SIMPLE ANALYSIS TO ASSESS THE EVACUATION OF TRANSPORT AIRPLANES

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Abstract

The present paper describes the work carried out with a number of already flying airplanes as a first step in the implementation of an evacuation model. The key questions that have been addressed are: 1) How the number and location of exits affect the global distribution of passengers escaping through each exit? 2) Which are the evacuation flow rates through each exit and how this flow rate depends upon the size of the exit? 3) Which is the role of the seat-to-exit distance as a variable in the evacuation of an airplane? It is shown that the overall airplane configuration as well as left to right asymmetries have important effects on occupant allocation to each exit. Limit evacuation flow rates have been determined for all types and sizes of emergency exits. Although the distance to be covered by evacuees seems to play a secondary role, histograms of seat-to-exit distance exhibits meaningful differences among exits in many of the reviewed aircraft.

Introduction

Safety has always been the "leit motiv" of aviation, particularly since civil regular operations were worldwide established in the 20s. This active awareness has leaded to a continuous decay in the accident rate along the years, up to becoming nowadays one of the safest method of mass transportation.[1]

Many of the aircraft accidents can result in impact-survivable crashes and about 10% are followed by fire or toxic gases in the cabin or in other potentially dangerous areas of the airplane. To decrease the number of injured and dead people, particularly in the aforementioned cases, cabin materials and structures are continually being developed to improve safety through assuring the integrity of the airframe and retarding burning or smoldering, but it is always important to conduct a fast evacuation.

Airworthiness authorities have been well aware of the importance of evacuation. Consequently, since earlier years they have established appropriate requirements on emergency evacuation, both in ground and on sea. These requirements include details on the number, size and location of exits, means of opening, etc, and real evacuation tests as proof of compliance.[2,3] According to FAR-JAR 25.803 the tests must be conducted in a dark ambiance, using only half the existing exits, and with a particular passenger mix which is assumed representative of real loading. Tables 1 and 2 reproduce the indications of FAA and JAA with respect to the number of exits for large passenger airplanes. As it will be later shown, designers closely follow such indications but giving themselves some freedom to interpret and slightly change the requirements according to their needs for the cabin arrangement. It is obvious that, in any case (i.e. with or without modifying the figures in the tables) the airplane manufacturer must demonstrate the fulfillment of the 90 seconds rule.

TABLE 1. Required emergency exits for each side of the fuselage

Passenger seating	Type I	Type III
40 to 79	1	1
80 to 109	1	2
110 to 139	2	1
140 to 179	2	2

TABLE 2. Increase in number of passengers per additional exit, for each side of the fuselage

Type of exit	Nº pax
A	110
I	45
II	40
III	35

In spite of the detailed description of 25.800s requirements, there are some minor inconsistencies. For example by comparing the number of exits required for an airplane with 109 passengers and another with 139 passengers, the designer must change a type III exit by a larger type I exit but, according to Table 2, the increase in the number of passengers with this change should only be 10 (plus 45 minus 35). Something similar applies between 139 and 179 passengers, since the extra type III exit could only account for 35 people and not 40. As it will be shown in following paragraphs, type I exit are of different size for turboprops and turbojet airplanes (always larger than the minimum stipulated in FAR-JAR 25.807), allowing different number of evacuees. This fact would need some refinement of the regulations in future editions.

Coming back to real evacuations, it is known that in an orderly environment the pattern may be represented by queues at the exits, since moving along the aisles is much faster than any other action to be undertaken by passengers or crew members.[4] This may also be the arrangement in initial phases when fire, other hazards or high disorder are present. It is important to realize that the view of the aircraft for any occupant is limited to the immediate environment, since darkness, smoke and the like avoid having a more global picture of the cabin, and makes it difficult to take the adequate choice. This factor adds to fuselage integrity, obstacles on the cabin floor and along the passageways, heat, passenger conflicts, etc, to conform the scenario in real situations.

