of frames read (duplicate readings by two analysts using two copies of each film), the number of frames that were unusable because of blinks, blurs, and other defects, the number of frames that could be used to obtain a fair approximation, and the number of frames that were reread because of disagreement between the two analysts

Table III also shows the percentage of photographic frames actually read, the percentage unreadable (such as blinks), and the percentage of those which were approximations or had to be reread If a photographic frame reading were approximated in either dimension or the reading were in disagreement in either dimension, it was tabulated as if the approximation or disagreement were in both dimensions If a photographic frame reading were an approximation in one dimension and in agreement in the other, it was tabulated as an approximation

The procedure used in tabulating results was as follows

1. The films were divided into phases of flight. Originally, it had been planned that these phases should be indicated in the film by a series of coded light signals In most of the reels, these light signals were used exactly as planned, in others, however, technical difficulties prevented their use. The division of the films into phases was done by careful individual analysis based on such information as the head and eye position of the pilot, whatever light signals were available, lip reading such as, "Wheels Up'", vibration of the airplane on touchdown, pilots' expressions (almost all showed a relaxation of facial expression and a broad grin after touchdown), comparisons of eye-movement photographs with the film taken straight ahead through the windshield, which gave a very good indication of the airplane's attitude The phases of flight into which the film was finally divided and the criteria which defined those phases are listed in Table IV

2 Tabulation sheets were prepared for analyzing the data These were in the form of a grid similar to that used for mounting the fixation photographs The grid lines represent 10° horizontal increments and 5° vertical increments This divided the sheet into rectangles

3 For each phase, and with all pilots included, the total number of frames that showed the pilots looking through a particular rectangle were noted in that rectangle on the tabulation sheets These included approximations and rereadings See Tables III and IV. Blinks, blurs, and other defects were not included. Frames showing the pilots looking at instruments were not listed

4 Percentages for the numerical data were then transferred to an identical set of grid tabulation sheets They were obtained for each phase by dividing the number of frames listed in any one rectangle by the total number of frames listed on that grid sheet.

5. One of the grid tabulation sheets was then used to combine the eye movements of all pilots and all phases on one sheet In each rectangle were listed all the frames

TABLE III

NUMERICAL RESUME OF EYE-MOVEMENT DATA

Pilot Identification	No of Frames Obtained	Duplicate Readings Using Two Copies of Each Film								
		Analyst	Frames Read	Blinks, and Other Defects	Approx-imations	Frames Reread	Per Cent Read*	Per Cent Blinks, and Defects*	Per Cent Approx-imations**	Per Cent Re-read**
1	4000	C	2488	1512		1088	62 2	37 8		43 7
		L	2366	1634		1088	59 2	40 8		46 0
2	3235	C	2958	277	1534	470	91 4	8 6	51 9	15 9
		L	2953	282	992	470	91 3	8 7	33 6	15 9
3	3561	C	3208	353	671	620	90 1	9 9	37.2	19 3
		L	3203	358	682	620	89 9	10.1	21 3	19 4
4	1530	C	1381	149	755	203	90 3	9 7	54 7	14 7
		L	1416	114	603	203	92 5	7 5	42 6	14 3
5	1250	C	1136	114	723	122	90 1	9 9	63 6	10 7
		L	1159	91	324	122	92 7	7 3	28 0	10 5
6	3300	C	2621	679	803	1118	79 4	20 6	30 6	42 6
		L	2661	639	279	1118	80 6	19 4	10 5	42 0
7	1982	C	1816	166	1115	366	91 6	8 4	61 4	20 2
		L	1863	119	721	366	94 0	6 0	38 7	19 6
8	2900	C	2770	130	1918	72	95 5	4.5	69 2	2 6
		L	2668	232	881	72	92.0	8 0	33 0	2 7
9	2330	C	2032	298	931	264	87 2	12 8	45 8	13 0
		L	2057	273	1222	264	88 3	11 7	59 4	12 8
10	3780	C	3513	267	1812	261	92.9	7 1	51 6	7 4
		L	3497	283	2873	261	92 5	7 5	82 2	7 5
11	1653	C	1066	587	747	78	64 5	35 5	70 1	7.3
		L	969	684	357	78	58 6	41 4	36 8	8 0
TOTALS	29521	C	24989	4532	11209	4662	84 6	15 4	44 9	18 7
		L	24812	4709	8934	4662	84 1	15 9	36 0	18 8

*Per Cent of Frames Obtained
**Per Cent of Frames Read

Note C and L identify the two film analysts

TABLE IV

PHASES OF FLIGHT AND THE CRITERIA USED

Phase		Criteria	No. of Frames	No. of Pilots
1	Taxi	Beginning of film to 120 photographic frames before one flash	1141	5
2	Pre-Take-Off	120 photographic frames before one flash to one flash	987	6
3	Take-Off	One flash to two flashes	3080	8
4	Post Take-Off (Climb)	Two flashes to 40 photographic frames before four flashes	5692	8
5L	Left Turn	40 photographic frames before four flashes to 120 photographic frames after four flashes	335	2
5R	Right Turn	40 photographic frames before four flashes to 120 photographic frames after four flashes	1217	5
6	Climb	120 photographic frames after four flashes to blank in film which indicated that the camera had been turned off	4513	8
7	Descent	Blank in film to six flashes	7342	9
8	Final Approach	Six flashes to seven flashes	4101	9
9	Landing Roll	Seven flashes to 200 photographic frames after seven flashes	2996	9
10	Taxi	200 photographic frames after seven flashes to end of film	4143	5
ALL PHASES		TOTAL	35817*	11**

*Photographic frames that showed glances at instruments were read but were not included in phase analyses or in the totals listed in this table.

**A total of eleven pilots were included

that showed pilots looking through that rectangle.

PRESENTATION OF DATA

The percentage tabulations discussed in the foregoing Paragraph 4 concerning tabulating procedures are presented in Figs 7 to 17, inclusive The numerical totals discussed in Paragraph 5 are presented in Fig 18

Each of the Figs. 7 to 18 includes two curves One of these (using dashed line) involves eye movements in a horizontal direction, while the other (using solid line) covers eye movements in a vertical direction Together, they show the relative usage of various portions of the windshields and windows The height of the horizontal eye-movement curve for each 10° increment of horizontal arc is the sum of the numbers in that vertical column In a similar manner, the heights of the vertical eye-movement curve are the sums of the numbers

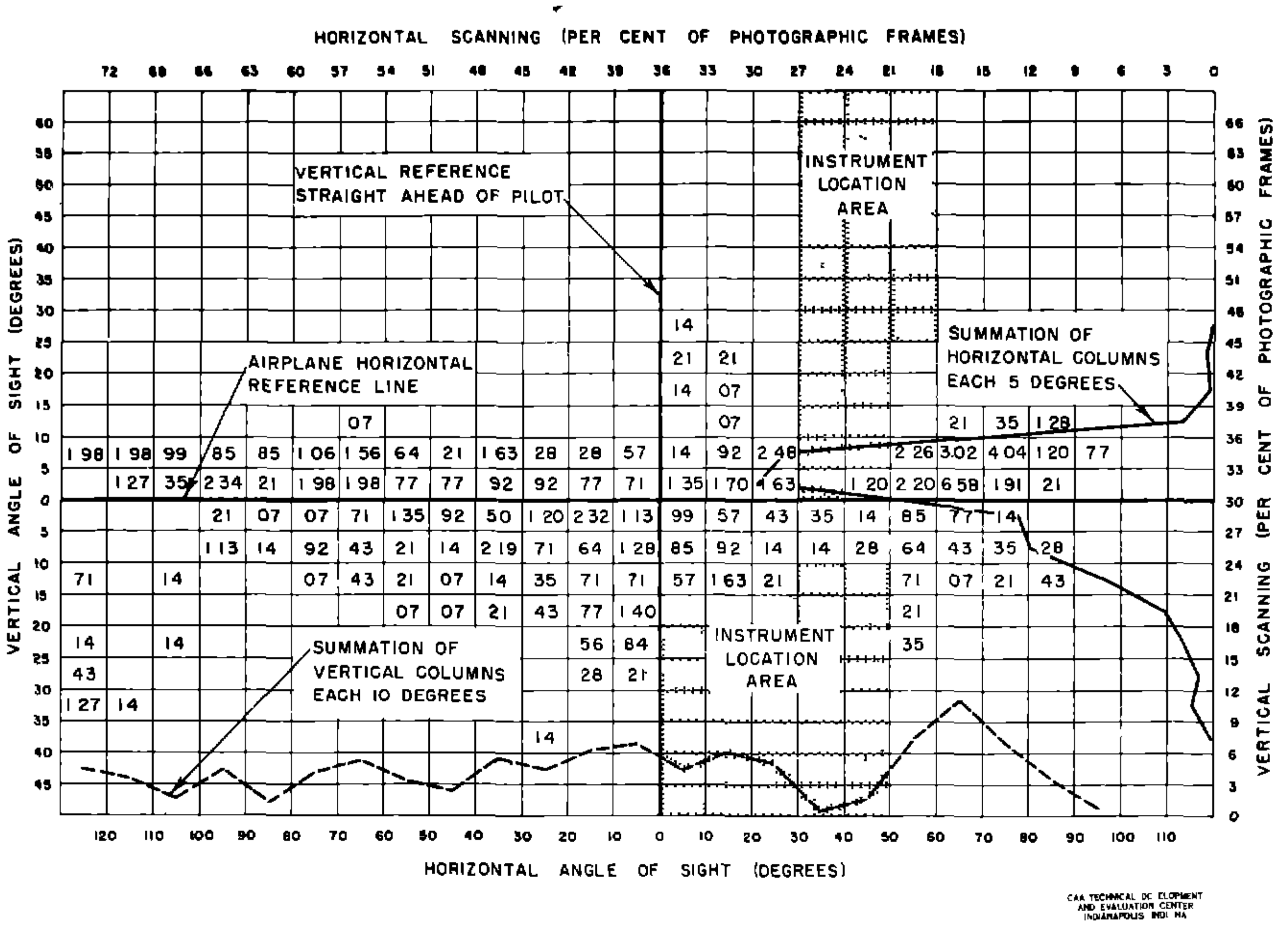

Fig. 7 Phase 1 – Windshield Usage During Taxi From Beginning of Taxi to Run-Up (5 Pilots, 1411 Photographic Frames)

in the horizontal columns for each 5° of vertical arc The grid lines provide plotting scales

