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Report on the Testing and Systematic Evaluation of the airEXODUS Aircraft Evacuation Model

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Report on the Testing and Systematic Evaluation of the airEXODUS Aircraft Evacuation Model

Report Prepared by E R Galea, S J Blake and P J Lawrence
Fire Safety Engineering Group
University of Greenwich
London

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Enquiries regarding the content of this publication should be addressed to:
Research Management Department, Safety Regulation Group, Civil Aviation Authority, Aviation House, Gatwick Airport South, West Sussex, RH6 0YR.

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Executive Summary

This report concerns the testing and evaluation of the airEXODUS aircraft evacuation model (CAA project 7D/S923/3). 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 model's predictive capabilities will be improved the more often it is shown to produce reliable predictions. This report examines the ability of airEXODUS to reproduce the certification evacuations of six aircraft.

The selection of these aircraft was based on a number of criteria, primarily being the availability of a detailed aircraft cabin layout description in the certification trial documentation. A major aim of this study was to demonstrate that airEXODUS is capable of predicting the potentially small differences that may arise between derivative aircraft belonging to a single aircraft family. Thus, derivative aircraft were selected – both narrow- and wide-bodied aircraft. In addition, it was desirable to select aircraft that had a variety of exit types and crew assertiveness levels. In total five different types of exits are considered in this report; Type-A, Type-A (canted), Type-III, Type-I and Type-C.

This validation exercise is not only a measure of the ability of airEXODUS to predict the outcome of certification evacuation trials, but it is also an indication of the suitability of the key data currently available for evacuation analysis. Furthermore, this project has highlighted the need to establish an evacuation protocol suitable for the application of evacuation models to aircraft certification applications.

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. As aircraft evacuation is a probabilistic process, 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. For this reason, it is necessary to repeat a simulation numerous times in order to generate a distribution of results. Each simulation case detailed in this report has been run 1000 times by airEXODUS to capture stochastic variations. The version of airEXODUS used in this report is Version 3.0.

airEXODUS makes use of 90 second certification data 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. 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. Another key parameter in airEXODUS is the Exit Ready Time. This attribute represents the time required by a crewmember or passenger to render the exit escape system ready for use.

For each aircraft under investigation, two settings for the passenger Exit Delay Time and Exit Ready Time parameters were used. The first setting is referred to as the 'Actual data'. This utilises the actual passenger exit delay and exit ready times extracted from video evidence of each exit on each aircraft for the simulation. This parameter represents the actual timings exhibited during the certification trials. Using the 'Actual data' setting should enable airEXODUS to model the Exit Delay Times and Exit Ready Times achieved on the day as accurately as possible. This will demonstrate the ability of airEXODUS to reproduce the results of a certification trial when given the actual data from the certification trial.

The second setting is referred to as the 'Generalised data'. The Generalised data represents a typical setting that has been derived from multiple certification trials. Use of the generalised passenger exit delay time data enables airEXODUS to make predictions of the evacuation

performance of new aircraft configurations, based upon the typical performance derived from the analysis of many previous certification trials. Generalised settings have been determined for each of the five exit types. The generalised data used in airEXODUS is based on data collected from another CAA project 049/SRG/R&AD. A generalised passenger Exit Delay Time distribution was determined for each exit type and was further categorised according to the performance of the cabin crew at the exit.

Thus another key aim of this project was to determine whether the generalised data could be used to produce representative evacuation simulations for aircraft. The results from the six test cases considered has shown that the same broad conclusions concerning aircraft performance can be derived from simulations utilising the generalised data for exit hesitation times and exit opening times as simulations using the actual data. This suggests that the generalised data represents a good approximation for how key aircraft components will perform under certification applications. This provides the modelling and regulatory community with strong evidence to support the use of the generalised data for aircraft certification applications in which the standard configurations and components are being considered. This general approach can be extended to situations in which the generalised data is not applicable, for example, when a new or significantly modified aircraft exit type is being used. In this situation, rigorous testing of the exit component under certification conditions is necessary in order to generate the appropriate data to use in the model. This approach is identical to that used in those simulations that made use of the actual data rather than the generalised data.

Using the mean of the airEXODUS generated total evacuation time distribution for each aircraft and the single time achieved by the aircraft in each of the trials to represent the typical evacuation performance, airEXODUS is capable of predicting the total evacuation time to within 5.3% or 3.8 seconds on average. It was also shown that the model is able to reliably predict the likely evolution of the evacuation from its start to its completion. These cases have shown that the model is capable of successfully reproducing the overall evacuation performance of both wide-body and narrow-body aircraft under certification conditions.

The analysis has also highlighted the inability of the current certification process to meaningfully rank aircraft evacuation performance, on the basis of a single trial result due to the probabilistic nature of the evacuation process. In order to rank aircraft performance it is necessary to undertake repeated evacuation trials. Alternatively, computer simulation could be used to generate the total evacuation time probability distribution and base a ranking system on the statistical information provided by such a distribution.

The analysis has also shown that even though an aircraft may pass a single one-off certification trial, there may be a finite chance that the aircraft will fail to meet the requirements of the certification process if the trial were repeated a number of times. This information is invaluable when attempting to assess the true evacuation performance of the aircraft. It provides insight into the design of the aircraft that can only be practically provided through evacuation simulation.

The success of airEXODUS in predicting the outcome of previous 90 second certification trials is a compelling argument of the suitability of this 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 essential that a protocol be developed for the acceptable use of computer simulations for aircraft certification applications. Until such protocols are in place, it is unlikely that the aviation industry will adopt the use of computer simulation for evacuation certification analysis. Based on experiences from the marine and building industries – which already accept evacuation modelling as part of the design and certification process – such a protocol should address five key issues:

a) **Model Validation and Demonstration Requirements**

The cases examined in this report could form the basis of validation/demonstration cases.

b) **Simulation Protocols**

This should cover the way in which the simulations are to be run and include the number of repeat simulations required, the nature of the data used in the simulations, the nature of the population to be used, etc.

c) **The Scenarios to be Investigated**

The analysis should consider a range of scenarios including the standard 90 second scenario as a base case and additional scenarios drawn from relevant accident analysis. The scenario specification should specify the following six key components:

- **Aircraft Configuration Specification:** consisting of cabin layout, exit configuration and exit availability.
- **Aircraft Environmental Specification:** consisting of the orientation of the aircraft and the nature of the cabin atmosphere with regard to heat, smoke and toxic gases.
- **Crew Behaviour:** consisting of the number and role of cabin crew, level of assertiveness displayed by the crew at exits and the exit ready times.
- **Passenger Population Distribution:** consisting of the nature of the population used in the simulation, either a standard 90 second population or other mix of passengers including for example disabled passengers.
- **Passenger Behaviour:** consisting of standard 90 second type non-competitive behaviour or accident specific assertive behaviour (e.g. seat jumping, aisle swapping, etc).
- **Passenger Exit Selection:** consisting of which exits the passengers will attempt to utilise during the evacuation, this is essentially one of three basic types, optimal exit, nearest exit, or case specific sub-optimal exit selection.

d) **The Acceptance Criteria**

Because of the probabilistic nature of the results produced from repeated simulations, it is essential that a rational acceptance criteria be developed. This should be based on meaningful statistical analysis.

e) **Supporting Documentation**

The evacuation analysis must be supported by appropriate documentary evidence. This should provide a thorough justification for the analysis presented – covering both the numerical technique and data used - and provide a means of reproducing the analysis in some way. The approach adopted by International Maritime Organisation provides the basis for developing such a system for aviation applications.

Future effort should be directed towards two goals, producing a framework for the application of aircraft evacuation models to the regulatory environment and the continued development of aircraft evacuation modelling technology to include additional behavioural features common in real accident scenarios.

With regard to model development, it is suggested that additional capabilities to explicitly represent the crew and their interactions with passengers should be developed. This should include the ability to simulate crew directed by-pass. Wherever possible these developments should be guided by evidence available from actual accidents. Additional capabilities relating to behaviours noted in actual accidents such as the ability for passengers to jump over seats and switch aisles should also be developed and where possible this development should be guided by accident analysis.

Finally, aircraft evacuation modelling has been shown to:

- be capable of reproducing the evacuation performance of aircraft, passengers and crew in full-scale certification trials,
- be a safer and more efficient process than full-scale evacuation trials,
- provide better insight into the actual performance capabilities of the aircraft by generating a performance probability distribution or performance envelope rather than a single datum, and
- be capable of easily and efficiently investigating a range of relevant certification scenarios rather than a single scenario.

These capabilities provide the aviation community (passengers, crew, manufacturers, airlines, regulators) significantly more than the current simple one-off testing procedure provides.

