THE airEXODUS EVACUATION MODEL AND ITS APPLICATION TO AIRCRAFT SAFETY

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1. ABSTRACT

Computer based mathematical models describing the aircraft evacuation process have a vital role to play in the design and development of safer aircraft, the implementation of safer and more rigorous certification criteria, in cabin crew training and post-mortem accident investigation. As the risk of personal injury and the costs involved in performing full-scale certification trials are high, the development and use of these evacuation modelling tools are essential. The airEXODUS evacuation model has been under development since 1989 with support from the UK CAA and the aviation industry. In addition to describing the capabilities of the airEXODUS evacuation model, this paper describes the findings of a recent CAA project aimed at investigating model accuracy in predicting past certification trials. Furthermore, airEXODUS is used to examine issues related to the "60 foot" rule concerning maximum exit separation. Finally, issues relating to the use of evacuation models for certification are discussed.

2. INTRODUCTION

In a bid to increase efficiency and passenger comfort aircraft manufacturers are striving to design and build larger aircraft such as the A380. In addition, stretches to existing aircraft aim to gain greater efficiencies from existing designs such as the A340-600. Even more ambitious are radical concepts consisting of Blended Wing Body (BWB) design, involving one or two decks and with five or possibly six aisles. This drive for increased efficiency, increased passenger capacity and aircraft size is balanced by the need to maintain, and if possible, improve current safety standards. One of the highest safety priorities for aircraft designers and regulators alike concerns the evacuation efficiency of aircraft design.

Regulators attempt to enforce and maintain safety standards through a set of essentially prescriptive rules that have evolved over time. In the USA the rules are known as the Federal Aviation Regulations (FAR) [1], while in Europe they are know as Joint Aviation Regulations (JAR) [2]. One of the rules relating to aircraft evacuation efficiency is the so-called "60-foot" rule. The rule appears in the FAR (i.e. 25.807 (f) (4)) [3] and there is an equivalent ruling in the JAR. The FAR rule states;

"For an airplane that is required to have more than one passenger emergency exit for each side of the fuselage, no passenger emergency exit shall be more than 60 feet from any adjacent passenger emergency exit on the same side of the same deck of the fuselage, as measured parallel to the airplane's longitudinal axis between the nearest exit edges." [3].

This regulation was introduced into the FAR as amendment 25-67. The origins of this amendment can be traced to a configuration modification to a B-747 aircraft. In 1984, Boeing

Commercial Airplane Group (Boeing) requested certification for a modification to the B-747 that required a pair of exits on the main deck to be deactivated. This resulted in the maximum exit separation increasing from 44 feet to nearly 70 feet. In deactivating the pair of exits, Boeing also reduced the maximum capacity of the main deck from 550 to 440 passengers in line with the regulations of the day.

Prior to this request and since 1967, the Federal Aviation Administration (FAA) had not specified a maximum exit separation. The FAA had however regulated through the FAR [4] that,

"…an exit be provided for every specified number of passengers, that an exit be located where it would allow the most effective means of passenger evacuation, and that exits be distributed as uniformly as practicable taking into account passenger distribution." [4].

While the FAA granted the Boeing request, they received many complaints from the public for allowing the deactivation of the exits. After much debate, the FAA introduced amendment 25-67 on June 16 1989 [4], setting an arbitrary limit of 60 feet to exit separation.

Intuitively, exit separation is an important parameter in determining aircraft evacuation efficiency. However, before rules can be correctly established limiting exit separation, it is essential to understand how exit separation influences evacuation efficiency. As with most prescriptive rules, amendment 25-67 suffers from the arbitrary nature of its specification. The rule is not founded on any fundamental understanding of evacuation dynamics, accident scenarios or human behaviour. The rule even ignores the nature of the exits (e.g. exit size) that exist at the end of the 60-foot separation. To take these and other relevant matters into consideration requires a holistic approach to evacuation.

In addition to satisfying the prescriptive rules, aircraft manufacturers must demonstrate that new aircraft designs or seating configurations will allow a full load of passengers and crew to safely evacuate from the aircraft within 90 seconds. The accepted way of demonstrating this capability is to perform a series of full-scale trials using the passenger compartments under question and an appropriate mix of passengers. Between 1969 and 1993 more than 20 full-scale evacuation certification demonstrations had been performed involving over 7000 volunteers [5].

The use of human volunteers in full-scale evacuation demonstrations poses considerable ethical, practical and financial difficulties. The ethical problems concern the threat of injury to the participants and the lack of realism inherent in the 90-second evacuation scenario. Between 1972 and 1991 a total of 378 volunteers (or 6% of participants) sustained injuries ranging from cuts and bruises to broken bones [5]. In October 1991 during the McDonnell Douglas evacuation certification trial for the MD-11, a female volunteer sustained injuries leading to permanent paralysis. Furthermore, as volunteers are subject neither to trauma nor to the physical ramifications of a real emergency situation such as smoke, fire and debris, the certification trial provides little useful information regarding the suitability of the cabin layout and design in the event of a real emergency. The Manchester disaster of 1985, in which 55 people lost their lives, serves as a tragic example. The last passenger to escape from the burning B737 aircraft emerged 5.5 minutes after the aircraft had ceased moving, while 15 years earlier in a UK certification trial, the entire load of passengers and crew evacuated the aircraft in 75 seconds [6].

On a practical level only a single evacuation trial is necessary to satisfy certification requirements. As such only a single scenario is assessed which involves half the available exits –

one from each exit pair. As a result, there can be limited confidence that the test - whether successful or not – reliably represents the evacuation capability of the aircraft under the test conditions, let alone other conditions. In addition, from a design point of view, a single test does not provide sufficient information to arrange the cabin layout for optimal evacuation efficiency, and does not even necessarily match the types of configuration flown by all the potential carriers. Finally, each full-scale evacuation demonstration can be extremely expensive. For instance an evacuation trial from a wide-body aircraft costs in the vicinity of $US2 million [5]. As aircraft size and capacity increase, all of these difficulties are compounded.

