Presented at the International Fire & Cabin Safety Research Conference Atlantic City 29 Oct – 1 Nov 2007

INVESTIGATING THE IMPACT OF EXIT AVAILABILITY ON EGRESS TIME USING COMPUTER BASED EVACUATION SIMULATION

E.R.Galea, M. Togher and P.J. Lawrence
Fire Safety Engineering Group
University of Greenwich
London SE10 9SL, UK
http://fseg.gre.ac.uk

ABSTRACT

This paper examines the influence of exit availability on evacuation time for a narrow body aircraft under certification trial conditions using computer simulation. A narrow body aircraft which has previously passed the certification trial is used as the test configuration. While maintaining the certification requirement of 50% of the available exits, six different exit configurations are examined. These include the standard certification configuration (one exit from each exit pair) and five other exit configurations based on commonly occurring exit combinations found in accidents. These configurations are based on data derived from the AASK database and the evacuation simulations are performed using the airEXODUS evacuation simulation software. The results show that the certification practice of using half the available exits predominately down one side of the aircraft is neither statistically relevant nor challenging. For the aircraft cabin layout examined, the exit configuration used in certification trial produces the shortest egress times. Furthermore, three of the six exit combinations investigated result in predicted egress times in excess of 90 seconds, suggesting that the aircraft would not satisfy the certification requirement under these conditions.

1.0 INTRODUCTION

The evacuation certification trial (see FAR 25.803 [1]) is the aviation industry benchmark of aircraft evacuation performance, and rightly or wrongly, is considered by the travelling public and safety professionals alike as the ultimate kite-mark of evacuation safety. However, for the benchmark to be effective it should serve as an indicator of safety, and to do so the benchmark should be both as representative of reality and challenging as practical.

While it is acknowledged that in the interests of safety it is not desirable or possible to make the evacuation certification trial closely resemble real accident situations, it is possible and indeed essential that the exit availability resemble as closely as possible challenging exit configurations likely to be found in accident scenarios. Furthermore, while it is true that no two accidents are alike, it is possible to investigate statistical data and identify frequently occurring exit combinations and from these select the most challenging exit combinations to use in evacuation certification analysis.

In the evacuation certification trial half the exits are usually made inoperative and usually all or the majority of the serviceable exits are on one side of the aircraft. Why half the exits, why generally on one side and why one exit in each exit pair? It is a commonly held (and not unreasonable) belief by safety professionals that this exit configuration is selected because it is most frequently found in survivable accident situations or that it is the most challenging evacuation exit configuration.

While the origins of this particular part of the evacuation certification demonstration are not clear, it possibly stems from the belief that in a crash/emergency situation fire is most likely to occur on one side of the aircraft (e.g. due to ruptured fuel lines/wing tank) and so it would be reasonable to assume that the exits on that side of the aircraft would be unavailable. Furthermore, the regulatory community would (rightly) argue that the evacuation demonstration is not intended to represent a real situation, but is intended to be a benchmark examination of evacuation performance allowing both absolute (i.e. better than 90 seconds) and relative (i.e. one aircraft configuration against another) performance. While it is understood that the evacuation certification trial is intended to benchmark aircraft evacuation performance, this does not mean that the selected benchmark evacuation scenario should be both unrepresentative of real incidents and unchallenging in terms of required evacuation performance. For the benchmark to be effective it should serve as an indicator of safety, and to do so the benchmark should be as representative of reality as practical, taking into account relevant and challenging scenarios based on accident data.

In this paper we use the AASK database [2-8] to suggest likely exit combinations found in aviation accidents and then using the airEXODUS [9-12] evacuation model, identify the most challenging exit combinations.

2.0 The AASK database and airEXODUS evacuation model

Both the AASK database and the airEXODUS evacuation model have been described many times in the literature and so only a brief description is presented here.

2.1 The AASK Database

The Aircraft Accident Statistics and Knowledge (AASK) database is a repository of survivor accounts from aviation accidents conducted by investigative organisations such as the U.S. National Transportation Safety Board (NTSB) and the U.K. Air Accident Investigation Branch (AAIB). Its main purpose is to store observational and anecdotal data from the actual interviews of the occupants involved in aircraft accidents. The quality and quantity of this data is variable ranging from short summary reports of the accident to transcripts from most of the surviving passengers and crew involved in the accident. The database has wide application to aviation safety analysis, being a source of factual data regarding the evacuation process.

Work started on developing the AASK database in 1997 with support from the UK Engineering and Physical Sciences Research Council (EPSRC) and the UK Civil Aviation Authority (CAA). The most recent version of the database, AASK V4.0 [4-8] contains accounts from over 2000 survivors of aviation accidents. The database consists of four main components which address; the nature of the accident (105 accidents), accounts from surviving passengers (1917 passengers), accounts from surviving cabin crew (155 cabin crew) and information relating to fatalities (338 fatalities) [4-8]. AASK V4.0 contains information from 105 accidents and detailed data from 1917 passengers and 155 cabin crew, with information relating to some 338 fatalities. The accidents included in AASK V4.0 cover the period 04/04/77 – 23/09/99. Access to the database is available on-line at http://fseg.gre.ac.uk/aask/index.html. The database has a powerful query engine allowing investigators to mine the data.

2.2 The airEXODUS evacuation model

The airEXODUS aircraft evacuation model is part of a suite of software tools designed to simulate the evacuation of large numbers of people from a variety of complex enclosures. Development of the EXODUS concept began in 1989 and today, the family of models consists of buildingEXODUS, maritimeEXODUS and airEXODUS for the built, maritime and aviation environments respectively. airEXODUS is designed for use in aircraft design, compliance with 90-second certification requirements, crew training, development of crew procedures, resolution of operational issues and accident investigation.