In all cases, but specially when there is an non orderly evacuation, the vital space plays an important role; the surrounding territory is seen as proper territory (belonging to one person if the passenger is alone or to more people in case of groups) that can not be occupied by anyone else. Since evacuations take place in a competitive way (everybody tries to reach the exit as soon as possible), the conflicts related to vital space can result in some passengers jumping over seat backs or adopting extraneous escaping strategies. Interestingly, frequent travellers do not pay too much attention to pre-flight briefings but have developed specific skills and good knowledge of the airplanes, and allow the aircraft to be evacuated more rapidly. Infrequent travellers, in spite of listening the briefing and reading the safety instructions card, normally show ignorance of emergency procedures.[5] On the other hand, passengers travelling accompanied tend to be more organized and cooperative, as it occurs in other emergency situations.[6] Cabin crew improve evacuation, particularly when apart from being well trained they have an assertive personality that control passenger flow and diminish hesitation at the exit.[7]

TABLE 3. List of aircraft considered in the present study

Type of aircraft	Name	Nº pax
Turboprops	ATR 72	66
	BAe ATP	72
	Dash 8-300	56
	Fokker 50	50
	Saab 2000	50
Narrow body turbojets	A320-200	176
	BAe 146-300	98
	B737-500	132
	B757-200	217
	Canadair Reg. Jet	50
	HS Trident	152
Wide body turbojets	A340-300	401
	B767-300	312
	DC-10-30	380

The present paper describes the work carried out as a first step in the implementation of a new evacuation model. The key questions that have been addressed in the paper are: 1) How the number and location of exits affect the global distribution of passengers escaping through each exit? 2) Which are the evacuation flow rates through each exit and how this flow rate depends upon the size of the exit? 3) Which is the role, eventhough secondary, of the seat-to-exit distance as a variable in the evacuation of an airplane? In concordance with these questions, the following headings will consider such factors one by one, after a shallow description of published evacuation models.

Aiming at the former objectives, a certain number of airplanes in various categories and sizes have been selected to assess their main features regarding evacuation. The list is depicted in Table 3. The underlying idea in utilizing these aircraft is that since they have already been awarded with the Type Certificate, they constitute a good testbed for the evacuation analysis. Cabin layouts (i.e., number and location of exits and seating arrangement) of all these aircraft have been taken from open literature (JANE's, Flight International, etc), airport planning manuals, and commercial brochures. No meaningful differences have been found with respect to exits when more than one cabin arrangement of the same airplane were available.

Evacuation Models

As indicated before, airplane manufacturers are obliged by airworthiness authorities to carry out evacuation tests under specified conditions. On reviewing such tests as well as those prepared for research purposes, it is seen that meanwhile the crew is opening the doors and deploying the slides, passengers have released their seatbelts, moved to the aisles and approached the exits. For several seconds there will be a holding pattern and, soon, the arrangement will resemble the queues at the exits pattern already mentioned.

As it will be clearly shown in next paragraphs, each exit has a maximum occupant flow rate; and this, together with the presence of obstacles in the surroundings of the exit, may produce blockages. As the scale and level of competition between escaping passengers escalates (stimulated by prices or money) so does the risk of personal damage. Thus it is easy to understand that very often during evacuation tests someone is injured which leads to abandoning the test, as shown in Fig. 1 (modified from Ref. 8).

Because of the risk of personal injury and of the cost of full-scale trials, airplane manufacturers are trying to reduce the number of tests to a minimum, and are pressing to change the rules for certification: for example, FAA has accepted the results of MD-11 evacuation tests in which passengers were permitted to use platforms instead of slides, by changing the emblematic 90 seconds figure by a less elegant 62 seconds lapse of time.

One of the ways for reducing the number of tests is to develop simulation models that, once validated, may help in interpreting the capabilities of different design layouts or in understanding accident histories. All simulation models, irrespectively of their complexity must reproduce the normal movements of passengers from the start of evacuation: i.e., releasing seatbelts, rising, moving towards the aisles or towards the next seat closer to the aisle, moving through the aisles, waiting at the door queue, and jumping out of doorways.[4] But, obviously, the minimum realism obliges to consider submodels to take into account all intervening factors: personal characteristics (age, sex, etc), personality, hazard (fire, smoke, heat) that may affect the personality and, hence, the whole process.

Computer simulations show that an evacuation may need as little as 25 seconds when all the exits are available and doors and slides are operated and active within the first few seconds,[4] but the time is dramatically altered if the FAR-JAR provisions are respected. On simulating extreme cases with many obstacles and hazards the computer code is even capable of counting the number of casualties[9]. In this point it is important to recall that in the 1985 Manchester B737 disaster, the last, 82nd surviving passenger escaped 5 minutes after the evacuation started (55 people died in this accident).