Computer based mathematical models describing the aircraft evacuation process have the potential of addressing all these issues. If evacuation models are to fulfil their promise, they must address the configurational, environmental, behavioural and procedural aspects of the evacuation process [7]. Configurational considerations are those generally covered by conventional methods and involve cabin layout, number of exits, exit type, travel distance etc. In the event of fire, environmental aspects need to be considered. These include the likely debilitating effects on the passengers of heat, toxic and irritant gases and the impact of increasing smoke density on travel speeds and way-finding abilities. Procedural aspects cover the actions of staff, passenger prior knowledge of the cabin, emergency signage etc. Finally, and possibly most importantly, the likely behavioural responses of the passengers must be considered. These include aspects such as the passengers' initial response to the call to evacuate, likely travel directions, family/group interactions etc.

The airEXODUS evacuation model [8-15] attempts to address all four of the contributory aspects controlling the evacuation process. In this paper we present some results from a recent airEXODUS validation study involving four wide body aircraft and some findings from a recent study of issues relating to exit separation. A brief description of the airEXODUS evacuation model follows, a fuller account may be found in [11] and [14].

3.0 THE airEXODUS EVACUATION MODEL: AN OVERVIEW

EXODUS is a suite of software tools designed to simulate the evacuation of large numbers of individuals from complex structures. Development on EXODUS began in 1989. EXODUS was originally designed for use with aircraft, however, its modular format makes it ideally suited for adaptation to other types of environment. As a result its range of application has grown, as has the number of specific EXODUS products. The family of models consists of buildingEXODUS [16,17], maritimeEXODUS [18,19] and airEXODUS [8-15] for the built environment, marine/off-shore industries and aviation applications respectively. airEXODUS is designed for applications in the aviation industry including, aircraft design, compliance with 90 second certification requirements, crew training, development of crew procedures, resolution of operational issues and accident investigation.

EXODUS comprises five core interacting sub-models: the Occupant, Movement, Behaviour, Toxicity and Hazard sub-models. The software describing these sub-models is rule-based, the progressive motion and behaviour of each individual being determined by a set of heuristics or rules. The spatial and temporal dimensions within EXODUS are spanned by a two-dimensional spatial grid and a simulation clock (SC). The spatial grid maps out the geometry of the structure, locating exits, internal compartments, obstacles, etc. Geometries can involve multiple floors, connected by staircases. The structure layout can be specified using either a DXF file produced by a CAD package, or the interactive tools provided. The grid is made up of nodes and arcs with each node representing a small region of space and each arc representing the distance between each node. Individuals travel from node to node along the arcs.

The Population Sub-model allows the nature of the passenger population to be specified. The population can consist of a range of people with different movement abilities, reflecting age, gender and physical disabilities as well as different levels of knowledge of the ship layout, response times etc. On the basis of an individual's personal attributes, the Behaviour Sub-model determines the occupant's response to the current situation, and passes its decision on to the Movement Sub-model. The Behaviour Sub-model functions on two levels. These levels are known as GLOBAL and LOCAL behaviour. GLOBAL behaviour involves implementing an escape strategy that may lead an occupant to exit via their nearest serviceable exit or most familiar exit. The desired GLOBAL behaviour is set by the user, but may be modified or overridden through the dictates of LOCAL behaviour, which includes such considerations as determining the occupants initial response, conflict resolution, overtaking and the selection of possible detouring routes. In addition a number of localised decision-making processes are available to each individual according to the conditions in which they find themselves and the information available to them. This includes the ability to customise their egress route according to the levels of congestion around them, the environmental conditions and the social relationships within the population. Social relationships, group behaviour and hierarchical structures are modelled through the use of a "gene" concept [20], where group members are identified through the sharing of social "genes". Passengers are able to adapt their evacuation strategy according to a rational use of the information available to them e.g. they may wish to communicate information to other passengers, identified as a group member

Figure 1: vrEXODUS generated scene from an airEXODUS evacuation simulation

The Toxicity submodel determines the physiological impact of the environment upon the occupant. To determine the effect of the fire hazards on occupants, EXODUS uses a Fractional Effective Dose (FED) toxicity model [21]. This model considers the toxic and physical hazards associated with elevated temperature, thermal radiation, HCN, CO, CO_2 and low O_2 and estimates the time to incapacitation. In addition to this behaviour, the passengers are able to respond to the environmental conditions by adjusting their behaviour. The thermal and toxic environment is determined by the Hazard submodel. EXODUS does not predict these hazards but can accept experimental data or numerical data from other models including a direct software link to the CFAST fire zone model [22]. EXODUS produces a range of output, both graphical and textual. Interactive two-dimensional animated graphics are generated as the software is running that allows the user to observe the evacuation as it takes place. The graphics are interactive allowing the user to interrogate occupants and events. In addition, a data output file is produced containing all the relevant information generated by the simulation, including a copy of the input data. To aid in the interpretation of results, a post-processor virtual-reality graphics environment known as vrEXODUS has been developed, providing an animated three-dimensional representation of the evacuation (see *Figure 1*).

airEXODUS makes use of 90-second certification data [23] to specify certain model parameters. In the work presented here, the most important parameter is the Passenger Exit Delay Time. This time represents two stages of the exiting process, the exit hesitation time and the exit negotiation time. In virtually all cases, the passengers exhibit a hesitation at the exit, before negotiating it. Typically, this starts when an out-stretched hand first touches the exit. The latter time considers the amount of time taken to pass through the exit.

In general, the exit hesitation time is due in main to passengers either waiting at the exit for the path to clear and/or contemplating how to negotiate the exit. In either case, the exit negotiation stage does not usually start until there is space for it to commence. Furthermore, the process of passing through the exit and travelling from the exit to the ground are considered as separate events that can occur in parallel.

Within airEXODUS the exit delay time distribution is segmented into subintervals described by uniform distributions. The technique is dependent on the user having a good representation of the actual delay time distribution. In the current version of the software this data is extracted from past certification trials [23]. For example, consider main deck Type-A exits with assertive cabin crew. Data from 11 previous certification tests involving Type-A exits with assertive cabin crew was available. The data was derived from the following aircraft: A310 (255 passenger), A310 (280 passenger), B747, B747-300, B747-SR, B767-300, B767-346, B777-200 (420 passenger), B777-200 (440 passenger), DC10 and MD11 [23]. In total, passenger exit delay time data from 20 exits representing some 2078 paxs is used to define the passenger exit delay time distribution.

The outcome of aircraft evacuations is highly dependent upon the presence and behaviour of cabin crew. While cabin crew are not modelled explicitly in the current version of airEXODUS, the varying effects produced by their actions may be simulated. These effects may be simply classified into two categories, Passenger Exit Selection and Exit Performance.