The EXODUS software takes into consideration people-people, people-fire and people-structure interactions. It comprises five core interacting sub-models: the **Passenger, Movement, Behavior, Toxicity and Hazard** sub-models. The software describing these submodels is rule-based, the progressive motion and behavior of each individual being determined by a set of heuristics or rules. These submodels operate on a region of space defined by the **GEOMETRY** of the enclosure. The model tracks the trajectory of each individual as they make their way out through the geometry, or are overcome by fire hazards such as heat, smoke and toxic gases. Each of these components will be briefly described in turn.

The **GEOMETRY** of the aircraft can be defined manually or read from a Computer Aided Design using the DXF format. Internally the entire space of the geometry is covered in a mesh of nodes that are typically spaced at 0.5m intervals. The nodes are then linked by a system of arcs. Each node represents a region of space typically occupied by a single passenger. The **MOVEMENT SUBMODEL** controls the physical movement of individual passengers from their current position to the most suitable neighboring location, or supervises the waiting period if one does not exist. The movement may involve such behavior as overtaking, side stepping, seat jumping or other evasive actions. The **HAZARD SUBMODEL** controls the atmospheric and physical environment. It distributes pre-determined fire hazards such as heat, radiation, smoke and toxic fire gases throughout the atmosphere and controls the opening and closing times of exits. The **TOXICITY SUBMODEL** determines the effects on an individual exposed to toxic products distributed by the hazard submodel. These effects are communicated to the behavior submodel which, in turn, feeds through to the movement of the individual.

The **PASSENGER SUBMODEL** describes an individual as a collection of defining attributes and variables such as gender, age, maximum unhindered fast walking speed, maximum unhindered walking speed, response time, agility, etc. Each passenger can be defined as a unique individual with their own set of defining parameters. Cabin crewmembers can also be represented and require an additional set of attributes such as, range of effectiveness of vocal commands, assertiveness when physically handling passengers and their visual access within certain regions of the cabin. Some of the attributes are fixed throughout the simulation while others are dynamic, changing as a result of inputs from the other submodels. Passengers with disabilities may be represented by limiting these attributes.

The **BEHAVIOUR SUBMODEL** determines an individual's response to the current prevailing situation on the basis of his or her personal attributes, and passes its decision on to the movement submodel. The behavior submodel functions on two levels, global and local. The local behavior determines an individual’s response to the local situation e.g. jump over seats, wait in queue, etc while the global behavior represents the overall strategy employed by the individual. This may include such behavior as, exit via the nearest serviceable exit, exit via most familiar exit or exit via their allocated exit. The local behaviour of the passenger may also be affected through the intervention of cabin crew. As certain behavior rules e.g. conflict resolution and model parameters e.g. passenger exit hesitation times, are probabilistic in nature, the model will not produce identical results if a simulation is repeated. In studying a particular evacuation scenario, it is necessary to repeat the simulation a number of times in order to produce a distribution of results.

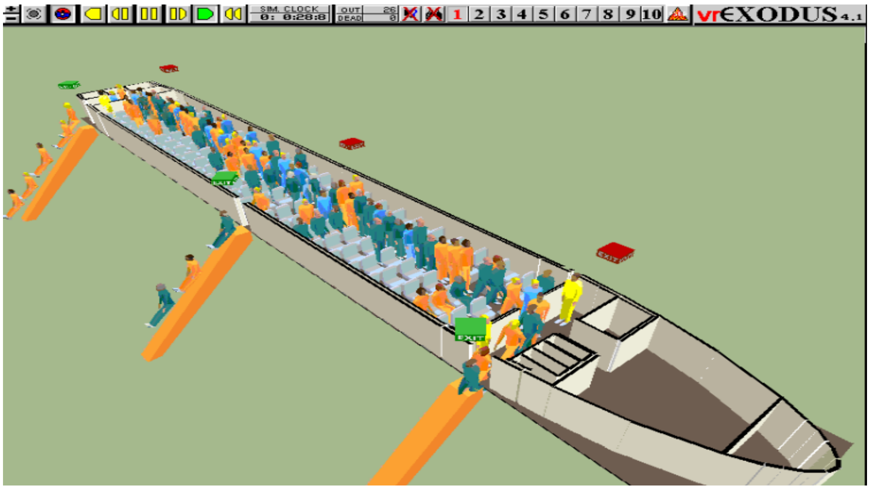


Figure 1: airEXODUS evacuation simulation depicted in the vrEXODUS software

3.0 Exit availability analysis conducted using AASK

A full account of the analysis of exit availability in aircraft accidents presented in this section may be found in [8]. Here we present a summary of the analysis and the main conclusions. As part of this analysis it is essential to define what is meant by an available exit. In this analysis an exit is considered to be ‘available’ when the exit and its evacuation assist means are physically and fully/safely functional, and passengers are permitted to use it by the crew. In addition, exits which may not meet the specified criteria, but which were actually used by at least one passenger are also considered to be ‘available’. Furthermore, here we consider exit availability as a function of the total number of exits on board the aircraft, irrespective of the exit position (e.g. forward, aft, left, right) or whether exits are associated with exit pairs or are single exits.

Incidents within the database which are classed as precautionary evacuations or post-incident deplaning are not included in this analysis. The analysis does include planned and unplanned emergency evacuations and can include situations in which the aircraft was involved with fire, partially or fully immersed in water or suffered a cabin rupture. Here the results for aircraft with three exit zones are presented however, an analysis involving aircraft with four exit zones may also be found in [8].

Within AASK V4.0, 42 accidents were found to meet the criteria, 31 accidents involving aircraft with three exit zones and 11 accidents involving aircraft with four exit zones.

In contrast to the evacuation certification requirements, the AASK V4.0 study suggests that a third (33%) of the emergency evacuations examined involve aircraft in which less than 50% of the exits are available (see Table 1). In addition, the data suggests that the available exit distribution for small (i.e. aircraft with three exit zones) and large aircraft (i.e. aircraft with four exit zones) is different with smaller aircraft having a greater tendency than larger aircraft to have less than 50% of their exits available during an emergency evacuation. Furthermore, the accident analysis suggests that over half (55%) of the accidents investigated involve a cabin section in which no exits were available [8].