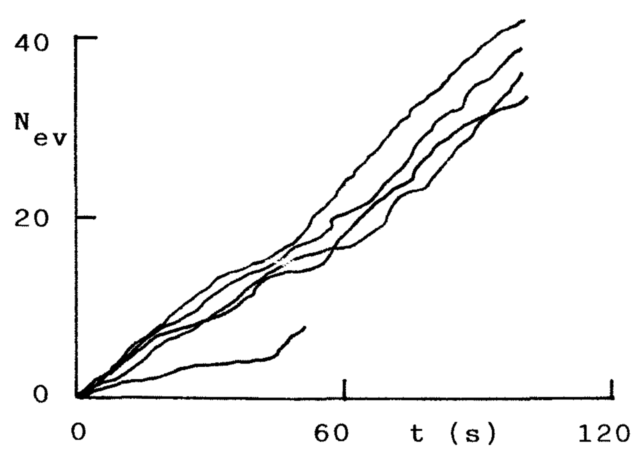

FIGURE 1. Graphical representation of evacuation trials, showing finalized and abandoned tests.

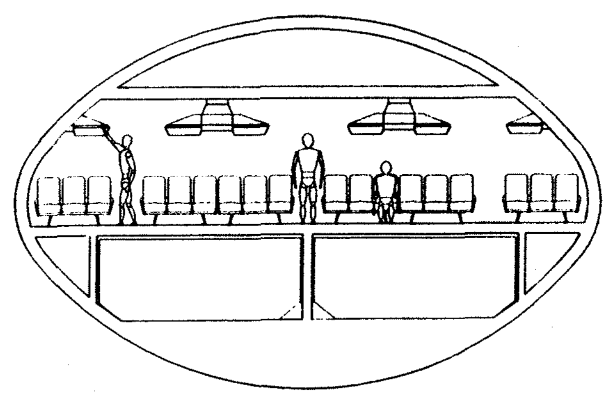

FIGURE 2. Horizontal oval cross section of an ultra-wide fuselage.

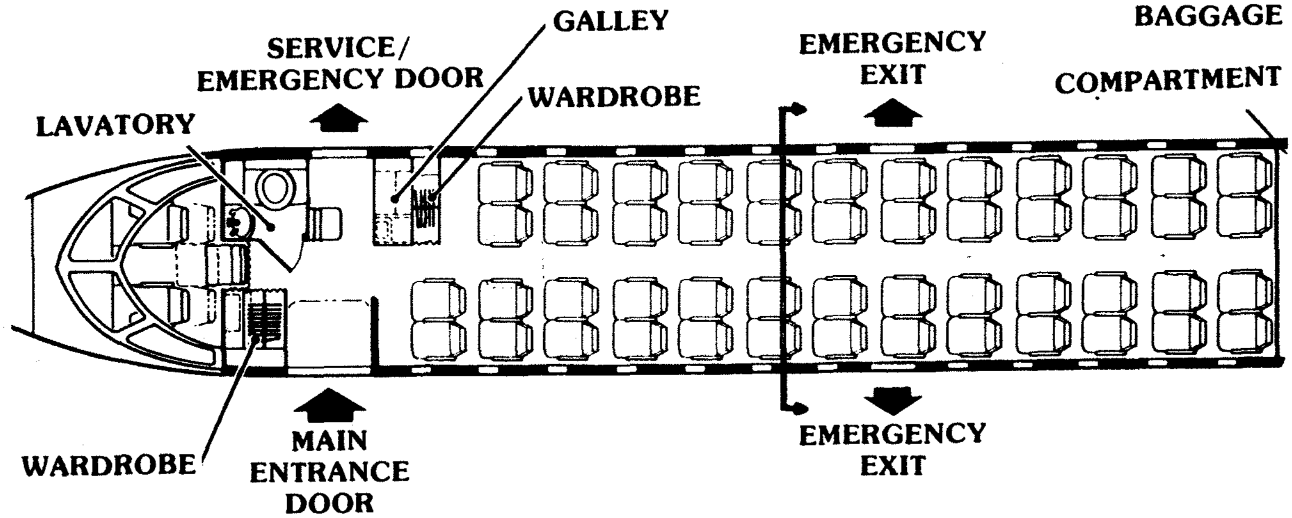

FIGURE 3. Cabin arrangement of Canadair Regional jet. The vertical line separates two zones corresponding to each usable exit.