The zero position shown in Figs. 7 to 19 is the point on the aircraft directly ahead of the pilot and coincident with the horizon when the airplane is in taxi attitude This statement does not hold true for Fig 20, in which the zero position is straight ahead of the pilot and on the horizon when the airplane is in cruise attitude on a level flight path

The curves superimposed over the numbers are intended to show the general characteristics of the data Both graphical and numerical data on each phase are shown so that evaluation can be made and a better understanding obtained of the interrelationship among upward, downward, left, and right vision angles Although it is of some interest to know the exact values, it is believed that if only one pilot makes just one glance to search for visual guidance while flying an airplane, the importance of that glance must be considered

DISCUSSION OF DATA

Phase 1 – Taxi Before Take-Off

A total of 1,411 photographic frames were analyzed for Phase 1 Five pilots representing all groups were included Fig 7 shows the percentage of use that these pilots made of various portions of the windshields and windows during the taxi phase of flight from the beginning of the taxi to engine check (called run-up) While taxiing, the nose of the airplane is pointed 2° above the horizontal This attitude is called nose up An attempt was made to remove all visual references to the aircraft instruments, however, because of the type of analysis that was required, an accuracy greater than 5° in the upward and downward directions and 10° to the left and right was not possible. Therefore, some small influence of instrument reading may be seen near the border of the instrument panel

The solid curve with vertical base, shown on the right side of Fig 7, indicates

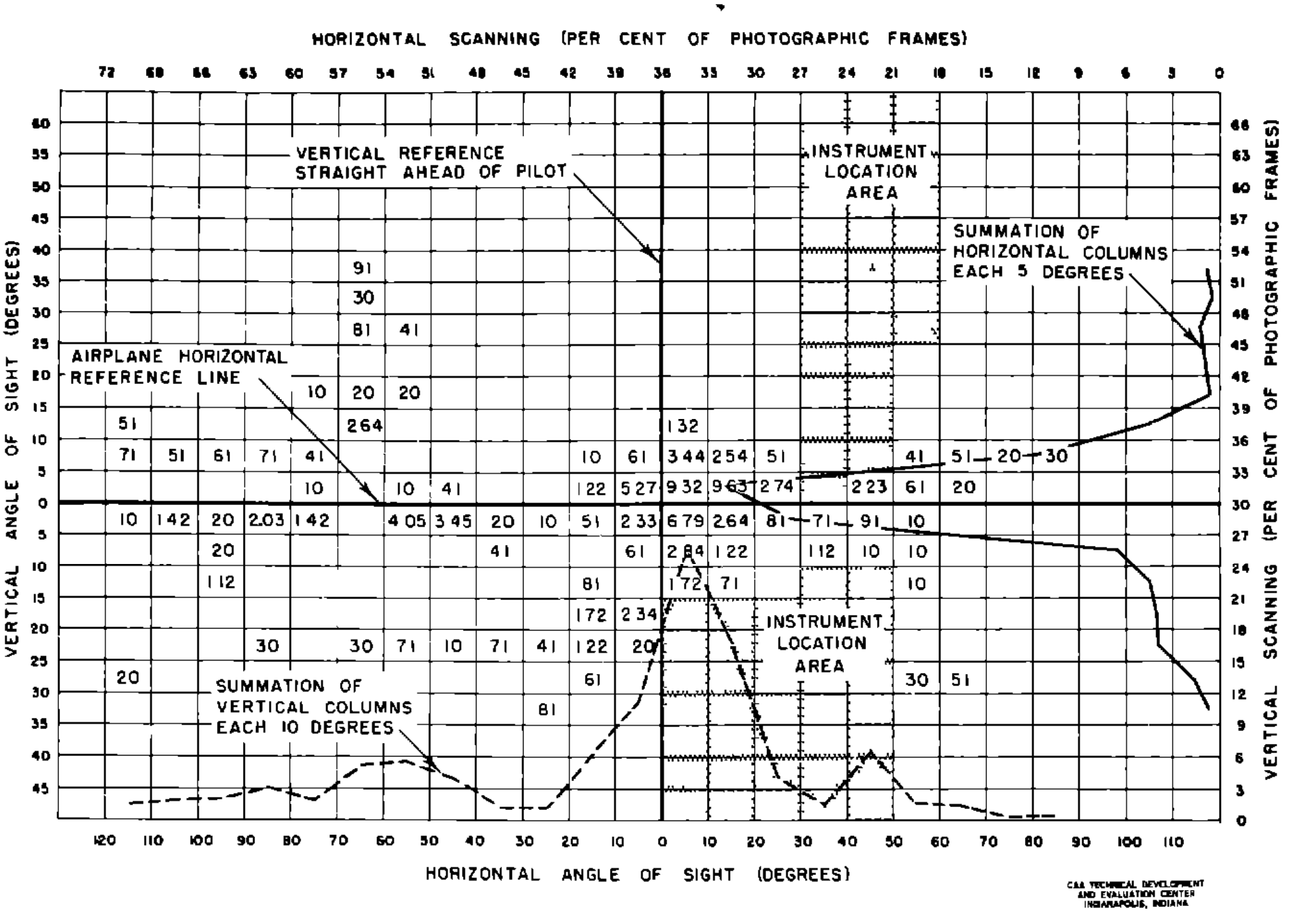

Fig 8 Phase 2 – Windshield Usage During Pre-Take-Off From Run-Up to Full Throttle (6 Pilots, 987 Photographic Frames)

the vertical scanning by the pilots The greatest percentage of photographic frames of glances made outside the airplane falls in the sector from 0 to 5° above the horizon, the next highest being in the sector from 5 to 10° above it Very little vision was desired above 15°. The curve also shows a strong tendency for the pilots to use as much as 20° downward vision, and it is relatively strong down to 35° below the horizon.

The dashed curve shown in Fig. 7 represents the percentage of photographic frames used for horizontal scanning This curve shows no strong tendency for the pilots to use any specific sector but shows a general use of the windshield at angles ranging from 125° left to 90° right The highest peak occurs in the sector 60 to 70° to the right which is located in the first window to the right of the co-pilot It may be significant that this is the first clear window that is available to the pilot in seeking right-hand vision By checking the numerical data shown in Fig. 7, it can be seen that 6.58 per cent of scanning of the photographic frames occurs on the horizon or slightly above it and 65° to the right. This is a very high percentage for this phase However, in checking the individual pilot data it was found that this peak was caused by one pilot who may possibly have been observing a particular airplane in that direction The very general distribution of the percentages over the entire lower windshield area indicates that all the vision this airplane affords was used during the taxiing maneuver

Phase 2 – Pre-Take-Off

Phase 2 starts the instant after run-up and continues until the throttle is opened for take-off Six pilots, in a total of 987 photographic frames, were used in this phase. All groups of pilots were included In every case, immediately after run-up, the airplane made a right turn onto the runway for take-off The taxi attitude of the aircraft was 2° nose up

The solid curve representing the upward and downward vision shows the peak of usage slightly above the horizon with