Table 1: Availability of exits in planned and unplanned emergency evacuations [8]

Type of Accident	Less than 50% of exits available	Exactly 50% of exits available	Greater than 50% of exits available
Aircraft involving 3 exit zones.	**36%**	**19%**	**45%**
Aircraft involving 4 exit zones.	**27%**	**9%**	**64%**
All Aircraft	**33%**	**17%**	**50%**

However, the statistics suggest that approximately 67% of the accidents investigated involve an exit availability of 50% or more. Thus, as the most frequently occurring exit availability involves more than 50% of the exits, it would not be unreasonable to require 50% exit availability in certification evacuation scenarios. Indeed, if frequency were the sole driver for selecting exit number in certification trials, taking 50% of the available exits would be considered conservative. This line of argument ignores the fact that a significant minority (33%) of the accidents investigated had less than 50% exit availability, resulting in a significantly more challenging evacuation scenario. In addition, based on the data, there would be a strong argument to assume a configuration in which at least one exit zone had no available exits.

In the previous analysis, exit availability was considered from a global perspective i.e. as a function of the total number of exits on board. Here we consider the availability of exits within exit pairs. The accidents used in this analysis ignore all those where the aircraft ended up in water or where substantial damage occurred to the aircraft fuselage, i.e. cases where there were significant breaks in the fuselage, and include only those accidents where information is known about all the exits. Unless passengers actually used an exit, the exit is only considered to be ‘available’ when the exit and its evacuation assist means are physically and fully/safely functional, and passengers are permitted to use it by cabin crew. Using this definition, 12 accidents were considered suitable for analysis, each one involving an aircraft with three pairs of exits. All cases included here have a strict arrangement of exit pairs in forward, mid and aft positions.

From these accidents it was concluded that at the FWD generalised location, two exits are available in the majority of cases (50%), with a single exit available being the next most likely (42%) [8]. In the case of MID positioned exits, the results suggest that in most cases (59% of the time) both exits are available while 33% of the time one exit is available. In both the FWD and MID generalised location, it is very unlikely for there to be no exits available (8% of the cases). Finally, the AFT positioned exits again show that having two exits available is most likely (42%) and having one exit available is next most likely (33%). However in a significant number of cases, (25%) there are no AFT exits available [8]. These results are summarised in Table 2.

Table 2: Proportion of exit availability in terms of generalised exit positions for three-exit pair aircraft [8]

	Availability (%) of exit in exit pair.		
Exit Position	**No Exits**	**One Exit**	**Both Exits**
FWD	8%	42%	50%
MID	8%	33%	59%
AFT	25%	33%	42%

As part of the evacuation certification exercise, the trial criteria stipulate that only half of the available exits can be used. Without exception, where aircraft have exit pairs, only one exit of each pair is selected. If this scenario represented reality we would expect to see the highest percentages in the "One Exit" column of Table 2. For aircraft with three exit zones, this data suggests that it is quite rare to have a situation in which no exits are available in the FWD or MID sections, but one in four cases involved no exits being available in the AFT section of the aircraft. Having one or two exits available in the AFT section is almost equally likely [8].

Based on this data, a suite of more representative exit combinations for aircraft with three exit pairs – while maintaining the certification required 50% availability condition – has been suggested [8]. These involve both exits in one of the locations and a single exit available in one other location. Suitable combinations of exits based on the frequency data identified in Table 2 in decreasing order of likelihood include [8]:

- (i) A single forward exit, both overwing exits and no exits in the aft section available.
- (ii) Both forward exits, a single overwing exit and no exits in the aft section available.
- (iii) Both forward exits, no exits in the overwing section and a single aft exit available.
- (iv) A single forward exit, no exits in the overwing section and both aft exits available.
- (v) No exits in the forward section, a single overwing exit and both aft exits available.

In the next section we use computer evacuation simulation to explore which of these exit combinations is the most challenging.

4.0 Evacuation modelling analysis

Here we use the airEXODUS evacuation model to explore each of the exit combinations identified in Section 3. A common evacuation scenario, based on the industry standard certification trial is used to investigate each of the exit combinations.

4.1 The geometry, model parameters and scenarios

The aircraft geometry used in this analysis is that of a narrow body aircraft with three exit pairs seating 149 passengers and containing three cabin crew (see Figure 2). The aircraft configuration used in this analysis represents an actual aircraft which successfully passed the evacuation certification test. Three exits were used in the certification trial, all on the right side of the aircraft, consisting of two Type C exits (R1 and R3) and the over-wing Type III exit (R2). The L1 and L3 exits were Type B. It should also be noted that the over-wing exits are not placed in the middle of the aircraft as determined by the passenger distribution. There are 10 seat rows between the front and over-wing exits and 14 seat rows between the over-wing and aft exits (see Figure 2).

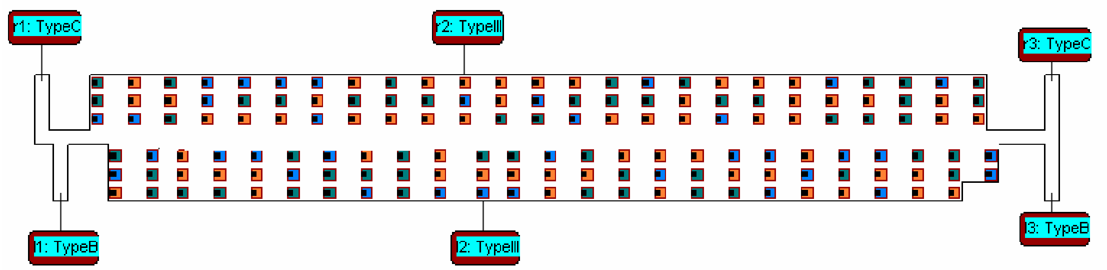


Figure 2: Schematic layout of the test aircraft showing seating configuration and exit location

In the simulations presented in this paper, the default generalised passenger exit hesitation time distribution (assuming assertive crew) appropriate for the various exit types were used with default exit ready times of 8.2 s for the R1 and R3 exits, 12.0 s for the passenger operated R2 and L2 exits and 9.4 s for the L1 and L3 exits. Passenger attributes are set from the default certification parameter set. The airEXODUS parameter “Off-Time distribution” (i.e. the time required to descend the slide or wing) was also assumed to follow the default distribution appropriate for the various exit types. Other model parameters are set to achieve optimal distributions of passengers between exits with non competitive behaviour e.g. seat jumping is not permitted.