Very few models have been published[4,10] and, in the same line, very few papers have addressed the assessment of cabin configurations with the perspective of evacuation.[11] However, the need for such models and assessments is sorely felt with the mid term advent of very large aircraft and, perhaps too, unconventional configurations. So, Fig. 2 depicts an ultra-wide body cross section for VLA.[12] The multiple intersection of passageways and the sill height are factors that need special treatment both in the development of tests and in the simulations.

Some cabin-safety researchers say that the forces which make accidents non-survivable are usually of such magnitude that any change in the corresponding regulations would have very little impact on survival rates. But researchers agree in the interest of the models and in the sense that computer models are more useful in comparing situations than in actually assessing a given scenario. Any way, within the percentage of accidents in which evacuation plays an important role (about 10% of all aircraft accidents) any help in clearifying the process would be mostly appreciated.

Number and Location of Exits

The analysis is carried out individually for each airplane of the list in Table 3. Before any other action, each aircraft is divided longitudinally and only the exits along one of the sides are considered as suitable for evacuation, as suggested in the L1011 certification process.[13] Then, the procedure to distribute the total number of occupants, passengers plus all crew members, among the various exits consists of three steps. The first step is to compute the maximum number of evacuees by summing up the allowed increase shown in Table 2 corresponding to all exits for one side of the fuselage; it was soon clear that the figure of 45 additional passengers had no sense for jet airplanes and should be replaced by a more reasonable 60 (about half the one corresponding to a Type A exit). Second, the number of evacuees for each exit is computed in proportion to the real number of occupants, which almost always is smaller than the maximum predicted in the first step (there is a little difference, since crew members are not accounted for in Table 2). And third, the definite number of evacuees of each exit is modified to include the effect of exit location; i.e. for single aisle airplanes it is considered that only a very small amount of people (if any) seated in the close neighbourhood of an exit would run to a different potential escape way (in darkness, etc). Figure 3 exhibits how this third step modifies the number of evacuees per exit, allocating 25 people (22 passengers plus 3 crew members) to the forward type I door and 28 (all of them passengers) to the type III exit, instead of a more reasonable 29 to 24 sharing. If the evacuation capability is assessed without introducing the latter modification results are overestimated by about 10%.[11]

The cabin layout is absolutely symmetric in most cases (Canadair Regional Jet, B767, A340, etc) and shows little shifts from symmetry in some occasions (B727 not considered here, with not fully paired doors in both sides of the fuselage). However, there are also aircraft whose shifts from symmetry are not all minor issues. Good examples are: Saab 2000 with a type I entrance door in the forward port fuselage and a type I service/emergency door in the rear right side; and Hawker Siddeley Trident (see Fig. 4) with a very different exit arrangement from left to right. In this last airplane, when the left hand side is the one used for evacuation, the sharing is 49 occupants at the type I fore door, 71 at the intermediate type I door and 39 at the type III exit; meanwhile through the right hand side the sharing would be 63, 36, and 60 for type I, type III and again type I exits, respectively. It is easy to see that the

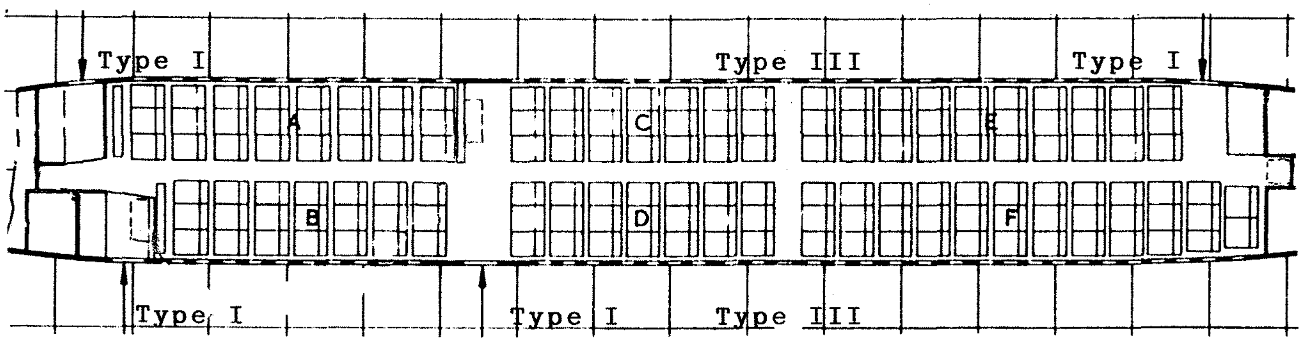

FIGURE 4. Cabin arrangement of Hawker Siddeley Trident.

location of the exits is very important for adequately distributing the occupants in case of evacuation. Moreover, since there is a limitation in flow rate for each type of emergency exit, this last factor could imply the presence of isolated areas in the cabin if doors are not properly located.