- **Effect of Cabin Crew on Passenger Exit Selection:** The effect of cabin crew on passenger exit choice can be profound. Data from aircraft accident reports, 90 second tests and full scale experimentation, suggests that sufficiently assertive cabin crew can redirect passengers from their nearest exits to others, thereby increasing their travel distance dramatically. The overall effect of this behaviour is to change the number of passengers using each exit. This effect is modelled in airEXODUS through the use of exit potentials.
- **Effect of Cabin Crew on Exit Performance:** It has been shown that the flow performance through various aircraft exits may be enhanced by cabin crew displaying assertive behaviour, i.e. encouraging passengers to travel through the exit with more speed [23,24]. Analysis suggests that the degree of assertiveness influences the number of passengers displaying slower delay times [23]. It is possible to model this effect by altering the passenger exit delay time distribution. To aid this process, airEXODUS supplies a range of default values based on the assertiveness level of the cabin crew. This data is based on information derived from past certification trials and includes Type A, Type I and Type III exits [23].

Associated with the development of airEXODUS is the need for comprehensive data collection/generation related to human performance under evacuation conditions. Three forms of existing data are being used as the source of the required information. Aircraft accident human factors reports produced by for example the NTSB and the AAIB [25], 90-second certification data generated by the aircraft manufacturers [23], and large-scale experimentation devised to answer operational questions [24].

4.0 airEXODUS VALIDATION STUDIES

airEXODUS has been used to simulate evacuation trials conducted at Cranfield University in their B737 cabin simulator [11,24]. In addition, a more challenging validation exercise was requested by the UK CAA, requiring airEXODUS to predict the performance of a modified Boeing B767 aircraft, (designated the B767-304ER), *prior to the actual test*, in order to establish the predictive capabilities of airEXODUS for 90 second certification trials. A confidential report [26] containing details of the model formulation and results of the simulations was produced by FSEG and distributed to the UK CAA and US FAA prior to the trial, and Boeing after the trial. A description of the results of the airEXODUS predictions may be found in [11].

In order to better assess the airEXODUS predictive capabilities, the UK CAA have sponsored systematic validation exercise involving past certification data. The certification exercise makes use of past wide and narrow body aircraft certification data. In this paper we summarise the results of a selection of the wide body results.

4.1 Relevant airEXODUS parameters.

Several airEXODUS parameters will be frequently referred to in this study. These are: Total Evacuation Time (TET), Personal Evacuation Time (PET), Cumulative Wait Time (CWT), Exit Ready Time, Passenger Exit Delay Time, and Off Time. The meaning of these terms is briefly explained below.

The TET is a measure of the evacuation time for the aircraft. It is measured from the start of the evacuation to when the last passenger exits the aircraft. A single TET is determined for each evacuation simulation. The evacuation of cabin crew is not modelled in these simulations. The Off-Time is the time required for the passenger to reach the ground once they have mounted the slide. Like the passenger Exit Delay Time, this is derived from certification data. However, in the present study, this is not used. If on-ground times are desired, a suitable slide time can be added to the TET. Thus, the TET parameter represents the time at which the last passenger evacuates the aircraft cabin.

PET is a measure of an individual's evacuation time. It is measured from the start of the evacuation to when the passenger has exited the aircraft. A PET is determined for each passenger in the evacuation simulation. The CWT measures the total amount of time a passenger has spent in congestion. This is measured after the passenger has completed their Response Time to when the passenger has exited the aircraft. This can include time spent in the seat row attempting to get into the aisle, time spent stationary in the aisle and time spent queuing at the exit. A CWT is determined for each passenger in the evacuation simulation.

The Exit Ready Time represents the time required by a crewmember or passenger to render the exit escape system ready for use. The Passenger Exit Delay Time parameter has already been discussed. In these simulations, generalised data has been used for both these parameters. This represents an “average” setting that has been derived from the study of past certification trials [23].

Finally, airEXODUS is stochastic in nature. This means that every time a simulation is repeated a slightly different evacuation time will result, as the individual passengers are unlikely to exactly repeat their actions. In addition, as the passenger Exit Delay Time is randomly attributed according to the specified distribution, passengers will not necessarily incur the same Exit Delay Time on exiting the aircraft in subsequent simulations. For this reason, it is necessary to repeat a simulation numerous times in order to generate a distribution of results. For the results presented here, each simulation case was run 1000 times by airEXODUS to capture stochastic variations.

4.2 The Validation Cases

In this paper we present a summary of the results for four wide body aircraft. Three of these aircraft belong to a “family” of derivative aircraft.

The first aircraft, denoted Case 1, contained 256 passenger seats and three exit pairs. One exit from each exit pair was disabled for the certification trial. Type-A exits were positioned at either end of the passenger cabin sections (identified as R1 and R3). A further pair of Type-III over wing exits accessible over seating was located at approximately the centre of the cabin section, approximately in line with the wing (identified as L2). In the certification trial, the TET achieved for this aircraft (i.e. time for the last passenger to exit the aircraft) was **83.7** seconds. The last passenger exited via the R1 exit. The second aircraft, denoted Case 2, seated 285 passengers. One exit from each exit pair was disabled for the certification trial. Type-A exits were located at both the forward and aft end of the cabin section and are labelled R1 and R4. Two Type-III over wing exits were positioned in the centre of the cabin section and are labelled R2 and R3. In the certification trial, the TET achieved for this aircraft was **72.6** seconds. The last passenger exited via the R1 exit.

The third aircraft, denoted Case 3, seats 351 passengers. The aircraft contains four pairs of exits. One exit from each exit pair was disabled for the certification trial. Type-A exits were positioned forward and aft of the cabin section and are labelled R1 and L4. A canted Type-A exit was positioned just before the leading edge of the wing and was labelled R2. A Type-I exit was positioned just after the trailing edge of the wing and was labelled L3. In the certification trial, the TET achieved for this aircraft was **71.7** seconds. The last passenger exited via the R1 exit. The forth aircraft, denoted Case 4, contained 440 passenger seats and four pairs of Type-A exits. From forward to aft the exits were labelled L1-L4. One exit from each exit pair was disabled for the certification trial. In the certification trial, the TET achieved for this aircraft was **74.4** seconds. The last passenger exited via the L1 exit.

