

1. Report No. FAA-AM-78-23	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle GPSS COMPUTER SIMULATION OF AIRCRAFT PASSENGER EMERGENCY EVACUATIONS		5. Report Date	
		6. Performing Organization Code	
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9. Performing Organization Name and Address FAA Civil Aeromedical Institute P.O. Box 25082 Oklahoma City, Oklahoma 73125		10. Work Unit No. (TRAIS)	
		11. Contract or Grant No.	
12. Sponsoring Agency Name and Address Office of Aviation Medicine Federal Aviation Administration 800 Independence Avenue, S.W. Washington, D.C. 20591		13. Type of Report and Period Covered	
		14. Sponsoring Agency Code	
15. Supplementary Notes Research leading to preparation of this report was conducted under Task AM-B-77-PRS-53.			
16. Abstract The costs of civil air transport emergency evacuation demonstrations using human subjects have risen as seating capacities of these aircraft have increased. Repeated tests further increase the costs and also the risks of injuries to participants. A method to simulate such evacuations, by use of a computer model based on statistics from measured components of the escape path, has been developed. This model uses the General Purpose Simulation System (GPSS) computer programming language to represent various features of the escape process; e.g., seating and exit configurations, passenger mix, door-opening delays, time on escape slides, slide capacity, and redirection of passengers to equalize escape lines. Results of simulated evacuations from the DC-10, L-1011, and B-747 aircraft and a military aircraft are reported. These results have been compared with results of certification demonstrations from the DC-10, L-1011, and B-747. Comparisons of exit size substitutions were evaluated as a means of estimating differences in escape potential for exit design optimization.			
17. Key Words Evacuation simulation Escape Computer model		18. Distribution Statement Document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 16	22. Price


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      MEAN = 1.57      SD = 0.76      FORWARD EXIT TIME FUNCTION
1      FUNCTION      RN3,C32      FORWARD EXIT FUNCTION (TYPE I)
0,0/.00132,20/.01662,40/.06162,60/.13949,80/.24221,100/.35722,120
.47262,140
.57971,160/.67340,180/.75173,200/.81485,200/.86423,240/.90190,260/
.93005,280/.95070,300/.96562,320/.97625,340/.98373,360/.98894,380/
.99254,400/.99500,420/.99667,440/.99779,460/.99854,480/.99904,500/
.99937,520/.99959,540/.99974,560/.99983,580/.99989,600/1.0000,700
*      MEAN = 1.73      SD = .45      FORWARD SLIDE TIME

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Figure 1. Example of the forward Type I exit function.

that elongates the top of the curve. Each evacuation pathway segment in the model references similar functions for random selection of passenger movement; i.e., time in each segment, until the passenger is on the ground.

The model limits the number of passengers allowed to occupy specific escape slides at one time to three on a single-lane slide, six on a double-lane slide, or to other numbers designated by the user. The length of an escape slide corresponds to the time-on-the-slide function in the model and, consequently, a delay could result in the rate at which passengers may enter the top of the slide.

The model has the capability to use differing mathematical routines, if needed, although none were used in this report. Such routines would be entered into the input listings along with the functions now used.

Transactions are accumulated in counting blocks that register passenger times, numbers of occupants using a facility (door, slide, etc.), and cumulative data during evacuations for each segment of the escape route. These data are then printed out in tabular or graphic form. The redirection of passengers in the cabin from longer waiting lines to an adjacent exit with shorter queues depends on the number programmed for the shorter line to contain before transfers take place. The model assumes that passengers reach the shorter exit line before a gap in the escape line occurs. This exit reassignment is similar to volunteer passenger transfers that take place in evacuation demonstrations.

The time at which the last person reaches the ground at each exit is defined as the evacuation time, and the time at the exit with the longest evacuation time is defined as the total escape time. A number of runs on a particular configuration can be made to permit random selections to represent human performance variables on each run and to enable statistical statements of evacuation predictions. Runs of 10, 20, 40, 50, and 100 repeated model evacuations were examined to assess the number of runs needed to confidently display the built-in randomness. The optimum number of runs to allow adequate distribution appears to be between 20 and 40. For each configuration, 20 evacuations were made during the majority of the developmental simulations; this number appeared to provide satisfactory results.

