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GPSS COMPUTER SIMULATION OF AIRCRAFT PASSENGER EMERGENCY EVACUATIONS

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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 programing 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  
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\[ \text{MEAN} = 1.57 \quad \text{SD} = 0.76 \]

FORWARD EXIT TIME FUNCTION

1  \quad \text{FUNCTION} \quad \text{RN3,C32} \quad \text{FORWARD EXIT FUNCTION (TYPE I)}
0.0 / .00132, 20 / .01662, 40 / .06162, 60 / .13949, 80 / .24221, 100 / .35722, 120
.47262, 140
.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
* \quad \text{MEAN} = 1.73 \quad \text{SD} = .45 \quad \text{FORWARD SLIDE TIME}

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 cumu-
lative 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 con-
tain 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 ade-
quate 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/passerger. 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/passerger), by 2.6, which maintains the ratio. The resulting Type A flow rate is 0.60 s/passerger 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:

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

Continuous flow rate is defined as:

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

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)**

<table>
<thead>
<tr>
<th>No. Pax.</th>
<th>Exits Used</th>
<th>Intracabin Redirection</th>
<th>Average Total Evacuation Time (s)</th>
<th>Average Total Evacuation Time (Range (s))</th>
</tr>
</thead>
<tbody>
<tr>
<td>356</td>
<td>A 3 1 I</td>
<td>N</td>
<td>93.5</td>
<td>77.4 - 120.0</td>
</tr>
<tr>
<td>356</td>
<td>A 3 1 Y</td>
<td>N</td>
<td>84.9</td>
<td>77.8 - 90.8</td>
</tr>
<tr>
<td>356</td>
<td>A 4 1 N</td>
<td>N</td>
<td>83.6</td>
<td>77.6 - 89.3</td>
</tr>
<tr>
<td>356</td>
<td>A 4 1 Y</td>
<td>N</td>
<td>79.6</td>
<td>76.7 - 83.9</td>
</tr>
<tr>
<td>411</td>
<td>A 4 1 N</td>
<td>N</td>
<td>83.6</td>
<td>77.6 - 89.3</td>
</tr>
<tr>
<td>411</td>
<td>A 4 1 Y</td>
<td>N</td>
<td>79.6</td>
<td>76.7 - 83.9</td>
</tr>
</tbody>
</table>

\(^1\)Total evacuation time for an actual demonstration was 101.1 s.
\(^2\)Total evacuation time for an actual demonstration was 82 s.
\(^3\)Total 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)**

<table>
<thead>
<tr>
<th>Exits Used</th>
<th>Intracabin Redirection</th>
<th>Average Total Evacuation Time (s)</th>
<th>Average Total Evacuation Time (Range (s))</th>
<th>Exit-Opening Time (s)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 1</td>
<td>- N</td>
<td>112.0</td>
<td>100.0 - 122.0</td>
<td>13 50 13 13</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 1</td>
<td>Y -</td>
<td>92.5</td>
<td>88.9 - 96.6</td>
<td>13 50 13 13</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 1</td>
<td>Y -</td>
<td>90.2</td>
<td>85.8 - 93.2</td>
<td>13 50 13 13</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 1</td>
<td>- N</td>
<td>85.0</td>
<td>76.0 - 99.0</td>
<td>13 13 13 13</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 1</td>
<td>- N</td>
<td>144.0</td>
<td>130.0 - 162.0</td>
<td>13 13 13 13</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 1</td>
<td>Y -</td>
<td>114.0</td>
<td>110.0 - 118.0</td>
<td>13 13 13 13</td>
<td>**</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 1</td>
<td>Y -</td>
<td>82.0</td>
<td>77.0 - 88.0</td>
<td>13 13 13 13</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 1</td>
<td>Y -</td>
<td>90.2</td>
<td>85.8 - 93.2</td>
<td>13 13 13 13</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*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)**

<table>
<thead>
<tr>
<th>Exits Used</th>
<th>No. Intracabin</th>
<th>Average Total Evacuation Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A B Pax</td>
<td>(s)</td>
</tr>
<tr>
<td>1 3 - 355</td>
<td>- N</td>
<td>106.0</td>
</tr>
<tr>
<td>- 3 1 355</td>
<td>- N</td>
<td>58.0</td>
</tr>
<tr>
<td>- 3 1 375</td>
<td>Y -</td>
<td>73.4</td>
</tr>
</tbody>
</table>

1 Single-lane slide used.  
2 Double-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**

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

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

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

<table>
<thead>
<tr>
<th>Exits Used</th>
<th>Average Evacuation Times (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. Pax</td>
</tr>
<tr>
<td></td>
<td>208</td>
</tr>
<tr>
<td>I A</td>
<td></td>
</tr>
<tr>
<td>1 2</td>
<td>87.19</td>
</tr>
<tr>
<td>0 3</td>
<td>62.89</td>
</tr>
</tbody>
</table>

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)

<table>
<thead>
<tr>
<th>No. Pax</th>
<th>Exits</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 Type A</td>
</tr>
<tr>
<td></td>
<td>Forward</td>
</tr>
<tr>
<td>208</td>
<td>68.65</td>
</tr>
<tr>
<td>248</td>
<td>82.48</td>
</tr>
<tr>
<td>309</td>
<td>102.48</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1 Type I and 2 Type A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward</td>
</tr>
<tr>
<td>208</td>
</tr>
<tr>
<td>248</td>
</tr>
<tr>
<td>309</td>
</tr>
</tbody>
</table>
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 intrinsic 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.
REFERENCES


APPENDIX A

TYPICAL GPSS EVACUATION PROGRAM

```
1 GENERATE 527.1
2 TRANSFER 200, FMUA 1
3 TRANSFER 250, FMUA 2
4 TRANSFER 333, FMUA 3
5 TRANSFER 500, FMUA 4
6 TRANSFER 750, FMUA 5
7 FMUA ASSIGN 4, 1
8 ASSIGN 5, 1
9 ASSIGN 6, 2
10 ASSIGN 7, 2
11 ASSIGN 8, 2
12 ASSIGN 9, 2
13 TRANSFER EXIT
14 MID Assign 4, 4
15 ASSIGN 5, 4
16 ASSIGN 6, 4
17 ASSIGN 7, 4
18 ASSIGN 8, 4
19 ASSIGN 9, 4
20 TRANSFER EXIT
21 AFTA ASSIGN 4, 7
22 ASSIGN 5, 7
23 ASSIGN 6, 7
24 ASSIGN 7, 7
25 ASSIGN 8, 7
26 ASSIGN 9, 7
27 TRANSFER EXIT
28 AFTA ASSIGN 4, 11
29 ASSIGN 5, 11
30 ASSIGN 6, 11
31 ASSIGN 7, 11
32 ASSIGN 8, 11
33 ASSIGN 9, 11
34 TRANSFER EXIT
35 AULT ASSIGN 4, 15
36 ASSIGN 5, 15
37 ASSIGN 6, 15
38 ASSIGN 7, 15
39 ASSIGN 8, 15
40 ASSIGN 9, 15
41 TRANSFER EXIT
42 EXIT TEST 26
43 BEGIN ENTER P4
44 ADVANCE FN2
45 LEAVE P4
46 QUEUE P4
47 LINK P1, PIF, AAA
```

---
BEGIN EXIT DELAY-INTERVALS

PATH 7 INCLUDES OVERWING SEGMENT, 6 IN P7

ENTER STORAGE FOR OVERWING RAMP

ENTER STORAGE FOR SLIDE TIME

RECLAD THE LATEST TOTAL TIME FOR EACH PATH

STORAGE CAPACITIES LISTED NEXT