Case 1 to Case 3 represent the derivative family of aircraft, while Case 4 represents an unrelated aircraft type.

4.3 Model Specification

As CAD DXF files were not available for these aircraft, each aircraft geometry was constructed manually using schematic drawings. While airEXODUS has the ability to represent “extreme” passenger behaviour of the type reported in actual aviation accidents [25], such as seat jumping, this type of behaviour is not included in these simulations. All the cases considered here are run under certification type evacuation conditions involving:

(i) Half the total number of aircraft exits,

(ii) Assertive cabin crew located at each Type-A exit,

(iii) Orderly passenger behaviour of the type found in certification evacuations,

(iv) Each exit being made ready in a representative time derived from past relevant certification tests.

The population used in the simulations complies with FAR requirements for certification testing. Passengers defined in airEXODUS are created using the 90-second Population function available in the software. This function generates the required numbers of passengers according to the specified mix (in terms of age and gender) as set out in FAR.

An optimal distribution of passengers to each exit was determined for all of the aircraft considered in this paper. In this way the model was configured so that it was likely that an optimal evacuation would be achieved. Thus, the results presented here are considered to be ***the best results possible*** for the aircraft under consideration, similar to that which can be expected in certification trials.

4.4 Model Results and Discussion

While each certification trial is performed only once, each airEXODUS simulation of a given configuration and scenario is repeated 1000 times. This produces a distribution of results for each aircraft and each scenario considered. In reality, a similar distribution of results would be produced for each of the actual certification exercises had they been repeated a number of times. However, as only one trial is performed only a single data point is available to represent the (unknown) certification distribution. This single data point could fall anywhere on the (unknown) certification distribution, it does not necessarily represent the mean of the distribution.

The distributions of results for the four cases considered in this paper are depicted in Figure 2 (solid lines). The predicted distributions are generally “pseudo normal” in nature with a tendency to produce several outliers in the tail leading to long evacuation times. Also depicted are the certification trial results achieved for each aircraft configuration (vertical dashed lines). As can be seen, in each case the trial result falls within the relevant predicted distribution.

The differences between the airEXODUS mean TET and the evacuation time of the certification trials is shown in Table 1 and Table 2. As can be seen, the difference between the predicted mean TETs and that measured in the certification trials range from **0.8%** to **4.7%** (0.5 to 3.5 seconds). Two of the cases generated mean TETs that were very close to the TET of the certification trial, i.e. **1.2%** (1.0 seconds) and **-0.8%** (-0.5 seconds). The remaining two cases were within **4.7%** of the measured result, namely **4.7%** (-3.5 seconds) and **4.7%** (3.4 seconds). The mean absolute difference across all cases was **2.8%** (2.1 seconds).

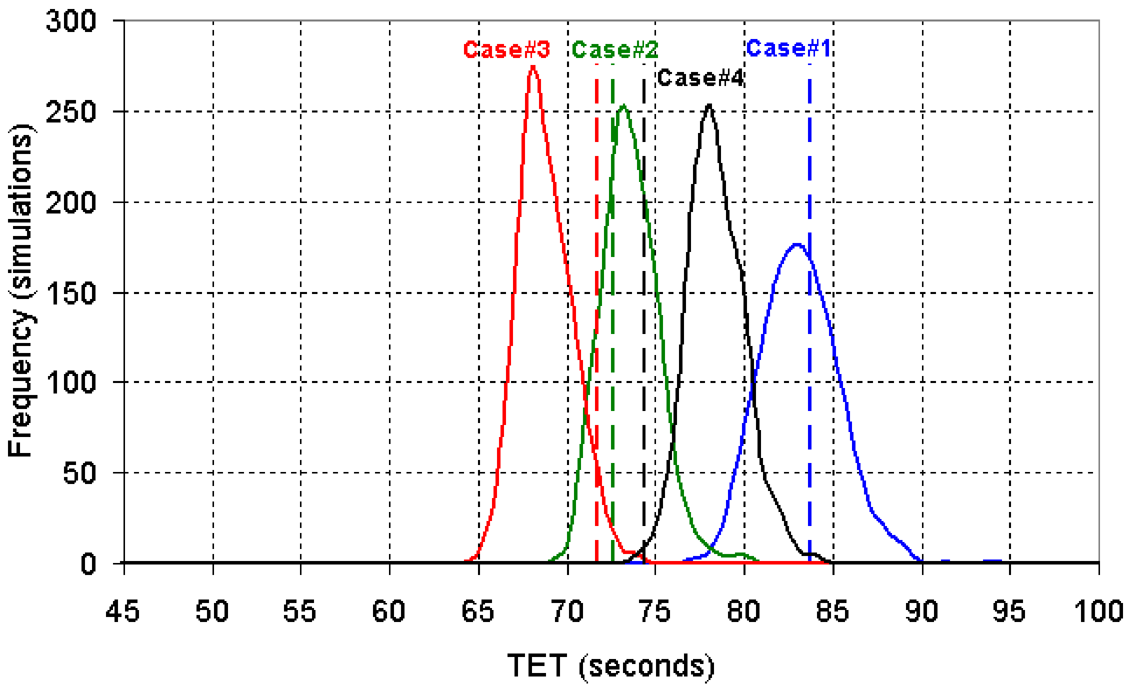


Figure 2: The frequency distributions of Total Evacuation Times (s) for the four wide body aircraft. (Continuous lines airEXODUS predictions, dashed line represents time achieved in trial).

Table 1: Trial and airEXODUS results and rank order for certification trial cases 1-4

Case / Aircraft	Trial Result (secs)	airEXODUS mean (secs)	Trial rank	airEXODUS rank
Case 1	83.7	82.7	4	4
Case 2	72.6	73.1	2	2
Case 3	71.7	68.3	1	1
Case 4	74.4	77.9	3	3

Examination of the results in Table 1 indicate that airEXODUS has correctly ranked the various aircraft in order of evacuation speed. The derivative family of aircraft (Case 1 to Case 3) are correctly ranked with the Case 1 being the slowest of the three aircraft and Case 3 being the fastest of the three aircraft. Furthermore, when the unrelated aircraft (Case 4) is compared with the derivative aircraft, it is correctly predicted to fall between Case 1 and Case 2 and produces the second slowest evacuation time.