The review has found two extreme cases in which there are different numbers of exits in both sides of the fuselage: BAe ATP with two type I plus one type III on the port side and one type I and one type III on the right hand side, and MD 83 (not included in the list of Table 3), with one extra type I door in the port side and a ventral door.

Table 4 presents the ranges of the number of occupants allocated to each exit type of all airplanes in Table 3. The narrowest range, as expected, corresponds to type A doors of wide body airplanes, since their high density versions are always very close to the maximum capability. And the most noticeable variation is seen in type I doors, due to the remarkable differences in real situations of turboprops and turbojet aircraft; the minimum of 25 belongs both to Canadair Regional Jet and Fokker 50, meanwhile the maximum of 71 is one of the aforementioned doors of the HS Trident.

TABLE 4. Range (minimum to maximum) of the variable "number of evacuees" per exit for all airplanes considered

Type of exit	Nº of occupants
A	88 to 112
I	25 to 71
III	18 to 39

Evacuation Flow Rate

The total time to evacuate an airplane is the sum of the time required to open the exits and, if this is the case, deploy the slides, plus the time needed by all occupants to move out the exit. According to FAR-JAR 25.803 such total time must be less than 90 seconds. It is important to realize that the evacuation time may be different for the various exits of a given airplane and the 90 seconds apply to the one requiring the longest utilization.

In a formal, mathematical manner, the former statement can be written as

$$t_{ev} = t_{op} + \frac{N_{oc}}{F} \qquad (1)$$

where t_{ev} is the time to evacuate an exit, t_{op} the time required to make the exit fully usable, N_{oc} the number of occupants that should move through that exit and F the flow rate of the given exit. For all exits $t_{ev}<90$. Figure 1 shows how well the former equation represents the situation in evacuation trials: after some delay, a more or less constant flow rate is established.

To compute limit evacuation flow rates is not an easy matter. But since all currently flying airplanes fulfill the rule, it is possible to act in an inverse way. Thus, first the required flow rate through all exits of the reviewed aircraft are determined and, then, the highest in the ranking for each type must be close to the searched value; i.e.

$$F \geq \frac{N_{oc}}{90-t_{op}} \qquad (2)$$

Figure 5 depicts Eq. 2 as the required flow rate (with the equal sign) in terms of t_{op}, for the number of occupants allocated to each exit in the former paragraph, corresponding to type A, type I and type III exits, respectively. FAR-JAR 25.805 also indicate maximum times for t_{op}: 20 seconds in the worst combination for larger doors and 10 seconds for