Each scenario was run 1000 times using 10 different populations which fitted the scenario description (i.e. each population was run 100 times). Simulations which produced suboptimal results (simulations in which the exits failed to complete passenger flow within ten seconds of each other) were discarded and re-run until optimal results were produced. The results from these simulations are intended to represent the best performance the aircraft configuration is likely to produce under certification conditions.

In total six exit combinations were examined as shown in Table 3. These are the base case, representing the standard certification scenario and five additional cases representing each of the exit combinations identified in Section 3. Scenario 1 represents the most likely exit configuration based on data from the AASK database and Scenario 5 represents the least likely of the 5 cases.

Table 3: Possible exit availability distribution assuming 50% of exits are available based on accident frequency data from [8] for a narrow bodied aircraft in descending order of likelihood

Scenario	Forward Exit Zone		Middle Exit Zone		Aft Exit Zone	
	R1 Type C (Forward Right)	L1 Type B (Forward Left)	R2 Type III (Right Over Wing)	L2 Type III (Left Over Wing)	R3 Type C (Aft Right)	L3 Type B (Aft Left)
1	Y	N	Y	Y	N	N
2	Y	Y	Y	N	N	N
3	Y	Y	N	N	Y	N
4	Y	N	N	N	Y	Y
5	N	N	Y	N	Y	Y
Base Case (Typical Certification scenario)	Y	N	Y	N	Y	N

4.2 Evacuation Simulation Results

The first scenario examined is the base case or actual evacuation certification scenario. As can be seen from Table 4 airEXODUS predicts that under strict evacuation certification conditions this aircraft is likely to produce on-ground times of between 67.0 s and 76.8 s with a mean of 71.2 s and a 95th percentile time of 73.8 s (see Figure 3). The time achieved by this aircraft in the actual certification trial falls on the predicted curve and is between the minimum and mean predicted times. This result, in addition to those presented in [12] suggests that the airEXODUS model is capable of predicting the likely outcome of evacuation certification trials.

We also note from this analysis that the passengers and crew travel an average distance of 6.5 m and require an average of 39.6 s to exit the aircraft. In addition, on average, the passengers spend 24.7 s caught in congestion (Cumulative Wait Time or CWT). This suggests that on average a passenger wasted 62% of their PET (Personal Evacuation Time) in unproductive congestion.

Furthermore, unlike the certification process which (currently) only requires a single trial, these simulations suggest that the outcome of all 1000 optimal evacuation simulations were sub-90 seconds and so this aircraft with 154 passengers and crew and all the exits on the right hand side available comfortably satisfies the “intent” of the evacuation certification trial. However, the certification pass-fail criterion clearly does not take into account the possibility of multiple trial executions. In an attempt to address this point and in anticipation of the eventual use of evacuation simulation tools to assess aircraft evacuation performance for certification, Galea [13] has suggested a procedure for the use of evacuation simulation models as part of the evacuation certification process. As part of this process he suggests that the 95th

percentile result from a distribution of simulated evacuation times should satisfy the 90 second criteria. Once again, clearly this aircraft undergoing the base case scenario clearly satisfies this condition producing a 95th percentile evacuation time of 73.8 s.

Table 4: airEXODUS optimal predicted results for base case scenario

Scenario		Out of aircraft time (s)	On-ground time (s)	Av. PET (s)	Av. CWT (s)	Av. DIST (m)
Base Case Certification (R1-R2-R3)	**Min**	65.5	67.0	37.8	23.1	6.4
	Mean	**69.3**	**71.2**	**39.6**	**24.7**	**6.5**
	Max	74.8	76.8	41.7	26.8	6.7
	95$^{th\%ile}$	71.7	73.8	40.8	6.6	25.8

Having established the certification performance of the aircraft we now turn our attention to the performance of the aircraft under certification conditions but with exit combinations as indicated in Table 3. The results from these five scenarios are summarised in Table 5 with the distribution of evacuation times produced for each scenario displayed in Figure 3.

The results for Scenario 1, in which one exit was available in the front of the aircraft (R1) and two over-wing exits (R2 and L2) were available, suggest the aircraft can produce on-ground times of between 79.5 s and 99.6 s with a mean of 87.7 s and a 95th percentile time of 92.4 s. In this case we note that the mean on-ground time has increased by 23% when compared to the base case. We also note that passengers travelled an average of 8.5 m representing an increase of 2 m compared to the certification scenario. The average PET increases to 46.6 s, while the average CWT is 29.3 s. So while the average PET and CWT has increased when compared to the certification case, we find that 63% of the PET is wasted in congestion, only 1% greater than in the certification case.

Using the 95 percentile pass/fail criterion, the aircraft with available exits configured as indicated in Scenario 1 just fails the evacuation certification trial (see Figure 3).

The results for Scenario 2, in which two exits were available in the front of the aircraft (R1 and L1) and one right over-wing exit (R2) was available, suggest the aircraft can produce on-ground times of between 86.7 s and 112.3 s with a mean of 98.1 s and a 95th percentile time of 105.4 s. In this case we note that the mean on-ground time has increased by 38% when compared to the base case. We also note that passengers travelled an average of 10.2 m representing an increase of 3.7 m compared to the certification scenario. The average PET increases to 49.8 s, while the average CWT is 31.0 s. Once again we find on average 62% of the PET is wasted in congestion which is the same as in the certification case.