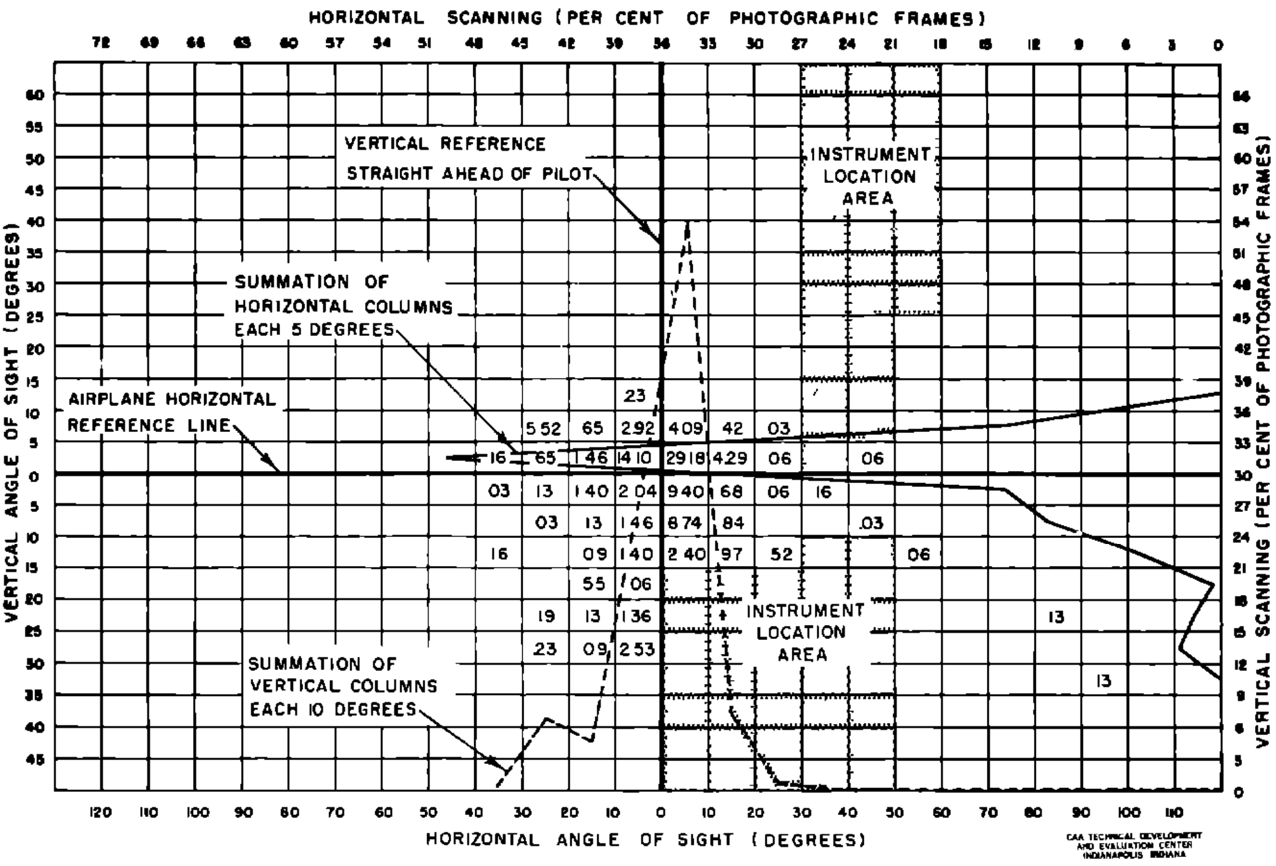

Fig 9 Phase 3 —Windshield Usage During Take-Off, Full Throttle to Airborne (8 Pilots, 3080 Photographic Frames)

extensive usage just below the horizon The curve also shows fairly general usage of the windshield, with a minor peak occurring approximately 25° above the horizon and extensive usage down to approximately 25° below the horizon.

The dashed curve in Fig 8 shows that the highest percentage in number of photographic frames occurs between 0 and 10° to the right. It is believed that this is the area where the pilots were looking when lining up the airplane with the runway, prior to opening the throttle. A minor peak is located between 50 and 70° to the left This peak was caused by pilots' glances to the left to see that the area was clear for landing aircraft. Another peak exists between 40 and 50° to the right This peak was probably caused by glances to see that the runway was clear before taxiing onto the runway for take-off It is interesting to note the use of the windshield in the 40 to 80° left sector. This was due to the pilots' attempts to make certain that there were no approaching airplanes prior to taxiing into take-off position.

The dashed curve of Fig 8 shows that during pre-take-off there is appreciable use of the windshield from 120° left to 70° right.

Phase 3 — Take-Off

Phase 3 of flight starts the instant the throttle is opened for take-off and ends the instant the airplane leaves the ground The attitude of the aircraft during the first 40 per cent of the time after the throttle is opened varies from 2° nose up to 1° nose down During the final 60 per cent of the take-off run, the aircraft attitude is 1° nose down All eight pilots are represented for a total of 3,080 photographic frames

The solid curve shown in Fig 9 indicates a major peak of usage from 0 to 5° above the horizon This indicates that there is strong similarity among pilots during the take-off phase The curve also shows extensive use in the 0 to 15° downward region, indicating that the pilots often look down in the area immediately in front of the airplane while taking off It is probable that the peak located 30° below the horizon is partially due

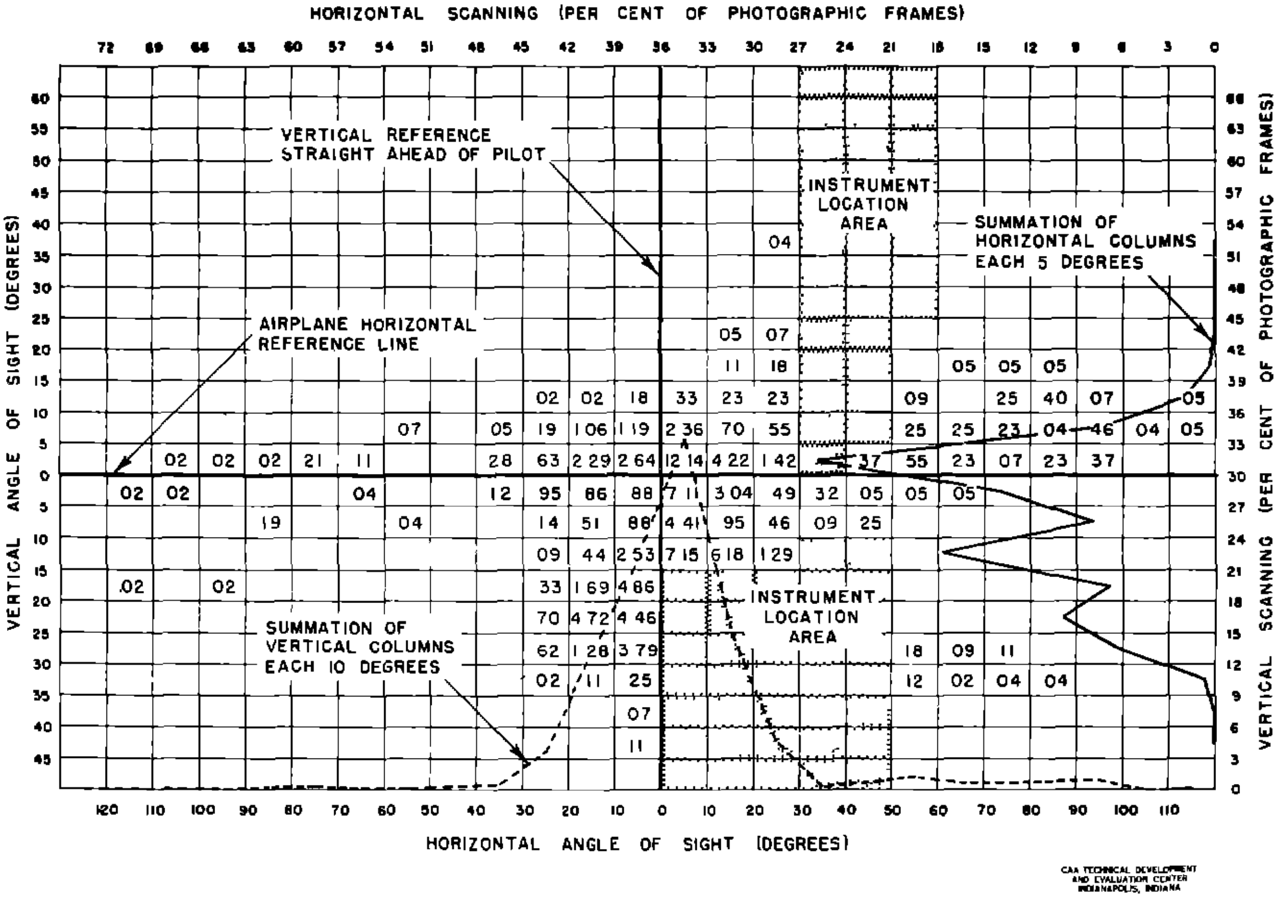

Fig. 10 Phase 4 – Windshield Usage During Post Take-Off, From Airborne to 400-Foot Altitude (8 Pilots, 5692 Photographic Frames)

to instrument readings

The dashed curve shows a peak of usage in the 0 to 10° right sector and again indicates a common tendency among pilots It is apparent that during take-off the pilot is seeking vision directly ahead and is not looking to one side or the other for more than a total of 30° The peak located 20 to 30° to the left was caused by one pilot, and the reason he used this area so frequently is not known

Phase 4 – Post Take-Off

Phase 4 begins the instant the wheels are off the ground and ends when the airplane reaches an altitude of 400 feet Immediately after the wheels leave the ground, the airplane attains an attitude of 7 to 10° above the horizon and stays in that attitude 30 per cent of the post take-off time. After a steep climb, the airplane settles down to an attitude of 5° nose up for 70 per cent of the post take-off time Fig 10 shows the percentage for eight pilots from all groups in 5,692 photographic frames.

The solid curve is spread throughout a range from 15° above the horizon to 35° below it, with major peaks occurring from 0 to 5° upward, from 10 to 15° downward, and from 20 to 25° downward The 0 to 5° peak above the horizon is the maximum The other two peaks in the vertical range are probably due to some influence of instrument reading However, downward vision appears to be of considerable importance in the post take-off phase It is believed that some of the emphasis on downward vision was due to the pilots searching downward and to the right or left prior to entering turns following the post take-off phase.