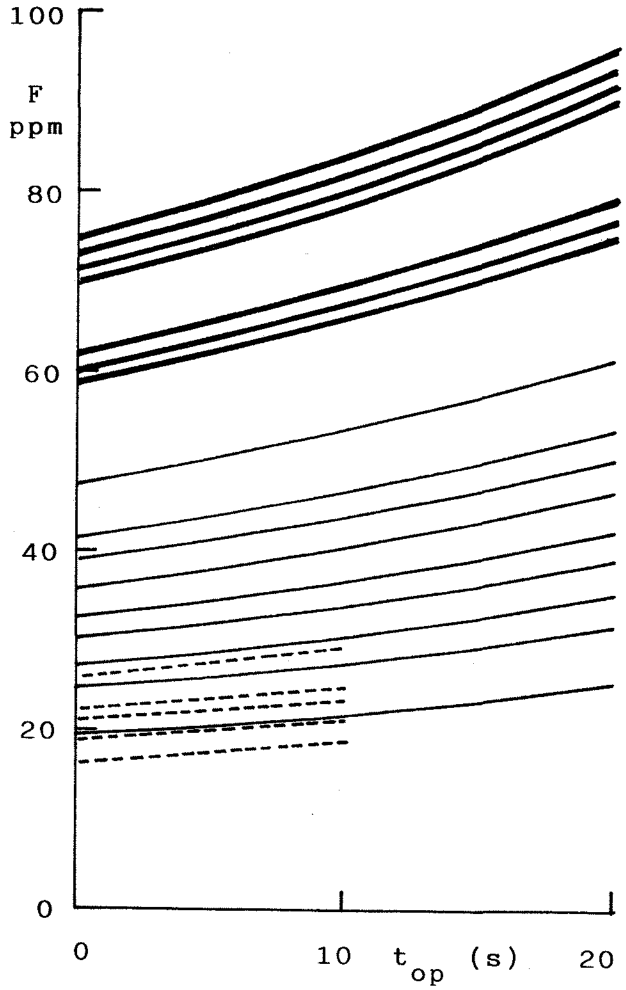

FIGURE 5. Evacuation flow rate, in persons per minute, for exits of aircraft in Table 3. Dashed line: window exit; thin line: type I; thick line: type A door.

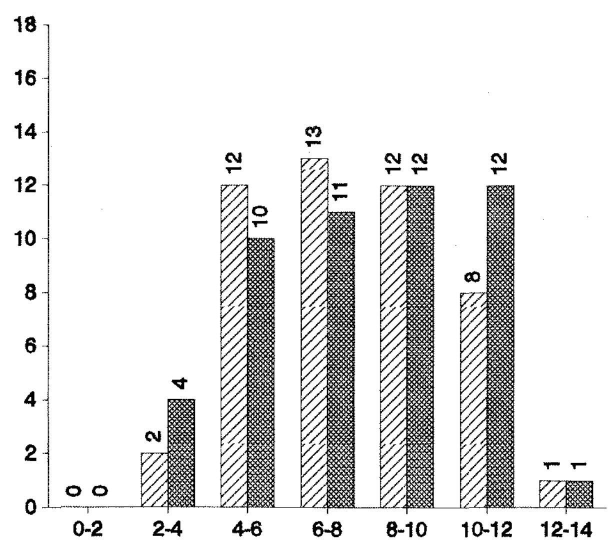

FIGURE 6. Histograms of seat-to-exit distance (in meters) for the two doors of BAe 146-300.

secondary emergency exits. Following the former reasoning, and including some allowance for initial delays, appropriate values of F are 90 persons per minute for type A exits, 52 and 32 ppm in large turbojets and turboprops type I doors, respectively, and 27 ppm in type III window exits. These values are in good agreement with flow rates[8] and evacuation times[4,9] reported in literature.

Seat-to-Exit Distance

It is evident that moving along the aisles is much faster than other actions during the evacuation process. Thence, seat to exit distance is a secondary variable. However, the differences found in the present work oblige to dedicate some considerations to that point.

Figure 6 depicts, by means of appropriate histograms, a fair sharing with very little differences between two type I exits, corresponding to BAe 146-300. The average seat to exit distance is 7.6 m for the forward door and 7.8 m for the rear one.

However, most aircraft have uneven distributions. Thus, for example, Fig. 7 depicts how different the situation for the three exits in an airplane is. All passengers that will come out over the window are very close to the exit; the average distance being only 3.3 m. On the other hand the passengers seating in the forward part of the cabin have to travel an average distance of 6.2 m, and for those at the back the mean is 7.5 m.

Last, DC-10 shows the most extreme case in its type A doors, as seen in Fig. 8. The type I door close to the cockpit, is not shown in the figure for clarity, and has a similar histogram to the one of the rear intermediate type A door. Apart from meaningful differences in the average distance, 7.2 m, 6.5 m and 10 m, the farthest passenger taking the tail door has to travel almost 18 m before reaching a safe outer environment. Although seat to exit distance is not a very important variable, since a person can move at about 1 meter per second (in darkness) along the aisle, any additional obstacle or problem may convert it into a major factor for safe evacuations.

Final Considerations

The location of the doors depends upon the relative position between wing and cabin and, it its turn, it affects to the distance to be covered during evacuation. Typically, large airplanes have the engines located under the wing which, because of the trimming, obliges to put the wing-fuselage junction a bit ahead of the mid cabin. If the airplane has to be evacuated through the exits in one of the sides only or, even worse, if only the forward doors can be used, some of the passengers seated at the back of the