Using the 95 percentile pass/fail criterion, the aircraft with available exits configured as indicated in Scenario 2 clearly fails the evacuation certification trial (see Figure 3).

The results for Scenario 3, in which two exits were available in the front of the aircraft (R1 and L1) and one aft right exit (R3) was available, suggest the aircraft can produce on-ground times of between 73.5 s and 85.3 s with a mean of 77.7 s and a

95th percentile time of 81.4 s. In this case we note that the mean on-ground time has increased by 9% when compared to the base case. We also note that passengers travelled an average of 8.3 m representing an increase of 1.8 m compared to the certification scenario. The average PET for a passenger was 41.9 s, while the average CWT is 25.5 s. Therefore approximately 61% of the PET is wasted in congestion which represents a reduction by 1% when compared to the certification scenario.

Using the 95 percentile pass/fail criterion, the aircraft with available exits configured as indicated in Scenario 3 comfortably passes the evacuation certification trial, albeit with a smaller margin than the base case (see Figure 3).

Table 5: airEXODUS optimal predicted results for the five exiting scenarios

Scenario		Out of Aircraft time (s)	On-ground time (s)	Av.PET (s)	Av.CWT (s)	Av.DIST (m)
1 (R1-R2-L2)	Min	77.5	79.5	43.6	27.1	7.7
	Mean	**85.7**	**87.7**	**46.6**	**29.3**	**8.5**
	Max	97.4	99.6	50.3	32.6	8.8
	95th%ile	90.5	92.4	48.4	30.9	8.7
2 (R1-L1-R2)	Min	84.8	86.7	46.5	27.5	9.7
	Mean	**96.1**	**98.1**	**49.8**	**31.0**	**10.2**
	Max	110.9	112.3	54.8	35.9	10.6
	95th%ile	103.4	105.4	52.3	33.4	10.4
3 (R1-L1-R3)	Min	71.4	73.5	39.3	23.1	8.3
	Mean	**75.8**	**77.7**	**41.9**	**25.5**	**8.3**
	Max	83.0	85.3	45.9	29.4	8.4
	95th%ile	79.3	81.4	43.7	27.3	8.3
4 (R1-R3-L3)	Min	68.7	70.8	39.0	22.3	8.5
	Mean	**74.5**	**76.5**	**41.7**	**25.1**	**8.5**
	Max	82.5	84.5	45.2	28.8	8.6
	95th%ile	78.6	80.5	43.6	26.9	8.5
5 (R2-R3-L3)	Min	78.8	80.7	44.2	25.8	8.6
	Mean	**89.2**	**91.1**	**48.3**	**29.9**	**9.9**
	Max	102.2	103.7	55.3	37.1	10.5
	95th%ile	95.8	97.8	50.8	32.4	10.3

The results for Scenario 4, in which one exit was available in the front of the aircraft (R1) and two exits were available in the aft (R3 and L3), suggest the aircraft can produce on-ground times of between 70.8 s and 84.5 s with a mean of 76.5 s and a 95th percentile time of 80.5 s. These results are very similar to Scenario 3. In this case we note that the mean on-ground time has increased by 7% when compared to the base case. We also note that passengers travelled an average of 8.5 m representing an increase of 2.0 m compared to the certification scenario. The average PET for a passenger was 41.7 s, while the average CWT is 25.1 s. Thus in this case approximately 60% of the PET is wasted in congestion which represents a reduction by 2% when compared to the certification scenario.

Using the 95 percentile pass/fail criterion, the aircraft with available exits configured as indicated in Scenario 4 comfortably passes the evacuation certification trial, albeit with a smaller margin than the base case (see Figure 3).

The results for Scenario 5, in which one exit was available in the over-wing area (R2) and two exits were located in the rear (R3 and L3), suggest the aircraft can produce on-ground times of between 80.7 s and 103.7 s with a mean of 91.1 s and a 95th percentile time of 97.8 s. While the configuration is similar to Scenario 2, with the two forward exits in Scenario 2 replaced by two aft exits in Scenario 5, the results are considerably quicker than those produced by Scenario 2. In this case we note that the mean on-ground time has increased by 28% when compared to the base case.

We also note that passengers travelled an average of 9.9 m representing an increase of 3.4 m compared to the certification scenario. The average PET for a passenger was 48.3 s, while the average CWT is 29.9 s. Thus in this case approximately 62% of the PET is wasted in congestion which is identical to the certification scenario.

Using the 95 percentile pass/fail criterion, the aircraft with available exits configured as indicated in Scenario 5 convincingly fails the evacuation certification trial (see Figure 3).