Model Input Data Sources. A central source to obtain all evacuation data relating to transport aircraft does not exist. The aircraft manufacturers, airlines, FAA headquarters and field offices, the National Transportation Safety Board, and the Evacuation Research Unit at the Civil Aeromedical Institute (CAMI) each have limited information. The largest publication thus far is of data assembled by the Aerospace Industries Association (AIA) in their study of evacuations in 1967-68 (4). Assembly and publication of similar data since 1968 has not been accomplished but would be desirable to support the selection of quantitative data for computer inputs. This is especially true since most wide-bodied aircraft were evacuation certified during the early 1970's and are not included in the earlier AIA report.

Passenger flow rates through Type I (24 x 48 in) and Type A (42 x 72 in) exits, described in the Federal Aviation Regulations (25.807), and used in the GPSS model, were derived from the results of an evaluation performed by CAMI in Oklahoma City (5). Overall flow rates through Type I exits averaged 46.8 passengers/min or 1.28 s/passenger. The overall rate for the Type A exit averaged 126.2 passengers/min or 0.48 s/passenger. A ratio of 2.6 has been used for Type A exit escape rates and appears in the GPSS as 10/26. The computer derives the Type A flow rate by dividing the mean Type I flow rate, entered as parameter function 1 (1.57 s/passenger), by 2.6, which maintains the ratio. The resulting Type A flow rate is 0.60 s/passenger and remains in use in the GPSS program until a more representative rate is established for validation of the model.

Calculation of passenger flow rates during the evacuations can be performed either by using the total time from test start to the last out or by considering the time from the first passenger out until the last has evacuated.

Thus, the overall flow rate for an exit is defined by the following ratio:

$$\frac{\text{Time (s) from start signal to last passenger on ground}}{\text{No. passengers evacuated}} = \text{Average overall flow rate (s/passenger)}$$

Continuous flow rate is defined as:

$$\frac{\text{Time (s) from first passenger on ground to last passenger on ground}}{\text{No. passengers} - 1} = \text{Average continuous flow rate (s/passenger)}$$

GPSS General Format. Appendix A is a typical GPSS evacuation program showing the analysis of 527 passengers evacuating a B-747 aircraft through five Type A exits. The first entries in Appendix A, four statements of model operational instructions, are followed by seven Function entities. The Functions permit computations of discrete functional relationships between an independent variable and dependent values of the function. For the B-747 evacuation, these functions are probabilistic distributions from which random

Table 2 lists results of a series of six simulated evacuations, each the average of 20 runs, on the L-1011 aircraft with 356 or 411 passengers. The objective of the runs was to comparatively evaluate a Type I exit vs. a Type A exit in the aft exit position in combination with three other Type A exits on the L-1011. Three of these simulations were comparable to aircraft evacuation demonstrations, the results of which are noted for comparison in Table 2.

TABLE 2. Evacuation Times and Conditions of GPSS Simulation of an L-1011 Evacuation (20 Computer Runs; Exit-Opening Time = 13 s)

No. Pax.	Exits Used		Intracabin Redirection		Average Total Evacuation Time (s)	Average Total Evacuation Time (Range (s))
	A	I	Yes	No		
356	3	1	-	N	93.5 ¹	77.4 - 120.0
356	3	1	Y	-	84.9 ²	77.8 - 90.8
356	4	-	-	N	83.6	77.6 - 89.3
356	4	-	Y	-	79.6	76.7 - 83.9
411	4	-	-	N	83.6	77.6 - 89.3
411	4	-	Y	-	79.6 ³	76.7 - 83.9

¹Total evacuation time for an actual demonstration was 101.1 s.

²Total evacuation time for an actual demonstration was 82 s.

³Total evacuation time for an actual demonstration was 89.7 s.

Table 3 consists of groups of 20 simulation runs and shows the total average escape times on a DC-10 with 391 passengers with two variables in the simulated conditions. Exit No. 2 (Type A) simulated a delayed exit-opening time of 50 s, with and without redirection of passengers in the cabin. The other variable shown is a blocked aft exit (Type A), with and without redirection.