The dashed curve, representing horizontal vision, shows a peak between 0 and 10° to the right This peak is quite broad covering a range from approximately 40° left to 40° right

Phase 5L – Left Turn

In Phase 5L, the pilots' eyes were recorded during a low altitude left turn. In this maneuver the airplane attains a bank of

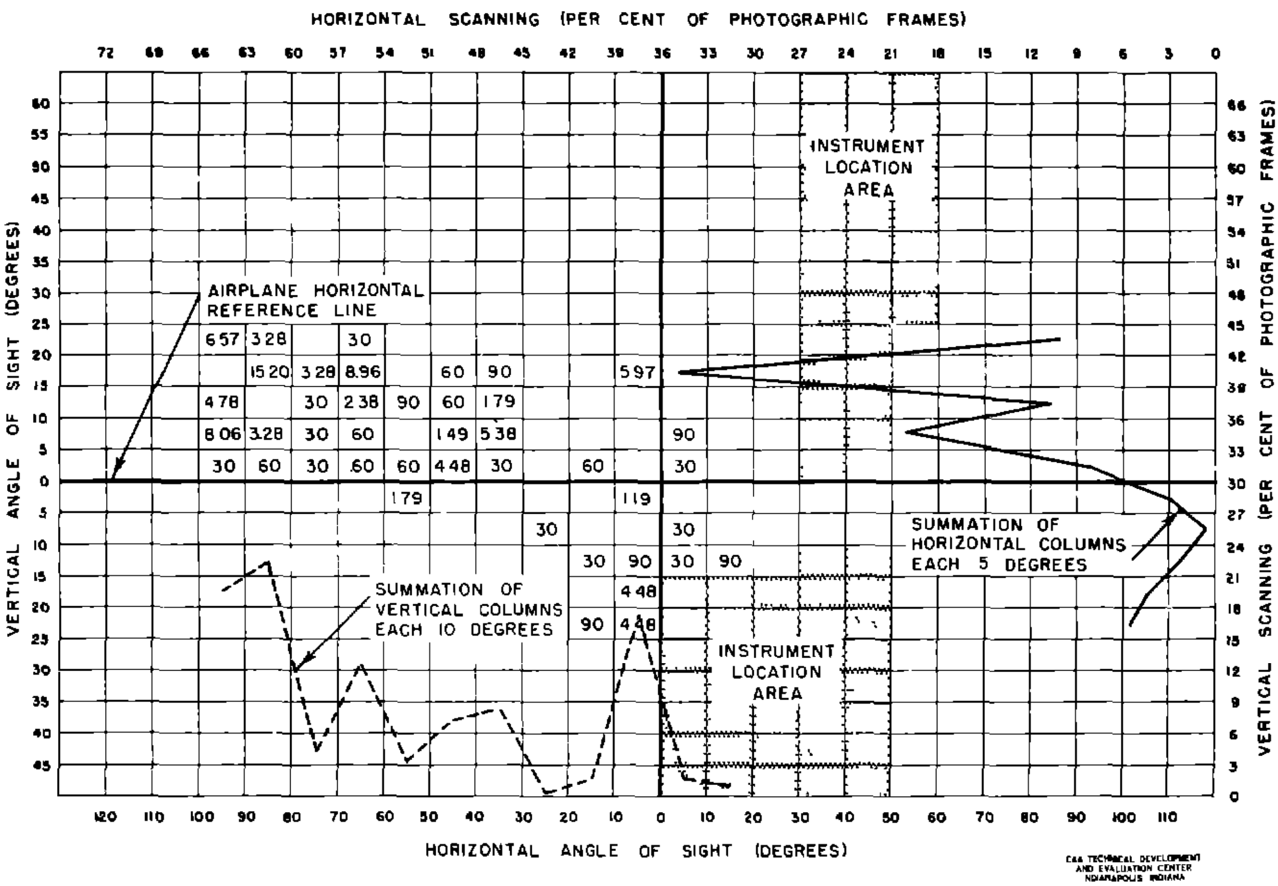

Fig 11 Phase 5L —Windshield Usage During Left Turn (2 Pilots, 335 Photographic Frames)

25° for 75 to 80 per cent of the phase time, and the bank is held constant. The remaining 20 per cent of time is used in going into and out of the bank A total of 335 photographic frames recording the directions of glances of two pilots were used for the analysis.

The solid curve in Fig 11 contains two peaks The major peak occurs between 15 and 20° above the horizontal reference line The second peak occurs in the sector from 5 to 10° above The rise in the curve at the sector 20 to 25° below the reference line can be attributed to instrument readings

The dashed curve shows that considerable vision to the left is needed for this maneuver. The major peak occurs in the left 80 to 90° sector, with other peaks occurring in the left 60 to 70° sector and the left 30 to 40° sector. Again it is felt that the peak in the 0 to 10° left sector is exaggerated by glances at the instruments, although there is also a high percentage in the portion 15 to 20° above the reference line

Phase 5R — Right Turn.

Phase 5R concerns low altitude right turns The total photographic frames represented are 1,217 Five pilots are involved The percentage of the total phase time held constant at 25° bank is 75 to 80 per cent The remaining 20 per cent of the time is used in going into and out of the bank Most of the turns were made below 300 feet and at a rather steep angle to prevent entering instrument conditions

The solid curve shown in Fig 12 shows a peak 5 to 10° above the reference point and shows extensive use in the 0 to 5° region above it Downward visibility, from the 0 to 15° region below the reference point, is also indicated as being used often The peak that is located 25° below the point indicates that the pilots made frequent use of the window to the right and below the co-pilot's position in completing this maneuver.

The dashed curve shows a broad peak at 20° to the right The smaller peak at 60°

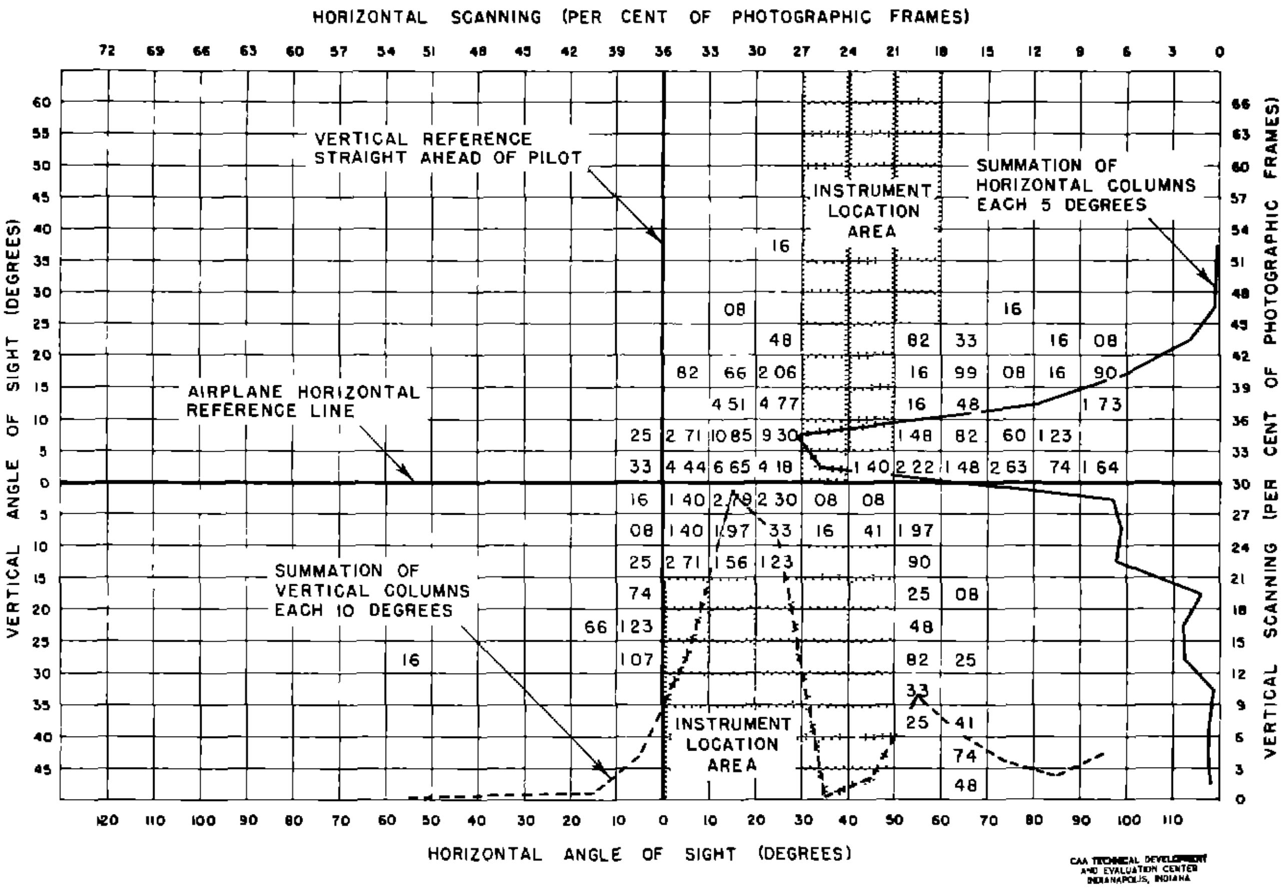

Fig 12 Phase 5R – Windshield Usage During Right Turn (5 Pilots, 1217 Photographic Frames)

to the right substantiates the fact that the pilots use a window to the right and below the co-pilot

It is indicated that a region bounded by 25° above and 35° below and by 20° left and 90° right of the reference point was used extensively

Phase 6 – Climb

Phase 6 covers the time of flight from the instant the turn is completed until the aircraft has reached an altitude of 1,000 feet Eight pilots from all groups were photographed in a total of 4,513 frames The attitude of the airplane was 6° nose up

The major peak of the solid curve shown in Fig 13 occurs from 0 to 10° above the reference line, and a small one occurs at 45° above it By leaning forward it is possible for a pilot to realize these upward angles of vision, even though the photograph of the windshield (Fig 4) indicates that the cockpit is cut off at a somewhat smaller angle. Another minor peak was observed to fall 15° below the horizon with fairly high intermediate values between this peak and the major one The peak located 25° below the horizon is considered to be influenced somewhat by instrument readings.