1 Introduction

This report concerns the testing and evaluation of the airEXODUS aircraft evacuation model (CAA project 7D/S923/3). 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 model's predictive capabilities will be improved the more often it is shown to produce reliable predictions. This report examines the ability of airEXODUS to reproduce the certification evacuations of six aircraft.

The selection of these aircraft was based on a number of criteria, the primary being the availability of a detailed aircraft cabin layout description in the certification trial documentation. As a main aim of this study was to demonstrate that airEXODUS is capable of predicting the potentially small differences that may arise between derivative aircraft belonging to a single aircraft family, derivative aircraft were primarily selected – both narrow- and wide-bodied aircraft. In addition, it was desirable to select aircraft that had a variety of exit types and crew assertive levels. In total five different types of exits are considered in this report; Type-A, Type-A (canted), Type-III, Type-I and Type-C.

This validation exercise is not only a measure of the ability of airEXODUS to predict the outcome of certification evacuation trials, but it is also an indication of the suitability of the key data currently available for evacuation analysis. This data describes the passenger exit hesitation time and exit ready time. This data was derived from a previous CAA funded project 049/SRG/R&AD. The suitability of the approach used to represent this data within the airEXODUS model is also examined.

For each aircraft under investigation, two settings for the passenger Exit Delay Time and Exit Ready Time parameters were used. The first setting is referred to as the 'Actual data'. This utilises the actual passenger exit delay and exit ready times extracted from video evidence of each exit on each aircraft for the simulation. This parameter represents the actual timings exhibited during the certification trials. The second setting is referred to as the 'Generalised data'. The Generalised data represents a typical setting that has been derived from multiple certification trials. Use of the generalised passenger exit delay time data enables airEXODUS to make predictions of the evacuation performance of new aircraft configurations, based upon the typical performance derived from the analysis of many previous certification trials. An important aim of this project is to assess the suitability of the generalised data in representing the exit hesitation time and exit ready times.

This project is now complete and this report describes the work undertaken, the key findings, conclusions and recommendations for the future development and acceptance of aircraft evacuation models within the regulatory environment.

2 The airEXODUS Evacuation Model

2.1 EXODUS Overview

EXODUS is a suite of software tools designed to simulate the evacuation of large numbers of individuals from complex structures. The EXODUS family of evacuation models currently consists of three distinct packages, buildingEXODUS [1,2,3,8], maritimeEXODUS [9,10] and airEXODUS [4,5,6,7,8]. buildingEXODUS is designed for applications in the built environment and is suitable for application to complex structures such as airport terminal buildings and rail stations. maritimeEXODUS is intended for the marine environment and is suitable for applications involving cruise ships, naval vessels, the off-shore industry, etc. 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. The version of airEXODUS used in this report is Version 3.0.

The airEXODUS model has been described previously [4,5,6,7,8] and so only a brief description is presented here. In addition, issues associated with its validation [4,5,6,7,8] and the validation of evacuation models in general [8] have been described previously and will not be repeated here. Suffice it to say that the validation of evacuation models must be viewed as an on-going activity, the more successful validation that is produced, the more confidence we have in the capabilities of the model. Predictions made using the airEXODUS evacuation model have successfully been compared with experimental data and data from evacuation certification trials [4,5,6,7,8].

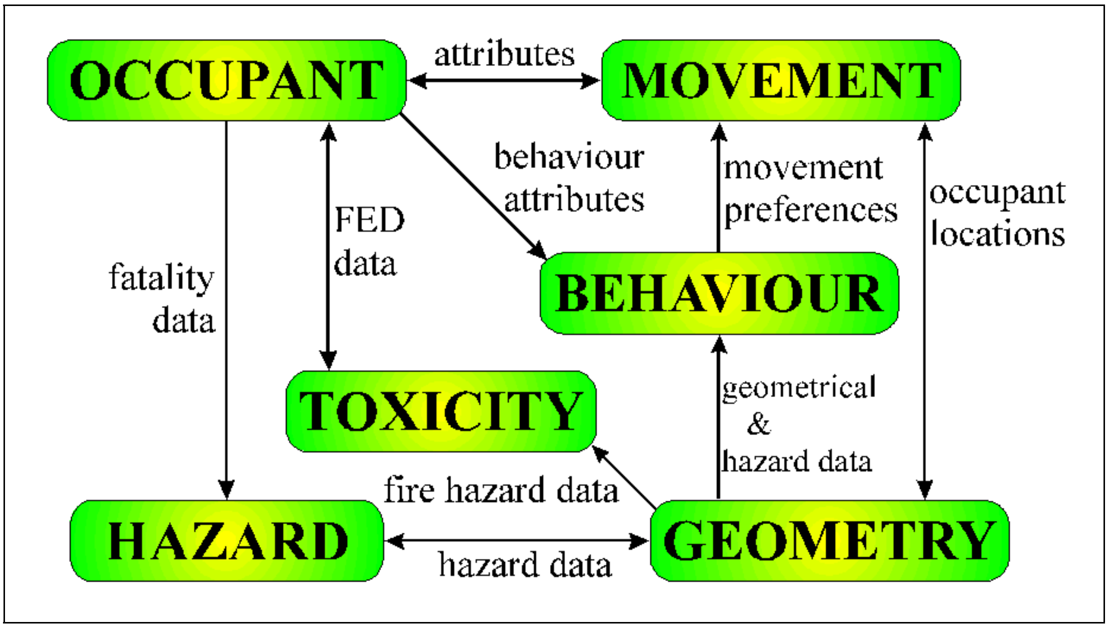


Figure 1 EXODUS Submodel Interaction

The EXODUS software takes into consideration people-people, people-fire and people-structure interactions. The model tracks the trajectory of each individual as they make their way out of the enclosure, or are overcome by fire hazards such as heat, smoke and toxic gases. The EXODUS software has been written in C++ using Object Orientated techniques and utilises rule base technology to control the simulation. Thus, the behaviour and movement of each individual is determined by a set of heuristics or rules. For additional flexibility these rules have been categorised into five interacting submodels, the PASSENGER, MOVEMENT, BEHAVIOUR, TOXICITY and HAZARD submodels (see Figure 1). These submodels operate on a region of space defined by the GEOMETRY of the enclosure. Each of these components will be briefly described in turn.

The GEOMETRY of the enclosure 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. However, the node size can be adjusted to fit space available within a set tolerance range.

The MOVEMENT SUBMODEL controls the physical movement of individual passengers from their current position to the most suitable neighbouring location, or supervises the waiting period if one does not exist. The movement may involve such behaviour as overtaking, side stepping, or other evasive actions.

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 behaviour submodel functions on two levels, global and local. The local behaviour determines an individual's response to the local situation e.g. jump over seats, wait in queue, etc while the global behaviour represents the overall strategy employed by the individual. This may include such behaviour as, exit via the nearest serviceable exit, exit via the most familiar exit or exit via their allocated exit. In addition, a new behavioural feature has been used in these simulations known as Impedance Nodes (see section 2.5).

The PASSENGER SUBMODEL describes an individual as a collection of defining attributes and variables such as name, gender, age, maximum unhindered running 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. 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 either by limiting these attributes to appropriate levels or through the use of the mobility attribute.

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 behaviour submodel which, in turn, feeds through to the movement of the individual.

2.2 Certification Data used in airEXODUS

airEXODUS makes use of 90 second certification data [12] to specify certain model parameters [6]. 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. This representation used within airEXODUS is discussed in more detail later.

Another key parameter in airEXODUS is the Exit Ready Time. This attribute represents the time required by a crewmember or passenger to render the exit escape system ready for use. This attribute represents a slightly different series of events depending upon the specific procedures of a particular exit type. Five different types of exits are utilised in this report. They are the Type-A, Type-A (canted), Type-III, Type-I and Type-C.

For the Type-A exit escape systems the Exit Ready Time attribute represents the time for the cabin crew member to react to the call to evacuate, get out of their seat, move to the exit, contact the exit, open the exit and fully deploy the exit slide.

The Exit Ready Time parameter for canted Type-A, Type-C and Type-I exits all represent a similar series of events. However, the Exit Ready Time parameter for the Type-III over wing exits represents a slightly different chain of events. It represents the time required for a passenger/crew member to react to the call to evacuate, get out of their seat, move to the exit, contact the exit, open the exit and dispose of the hatch.

2.3 Definition of Key Parameters within airEXODUS

Two settings for the passenger Exit Delay Time and Exit Ready Time parameters are used for each certification trial case that is considered in this report

The first setting is referred to as the 'Actual data'. The Actual data settings represent the actual passenger exit delay and exit ready times extracted from video evidence of each exit on each aircraft. This parameter represents the actual timings exhibited during the certification trials.