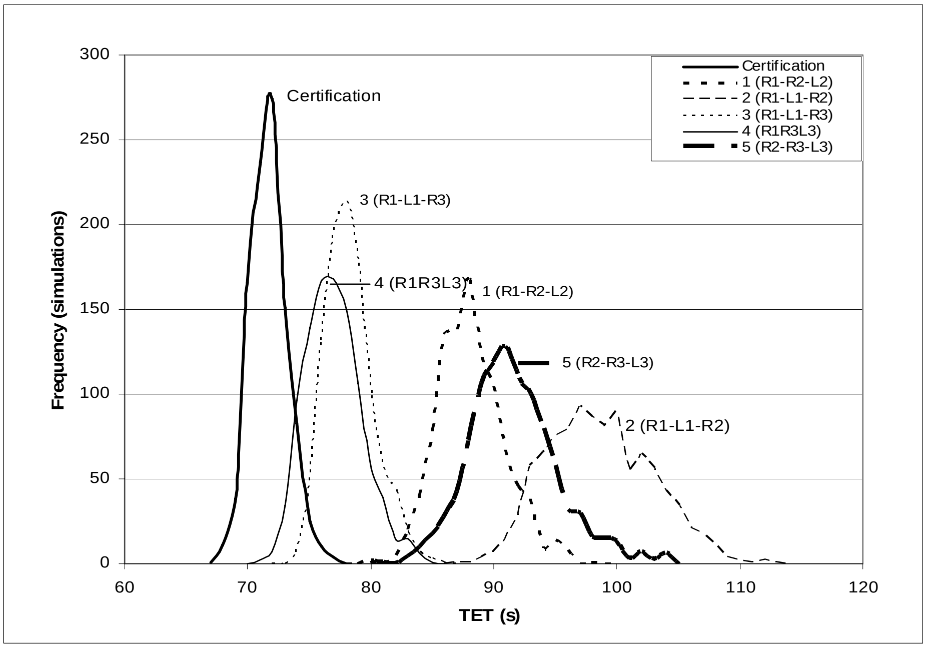


Figure 3: Frequency Distribution for TET (On-Ground Times) for all Scenarios

Furthermore, we note from Figure 3 the wide distribution in evacuation times produced by the various exit combinations. This figure emphasises the significant difference in egress times that can result from taking different combinations of 50% of the available exits. It also strongly emphasises that the certification combination of exits is the least challenging of the exit combinations.

From these results we note a number of interesting outcomes:

- The certification exit configuration produces the quickest on-ground times and is therefore the least challenging of the six configurations.
- The worst performing exit configuration which also fails to meet the certification criterion is the second most likely exit configuration i.e. Scenario 2.

- Three exit configurations produce on-ground times that actually fail to meet the certification criterion.
- The two most frequently occurring exit configurations i.e. Scenarios 1 and 2, fail to meet the certification criterion.
- Two of the exit configurations that fail the certification criterion have the same exit capacity as the certification case.
- Scenarios with greater exit capacity than the base case i.e. Scenarios 3 and 4 produce slower on-ground times albeit satisfying the certification requirement.
- Two scenarios with similar exit configurations i.e. Scenario 2 (two forward and one over-wing exit) and Scenario 5 (two aft and one over-wing exit) and hence similar exit capacities produce very different on-ground times.

At first sight these results may appear surprising but can be explained by the evacuation dynamics. Presented in Table 6 are the average exit flow rates achieved for each of the exits as predicted by airEXODUS. We note from this table that when there is a single exit operating out of an exit pair, the flow rates achieved by the exit is greater than when both exits in a pair are operating and the predicted average value is quite close to the expected values for the particular exit type. In particular we note that the Type III exit achieves an average flow rate of 37.2 ppm while the Type C exit achieves an average flow rate of 59.0 ppm. The predicted Type III exit is some 2.5% faster on average and the Type C is some 8% slower on average than the measured average from certification trials.

Table 6: Average flow rates achieved for each exit in all scenarios

Scenario	Average Flow Rates (ppm) Forward Exit Zone		Average Flow Rates (ppm) Middle Exit Zone		Average Flow Rates (ppm) Aft Exit Zone	
	R1 Type C (Forward right)	L1 Type B (Forward Left)	R2 Type III (Right Over Wing)	L2 Type III (Left Over Wing)	R3 Type C (Aft Right)	L3 Type B (Aft Left)
Certification (R1-R2-R3)	**58.8**	0.0	**39.2**	0.0	**58.9**	0.0
1 (R1-R2-L2)	**58.7**	0.0	**32.9**	**33.8**	0.0	0.0
2 (R1-L1-R2)	**38.4**	**35.2**	**35.1**	0.0	0.0	0.0
3 (R1-L1-R3)	**41.2**	**38.0**	0.0	0.0	**59.0**	0.0
4 (R1-R3-L3)	**58.8**	0.0	0.0	0.0	**41.1**	**41.0**
5 (R2-R3-L3)	0.0	0.0	**37.5**	0.0	**41.5**	**41.4**

When we consider situations in which the both exits in a pair are available and there are no other complicating factors, such as proximity of another functioning exit (e.g. Scenarios 3 and 4) we note that the exits produce a considerably reduced average flow rate. In Scenario 4 we note that the pair of exits, Type B and Type C in the rear produces an average flow rate of approximately 41.0 ppm, some 30% less than the flow rate for the Type C exit when functioning alone.

This reduced flow rate is a direct result of the single aisle feeding both exits. When only a single exit from a pair is functioning, the limiting factor on exit performance is the capacity of the exit, the aisle being able to feed sufficient passengers to keep the exit functioning at its full capacity. However, when two exits in a pair are functioning the single aisle cannot supply sufficient passengers to keep both exits working at full capacity and hence a drop in exit flow rate is achieved.

In Scenario 2 a similar phenomenon occurs, however this configuration has the added complication that the two exits within the pair are off-set. Thus there is a slight added hesitation and conflict in the exit intersection region as some passengers are persuaded to go slightly forward to exit via the right exit rather than being drawn to the nearer left exit. This exit configuration appears to be less efficient than having two exits aligned in a pair and so the combined flow rate is slightly less than the configuration in the rear of the aircraft.

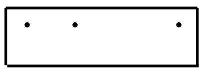
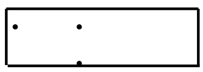
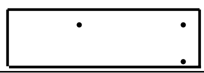
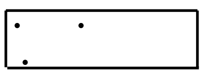
A similar situation occurs in Scenario 1 with the pair of Type III exits. In this case we find that the pair of Type III exits in the over-wing position produces an average flow rate of approximately 33.4 ppm, some 10% less than the flow rate for the Type III exit when functioning alone. The reduction in efficiency for the pair of Type III exits is considerably less than that noted for the pair of Type C/B exits. This is due to the flow capacity of the Type III exit being significantly less than that for the Type C/B exits. As a result the aisle feeding the Type III exit has considerably more capacity then can be accommodated by the single Type III exit. Therefore, in situations where a second Type III exit becomes available, the imbalance in aisle flow capacity feeding the exits and exit flow capacity of the two exits will be less than that for the pair of Type C/B exits resulting in the noted smaller decrease in net exit flow capacity.