To summarise, airEXODUS is able to predict the results of the certification trials with reasonable accuracy, the mean absolute difference between the distribution means and the trial result being 2.8%. In all of the cases examined, the measured evacuation time of the certification trial is within the bounds of airEXODUS predictions. Furthermore, the general rank order of evacuation times achieved in the trials is also predicted by airEXODUS.

Table 2: Summary of comparisons between the certification trial results and airEXODUS predictions

	Case 1	Case 2	Case 3	Case 4	Mean absolute difference
airEXODUS mean from trial TET (%)	1.2%	-0.8%	4.7%	-4.7%	2.8%
airEXODUS mean from trial TET (secs)	1.0	-0.5	3.4	-3.5	2.1
Trial TET within bounds of airEXODUS TETs	YES	YES	YES	YES	N/A
Number of simulations in excess of 90 seconds (simulations)	3	Nil	Nil	Nil	N/A
Number of simulations in excess of 90 seconds (%)	0.3%	Nil	Nil	Nil	N/A
Distance between 90 second and airEXODUS mean (standard deviations)	3.3	Nil	Nil	Nil	N/A

The above comparisons are based on essentially a single event, the time for the last passenger to exit the aircraft. A more meaningful comparison is based on the cumulative exit times for each passenger. For the certification trials this is determined from the video record of the actual trial [23]. This produces a continuous curve representing the cumulative number of passengers to exit the aircraft during each second of the evacuation (see *Figure 3*). A similar curve is produced for each of the 1000 airEXODUS simulations. Rather than show each of the 1000 predicted curves, the predicted cumulative exit window is depicted in *Figure 3* along with the median of the predicted curves. The window represents the maximum and minimum number of passengers to have exited the aircraft in each second. As such it represents the natural variation in the number of passengers that can be evacuated for this scenario at each second. Depicted in this figure are the relevant curves for Case 2. The other three cases produce essentially similar results.

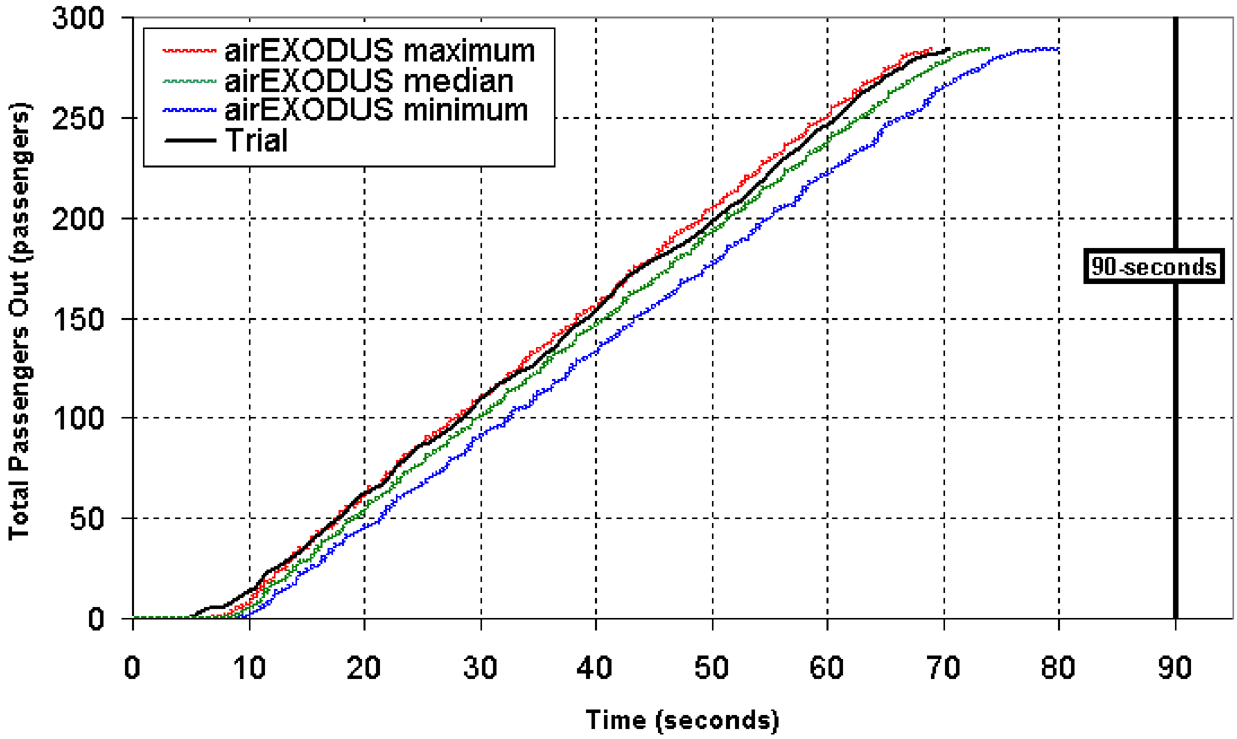


Figure 3: Cumulative exit times for CASE 2 trial result (Black) and predictive envelope created from airEXODUS simulations.

As can be seen, initially there is a period during which no passengers evacuate whilst the doors are readied for use. This is typically followed by a short period during which the passenger flow is established. This is marked by the rapid initial increase in gradient at around 10 seconds. Very quickly the exits are at near maximum flow capacity, indicate in *Figure 3* by a near constant positive gradient. This state persists for the majority of the evacuation. Near the end of the evacuation, when the supply of passengers to exits begins to diminish, the gradient also begins to diminish. The flow terminates when there are no more passengers to evacuate.

From Figure 3 it is clear that the airEXODUS predicted curves have a similar structure to the curve derived from the certification trial. This suggests that airEXODUS is predicting a similar chain of events to that which occurred during the certification trial. Furthermore, with the exception of the start up portion (approximately the first 10 seconds), the trial curve falls within the airEXODUS generated window throughout the trial. The start up differences are due to the exit ready time of the trial not corresponding precisely to that used in the simulation.

5.0 EXIT SEPARATION ANALYSIS

The purpose of this study is to take the first step in a systematic study of exit separation and evacuation efficiency. The study makes use of the evacuation modelling tool airEXODUS to define the scenarios, describe the evacuation dynamics and human behaviour. As in any experimental or theoretical study involving human behaviour, the numerical results and conclusions quoted in this study are very much dependent upon the scenarios posed, in terms of passenger abilities, cabin section layout and passenger behaviour. Different evacuation times may result if different parameters and different scenarios are examined. Indeed, it should be noted that this study is restricted to passenger behaviour observed during ***certification type evacuation conditions***. Therefore, while the precise nature of the numerical results are not considered important in themselves, the overall trends in the results are of more importance. Needless to say, the main conclusions from this study can be substantiated through targeted experimental trials. Finally, the results described in this section are a summary of a more detailed report [14].