Using the 'Actual data' setting should enable airEXODUS to model the Exit Delay Times and Exit Ready Times achieved on the day as accurately as possible. This will demonstrate the ability of airEXODUS to reproduce the results of a certification trial when given the actual data from the certification trial.

The second setting is referred to as the 'Generalised data'. The Generalised data represents an average setting that has been derived from multiple certification trials. Use of the generalised passenger exit delay time data enables airEXODUS to make predictions of the evacuation performance of new configurations, based upon the average performance derived from the analysis of many previous certification trials. Generalised settings have been determined for each of the five exit types.

As an example of the analysis that has been conducted on passenger behaviour at exits, consider main deck Type-A exits with assertive cabin crew. Here, assertive cabin crew are taken to be crew who displayed a vocal and physical assertiveness during the majority of the passenger flow through their exit. Vocal assertiveness is taken to mean crew members who continuously yelled clear instructions to the passengers and physical assertiveness is represented by crew members who made physical contact with the passengers.

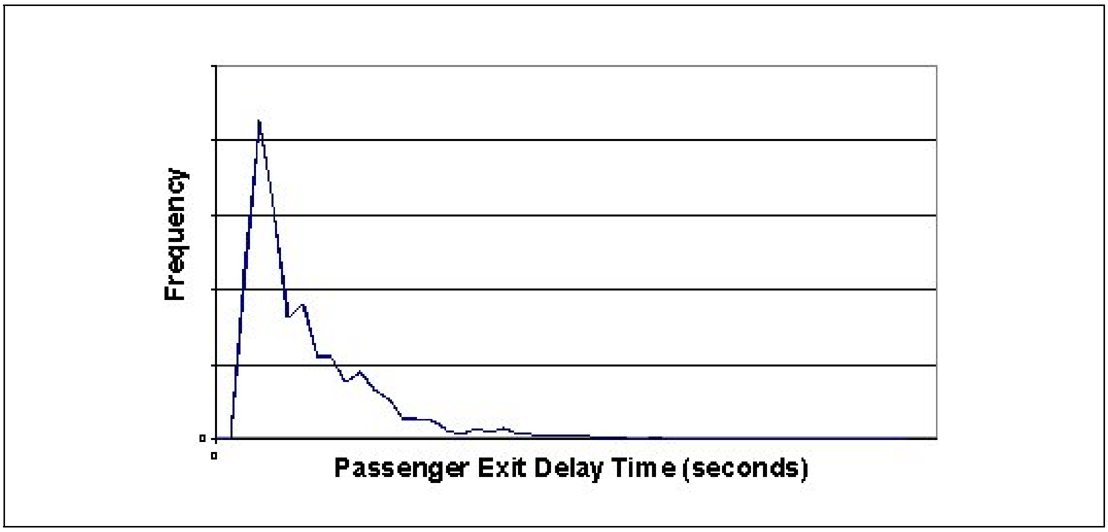


Figure 2 Passenger Exit Delay Time Distribution for Main Deck Type-A Exits with Assertive Crew

From the FSEG analysis, suitable data from 11 previous certification tests involving Type-A exits with assertive cabin crew was found. The aircraft meeting these selection requirements were drawn from Boeing, Airbus and Douglas aircraft. It is also worth noting that three of these aircraft failed to meet the FAR part 25.803 certification requirements. In total, passenger exit delay time data from 20 exits representing some 2078 passengers was used to determine the passenger exit distribution. For each exit meeting the selection criteria (i.e. Type-A, main deck, assertive crew) a frequency distribution curve of passenger exit delay time can be generated. The shape of these distributions are remarkably similar, resembling an exponential/poisson distribution that peaks at the low end of the delay time distribution and tails off towards the higher end of the distribution. This suggests that the majority of the passengers display a short delay time (associated with a rapid jump onto the slide) while a sizeable number of passengers have a relatively long delay time (associated with sitters). On the whole, the slowest passengers exit delay times are associated with personal attributes of being elderly and being female. From this data we note that the minimum delay time is approximately 0.2 seconds and the maximum delay time is 4.7 seconds. The typical distribution of delay times for main deck Type-A exits with assertive crew is depicted in Figure 2. The shape of the curve for unassertive crew is similar to that shown in Figure 2 with the fastest times being unaffected but with more passengers displaying the slower times.

A generalised passenger Exit Delay Time distribution was determined for each exit type and was further categorised according to the performance of the cabin crew at the exit [12]. The number of exits which comprise each of the Exit Delay Time settings is shown in Table 1.

From the collection of 22 video recordings of 90 second certification trials available to FSEG, no evacuation involving unassertive cabin crew positioned at exits of Type-C dimensions have been witnessed. This category is therefore empty (see Table 1). Furthermore, there were insufficient evacuations through Type-I exits to support being split into ASSERTIVE, INBETWEEN and UNASSERTIVE tiers. Thus for this exit type, an assertiveness category has not been defined for the curve that has been formed representing exit delays across the spectrum of crew assertiveness (see Table 1).

In addition during the development of passenger Exit Hesitation Delay distributions it was decided that cabin crew did no exert a significant affect on the exit hesitations delays experienced by passengers at canted Type-A exits. Thus, a single category of passenger exit hesitation delays was extracted (see Table 1). Likewise, cabin crew generally to do not assist passengers at Type-III exits due to the narrow width of Type-III through seating exit passageway(s). Instead, they tend to stand in or near the aisle and usher passengers into the exit seating row(s). As such, categorisation of exit hesitation delays by cabin crew assertion was considered irrelevant for this type of exit and only a single passenger exit hesitation delay was developed (see Table 1).

Table 1 Data used in Forming the Generalised Parameter Settings

Number of Exits on which the Generalised Setting is Based				
Exit Type	**Exit Ready Time parameter (exits)**	**Assertive Exit Delay Time parameter (exits)**	**In-between Exit Delay Time parameter (exits)**	**Unassertive Exit Delay Time parameter (exits)**
Type-A	38	20	12	3
Canted Type-A	7		7	
Type-C	8	5	2	No data (as in between)
Type-I	4		3	
Type-III (passenger operated)	9		12	
Type III (crew operated)	1		12	

2.4 Relevant airEXODUS Parameters

Several airEXODUS parameters will be frequently referred to in this study. Total Evacuation Time (TET), Personal Evacuation Time (PET), Cumulative Wait Time (CWT), First-out, Exit Ready Time, Passenger Exit Delay Time, Off Time, OPS and Flow rates (see [6] for details).

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 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, the Off-Time variable used within airEXODUS is represented by statistical distributions based on data derived from certification data. Off-Time distributions for a variety of slide/exit combinations are available and typically range between 1 and 2 seconds depending on the nature of the slide and the sill height. As the present study has focussed on the simulation of the evacuation dynamics to the point of exiting the aircraft, all predicted evacuation times presented in this report do not include the Off-Time.

Thus within this report, when airEXODUS generated evacuation times are quoted they represent the time for the last passenger to leave the aircraft and not the on-ground times. For consistency, the experimental evacuation times derived from certification trials quoted within this report also refer to the time for the last passenger to exit the aircraft. This enables a direct comparison between airEXODUS predicted evacuation times and evacuation times derived from certification trials. If on-ground times are desired, a suitable slide time can be added to the TET.

The PET is a measure of the personal evacuation time for an individual passenger. It is measured from the start of the evacuation to when the particular passenger exits the aircraft. A single PET is determined for each passenger within a simulation.

The CWT is a measure of the total time that a passenger spends in congestion where they are unable to move. It is measured from the start of the evacuation when the passenger responds to the call to evacuate to when the passenger exits the aircraft. A single CWT is determined for each passenger within a simulation.

The Flow Rate parameter calculates the number of passengers that would evacuate within one minute of flow (see Equation (1)). The total number of passengers that have evacuated (PAX) is divided by the total flow time (TFT) for each exit (i). This yields the average number of passengers that evacuate for each second of the total flow time. This is multiplied by sixty to convert the measure to passengers/minute.

$$\text{Flow rate (passengers/minute)} = \frac{\mathrm{PAX_i}}{\mathrm{TFT_i}} \quad 60 \tag{1}$$

TFT_i = Total Flow Time for exit i

PAX_i = Number of passengers that evacuated via exit i

The flow rate calculation reflects an average flow rate calculated from the total flow time of the exit. It does not provide information regarding the quality of the flow during specific periods, but merely forms an average for the total period of flow. Thus two very different patterns of flow could yield the same flow rate. It is therefore important to consider the pattern of flow in conjunction with the flow rate calculation.

Both the Exit Ready Time and the passenger Exit Delay Time parameters have already been discussed. The exact settings of these parameters are detailed as part of the scenario case definition.