Another surprising result is that two scenarios with similar exit configurations i.e. Scenarios 2 and 5 produce 95th percentile results which are some 8% different. Both scenarios involve a single overwing exit and a pair of Type C/B exits, Scenario 2 with the active pair in the forward position producing a slower evacuation then Scenario 5 which has the pair of Type C/B in the rear. This difference is due to the Type III exit not being located in the centre of the aircraft. The Type III exit is located closer to the front of the aircraft, being some 10 seat rows from the front and some 14 seat rows from the rear. The front exit pair therefore has a smaller catchment of passengers to readily supply the exits than the rear exit pair. As the pair of Type C/B exits has a greater flow capacity than the single Type III exit they require a greater supply of passengers in order to keep them functioning at full capacity. As a result, more passengers in Scenario 2 are required to bi-pass the over-wing exit to keep the exit pair working than in Scenario 5. This results in Scenario 2 being less efficient than Scenario 5. If the over-wing exit was more centrally located, the overall egress time for Scenario 2 would decrease, while that for Scenario 5 would increase.

This effect is demonstrated by moving the pair of over-wing exits in Scenario 1 to the middle of the aircraft. The scenario is then re-run 1000 times producing a 95th percentile on-ground time of 83.7 s some 8.7 s or 10% faster than the original configuration used in Scenario 1. This slight change to the location of the over-wing exits makes a difference between passing or failing the certification requirements. More importantly, such a change would make the base case, Scenario 1 and Scenario 2 quicker and hence more survivable.

The results are summarised in Table 7 where the 95th percentile on-ground times are presented along with the average total exit flow rates for the six scenarios ranked from the fastest to the slowest evacuations.

Table 7: Average 95th Percentile on-ground times, average distance travelled and average total exit flow rate for the various configurations ranked from the fastest to the slowest

Rank	Scenario	95th Percentile on-ground time (s)	Av. Dist (m)	Av. Total Exit Flow rate (ppm)
Base case	(R1-R2-R3) 	73.8	6.5	156.9
1	4 (R1-R3-L3) 	80.5	8.5	140.8
2	3 (R1-L1-R3) 	81.4	8.3	138.2
3	1 (R1-R2-L2) 	92.4	8.5	125.4
4	5 (R2-R3-L3) 	97.8	9.9	120.4
5	2 (R1-L1-R2) 	105.4	10.2	108.7

With the above explanations of the evacuation dynamics, the ordering of the scenarios found in Table 7 and the noted interesting results can now be understood.

If a single exit from an exit pair is functioning, the flow rate achieved through the exit will be optimal. This is because a single cabin aisle cannot provide sufficient supply of passengers to maintain maximal flows through both exits in an exit pair. As a result, flows achieved through exit pairs are predicted to be on average 30% lower per exit for Type C exits and 10% less on average for Type III exits.

Thus for a narrow body aircraft with three exit pairs consisting of Type B/C/I exits in the forward and aft and a pair of Type III exits in the over-wing position, if only 50% of the exits are available, selecting a single exit from each exit pair is likely to produce the greatest overall exit flow rate. In addition, this distribution of exits will produce the smallest average travel distance for the passengers as it results in the most number of passengers being close to an exit. These two factors combine to produce the shortest total egress times.

Other combinations of two Type B/C/I exits and a Type III exit (i.e. Scenario 2 and 5) will produce significantly slower egress times due to the 30% reduction in exit efficiency for the paired Type B/C/I exits. For the particular aircraft examined, the combination involving the forward and over-wing configuration (i.e. Scenario 2) is likely to produce slower egress times due to the proximity of the Type III exit to the forward exit creating a greater need for exit by-pass in order to keep the forward exits working.

Combinations of three Type B/C/I exits (i.e. Scenarios 3 and 4) will produce better egress times than paired Type B/C/I exits and a single Type III exit (i.e. Scenarios 2 and 5) due to the greater flow rate achieved by the single Type B/C/I compared to the single Type III. There should be little difference between having the pair located in the front or the rear. However, in this particular case, the exit off-set in the front of the cabin made this case (Scenario 3) slightly less efficient than the case with the pair in the rear of the cabin (Scenario 4).

The configuration with a pair of Type III exits is more difficult to place (Scenario 1). The pair of Type III exits will only suffer a 10% degradation in performance due to being paired. However, this will produce a performance for the pair of Type IIIs which is less than that for a pair of Type B/C/I exits. Thus we would expect the performance of this configuration to be slower than that for the case with three Type B/C/I exits (i.e. Scenarios 3 and 4). While the pair of Type III exits will produce a slower flow rate than a pair of Type B/C/I exits, the single Type B/C/I exit (Scenario 1) will produce a much better flow rate than the single Type III exit (Scenario 2 and 5). We could therefore expect the configuration with a pair of Type III exits and single Type B/C/I (Scenario 1) exit to outperform the configurations with a pair of Type B/C/I exits and a single Type III exit (Scenarios 2 and 5). However, this result may not be generally true as it is affected by the particular configuration of exits found in this study i.e. none centrally located Type III exit and off set forward exits.

It should be remembered in viewing these results that they are all based on model simulations and not actual experiments. To the best knowledge of the authors, full scale experiments have not been conducted (or at least reported in the academic or professional press) to substantiate the findings from these simulations. However, while the precise timings produced by these simulations may be questioned and as a result the precise resultant ranking of the scenarios, it is likely that the main conclusion that the exit configuration used in the current evacuation certification trial is neither representative of likely real accident scenarios nor particularly challenging is valid.

The findings of this work have implications as to the appropriateness of the current evacuation certification trial as a relevant and informative benchmark of egress performance and safety. Galea [13] has suggested that it would be more appropriate to investigate several exit combinations as part of the certification process using computer egress simulation. Furthermore, if 90 seconds is considered to be a real and valid measure of the required evacuation performance of aircraft in the event of a fire, these results convey even more significance. This point will be explored in another paper presented by the authors at this conference.