TABLE 3. Evacuation Times and Conditions of GPSS Simulation of a DC-10 (20 Computer Runs; 391 Passengers)

Exits Used		Intracabin Redistribution		Average Total Evacuation Time (s)	Average Total Evacuation Time Range (s)	Exit-Opening Time (s)			
A	I	Yes	No			1	2	3	4
3	1	-	N	112.0	100.0 - 122.0	13	50	13	13
3	1	Y	-	92.5	88.9 - 96.6	13	50	13	13
3	1	Y	-	90.2	85.8 - 93.2	13	50	13	13
3	1	-	N	85.0	76.0 - 99.0	13	13	13	13
2	1	-	N	144.0	130.0 - 162.0	13	13	13	---
2	1	Y	-	114.0	110.0 - 118.0	13	13	13	---
3	1	Y	-	82.0	77.0 - 88.0	13	13	13	13
3	1	Y	-	90.2	85.8 - 93.2	13	13	13	13

*The aft Type A (Exit 4) was blocked.

Table 4 lists three sets of 20 evacuation simulations that compare evacuation times for: (1) 355 passengers through three Type A and either a Type I (24 x 48 in with a single slide) or a Type B (32 x 72 in with a double slide) exit in the forward position, and (2) 375 passengers through three Type A exits and a Type B exit in the forward position.

TABLE 4. Evacuation Times and Conditions of GPSS Simulation of a DC-10 to Compare Type I and Type B Exit Times (20 Computer Runs)

Exits Used			No. Pax	Intracabin Redirection		Average Total Evacuation Time (s)	Average Total Evacuation Time Range (s)
I ¹	A	B ²		Yes	No		
1	3	-	355	-	N	106.0	94.0 - 119.0
-	3	1	355	-	N	58.0	55.0 - 61.0
-	3	1	375	Y	-	73.4	67.9 - 79.4

¹Single-lane slide used.

²Double-lane slide used.

Special Applications of the GPSS Evacuation Model. The GPSS model was used to simulate a unique evacuation of 114 passengers from a military command post aircraft. In lieu of flight attendants, military personnel working aboard the aircraft at other duties were assigned to prepare the exits for evacuation. The time required for them to reach the exits from their respective work stations was added to door/slide preparation time. Groups of 25 passengers were evacuated from each exit, one exit at a time, to obtain basic input data for statistical controls. The test results (Table 5) were applied to the flow rate determinations for computer functions. Results of simulated evacuations through five and nine Type A exits are shown in Table 6. The total evacuation times and number of passengers out each exit were averaged from 50 computer runs for each exit configuration.

TABLE 5. Evacuation Time-Path Data Obtained From
Evacuations of 25 Passengers From a Military
Command Post Aircraft

Test No.	Exit	Time to Exit (s)	No. Pax Out Exit	Time 4th Pax Out Exit (s)	Time 8th Pax Out Exit (s)	Time Last Pax Out Exit (s)
1	L-2	7.1	9	22.2	25.5	27.0
2	L-1	6.8	9	22.2	24.6	26.0
3	R-1	9.2	9	24.0	27.0	28.5
4	R-2	5.3	16	21.0	24.3	31.5
5	L-3	9.2	16	25.2	30.6	42.0
6	R-3	5.4	16	--	20.4	30.0
7	R-4	6.8	16	23.4	29.4	40.5
8	L-5	9.6	16	24.0	29.4	40.0
9	R-5	5.6	9	25.2	31.2	33.0

TABLE 6. GPSS Computer Model Evacuation Simulation
Results: Escape by 114 Passengers From a
Command Post Aircraft via 5 and 9 Exits

Exit No.	Total Evacuation Time (s)	Average No. Evacuees Through Exit
<u>5 Exits</u>		
R-1	35.34	23.1
R-2	36.72	25.5
R-3	39.45	23.2
R-4	34.70	22.9
R-5	32.47	19.3
<u>9 Exits</u>		
R-1	28.90	12.4
R-2	31.49	11.4
R-3	36.33	11.8
R-4	28.37	12.7
R-5	28.37	13.2
L-1	28.10	13.2
L-2	28.82	13.4
L-3	35.88	12.6
L-5	28.80	13.3

A second use of the GPSS evacuation model was as a new aircraft design tool. Two exit configurations and three passenger loads for each configuration were presented for exit optimization in a new civil air transport aircraft. The existing five-exit model program was adjusted to a three-exit program by bypassing operational statements for two nonessential exits. Three Type A exits, and one Type I and two Type A exits in combination, were evaluated, each with 208, 248, or 309 passengers. Table 7 displays the evacuation times for the exit combinations and load factors given. It can be seen that 30 percent less time was required for evacuation with the three Type A exits.