In aircraft which have more than one exit available for evacuation, the total evacuation time will typically be reduced if the flow through each exit terminates at the same time. In optimal evacuation situations exit flows will be completed at approximately the same time. Sub-optimal cases occur when one or more exits exhaust their supply of passengers before the remaining exits.

As a measure of optimal performance FSEG have developed a statistic known as the OPS or Optimal Performance Statistic. The OPS measure has been described in detail in previous papers [5]. The OPS can be calculated for each evacuation, providing a measure of the degree of performance. The OPS is defined as follows,

$$OPS = \frac{\sum_{i=1}^{n} TET - EET_i}{(n-1) * TET} \tag{2}$$

n = number of exits used in the evacuation,

EET_n = Exit Evacuation Time (time last pax out) of Exit *n* (seconds),

TET = Total Evacuation Time (seconds) i.e. max[*EET*].

While it is unlikely that an aircraft will achieve an OPS = 0, near optimal performance will be marked by very low values of OPS. Selecting an acceptable value for OPS is somewhat arbitrary. For the purposes of this report we will consider OPS values of 0.1 or less as being optimal.

It is informative to plot the total evacuation time for an evacuation trial (or evacuation simulation) against the OPS, producing a plot similar to Figure 3.

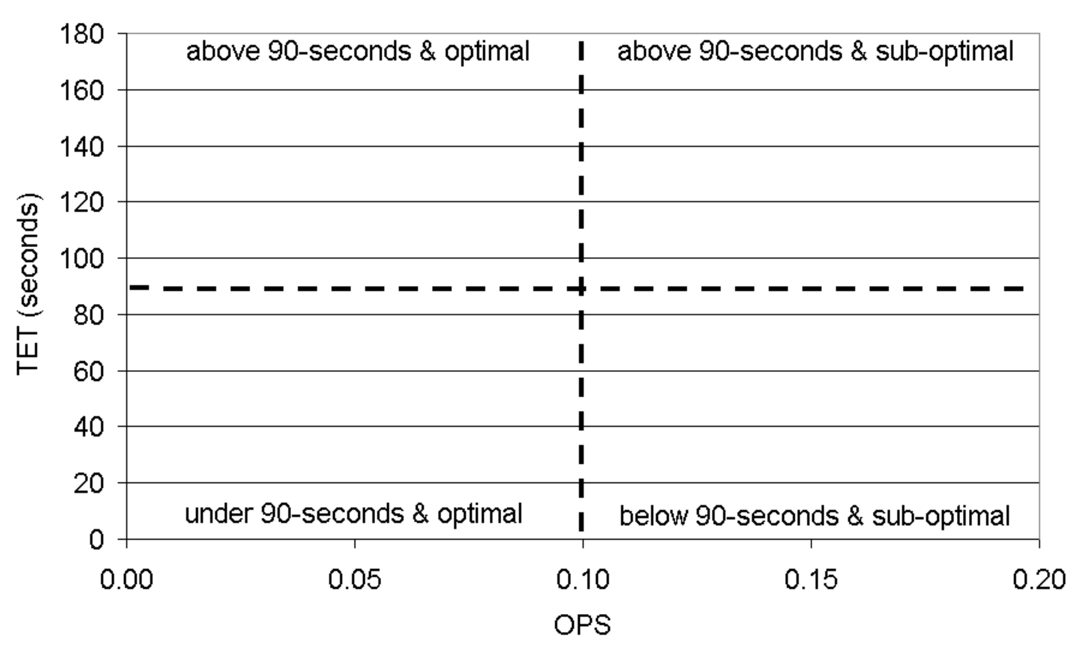


Figure 3 The Four Quadrants of Evacuation Time and Performance Level

The graph can be segmented into four quadrants linking the efficiency with which the aircraft evacuation was accomplished with the time required for the evacuation. These quadrants represent:

Quadrant 1, Bottom left:	Optimal evacuation with TET below 90 seconds
Quadrant 2, Top left:	Optimal evacuation with TET above 90 seconds
Quadrant 3, Bottom right:	Sub-optimal evacuation with TET below 90 seconds
Quadrant 4, Top right:	Sub-optimal evacuation with TET above 90 seconds

Depending on where the data point falls, various conclusions can be drawn concerning the performance of the aircraft. If the evacuation is repeated many times a scatter plot can be created. Whilst it is interesting to note where the bulk of the evacuations are positioned it is also useful to note the location of outliers.

An aircraft that repeatedly produces data points that are optimal and above 90 seconds (Quadrant 2) suggests that even when an evacuation is performed in an optimal manner the aircraft cannot achieve a TET of less than 90 seconds. In such aircraft, the evacuation procedures appear to be working as the passengers are well distributed between exits, yet the evacuation time is excessive. This would suggest that there is a fundamental design problem with the configuration of the aircraft.

At the opposite end of the spectrum are aircraft that produce evacuation times that are sub-optimal yet the TET is below 90 seconds (Quadrant 4). These aircraft are capable of generating acceptable evacuation times even when the evacuation is sub-optimal. Aircraft with the majority of evacuations within this quadrant demonstrate the desirable quality of being robust, as they are able to pass the 90 second criteria even when the evacuation efficiency is relatively low. This is a desirable property as it suggests that even when things go wrong with the crew procedures, it may still be possible to produce fast evacuation times. Furthermore, aircraft displaying this property are capable of producing improved evacuation times through procedural improvements such as the introduction of better passenger management procedures or better trained crew or configurationally through the introduction of an improved passenger distribution within the cabin.

An aircraft that generates evacuation times that are sub-optimal and above 90 seconds (Quadrant 3), while failing the 90 second criteria may still have the potential to improve its performance without requiring a major change to the configuration of the cabin. This suggests that the introduction of improved procedures or better trained crew may result in a reduction in evacuation times. However, this also suggests that the aircraft evacuation time is susceptible to suboptimal crew performance. If the crew perform in a suboptimal manner the evacuation time may become excessive. It should be noted that it is not recommended that complex and elaborate crew procedures be introduced simply to pass the 90 second criteria. It is also essential that the crew procedures are viable under actual emergency situations possibly involving fire.

Evacuation times that fall within the Quadrant 1 are both optimal and have TETs under 90 seconds. These aircraft have performed well and represent a good balance between procedures and configuration. It is unlikely that better times can be achieved for aircraft in this quadrant through procedural improvements. Evacuations within this quadrant are to be expected from a well orchestrated evacuation of a relatively good design. It should be recalled that the TET produced by airExodus does not include the off-time while the 90 seconds certification limit refers to the on-ground time.

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. Each simulation case detailed in this report has been run 1000 times by airEXODUS to capture stochastic variations.

To summarise, the evacuation of cabin crew is not modelled in these simulations. Furthermore, the time taken by passengers in traversing exit slides is not included - i.e. the off-time is set to zero. The net result is that the TET parameter represents the time at which the last passenger exits the aircraft cabin and mounts the slide or wing.

2.5 Passenger Behaviour

While airEXODUS has the ability to represent "extreme" passenger behaviour of the type reported in actual aviation accidents [13, 14], 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:

a) Half the total number of aircraft exits;

b) Assertive cabin crew located at each Type-A exit;

c) Orderly pax behaviour of the type found in certification evacuations;

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

An optimal distribution of passengers to each exit was determined for all of the aircraft considered in this report. In this way the model was configured so that it was likely that an optimal evacuation would be achieved. As the model was set up to produce optimal results, adaptive procedures such as cabin crew initiated bypass or passenger initiated redirection were not explicitly modelled. In addition, one new modelling feature and a modification to the meshing procedures have been introduced to airEXODUS in order to improve the representation of aircraft cross-aisles and vestibules [16]. These features form part of airEXODUS V3.0 beta version used in this analysis. In order to better represent passenger behaviour in congested areas around exits 'impedance nodes' were developed. Impedance nodes are used to slow the movement of passengers in areas by exits where cabin crew may partially obstruct the exit. Finally, the approach to representing packing densities in vestibule areas around Type-A exits was reviewed and modified to better represent the situation in these areas.

2.5.1 Cabin Crew Impedance

Whilst motivating passengers to rapidly exit the aircraft, cabin crewmembers often move from their dedicated assist space into the exit path of on-coming passengers. In doing so cabin crewmembers sometimes partially obstruct the exit (see Figure 4). Video recordings of 90 second certification trials support this view and reveal that sometimes the movement of passengers towards exits may be partially obstructed by the presence of the crewmember. This type of event is referred to as physical cabin crew impedance.

The partial physical blockage of the exit path has two effects. Firstly the passenger will have their path partially obstructed and will thus divert their forward movement in order to avoid the blockage. Secondly, the forward speed of movement of the passenger is slightly reduced as the passenger is forced to by-pass the blockage.