The dashed curve has a very broad peak 10° to the right and indicates a general spread from 15° left to 35° right of the reference point The peak in the dashed curve located 60° to the right indicates that the pilots make considerable use of the window just to the right of the co-pilot The dashed curve indicates that the windshield area used extends from 60° left to 100° right

Phase 7 – Descent

Percentages of total photographic frames are shown in Fig 14 for nine pilots This phase includes a total of 7,342 photographic frames with all groups of pilots included. Phase 7 of flight coincided with the descent of the airplane from 1,000 feet to 200 feet altitude, preparatory to landing

During the first 75 per cent of the descent phase, the attitude of the airplane is relatively constant at 3 to 4° nose down. In

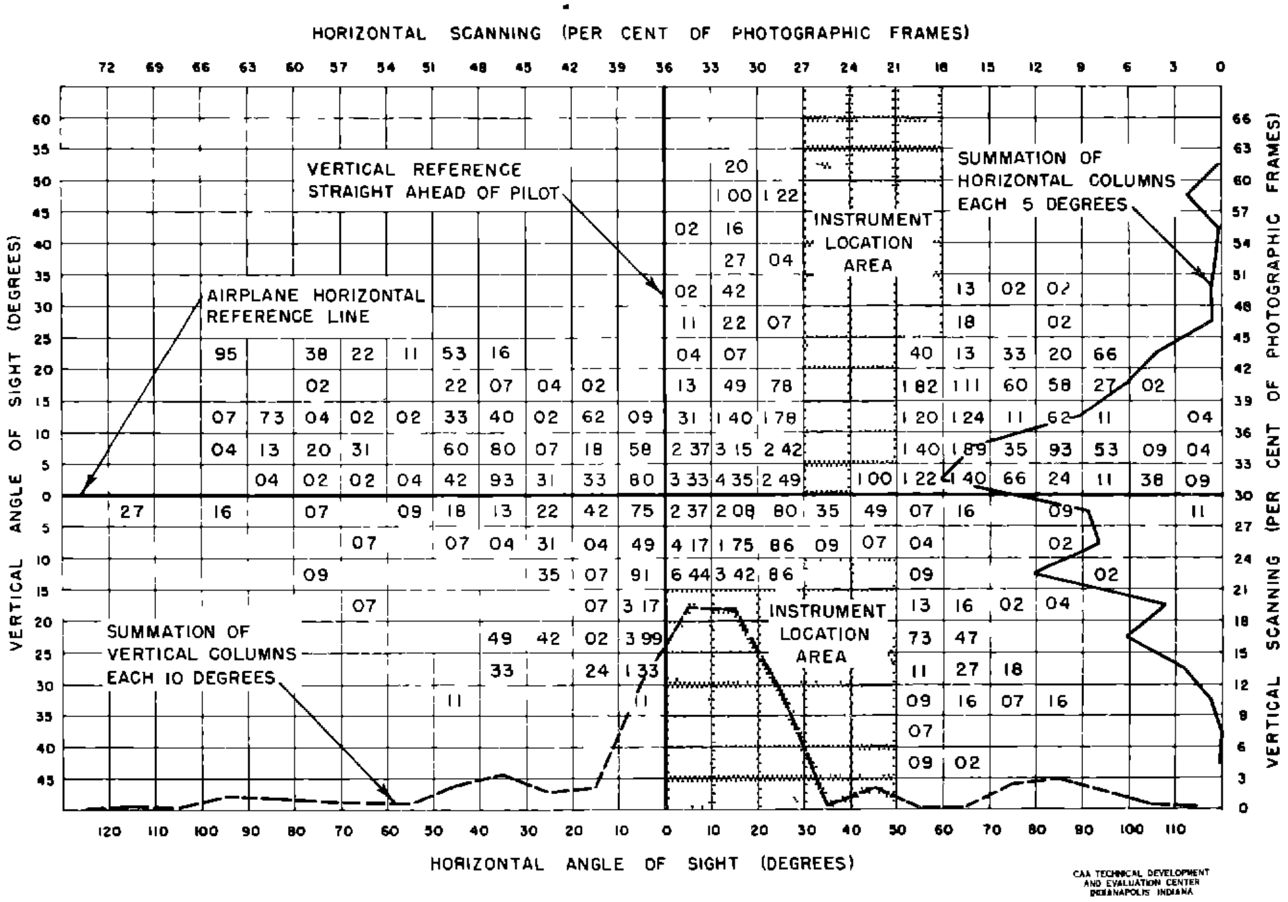

Fig. 13 Phase 6 — Windshield Usage During Climb, After Turn to 1,000-Foot Altitude (8 Pilots, 4513 Photographic Frames)

the final stages at 200-foot altitude, or 25 per cent of the phase time, the attitude drops sharply to 6 or 8° below the horizon There is a decided and sudden increase in downward attitude in the final stages of this phase

The solid curve shows a major peak between 0 and 5° above the reference line The peak shown at 15° below the line was caused by the pilots' glances as far down as the airplane would permit in the area from 0 to 30° to the right There may be some slight influence of instruments causing this The relatively broad peak located 30° below the airplane reference line is a strong indication that the pilots used all the downward visibility available in this particular airplane.

The dashed curve shows at 5° to the right a peak which is very broad at the base and which extends from 35° right to 25° left. This indicates that there was a considerable difference among pilots in the visual cues used while descending It is believed, however, that this indicates a critical need for appreciable visibility in this area during descent Since the visibility requirements apparently vary from one pilot to another and since it is very difficult to change the visual habits of a pilot, it is necessary to provide sufficient vision angles to satisfy all pilots The peak located 35° to the left was caused by two pilots who had often flown this airplane.

Phase 8 — Final Approach.

Phase 8 starts when the airplane is 200 feet above the ground on the final approach and ends the instant the wheels touch the ground The percentages of 4,101 photographic frames for nine pilots are shown in Fig 15 All types of pilots are included The attitude of the airplane during 75 per cent of the final approach is 8° nose down This downward attitude is continuous from the previous phase The remaining 25 per cent of the phase time is spent at an airplane attitude of 1 to 8° nose down and in leveling off to a touchdown attitude

The peaks are very high and very narrow, indicating that there was little

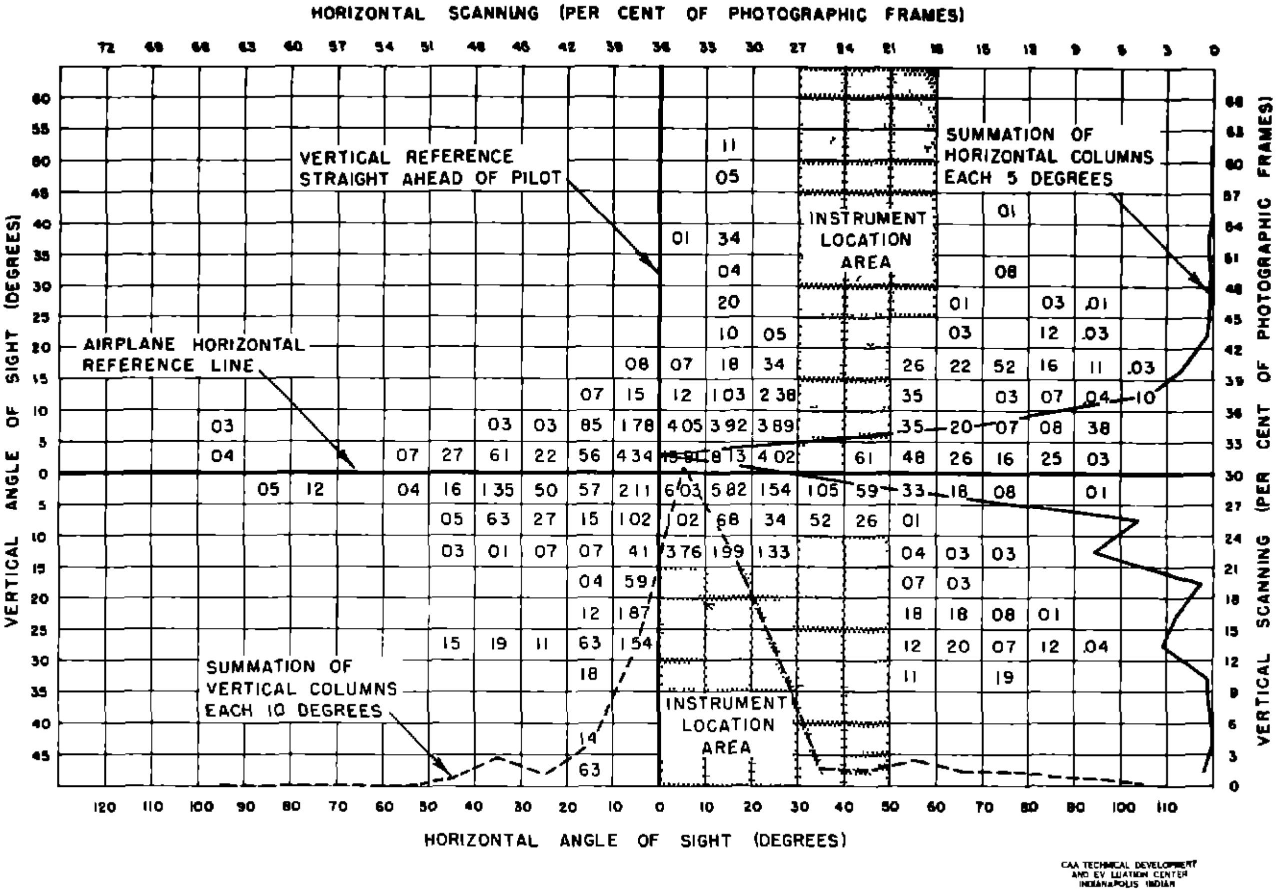

Fig 14 Phase 7 – Windshield Usage During Descent From 1,000- to 200-Foot Altitude (9 Pilots, 7342 Photographic Frames)

disagreement among pilots and very little shift in vision from a center point of 5° above the horizontal reference and 5° to the right of the vertical reference This exemplifies the fact that very little of the windshield is actually used during the final approach It is believed that the small peak occurring in the solid curve, 15° down, may have been influenced by the pilots' reading aircraft instruments

Phase 9 – Landing Roll

Phase 9 begins the instant the wheels touch the runway and ends when the airplane has stopped rolling after touchdown The percentages of photographic frames are shown in Fig 16 Included in this figure are nine pilots of all groups and a total of 2,996 photographic frames The attitude of the airplane is 2° nose up

The peaks of the curves again are very high, however, there is some spreading in the horizontal direction, indicating that there is a shift of vision from right to left during landing roll

Phase 10 – Taxi After Landing

The windshield usage of five pilots from a total of 4,143 photographic frames is shown in Fig. 17 All groups of pilots are included in Phase 10 The attitude during taxi phase is 2° nose up

The solid curve has a relatively high peak and falls in the 0 to 5° sector above the horizontal reference line Extensive use is shown below the reference line, indicating that much downward vision is used A low, flat peak occurring 25 to 30° below the reference line indicates that this is an important visual area during a certain phase of taxiing.