4 CONCLUSIONS

This work has shown – through computer based evacuation simulation - that the certification practice of using half the available exits predominately down one side of the aircraft is neither statistically relevant nor challenging – at least for aircraft with three exit pairs. Indeed, for the aircraft cabin layout examined, of the six exit combinations investigated involving 50% of the available exits, the exit configuration used in certification trials produced the shortest egress times. Furthermore, three of the six exit combinations investigated resulted in (95^{th} percentile) egress times of greater than 90 seconds, suggesting that the aircraft would not satisfy the certification requirement under these conditions.

These results draw into question the appropriateness of the current evacuation certification trial as a relevant and informative benchmark of egress safety. Demonstrating that the aircraft can be evacuated in 90 seconds using the current exit certification combination says little about how the aircraft is likely to perform in more realistic and challenging exit combinations. Using the current certification trial as a performance measure or “yard-stick” to guide aircraft design may obscure in-built design deficiencies which only come to light in more realistic accident situations. Indeed, if 90 seconds is considered to be a real and valid evacuation performance measure, demonstrating compliance using the current exit selection criteria may be considered as “setting the bar” too low!

By addressing issues associated with the certification and acceptance of aircraft configurations we may achieve the goal of producing safer aircraft, which the industry claim they desire and the traveling public certainly deserve.

The work presented in this paper is currently being extended to wide body aircraft involving four exit pairs.

8 ACKNOWLEGMENTS

Professor Galea is indebted to the UK CAA for their financial support of his personal chair in Mathematical Modelling at the University of Greenwich. Ms Togher gratefully acknowledges the financial support of the FSEG of the University of Greenwich in providing her with a bursary under its Doctoral Programme.

9 REFERENCES

1. FAR Part 25.807 Airworthiness Standards. Transport Category Airplanes. Including amendment 25-67 as published in the Federal Register on June 16th, 1989, Washington DC, USA, 1989.

2. Owen, M., Galea, E.,R., Lawrence, P.,J., and Filippidis, L. AASK – Aircraft Accident Statistical Knowledge: A Database of Human Experience in Evacuation Reports, The *Aeronautical Journal of the Royal Aeronautical Society*, August/September 1998, pp 353- 363.

3. Galea, E.R., Finney, K.M., Dixon, A.J.P., Siddiqui, A. and Cooney, D.P., An analysis of human behaviour during aircraft evacuation situations using the AASK V3.0 database. *The Aeronautical Journal of The Royal Aeronautical Society*, Vol 107 No 1070 April 2003, pp 219-231.

4. Galea, E.R., Finney, K.M., Dixon, A.J.P., Siddiqui, A. and Cooney, D.P. THE AASK DATABASE V4.0: Aircraft Accident Statistics and Knowledge. A Database to Record Human Experience of Evacuation in Aviation Accidents. Report for CAA Project 560/SRG/R+AD, December 2003.

5. Galea, E.R., Finney, K., Dixon, A.J.P., Cooney, D. and Siddiqui, "The AASK Database V4.0: Aircraft Accident Statistics and Knowledge, A Database to Record Human Experience of Evacuation in Aviation Accidents", In Proceedings of the International Aircraft Fire & Cabin Safety Conf, Nov 15-18, 2004, Lisbon Portugal. http://www.fire.tc.faa.gov/2004Conference/html/evac.htm

6. Galea, E.R., Finney, K., Dixon, A.J.P., Siddiqui, A., and Cooney, D.P. "An analysis of the passenger to cabin crew ratio and exit reliability based on past survivable aviation accidents.". Human Factors and Aerospace Safety, Ashgate publishing, 5(3), pp 239-256, 2005.

7. Galea, E.R., Finney, K., Dixon, A.J.P., Siddiqui, A., and Cooney, D.P. "Aircraft Accident Statistics and Knowledge Database: Analyzing Passenger Behaviour in Aviation Accidents.", AIAA Journal of Aircraft, Vol 43, Number 5, pp 1272-1281, 2006.

8. Galea, E.R., Finney, K., Dixon, A.J.P., Siddiqui, A., and Cooney, D.P. "An analysis of exit availability, exit usage and passenger exit selection behaviour exhibited during actual aviation accidents.". The Aeronautical Journal of the Royal Aeronautical Society, Vol 110, Number 1106, pp 239-248, 2006.

9. Blake S., Galea E.R., Gwynne S., Lawrence P., and Filippidis, L. "Examining The Effect Of Exit Separation On Aircraft Evacuation Performance During 90-Second Certification Trials Using Evacuation Modelling Techniques". The Aeronautical Journal of the Royal Aeronautical Society, pp1-16, January 2002.

10. Galea E.R., Blake S., Gwynne S. and Lawrence P. "The use of evacuation modelling techniques in the design of very large transport aircraft and blended wing body aircraft". The Aeronautical Journal, Vol 107, Number 1070, pp 207-218, 2003**.**

11. Galea E.R., Blake S., Gwynne S. and Lawrence P., "Simulating the Interaction of Cabin Crew with Passengers During Aircraft Emergency Evacuation Conditions." In Proceedings of the International Aircraft Fire & Cabin Safety Conf, Nov 15-18, 2004, Lisbon Portugal. http://www.fire.tc.faa.gov/2004Conference/html/evac.htm

12. Galea E.R., Blake S. and Lawrence P.J., Report on Testing and Systematic Evaluation of the airEXODUS aircraft evacuation model. ISBN 0860399664, CAA PAPER 2004/2005. April 2005

13. Galea E.R., "Proposed Methodology for the Use of Computer Simulation to Enhance Aircraft Evacuation Certification.", AIAA Journal of Aircraft, Vol 43, Number 5, pp 1405-1413, 2006.