TABLE 7. Averages of Evacuation Times for Exit Combinations and Passenger Load Factors Proposed for a New Design Transport Aircraft (20 Computer Runs)

Exits Used		Average Evacuation Times (s)		
I	A			
			No. Pax	
		208	248	309
1	2	87.19	99.70	120.40
0	3	62.89	70.49	83.32

The chart listing the number of passengers using each exit demonstrates the effect of passenger transfers to exits with faster escape rates. The transfers are particularly evident with the smaller Type I exit in the forward position combined with two Type A exits when compared with the configuration of three Type A exits as shown in Table 8.

TABLE 8. Effect of Passenger Transfers Showing Average Number Out Each Exit (20 Computer Runs)

No. Pax	Exits		
		3 Type A	
	Forward	Overwing	Aft
208	68.65	71.22	68.13
248	82.48	83.10	83.42
309	102.48	104.04	102.48
	1 Type I and 2 Type A		
	Forward	Overwing	Aft
208	42.75	95.75	69.50
248	51.00	114.28	82.72
309	63.68	140.95	104.37

IV. Discussion.

The program of civil air transport evacuation simulation was undertaken to provide a better understanding of the factors that influence evacuation. Existing certification procedures for demonstrating the safe evacuation potential of an aircraft have proven costly and may result in injury to the participants. The present simulation model program is designed with the exit and slide segments of an evacuation as the major determining factors for total evacuation times. In addition, redistribution or reassignment of passengers to equalize waiting lines to escape contributes significantly to the total evacuation time and this is included in the program. The effects of adverse conditions, such as smoke, fallen ceiling panels, and debris in the aisles, on evacuation times have not been simulated because of the lack of available data for any specific condition.

The knowledge gained from the evacuation demonstrations and accident histories has provided a valuable source of information on which judgments for simulation can be based. Criteria must be determined for the simulation that will provide assurance of adequate escape potential from civil transport aircraft and detect factors inimical to escape and survival. The GPSS-language computer model has the potential to simulate much more sophisticated entities than are shown in this report. An example is the inclusion of the effects of crew effort on evacuation times. Graded on a scale from 1 to 10, a Factor could be entered that would directly influence passenger flow rates through an exit. Computer runs could be made with both easy and low effort (grade 1) to the most enthusiastic effort (grade 10) to evaluate the effects of crew effort. Of course, data would be required to establish the delay function of the Factor. Another example would relate to exit design evaluations to establish optimum distances between exits while considering exit capacities to provide optimization of a total aircraft exit configuration. Until encumbrances on passenger movement to exits override the limiting flow rates, modeling exit flow and escape slide patterns will provide adequate evacuation performance evaluations. Although some rudimentary information is available on interior cabin movement by individual passengers, group tests will be required to substantiate data for more precise simulations.

V. Conclusions.

1. The capability and potential of the GPSS evacuation model have reached the stage in development that allows it to closely simulate actual evacuations from current transport aircraft. With refined inputs, based on additional test results, the model may provide a valid means to certify evacuation systems or evaluate escape system designs while the aircraft are in the early planning stages.

2. A group knowledgeable in evacuation simulation should develop a program to provide the data and formulate simulation criteria for potential use as a certification and/or design tool.

3. All evacuation tests, research, and actual performance data should be assembled at one source and analyzed to obtain pertinent material for model input functions.

4. A final model should be refined and subjected to a rigorous validation process.

5. A practical, validated, evacuation simulation model should then be considered for acceptance as a certification and/or design tool.

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TYPICAL GPSS EVACUATION PROGRAM