The dashed curve has a peak 5° to the right of the vertical reference line and shows considerable use from 60° left to 70° right The peak occurring 55° to the right coincides with the small window located below and to the right of the co-pilot

All Phases

Shown in Fig 18 are the 35,817 photographic frames for all phases of flight and for all pilots This is the total of both

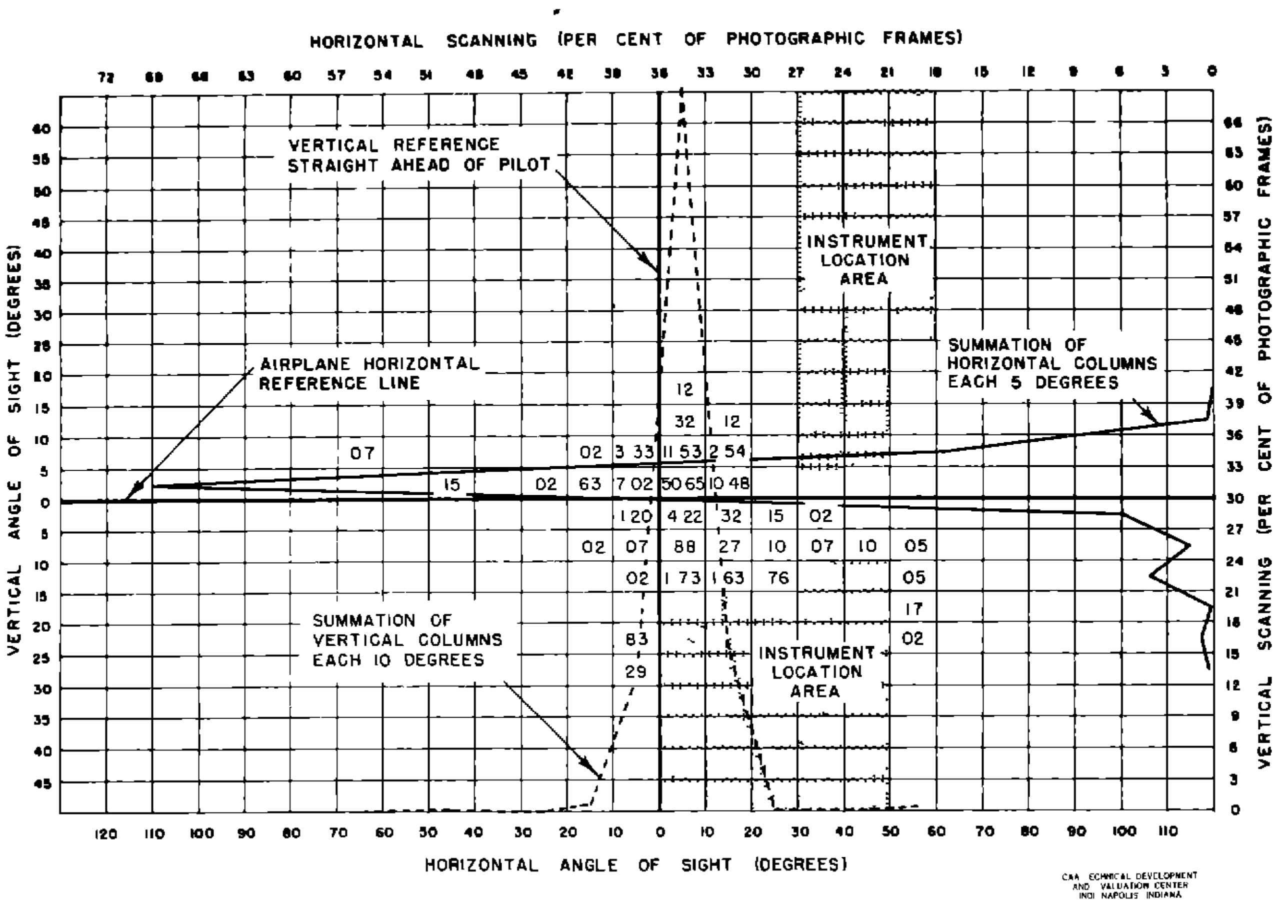

Fig 15 Phase 8 – Windshield Usage During Final Approach, 200-Foot Altitude to Touchdown (9 Pilots, 4101 Photographic Frames)

analysts The actual numbers of photographic frames are shown so that the use made of the various extremities of the windshield area can be evaluated exactly The highest peak of the solid curve falls in the 0 to 5° sector above the reference line Another peak occurs 15° down and still another 25° down These last two peaks were influenced considerably by taxiing and turns but only slightly by instrument reading

The maximum value of the dashed curve is lower than the maximum value of the solid curve, indicating that a pilot moves his head from side to side more frequently than up and down and seeks more visibility in the horizontal direction than in the vertical direction The small peak in the dashed curve, occurring 55° to the right, indicates the use of the small window below and to the right of the co-pilot in this airplane

GENERAL DISCUSSION

Fig 19 shows the photographic frames for all pilots during all phases Superimposed on this figure, the long dashed curve is the outline of the cockpit visibility angles afforded by the Boeing 377 Stratocruiser airplane The solid curve, also shown in Fig 19 represents the outline of vision angles that were considered excellent by airline pilots in the study made by the use of questionnaires,[3] while the short dashed curve represents the outline of vision angles that were considered minimum but adequate, by airline pilots

It is shown in Fig 19 that many of the photographic frames fall outside the windshield area of the Model 377 airplane or on structural members in the windshield Normal reading inaccuracies and the fact that a pilot's eyes must pass over areas which are not windshield account for some of these The pilots frequently leaned forward and to either side for the purpose of increasing

[3]Pigman and Edwards, op cit

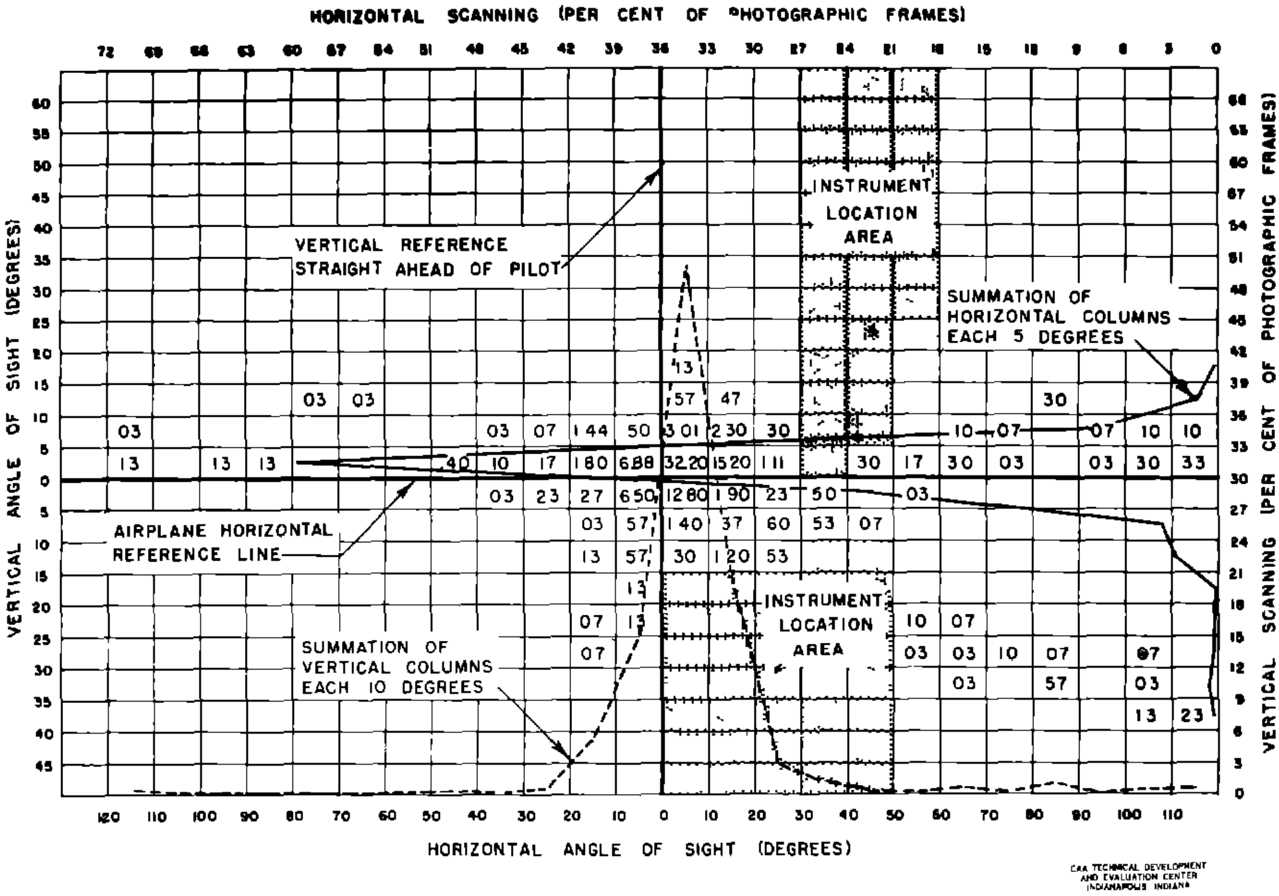

Fig 16 Phase 9 — Windshield Usage During Landing, Touchdown to End of Roll (9 Pilots, 2996 Photographic Frames)

their field of view This was especially true when seeking visual guidance 70° to the right, to the extreme left, straight ahead, or down over the nose

Pilots flying the Model 377 airplane frequently moved their heads forward and downward to obtain visual guidance in the area that is obstructed by the heavy horizontal structural member in the 15 to 20° upward vision area This wide horizontal member has a tendency to restrict the pilot's vision to the lower windshield Fig 19 shows that the flights included in this study involved very little use of the windshield area above this structural member However, relative collision causes that make vision in this sector important can exist Figs. 13 and 14 indicate use of this area for climb and descent.