5.1 The Scenarios Described

To investigate the impact of exit separation on evacuation efficiency we define an aircraft test section that represents a "typical" section of a wide-body aircraft located between two pairs of main deck Type-A exits (see Figure 4). The study is limited to scenarios in which half the provided exits are made available for the evacuation. This situation is consistent with FAR regulations for full-scale evacuation certification.

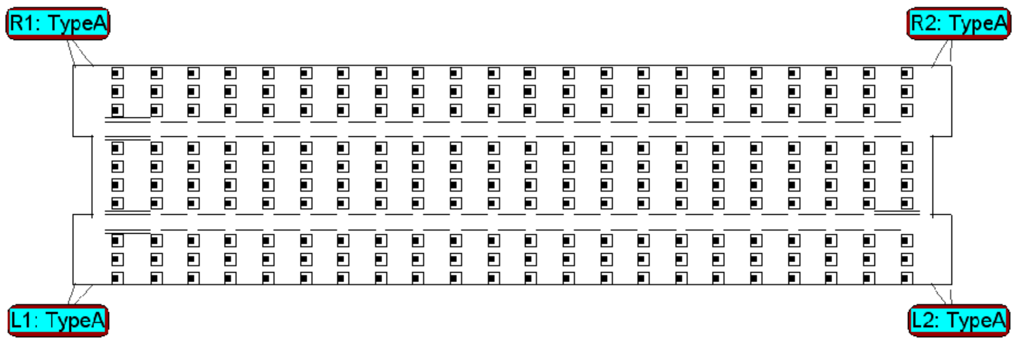


Figure 4: The airEXODUS representation of the base-case cabin section geometry

In the current investigation only the central section is considered. In this way we limit the passenger flow into each exit to be made up of two components: the flow from the aisle closest to the exit and the cross aisle flow. This represents the simplest possible combination to occur in a wide body aircraft. Indeed sections of this type may be found on current wide body aircraft. A total of 220 passenger seats are located between the two pairs of exits. This is the maximum number of passengers, under FAR, that can be accommodated when two pairs of Type-A exits are provided.

The base-case model will simulate a regulatory compliant cabin section. The door to door distance in the base-case, measured from the centre of each door, is 18.1 metres or 59 ft 4 inches. This conforms to FAR 25.807.(f)(4) and is therefore regulatory compliant.

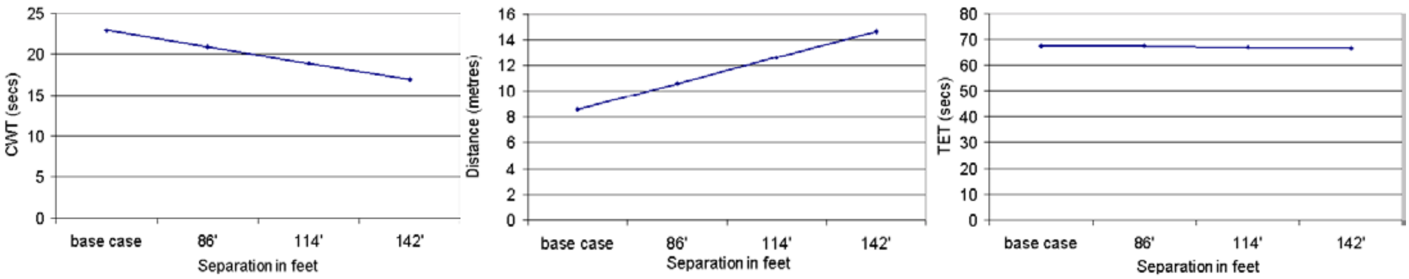
Each row of seating is arranged from left to right as follows: three seats, an aisle, four seats, an aisle, and three seats. Each row of seating contains 10 seats. There are 22 rows of seating in the cabin section. Each Type-A exit is linked to a clear space vestibule area. The vestibule area is of sufficient size to allow six passengers to pack into it with another two passengers in the main aisle space adjoining the vestibule. A small cross-aisle joins the two main aisles and forward vestibule areas. The initial row of seating has direct access to the forward vestibule and cross aisle. The cross-aisle is sufficiently deep to allow a single passenger to stand in the aisle and sufficiently wide to allow a total of four passengers to be accommodated between the main aisles. A similar cross-aisle and vestibule area exists at the rear of the cabin section. The base case is then stretched to construct several other cabin sections with longer door to door distance while maintaining the number of seats and passengers.

As this is a theoretical exercise, some of the exit separations will be increased beyond limits that may be considered practical. This is done in order to derive a theoretical understanding of the relationship between exit separation and evacuation efficiency for a fixed number of passengers. In the results presented here a total of 13 exit separations are considered ranging from the base-case of 59’5” (18.1m) to 390’2” (118.9m). In these scenarios the R1 and R2 exits will be made available. All the cases considered here are run under certification type evacuation conditions as described earlier. Similarly, the population are considered to represent a typical certification mix of people.

5.2 Results and Discussion

The first four simulations consider cabin sections ranging from 60 to 142 feet (see Figure 5). It can be seen in that as the size of the stretch increases, the average amount of time passengers waste in congestion decreases from **22.9** seconds in the base-case to **16.9** seconds. This suggests that the level of congestion is decreasing as the length of the cabin section is increased. This point is illustrated in Figure 4(a), which plots the average CWT for each simulation run. Similarly, we note that as the size of the stretch increases, the average distance travelled by the passengers increases from **8.6** m in the base-case to **14.6** m. This is graphically represented in Figure 4 (b).