(a) (b)

Figure 4 Impedance during a 90 second Certification Trial

This is similar to the behaviour noted in the built environment known as the 'edge gap' effect where pedestrians will attempt to keep a small distance between themselves and the boundary and that pedestrians moving within this region effectively reduce their travel speed from that of the main stream velocity [15]. In seeking to reduce the likelihood of being obstructed by the cabin crewmember, passengers attempt to maintain a small edge gap between themselves and the cabin crewmember, see

Figure 5(b). The net impact of both factors has the effect of slightly reducing the potential exit flowrate.

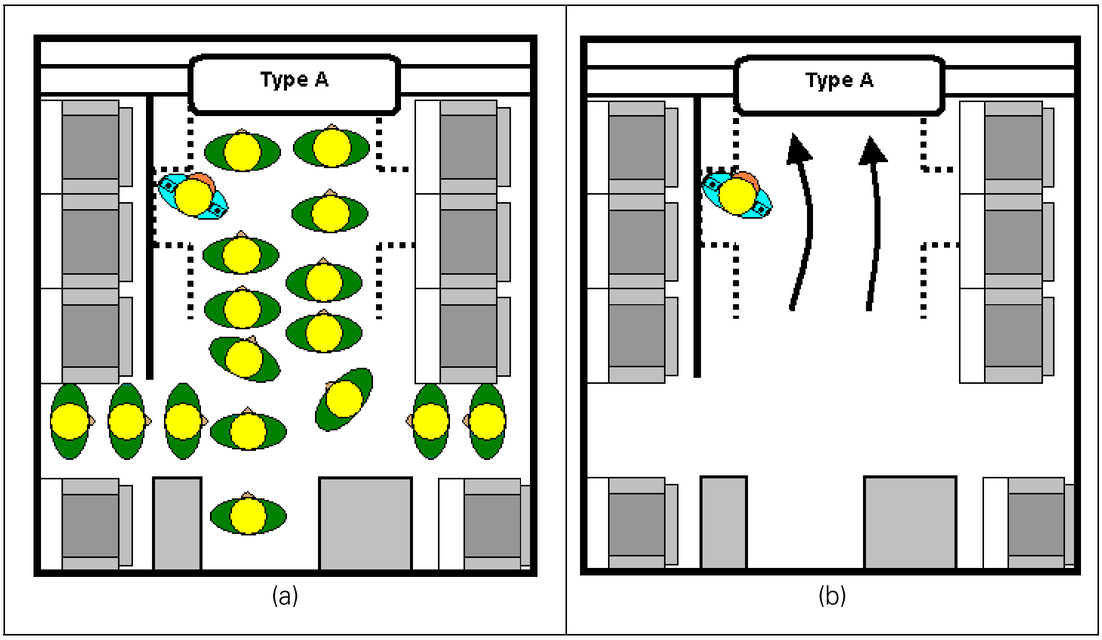


Figure 5 Cabin Crew Generated Impedance at Exits: (a) the cabin crewmember actually physically impedes the forward movement of passengers towards the exit and (b) the likely path of passengers attempting to avoid contacting the cabin crewmember

A first attempt at representing the impeding effect of cabin crew at exits has been developed through the introduction of boundary nodes within the exit vestibule area. Boundary nodes are currently utilised in the buildingEXODUS software to reflect the "edge gap" effect found in buildings. Placing a single boundary node at the exit vestibule in the assist space region where the crewmember is positioned has the affect of slowing the rate of passenger movement. In addition passengers within airEXODUS have a propensity to avoid moving over boundary nodes when possible. Thus the subsidiary effect of physical cabin crew impedance is also modelled.

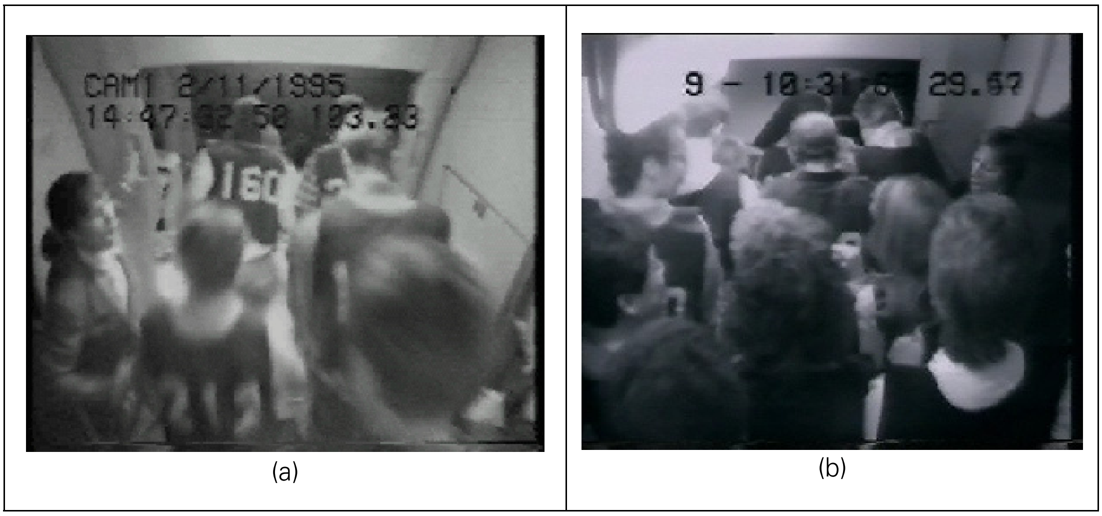
When modelling Type-A exits an impedance node was placed in the vestibule at the Dedicated Assist Space (DAS) locations actually occupied by the crew during the evacuation. In all the evacuations studied as part of this report, only a single crewmember was stationed in the DAS associated with each Type-A exit. As such, in these models a single impedance node was placed at the DAS location that the crew occupied. In these cases the impedance nodes at the Type-A exits only affected one of the lines of passengers that fed into the Type-A exits.

Depending upon the geometry of the aircraft, a series of single nodes may be employed when modelling the approach to Type-B, Type-C and Type-I exits. This has the affect of only modelling a single file of passengers feeding into the exit. The application of a 'standard' impedance node at the DAS in these types of geometries is not consistent with observations from video evidence as passengers would be impeded 100% of the time. Thus, a modified boundary node was generated that hindered passenger movement only 50% of the time. The 50% impedance node was only utilised at narrow exits where single nodes were used to represent the exit approach.

For the Type-I exit geometry found in Case 3, the approach is sufficiently wide to allow two passengers abreast and hence is represented within airEXODUS using two nodes. Since the exit approach was similar to that of a standard Type-A exit, a standard impedance node was employed at the DAS location.

2.5.2 Representation of packing densities in approaches to Type A exits analysis of exit flow rates at Type-A exits suggests that on average mid-section exits generate faster exit flow rates than end section exits [16]. This analysis suggests that the higher exit flow rates are the result of the number of passenger flows into the exit vestibules.

The data suggests that for mid-section Type-A exits there are essentially three distinct passenger flows into the exit - two from the near main aisle (i.e. ahead and to the rear of the exit), and one from the cross-aisle. During periods of triple aisle feed, mid-section exits tend to generate higher exit flow rates than end of section exits. It is the increased supply of passengers that leads to the increased exit flow rates of mid-section exits. In addition, when triple aisle flow was achieved, higher than expected packing densities could be achieved within the exit vestibule area.



(a) (b)

Figure 6 Typical Passenger Density at (a) an End of Section Exit and (b) a Mid-section Exit

Video footage of 90 second certification trials was examined to determine flow characteristics in exit vestibules and to develop an understanding of the rationale for the apparent differences in exit flow rates at mid-section and end of section exits. Firstly, the density of passengers at each exit during each different flow condition was categorised as either high or low density. In total 27 flow conditions were examined from 21 different exits. Of these, 7 represented tri-directional flow conditions and 20 bi-directional flow conditions. Secondly, the speed of passenger movement through the exit vestibule was categorised as being either fast or slow. It is important to note that the terms slow and fast refer to the movement velocity of the passengers through the exit vestibule not the exit flow rate.

Examination of this data revealed that tri-directional flows into exit vestibules tended to result in flows that were high density and slow moving. By contrast, bi-directional flows into exit vestibules tended to generate flows that were low density and fast moving.

It was further noted that tri-directional flows into mid-section exits could not be sustained for the entire flow period. The flow into these exits was characterised by two phases of passenger supply. In the first phase, the passenger flow into the vestibule was feed by three aisles, while in the second phase, the flow of passengers into the vestibule was feed by two aisles.

Mid-section exits with vestibules that were receiving three flows of passengers were generally characterised as slow moving and high density. When the number of flows into mid-section vestibules was reduced to two, the flow was generally characterised as fast moving and low density.

Exits located in the cabin end sections were never categorised as high density.