Ninety per cent of all photographic frames fall inside the windshield area bounded by the solid line in Fig 19 This is the area that the airline pilots considered excellent This percentage would be increased if it were possible to separate the external vision from the instrument fixations which occur in the 0 to 30° left and 15 to 30° downward area The instrument panel actually extends 5° to the left of the vertical reference line The photographic frames that include observations made during the climb and descent phases appear in the area 7° right and 35° down It is felt that some of these include observations made on objects that were inside the airplane, such as engine and propeller controls

Seventy-nine per cent of the total number of photographic frames fall inside the windshield area that was selected by airline pilots as minimum, but adequate

The particular type of aircraft used in the tests has a very spacious cockpit and was convenient for conducting the tests In designing a cockpit of this width, however, it is difficult to obtain satisfactory visibility angles to the extreme left and right The windshield area shown outlined by a long dashed curve in Fig 19 is in an airplane having a cockpit width of approximately 100 inches at the pilot's eye level, and the

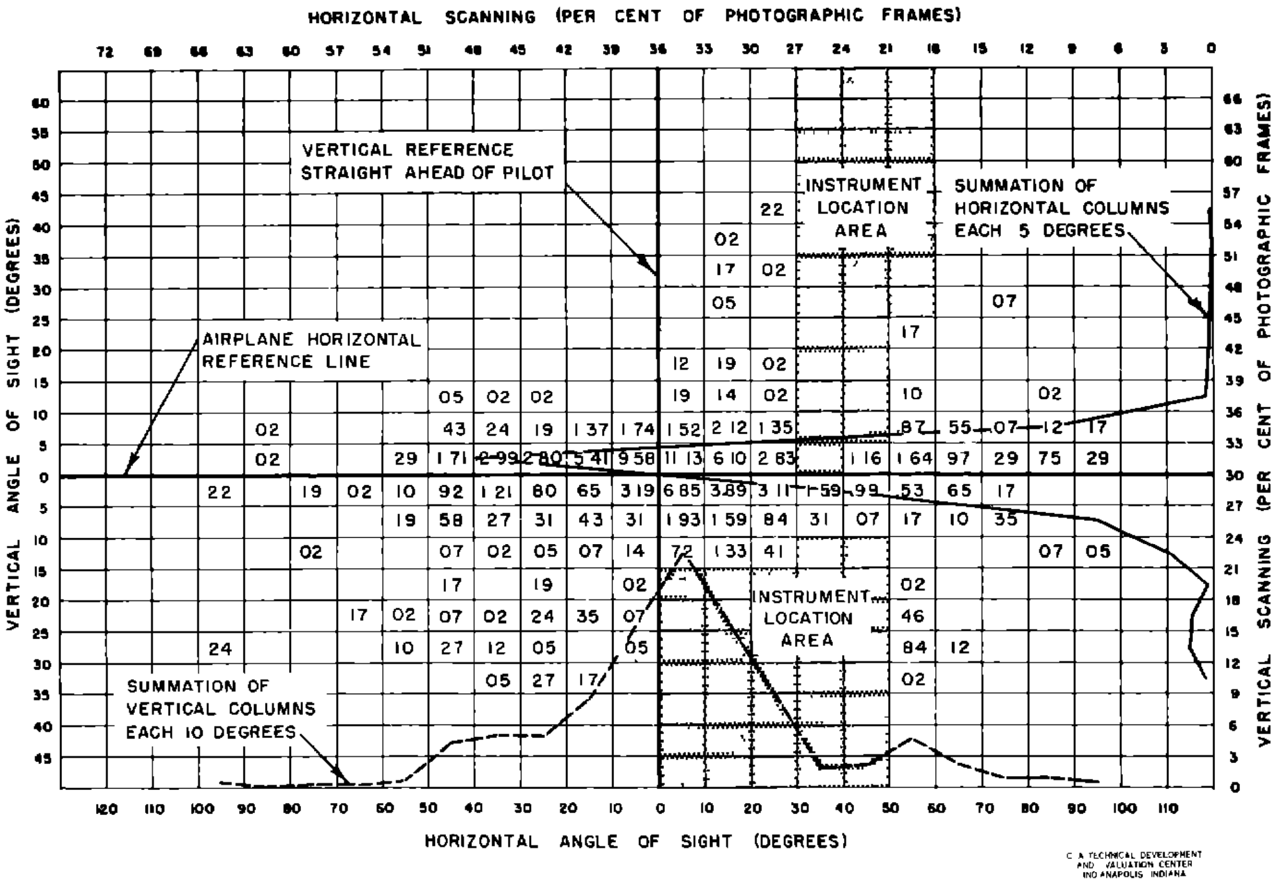

Fig 17 Phase 10 – Windshield Usage During Taxi After Landing (5 Pilots, 4143 Photographic Frames)

windshield area that is shown solid is in a hypothetical airplane having a cockpit width of approximately 72 inches at the pilot's eye level In general, it can be said that it is possible to locate the pilot's eyes closer to the windshield with a narrower cockpit than with a wider one The closer a pilot's eyes are to the windshield, the more visibility he can obtain by a slight head movement It is possible, however, to locate the pilot's eyes too close to the windshield. This will cause them to become excessively tired, because the windshield heat dries out the eye fluid A horizontal distance of 20 inches from the pilot's eyes to the windshield is considered acceptable Precipitation aggravates the visibility problem when the windshields are located at a greater distance

Observations made by the authors indicate that while searching the skies for other aircraft, there is a basic psychological urge for a pilot to improve his vision by head and shoulder movement It is believed that this would be true regardless of the amount of visibility offered by the windshield

CONCLUSIONS

1 Pilot usage of the windshields and windows includes looking to the far left, to the far right, and near the top and bottom of those general areas for less than one per cent of the total time photographed Since there were few photographic frames for those directions, it is evident that the pilot required only a fraction of a second to investigate them It would be an unusual situation when a pilot would fly with his eyes turned 120° to the left for a long period of time A quick glance is all that most pilots have time for, but one glance makes the difference between knowing or not knowing whether there is another airplane in that vicinity The actual magnitude of the percentage is not in itself crucial That such observations occur at all in these positions is important The areas on the windshield that show high percentages of usage are generally the areas through which the pilot is obtaining visual cues necessary to operate his aircraft and not the areas of the windshield which are used to

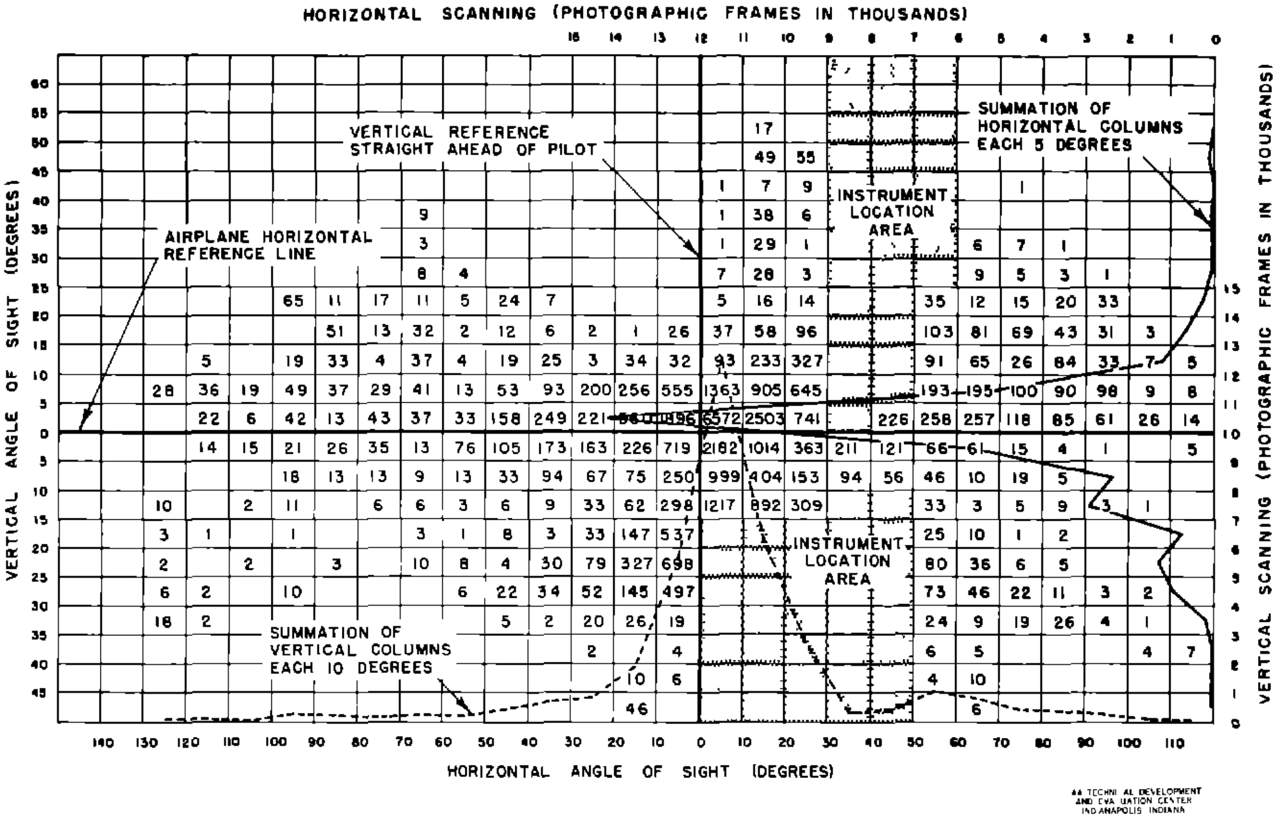

Fig 18 Windshield Usage for All Pilots and All Phases of Flight (35,799 Photographic Frames)