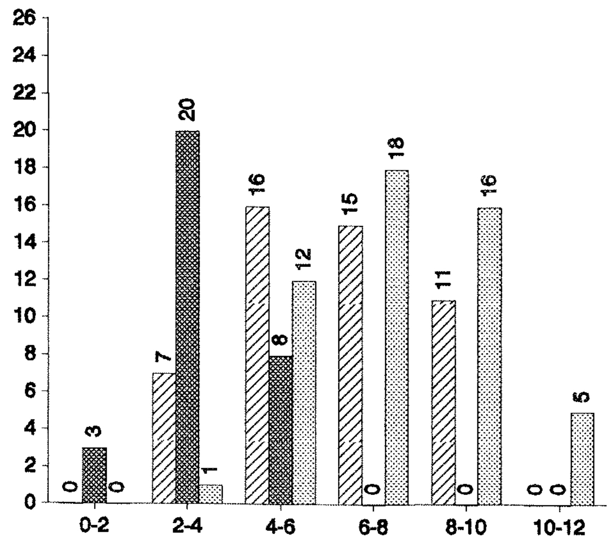

Figure 7. Histograms of seat-to-exit distance (in meters) for the three exits of B737-500. Dark grey: window exit; dashed: forward type I door; light grey: rear type I door.

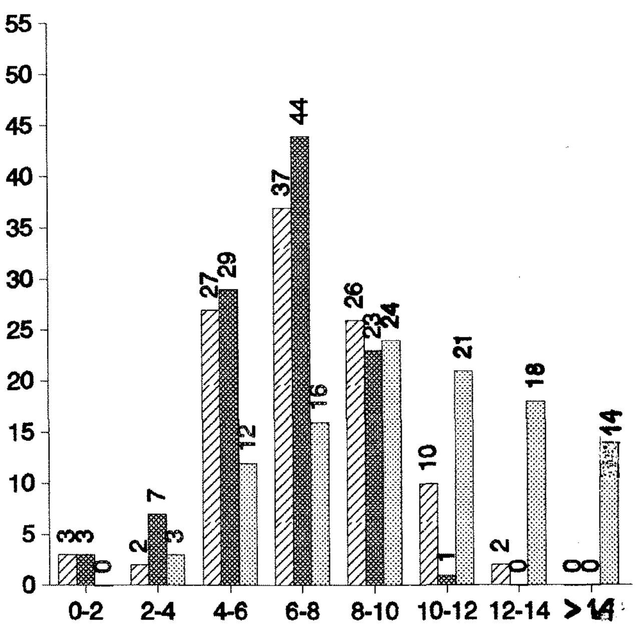

Figure 8. Histograms of seat-to-exit distance (in meters) for the three type A exits of DC-10-30. Dashed: intermediate forward door; dark grey: intermediate rear door; light grey: rear door.

cabin will have to cover remarkably greater distances than aforementioned averages, which poses additional difficulties in assessing and analyzing cabin arrangements at design level or tests results at certification level. The equivalent statements apply to aircraft configurations with the engines at the sides of the fuselage, but in this case the wing is shifted rearward.

Seat-to-exit distance histograms may help to interpret how the evacuation flow rate can be established. At the beginning, except for type III, there is nobody in the immediate neighbourhood of an exit. Crew members or active passengers attempt to open the doors and deploy the slides. The very few people at short distance approach the door, and the others take their positions. By the time most passengers are standing on the aisle or by their seats, the first passengers start jumping out. Depending on the number of passageways leading to a given exit, and the intersections among them, there will be high or low probability of blockage at the exit.

Although not included in the present paper, certain relationship between sill height and maximum flow rate seems to sharply diminish the capability of upper deck doors. Both for the hesitation factor in front of the slide as well as for the time needed to reach the ground, this variable should be properly considered in models. A possible solution to reduce or eliminate the hesitation is the use of tunnel-like slides, in which the passenger feels no fear of the vertical gap, although the length of the slide (and the time to run it over) will remain a challenging problem.

The aforementioned tunnel-like slides imply extra weight. In the same sense, locking the overhead bins to avoid passengers collecting personal belongings, as happened in several accidents,[14] requires also additional weight, as well as water sprays and other devices envisaged to improve cabin safety, but at a cost to be duly assessed.

On the other hand, in spite of the detailed picture of FAR-JAR 25.803, it is an unaccurate representation of current passenger loading; mainly in the percentage of women, elderly people and children, since leisure and family visit trips are increasingly frequent.

Last, future extensions of this work will include comparisons of longitudinal versus transverse divisions of the cabin for occupant to exit allocation, the effect of sill height in flow rate for wide bodies, and evaluation of the global anxiety and trend to disorder in relation to possible blockages of passageways or exits.

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