In previous applications of airEXODUS, the methodology adopted failed to capture these details. The general methodology adopted was such that when representing Type-A vestibules:

"Type-A exit vestibules should be modelled such that two passengers can stand abreast."

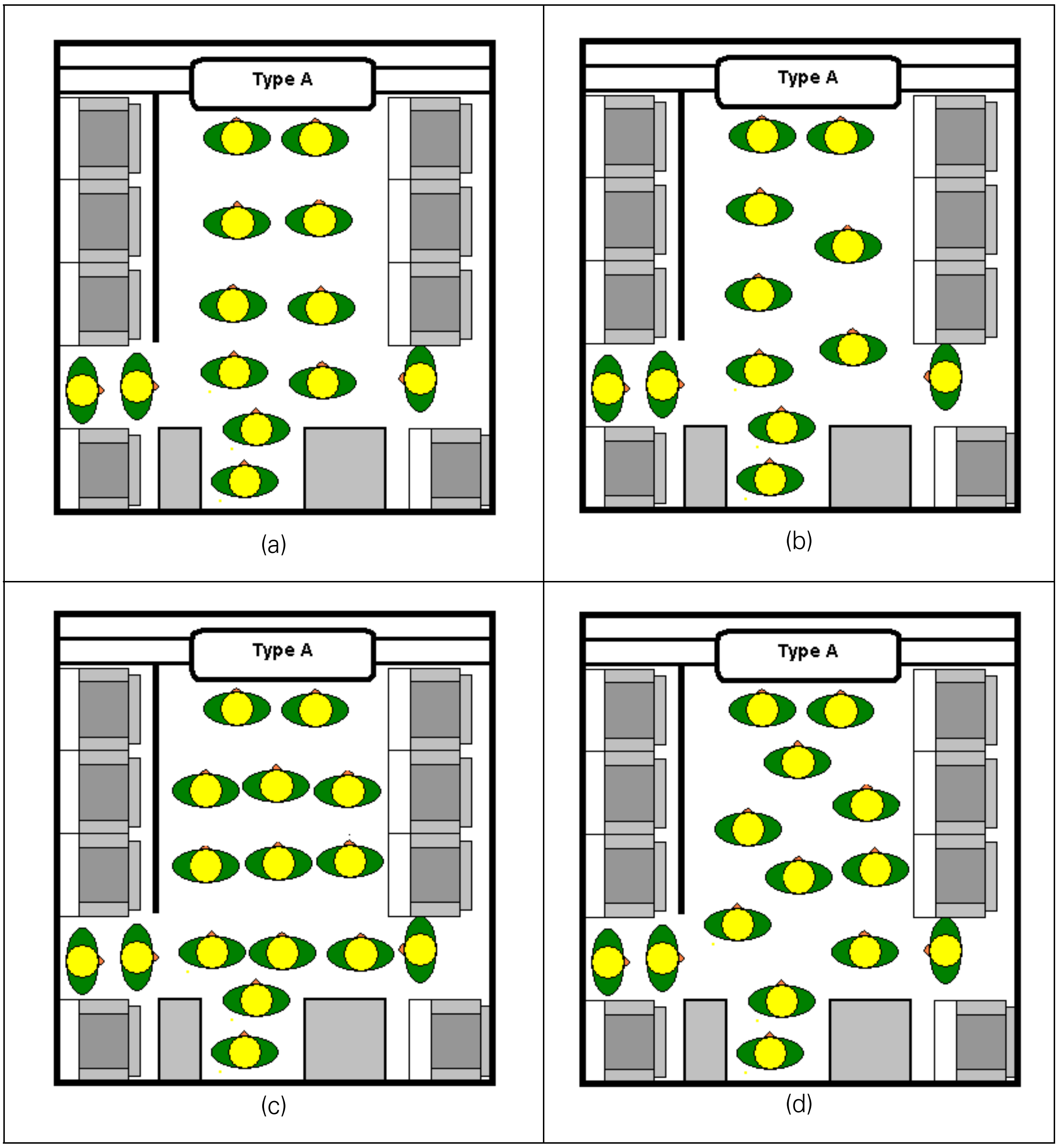
This was enforced irrespective of the nature of the exit i.e. whether it was located at the cabin end sections or cabin midsections and ignored the higher packing densities that can arise at mid-section exits. In some cases, this rule can result in the density at mid-section exits being too low as shown in Figure 7. This figure illustrates both the previous meshing methodology (Figure 7 (a) and (b)) and the newly developed methodology (Figure 7 (c) and (d)). In Figure 7(a) the maximum passenger density using the previous method is depicted while typical packing in less dense situations is depicted in Figure 7(b). In the high packing situation, passenger density could not exceed 4 passengers/metre^2.

Table 2 Frequency of Flow Characteristics by Flow Type and Exit Location

		Low density	**High density**
Tri directional flow conditions	Slow moving	1	**5**
	Fast moving	-	1
Bi-directional flow conditions	Slow moving	5	1
	Fast moving	**14**	-
Mid-section under tri-directional flow conditions	Slow moving	1	**5**
	Fast moving	-	1
Mid-section under bi-directional flow conditions	Slow moving	1	1
	Fast moving	**4**	-
End of section under bi-directional flow conditions	Slow moving	4	-
	Fast moving	**10**	-

To represent denser mid-section exit vestibules within airEXODUS some modifications to the meshing methodology adopted in vestibule areas was necessary. Increased density and slower moving flows are achieved through increasing the maximum packing density within mid-section exit vestibules. The change to the airEXODUS meshing methodology is:

"Mid-section exit vestibules of Type-A exits should allow two passengers to stand abreast immediately adjacent to the exit. This should then increase to three passengers abreast where feasible, i.e. where the node width does not decrease to below 0.4 metres."



(a) (b)

(c) (d)

Figure 7 Hypothetical Examples of the Maximum Possible Density - (a) and (c) - and a Typical Less Dense Situation - (b) and (d) - using the Previous Methodology (a) and (b) and the New Method (c) and (d)

This rule results in increased density at mid-section exits commensurate with the observations from 90 second certification trial video evidence. The outcome of this new procedure is represented by Figure 7(c) which illustrates the maximum passenger density that can now be achieved and the packing that can be achieved during less packed situations i.e. Figure 7(d).

This approach was adopted for the simulations presented in this report.

2.6 Population Specification

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 25.803 [17]. In airEXODUS, simply specifying the age and gender of each passenger is not sufficient. Each person has 21 defining attributes, each of which must be assigned a value. The population tools in airEXODUS allow a range for each attribute to be specified, so that when a person is created, each attribute is assigned a random value between the limits set. In addition, the Patience attribute was set at a very large value for all the simulations in order to model a compliant (non-competitive) population. Passengers when attributed with infinite patience will always wait patiently in queues whilst moving towards their nearest exit. Listed in Table 3 are the range of core attributes generated for the passenger populations.

Table 3 Core Passenger Attribute Ranges used in the airEXODUS Simulations

Attribute	Min	Max	Mean
Drive	1.19	14.99	9.82
Walk (m/s)	0.26	0.60	0.49
Fast Walk (m/s)	0.52	1.20	0.99
Response Time (s)	0.02	8.00	3.93

3 The Certification Trial Cases

This section details the certification trial cases that will be utilised in the validation analysis presented in this report.

3.1 The Limitations of 90 Second Certification Trial Data for the Validation of Evacuation Models

Data derived from certification trials is very useful for validating aircraft evacuation models. However, it is important to appreciate some of the limitations inherent with data of this type. This section provides a brief discussion of the use of certification trial data for validating aircraft evacuation models. More general information concerning the validation of aircraft evacuation models can be found in [8].

The 90 second certification test is a full-scale evacuation trial for commercial aircraft. It is a measure of the performance of the aircraft design, evacuation equipment, crew performance and the appropriateness of the crew procedures. The demonstration is performed with a representative cross-section of the travelling public (age and gender distribution), in conditions of low visibility (darkness) and utilising only half the normally available exits. Crew and passengers do not know before hand which exits will be made available. The aircraft is deemed to have passed the test if all passengers and crew are evacuated – to the ground - within 90 seconds. A complete video record is made of the event including behaviour within the cabin and at the exits. In addition, detailed analysis is performed concerning achieved flow rates etc. For each new aircraft design only a **single** 90 second certification test is performed and so data derived from the repetition of the test is not available, however all the relevant information required to perform an evacuation simulation is collected.