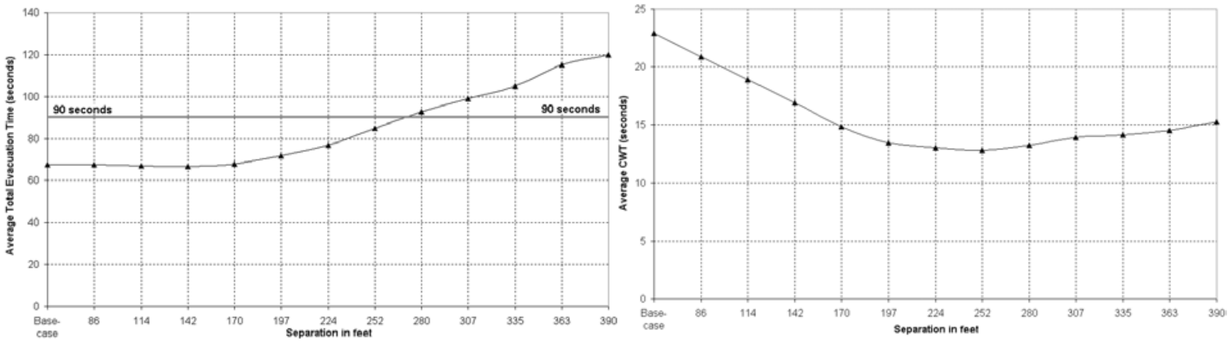
As the distance between the exits increases, on average passengers must travel further to evacuate. While this results in an increase in movement time this is compensated for by an equivalent reduction in the levels of congestion encountered, resulting in both the personal evacuation time (PET in airEXODUS) and the total evacuation time (see Figure 4 (c)) remaining unchanged. In these cases, stretching the cabin section has no significant impact on the overall evacuation time (i.e. TET) and, more importantly, from an individual passengers perspective the average time required for a passenger to evacuate (i.e. PET).



(a) **(b)** **(c)**

Figure 5: Results from stretched cabin sections showing (a) the average CWT, (b) the average travel Distance and (c) Total Evacuation Time as a function of exit separation (60 to 142 feet)

If we continue to stretch the cabin section we find that the TET remains approximately constant at **67** seconds until the exit separation exceeds **170** feet. At this point the TET starts to rise as the cabin section is further stretched (see Figure 6).



(a) **(b)**

Figure 6: ***Results from stretched cabin sections showing (a) TET as a function of exit separation and (b) Average CWT as a function of exit separation (60 to 390 feet).***

With a mixed ability population, as the exit separation is gradually increased from **60** feet up to **170** feet, the total evacuation time remains essentially unchanged (see Figure 6a). This is due to the increase in travel distance being off-set by the reduction in exit queue congestion experienced by the passengers as they take longer to reach the exit. As the exit separation increases beyond **170** feet, the TET begins to increase (see Figure 6a). The levels of congestion within the cabin are now no-longer sufficient to balance the increase in travel distance and so the TET begins to increase. However, we note that the congestion levels experienced by the passengers in these certification type evacuations has not decreased to near zero (see Figure 6b). This somewhat counter intuitive result is thought to be due to sub-queue formation (see [14] for details). Sub-queues are formed when people of mixed abilities travel long distances. The slower people at the head of the queue effectively cause a delay for the faster people caught in the queue behind them.

These results suggests that for ***these configurations*** and ***under certification type conditions*** an exit separation of **170** feet is the **'practical exit separation threshold'** that cannot be exceeded without an adverse effect on evacuation times. This is not to say that in designing a "safe" aircraft it is acceptable to have exit separations greater than 60 feet. Other factors apart from evacuation time under the current FAR 25.803 evacuation scenario should be considered when determining maximum exit separations.

The intuitive feeling that exit separation is an important parameter in determining aircraft evacuation efficiency has been substantiated. However, this work has revealed that there is a complex relationship between the two. Indeed, other factors such as exit flow rate and exit availability have been shown to exert a strong influence on the critical exit separations [14]. By implication, the number of passengers located between the two exits is also an important parameter as it will obviously influence the levels of congestion. (see [14] for a detailed discussion). These results suggest it is not advisable to mandate a maximum exit separation without taking into consideration exit type, exit availability, occupancy load and aircraft configuration. This has implications when determining maximum allowable exit separations for wide and narrow body aircraft. It is also relevant when considering the maximum allowable separation between different exit types on a given aircraft configuration.

6.0 COMMENTS ON CERTIFICATION APPLICATIONS OF EVACUATION MODELLING SOFTWARE

Before computer models can reliably be used for certification applications they must undergo a range of validation demonstrations. While validation will never prove a model correct, confidence in the models predictive capabilities will be improved the more often it is shown to produce reliable predictions. The work presented in this paper and in earlier studies (e.g. references [11] and [26]) contributes to the validation history of the airEXODUS evacuation model. The success of the airEXODUS evacuation model in predicting the outcome of previous 90-second certification trials are compelling arguments of the suitability of the model for evacuation certification applications - at least for derivative aircraft. For aircraft involving truly 'new' features it is expected that evacuation models in conjunction with component testing of the new feature will be necessary. Examples of new features include a new exit Type or an established exit configuration placed at a sill height surpassing that previously used. In both these examples it is assumed that sufficient data does not exist that would allow a reliable representation within the evacuation model. In these cases, the combination of computer model and component testing offers a sensible and reliable alternative to full-scale live evacuation trials.

However, it is not sufficient to simply replace full-scale testing of aircraft with a combination of computer modelling and component testing. While this may make testing the aircraft a safer and more efficient process, can we also make the aircraft itself safer by design? If we are to rise to this challenge it is essential that we begin to question some of our current preconceptions concerning certification.

Evacuation models have the capability of examining many different types of evacuation scenario. What scenario should be considered for certification by computer model? Should the current certification scenario be maintained or should a range of scenarios be considered? Perhaps a selection of the most likely evacuation scenarios should be considered or simply the most severe likely evacuation scenario? The selection of suitable evacuation scenarios could be guided through analysis of past accident data [25]. For example, the analysis of past accidents can suggest which exit combination is most likely to occur. This could be used to assist in selecting the number and location of exits to assess in the certification trial.

Furthermore, unlike full-scale testing, evacuation models allow the possibility of performing many repeat simulations for any particular scenario thereby producing a range of results for any given scenario or collection of scenarios (as shown in this paper). Indeed, it may even be argued that rather than simply testing a single interior layout configuration, each layout flown by a carrier should be tested by computer simulation.

Regardless of the accident scenario selected for certification testing, how do we determine that an aircraft has met the pass/fail criteria, how do we establish the "deemed to satisfy" requirement? For a particular scenario should the requirement stipulate that ***every*** simulation be sub-90 seconds? Or should the distribution mean or the 95 percentile result be sub-90 seconds?