search the air space for other aircraft

2. The windshield area used by the pilots during the pilot eye-movement study substantiates, to a considerable extent, the conclusions drawn from the airline pilot questionnaire study Fig 19 shows that 79 per cent of the fixations made during the study fall within the "minimum, but adequate" area evaluated by airline pilots Ninety per cent of the fixations fall within the "excellent" vision area, as evaluated by airline pilots This difference is significant enough to substantiate a recommendation of adopting the "excellent" vision area rather than the "minimum, but adequate" area as a basis of pilot cockpit visibility needs An example of such vision limits is shown in Fig 20

3 By referring to Fig 19 it can be seen that many observations fall outside the Boeing 377 airplane windshield area Some of the reasons for this are

a There were some normal reading inaccuracies

b At some moments a pilot's eyes must pass over some areas which are not windshield

c The airplane did not always provide sufficient angular vision in the areas needed

d The pilot moved his head and shoulders to improve his field of view

e Working under difficult circumstances caused minor errors in some of the data There is a possibility that the subjects may have had a tendency to overemphasize visibility problems, and thereby they may have created a false indication for certain vision angles This may be true during a few phases of flight In observing the film, it was apparent that very little of this actually occurred, and it is believed that this condition had very little, if any, effect on the results

4 The results show that transport pilots attempt to search for other airplanes but may be prevented from seeing them by the structure of the airplane

5 There are well-defined characteristic differences between phases These differences conform to what might logically be deduced concerning the necessity of angular vision in the various phases of flight

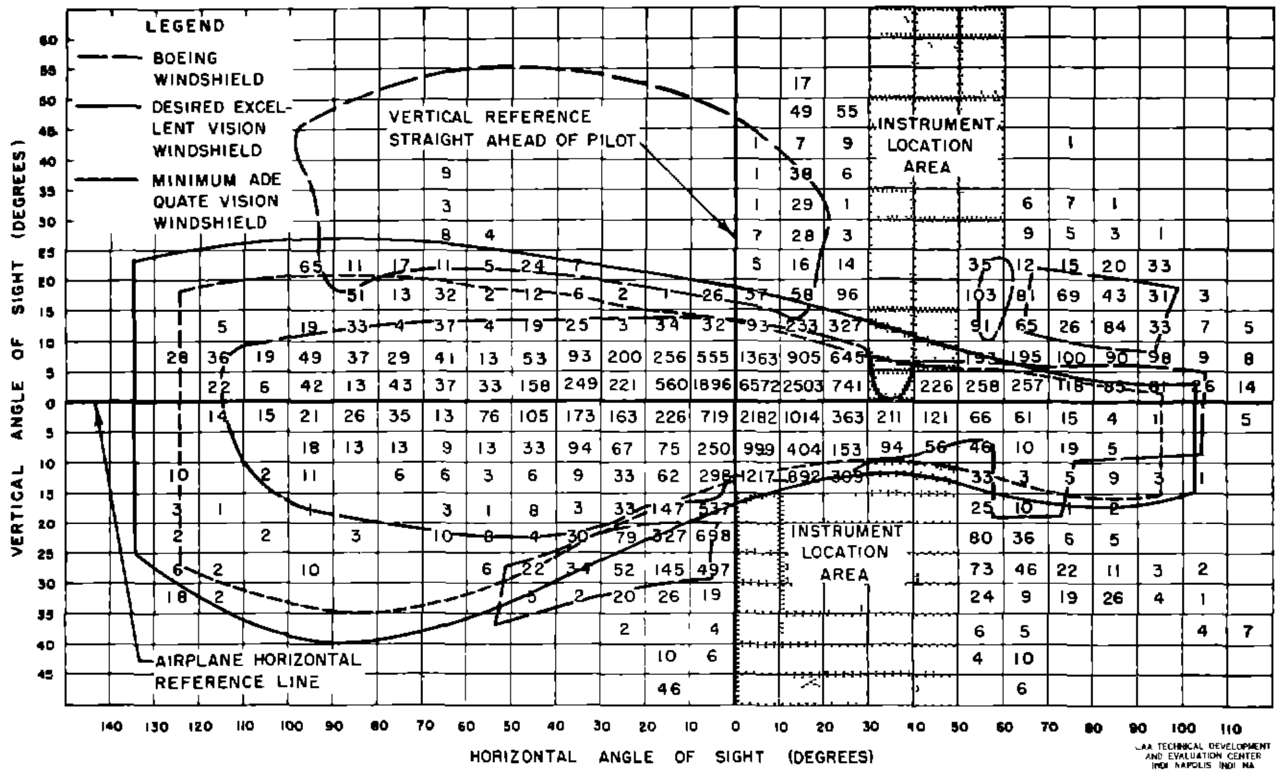

Fig 19 Total Photographic Frames for All Pilots and All Phases Comparing Boeing 377 Windshield, Desired Excellent-Vision Windshield, and Minimum Adequate-Vision Windshield (35,817 Photographic Frames)

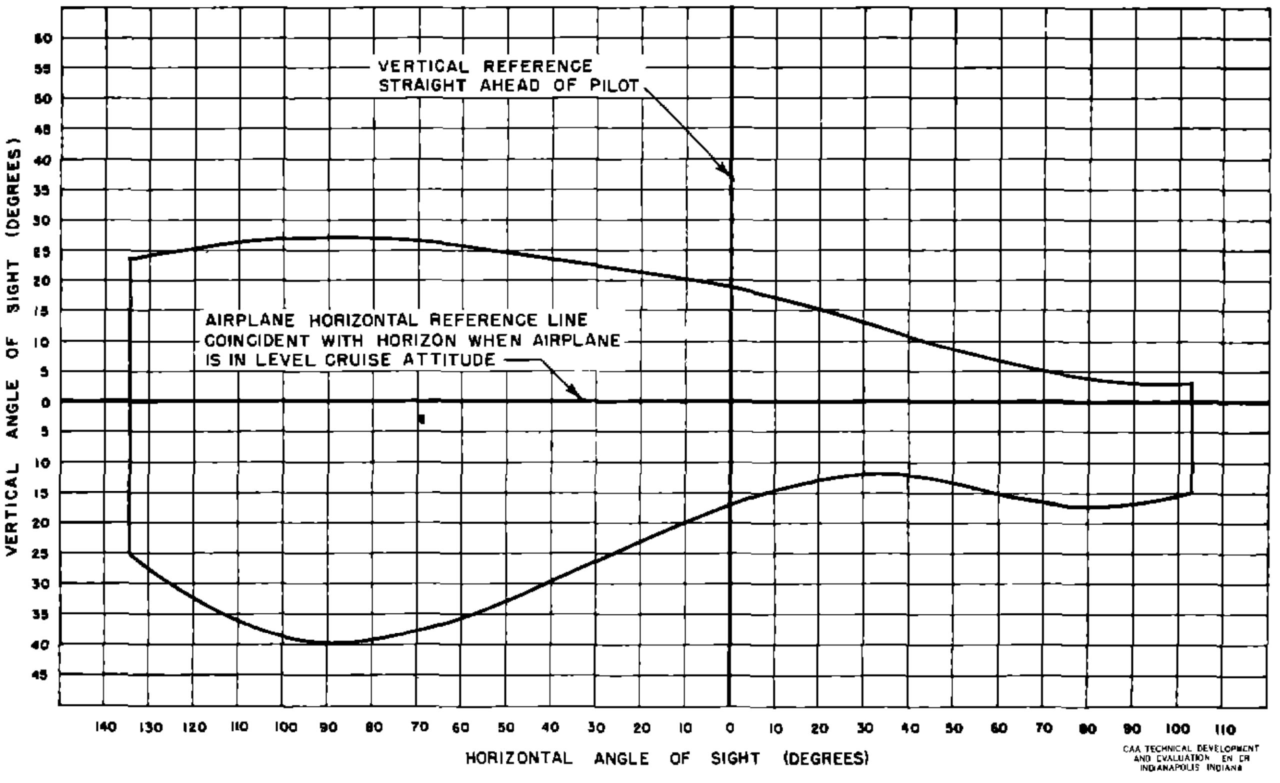

Fig. 20 Example of Visibility Angles, As Determined From the Pilot Eye-Movement Study

ACKNOWLEDGMENT

Acknowledgment is made to United Air Lines, Inc , and Pan American World Airways, Inc , who made this study possible by permitting TDEC personnel to use their aircraft and pilots for the flight tests, to the Aero Medical Laboratory of the Department of the Air Force for their technical assistance, to Virginia L Senders, Ph D., psychologist, Antioch College, who directed the analysis of the films, to Mr Jay Chidsey and Miss Olga Livingston, Antioch College, advanced psychology students who analyzed the films, and to Mr A. A Foggatt, CAA TDEC, who handled all photographic work in this study

GPO 81-106478