In many respects the certification trial is a good source of validation data however, the 90 second certification trial represents the result of only a single evacuation event. As such, it is not a true representation of the performance of the passengers, crew and aircraft under the imposed arbitrary test conditions. A better representation would be achieved if repeated trials were undertaken. The need to perform repeated experiments should come as no surprise as, even under the most controlled experimental conditions, no evacuation exercise involving crowds of real people will produce identical results if the exercise is repeated - even if the same people are used. Hence it is unwise to make definitive statements such as “the evacuation time for the aircraft is 85.7 seconds” on the basis of a simple one-off experimental analysis. For any aircraft/population/scenario combination, the evacuation performance of the combination is likely to follow some form of distribution as indicated in Figure 8. A single observation of evacuation performance will produce an evacuation time that falls anywhere on the curve. Since the certification trial was run only once, it is impossible to determine the level of variation present within the experimental scenario.

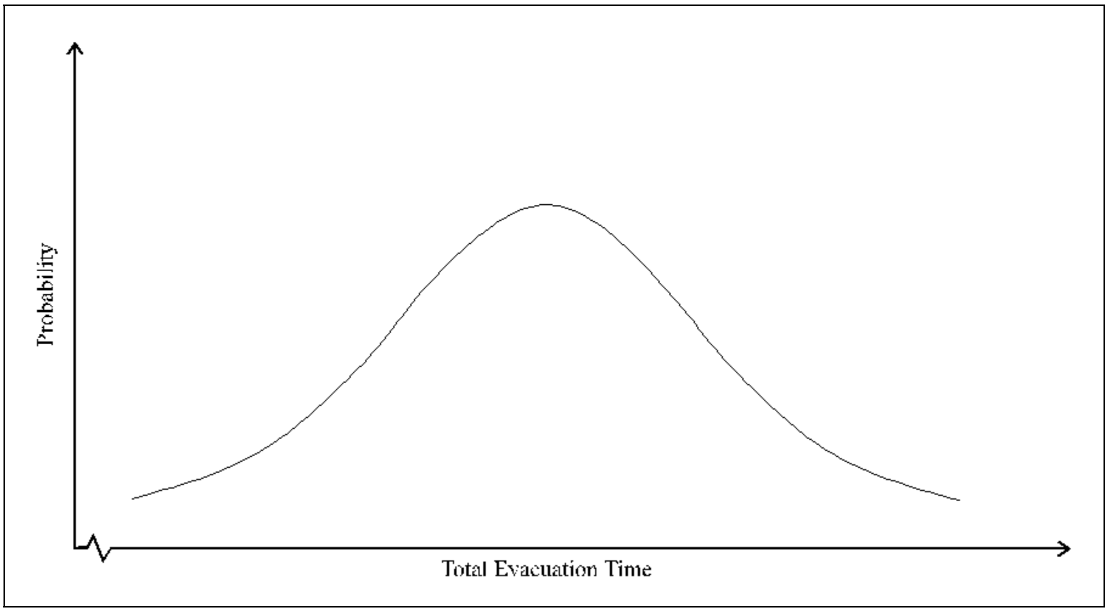


Figure 8 Hypothetical Distribution of the Total Evacuation Time for a Given Aircraft/ population/scenario Combination

It is important to appreciate that a single certification trial result for a particular aircraft should not be taken or assumed to represent the mean TET for the trial, as the single data point could lie anywhere on a frequency distribution of likely results (see Figure 8).

In the same way, a single airEXODUS simulation generates only a single TET data point. However, unlike certification trials, it is possible to run airEXODUS many times to generate a distribution of TETs that reflects the variation within the experimental scenario. Thus, airEXODUS is generally used to generate a TET distribution. It is from the airEXODUS generated TET distribution that a mean TET can be derived.

Difficulties arise when comparing a mean TET generated by airEXODUS with a single data point from a single 90 second certification trial. When comparing model predictions with the trial result, a positive agreement would be achieved if the actual certification trial result falls within the predicted distribution. It is difficult to make a more definitive statement concerning the actual trial result and the model predictions. A more demanding comparison between model predictions and experimental results can be made by comparing the predicted time out for each passenger with that derived from the certification trial. In this case, the trial results are compared with the window of predicted results generated by taking the maximum and minimum time out for each passenger throughout the entire range of repeat simulations.

3.2 Selection Criteria

In order to undertake a detailed evacuation analysis requires a significant amount of effort. It was therefore not practical to attempt to perform validation analysis on all the certification trials available. It was therefore necessary to select appropriate cases for analysis. Primary selection was dictated by the provision of a detailed aircraft cabin layout description in the certification trial documentation. Having established that a suitable diagram existed and that a model could therefore be defined, additional filtering criteria were applied to the certification trials.

A primary aim of this study was to demonstrate that the model was capable of predicting the potentially small differences that may arise between derivative aircraft belonging to a single aircraft family. Thus, derivative aircraft were favoured by the authors – both narrow- and wide-bodied aircraft. In addition, it was desirable to select aircraft that had a variety of exit types and crew assertive levels.

In order for the results of airEXODUS to be comparable to the results of a certification trial the OPS values for both should be similar. Optimality, as measured by the OPS parameter - i.e. OPS values less than 0.1 - is a good baseline to adopt as it indicates that the aircraft evacuation was well executed. An OPS score was calculated for each of the candidate cases. Where the optimality was above the critical value of 0.1, the certification trial case was rejected. Problems may arise when cases are selected with an OPS = 0.1. These are boarder line cases that may display considerable sub-optimality.

Those certification trial cases that were considered optimal - i.e. OPS < 0.1 - were then examined for significant cabin crew intervention such as directed bypass or passenger initiated redirection. Cabin crew directed bypass is defined as a procedure in which a cabin crewmember redirects passengers past an exit in the cabin section to another exit in the cabin section. This is employed to more evenly balance passengers to exits. Passenger initiated redirection is where passengers redirect from their initial exit choice to an alternative exit. Both of the above could lead to significant periods of exit non-flow or single lane flow.

Where cabin crew directed bypass and/or passenger initiated redirection had a major affect on the evacuation the cases were discounted. A final check for serious abnormalities - such as passengers refusing to evacuate - was then undertaken. Where found these cases were also rejected. The selection process resulted in a total of six certification trials. Four aircraft were wide bodied and two were narrow bodied. Of the four wide-bodied aircraft three were derivatives of the same series. Both of the narrow-bodied aircraft were derivatives of the same series. Finding suitable narrow-body cases for examination was difficult either because the certification video footage was quite old and difficult to study in detail, or the cases failed or nearly failed the selection criteria. As a result, the two narrow-body cases finally selected are less than ideal but are the best of the cases available.

3.3 Descriptions of Cases

3.3.1 Certification Case 1 (255 passengers)

This certification trial was the first in a series of derivative wide-bodied aircraft that are studied. The aircraft seated 255 passengers and was configured with three pairs of exits. Type-A exits were positioned at either end of the passenger cabin sections. These exits were labelled R1 and R3. A 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. This exit was designated L2. Seat rows were in a 2-3-2 configuration with each seat row separated by an aisle. The cabin section was divided into two sections by a cross aisle in the centre of the cabin.

The last passenger evacuated the cabin section via the R1 exit after 83.7 seconds. Calculating an OPS score (see Equation 2) for trial Case 1 reveals that this aircraft meets the OPS criterion ($OPS \leq 0.1$) scoring a value of 0.1. The majority of the passengers evacuated via the forward and aft Type-A exits. The Type-III overwing exit generated much lower flowrates than the forward and aft Type-A exits. Manufacturer procedures for this aircraft indicated to the crew that only a small number of passengers should use the over wing exits as their flow rates were likely to be low. Some cabin crew directed passenger bypass occurred during this certification trial. In the certification trial approximately 6% of those passengers that evacuated via the R1 exit were bypassed from the Type-III over wing exit. This resulted in a 3 second period of passenger 'no-flow' at the R1 exit towards the end of the evacuation. No bypass to other exits was observed.

3.3.2 Certification Case 2 (285 passengers)

This aircraft seated 285 passengers. Type-A exits were located at both the forward and aft end of the cabin section and were labelled R1 and R4. Two Type-III over wing exits were positioned in the centre of the cabin section and were labelled R2 and R3. The two Type-III exits were positioned adjacent to each other. These Type-III exits were accessed via a small clear space vestibule common to both Type-III exits. Seat rows were in the 2-3-2 configuration with an aisle separating each seat block. The total passenger seating was divided into two sections by a cross aisle in the centre of the cabin section adjacent to the two Type-III exits. The last passenger evacuated the cabin at 72.6 seconds via the R3 Type-III over wing exit. This trail generated an OPS score of 0.06, thereby satisfying our certification criterion ($OPS \leq 0.1$). The Type-A exits evacuated the majority of the passengers which conformed to the manufacturer's procedures for this aircraft, which indicated to cabin crew that these exits would achieve higher flow rates than the Type-III exits and should therefore receive more passengers. During the certification trial the R1 and R4 exits generated much higher flow rates than the mid-section Type-III exits. The cabin crew at the Type-III exit bypassed some passengers. The bypass resulted in passengers switching from one Type-III exit to another. The alternative Type-III exit was positioned immediately adjacent (within 0.5 metres). Any resulting delay to passengers' evacuation is considered minimal.