Consider the example provided by Case 1 in section 4.4. In this example the aircraft achieved an actual certification performance of 83.7 seconds with a mean predicted evacuation time of 82.7 seconds (see *Table 1*). While these times represent the out of aircraft time for the passengers, the actual certification on-ground time for the passengers and crew was such that the aircraft clearly passed the certification requirement. However, examination of *Table 2* reveals that of the 1000 simulations, three or 0.3% are predicted to marginally fail the certification requirement. If the median rule (i.e. 50% less than 90 seconds) or the 95% rule were adopted the aircraft would clearly satisfy these requirements and be considered acceptable. However, if the 100% requirement were adopted the aircraft would not be considered acceptable. As this aircraft is considered to be acceptable (on the basis of the single actual certification trial result) perhaps the deemed to satisfy limit should be placed at 99.7%? If this general approach were considered viable, it would require all of the past aircraft that have undergone the certification process to be assessed using computer simulation and a suitable acceptance level derived from this analysis.

Any aircraft configuration will produce a range of evacuation times over a number of tests, some of which may well be over the 90 seconds. Under the current 'make or break' single test regime, a single performance result is selected from this 'unknown' distribution of possible evacuation times and put forward as the certification performance. The aircraft will pass as long as the result is below the 90 second threshold. It is impossible to know whether or not the outcome is a fair reflection of the aircraft's evacuation capability. In contrast, the multiple tests enabled by computer simulation generate a distribution of times, reflecting what would happen if the full-scale evacuation could be repeated. It has been argued by some that to achieve parity with the current certification process, 100% of the generated simulations should produce times less than 90 seconds to pass. Clearly, this would not achieve parity with the current certification process.

For those who which to achieve some form of parity with the current certification process, an alternative approach may be to generate only a single evacuation time from the modelling analysis. As part of this methodology it would still be necessary to first generate the evacuation time distribution using many repeat simulations. This would generate the probability space of possible evacuation times for the aircraft configuration under the selected certification scenario. From this probability distribution a single evacuation time would be selected at random and deemed to be the certification performance of the aircraft. This in essence is equivalent to the current practice of performing only a single trial for certification. Using this approach the same acceptance criteria could be applied to the numerically generated certification time as that applied to the full-scale trial generated certification time. In this way, the modelling process would replicate the current certification process where only a single evacuation time is put forward and so provides a means to circumvent the need to re-define acceptable performance. However, a significant downside of this methodology is that a considerable amount of potentially useful information regarding the performance of the aircraft is disregarded. Rather than attempting to achieve parity with the current standard the industry should be endeavouring to produce a more meaningful measure of aircraft evacuation performance.

This discussion raises the question, does the "magic number" 90 seconds have any actual meaning under these circumstances? Internationally, throughout the building industry, similar issues are being addressed through the replacement of the old prescriptive building requirements with performance based regulations. Prescriptive building regulations the world over suggest that if we follow a particular set of essentially configurational regulations concerning travel distances, number of exits, exit widths, etc it should be possible to evacuate a building within a pre-defined acceptable amount of time. In the U.K. for public buildings this turns out to be the "magic number" 2.5 minutes. Part of the risk analysis process involves the concept of the Available Safe Egress Time or ASET and Required Safe Egress Time or RSET. For a particular application the ASET may be based on the time required for the smoke layer to descend to head height while the RSET may be the time required for the occupants to vacate the structure. Put simply, the ASET must be greater than the RSET. The circumstances of the scenario under consideration dictate both the ASET and RSET and several scenarios may need to be examined before any conclusions can be reached. As part of this risk analysis process credible fire scenarios (including fire loads, fire evolution, fire size etc) are postulated along with credible evacuation scenarios (including number and type of people, occupant response characteristics, etc). Computer based evacuation and fire models are being used to assist in the determination of both the ASET and the RSET. In this way evacuation models are providing a means by which the complex interacting system of structure/environment/population can be assessed under challenging design scenarios. A similar approach should be considered for aviation.

7.0 CONCLUSIONS

We have demonstrated that airEXODUS is able to predict the results of four certification trials with reasonable accuracy, the mean absolute difference between the distribution means and the trial result being 2.8%. In all of the cases examined, the measured evacuation time of the certification trial is within the bounds of airEXODUS predictions. In addition, the general rank order of evacuation times achieved in the trials is also predicted by airEXODUS. Furthermore, the cumulative exit curves produced during each of the trials falls within the predicted window produced by airEXODUS. This suggests that not only is airEXODUS producing a reasonable approximation to the total evacuation time, it is also predicting a similar chain of events to that which occurred during the certification trials.

airEXODUS was also used to examine issues concerning the maximum exit separation. A main finding of this work is that for the ***population and cabin section investigated and under certification conditions***, exit separations of **60** to **170** feet will result in approximately constant total evacuation times and personal evacuation times. This suggests that with this cabin section under these conditions, an exit separation of **170** feet is the **'*practical exit separation threshold*'** for Type-A exits that cannot be exceeded without an adverse effect on evacuation times.

This is not to say that in designing a "safe" aircraft it is acceptable to have exit separations greater than 60 feet. Other factors apart from evacuation time under the current FAR 25.803 evacuation scenario should be considered when determining maximum exit separations. For instance, passenger disability, the presence of fire and smoke, the orientation of the aircraft, changes in passenger behaviour associated with these hazards, reduced passenger numbers are important parameters that need to be taken into consideration. To correctly take all these factors into consideration when designing and approving new aircraft types requires a performance based regulatory environment that takes a holistic view of safety rather than the existing piece meal prescriptive environment.

It has been suggested in this paper that evacuation models offer a possible alternative to the current practice of performing a single evacuation demonstration with live people. While the introduction of computer models for aircraft evacuation will potentially solve some of the existing difficulties and shortcomings posed by current certification testing, it will introduce new questions, pose new challenges and offer new opportunities that need to be addressed. However, by addressing these new challenges we may achieve our goal of producing safer aircraft.

Furthermore, the challenge facing regulators and approval authorities is to develop an understanding of the modelling technology being developed and with that understanding specify relevant design protocols and standards. It is hoped that industry and regulatory authorities will explore these issues as they hold the potential to make an already safe form of transport safer by design and assist in removing some of the "magic" from the "magic numbers" that plague safety analysis.

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