A-1

49	44	GATE NO.	P5	HOLD FOR EXIT REASSIGNMENT	118
50		UNLINK	P1,AAA,1		119
51		TEST GE	Q9,KO,SEZ		120
52		TEST N	P9,21,NCLNE		121
53		TEST NE	P9,24,NJFCR		122
54		TEST NE	P9,27,NJSEV		123
55		TEST NE	P9,30,NJTEH		124
56		TEST NE	P9,33,NJTHI		125
57		TEST E	JVSSIDE2,KO,CNE4		126
58		TRANSFER	ASGN2		127
59		TEST E	JVSSIDE2,KO,SEZ		128
60		TRANSFER	ASGN4		129
61		TEST E	JVSSIDE1,KO,FJR2		130
62		TRANSFER	ASGN1		131
63		TEST E	JVSSIDE2,KO,FJR4		132
64		TRANSFER	ASGN2		133
65		TEST E	JVSSIDE4,KO,SEZ		134
66		TRANSFER	ASGN4		135
67		TEST E	JVSSIDE1,KO,SEV2		136
68		TRANSFER	ASGN1		137
69		TEST E	JVSSIDE2,KO,SEV3		138
70		TRANSFER	ASGN2		139
71		TEST E	JVSSIDE3,KO,SEV4		140
72		TRANSFER	ASGN3		141
73		TEST E	JVSSIDE4,KO,SEZ		142
74		TRANSFER	ASGN4		143
75		TEST E	JVSSIDE1,KO,TEN2		144
76		TRANSFER	ASGN1		145
77		TEST E	JVSSIDE2,KO,TEN3		146
78		TRANSFER	ASGN2		147
79		TEST E	JVSSIDE3,KO,SEZ		148
80		TRANSFER	ASGN3		149
81		TEST E	JVSSIDE1,KO,THI3		150
82		TRANSFER	ASGN1		151
83		TEST E	JVSSIDE3,KO,SEZ		152
84		TRANSFER	ASGN3		153
85		ASSIGN	4-1,3		154
86		ASSIGN	5-1,3		155
87		ASSIGN	6-1,3		156
88		DEPART	P9		157
89		ASSIGN	9-1,3		158
90		QUEUE	P9		159
91		QUEUE	P10		160
92		DEPART	P10		161
93		TRANSFER	SEZ		162
94		ASSIGN	4-1,3		163
95		ASSIGN	5-1,3		164
96		ASSIGN	6-1,3		165
97		DEPART	P9		166
98		ASSIGN	9-1,3		167
99		QUEUE	P9		168
100		QUEUE	P10		169
101		DEPART	P10		170
102		TRANSFER	SEZ		171
103		ASSIGN	4-1,3		172
104		ASSIGN	5-1,3		173
105		ASSIGN	6-1,3		174
				SEND PAX TO NEXT EXIT FORWARD	
				SEND PAX TO NEXT EXIT AFT	

106	DEPART	P6	CB161630	175
107	ASSIGN	9-1,6	CB161640	176
108	QUEUE	P5	CB161650	177
109	QUEUE	P10	CB161660	178
110	DEPART	P10	CB161670	179
111	TRANSFER	1SE2	CB161680	180
112	ASSIGN	4+6	CB161690	181
113	ASSIGN	5+6	CB161700	182
114	ASSIGN	6+6	CB161710	183
115	DEPART	P9	CB161720	184
116	ASSIGN	7+6	CB161730	185
117	QUEUE	P9	CB161740	186
118	QUEUE	P10	CB161750	187
119	DEPART	P10	CB161760	188
120	TRANSFER	1SE2	CB161770	189
121	QUEUE	P5	CB161780	190
122	SLIZE	P5	CB161790	191
123	DEPART	P9	CB161800	192
124	MARK	8	CB161810	193
125	ADVANCE	V#9	CB161820	194
126	RELEASE	P5	CB161830	195
127	TEST F	P4,7,QUE4	CB161850	196
128	ASSIGN	7+6	CB161860	197
129	ENTER	P7	CB161870	198
130	ADVANCE	V#7	CB161880	199
131	LEAVE	P7	CB161890	200
132	DEPART	P7	CB161900	201
133	DEPART	P4	CB161910	202
134	QUEUE	P4	CB161920	203
135	ENTER	P5	CB161930	204
136	ADVANCE	V#4	CB161940	205
137	LEAVE	P5	CB161950	206
138	DEPART	P4	CB161960	207
139	DEPART	P5	CB161970	208
140	SAVEVALUE	P5,M1	CB161990	209
141	TERMINATE	1	CB162000	210
			CB162010	211

BEGIN EXIT DELAY-INTERVALS

PATH 7 INCLUDES OVERWING SEGMENT, 6 IN P7

ENTER STORAGE FOR OVERWING RAMP

ENTER STORAGE FOR SLIDE TIME

RECORD THE LATEST TOTAL TIME FOR EACH PATH

STORAGE CAPACITIES LISTED NEXT