3.3.3 Certification Case 3 (351 passengers)

This aircraft seats 351 passengers and contains four exit pairs. Type-A exits were positioned in the forward and aft sections 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. The cabin section was divided into three seating sections by a cross aisle and clear space vestibule area. In each seating section the seat rows were generally in the 2-4-2 configuration with each seat block separated by an aisle.

The last passenger evacuated the cabin section after 71.7 seconds via the R1 exit. Calculating an OPS score for this case yields a value of 0.05 and therefore meets our optimality criterion ($OPS \leq 0.1$). The three Type-A exits generated higher flow rates than the mid-section Type-I exit. Some cabin crew directed bypass occurred during this certification trial. Ten percent of those passengers that evacuated via the R1 exit were bypassed from the mid-section. Of the passengers that evacuated via the aft exit (L4), eight percent were bypassed from the mid section. None of these bypass operations resulted in periods of exit 'non-flow'.

3.3.4 Certification Case 4 (440 passengers)

This aircraft is from a different family of wide-bodied aircraft to the previous derivative aircraft series. The aircraft seated 440 passenger and was configured with four Type-A exits. The two mid-section exits were canted. From forward to aft the exits were labelled L1-L4. Seat rows were generally in the 3-4-3 configuration with each seat block separated by an aisle. The fuselage tapered at the forward and aft positions, thus the number of seats abreast was reduced in these areas. The cabin section was broken into three sections by cross aisles and clear space vestibule areas adjacent to the mid-section exits.

The last passenger evacuated the cabin section via the L1 exit after 74.4 seconds. An OPS score of 0.05 was generated by this certification trial and the evacuation is therefore classed as optimal ($OPS \leq 0.1$). The majority of passengers evacuated via the mid-section exits. The bias towards more passengers evacuating via the mid-section exits, resulted from the mid-section exit's comparatively high flow rates coupled with a low OPS value for the aircraft as whole. Some cabin crew directed bypass occurred during this certification trial. This resulted in approximately a third of the passengers that evacuated via the R1 exit and 13% of passengers that evacuated via R4 exit being bypassed from the mid-section.

3.3.5 Certification Case 5 (159 passengers)

This certification trial is the first in a series of derivative narrow-bodied aircraft that was examined. The aircraft seated 149 passengers and had three pairs of exits in total. Type-C exits were positioned at either end of the passenger cabin sections. These exits have been labelled 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. This exit was designated as R2. Seat rows were in a 3-3 configuration with a central separating aisle.

The last passenger evacuated the cabin section through the R2 exit after 64.1 seconds. This aircraft meets the optimality criterion ($OPS \leq 0.1$) scoring a value of 0.02. The majority of passengers evacuated via the forward and aft exits (R1 and R3). These exits generated the highest flow rates. A small number of passengers evacuated through the centrally located over wing exit (R2). This exit generated the lowest flow rate. Some cabin crew directed passenger bypass occurred during this certification trial. Flight and cabin crew had taken up positions in an aisle seat two/three rows forward and aft of the Type-III exit and performed some passenger redirection. In the certification trial approximately 5% of those passengers that evacuated via the R1 exit were bypassed from the Type-III over wing exit. The bypass did not result in any major periods of exit inactivity, i.e. non-flow. Bypass was not observed to other exits.

3.3.6 Certification Case 6 (188 passengers)

This certification trial was the second in the series of derivative narrow-bodied aircraft examined in this report. This aircraft seated 188 passengers and was configured with four pairs of exits in total. Type-C exits were positioned at either end of the passenger cabin. These exits were labelled R1 and R4. Two pairs of Type-III over wing exits accessible over seating were located at approximately the centre of the cabin section, roughly in line with the wing. These exits were designated as R2 and R3. The two Type-III exits were positioned in adjacent seat rows. Seat rows were in a 3-3 configuration with a central separating aisle.

The last passenger evacuated the cabin section at 78.5 seconds through R2. An OPS score of 0.1 was be calculated from the exit finishing times and just met our optimality criterion ($OPS \leq 0.1$). The two Type-C exits generated relatively high flow rates compared with the two Type-III exits. The cabin crew created a split in the cabin section such that the majority of passengers evacuated via the Type-C exit positioned at the forward and aft of the aircraft. Examination of video footage of this certification trial revealed that the only bypass that occurred was locally between the adjacent R2 and R3 exits. The forward exit (R1) finished evacuating passengers before the other exits. This is reflected in the OPS score of 0.1 generated by the certification trial. This indicates that some passengers at the R2 and R3 exits could have been bypassed towards the R1 exit. Should this have occurred, it is likely that both the evacuation time and optimality score of this certification trial would be reduced.

4 The Generation of the airEXODUS Models

This section details the definition of the airEXODUS models.

4.1 Constructing airEXODUS Geometries

A schematic of the interior cabin arrangement of each aircraft was provided with each of the certification trial reports. From these diagrams, the aircraft geometries were constructed within the model using techniques that have been described in previous work [1,2,3,4,5,6,7,8] and this report.

4.2 Defining the Scenarios

Once the aircraft geometries were defined within airEXODUS and populated with representative passengers, two different sets of scenarios were defined. To ensure that the base models for each of the scenarios were identical in every respect the aircraft models were cloned.

To define the two scenarios the first clone was assigned passenger exit delay times and exit ready times in accordance with the actual data (see Section 3). The passenger exit delay times and exit ready times of the second clone were then set in accordance with the generalised settings (see Section 3). This procedure yielded two slightly different scenarios for each aircraft (see Table 4). The first scenario made use of the actual data from the certification trial whereas the second scenario made use of generalised data.

Table 4 Scenario Description for each of the Validation Cases

Aircraft	Scenario 1 (Data utilised in clone 1)	Scenario 2 (Data utilised in clone 2)
Case 1	Actual data	Generalised data
Case 2	Actual data	Generalised data
Case 3	Actual data	Generalised data
Case 4	Actual data	Generalised data
Case 5	Actual data	Generalised data
Case 6	Actual data	Generalised data

5 airEXODUS Validation using Wide-bodied Certification Trial Data

5.1 Reconstructing the Results of Wide-bodied Certification Trials using the Actual Exit Hesitation Time Data

This section evaluates the ability of airEXODUS to reproduce the results of the certification trials using the actual passenger exit delay times and exit ready times. This series of validation cases will give an indication of how close airEXODUS can get to the results of the actual certification trial.

5.1.1 Results and Discussion: Case 1 Generated using the Actual Data

The aircraft examined in Case 1 is the first of three aircraft belonging to the same family of wide-body aircraft to be studied in this report. The airEXODUS predictions for Case 1 are presented in Table 5. From Table 5 it can be seen that airEXODUS generated TETs ranging between 80.2 and 93.8 seconds with a mean TET of 86.6 seconds. The TET generated in the actual certification trial was 83.7 seconds. This falls within the range of TETs generated by airEXODUS.

The mean TET generated by airEXODUS was 3.5% (2.9 seconds) higher than the measured evacuation time of the certification trial. In this case airEXODUS appears to be predicting marginally longer TETs (by on average 3.5% or 2.9 seconds) than the evacuation time actually achieved for Case 1.

Whilst comparisons of this sort are useful in gauging the accuracy of airEXODUS it is important to recall that the evacuation time of the certification trial is not a mean value but is the result of a single evacuation. The evacuation time generated by the certification trial represents one possible data point on a hypothetical frequency distribution of data points [8]. It is not possible to determine whether the TET generated by the certification trial is situated towards the middle or in the tail of such a distribution.

Table 5 Summary of airEXODUS Predictions for Certification Trial Case 1 using the Actual Data

	First out (secs)	TET (secs)	CWT (secs)	PET (secs)	OPS
Min	12.0	80.2	27.3	43.4	0.00
Mean	**12.3**	**86.6**	**30.6**	**46.9**	**0.06**
Max	13.3	93.8	33.8	50.1	0.17
STD	0.19	2.18	0.93	0.97	0.03

We can better appreciate exactly where the evacuation time of the certification trial is positioned relative to the results of airEXODUS through examining the airEXODUS generated TET frequency distribution (see Figure 9). Examination of Figure 9 indicates that the measured evacuation time of the certification trial, indicated by the dashed line, is positioned in the lower tail of those TETs generated by airEXODUS. According to Figure 9, the majority of simulations (96.2%) of the TETs generated by airEXODUS are greater than the evacuation time of the certification trial. Only 3.8% of the TETs generated by airEXODUS are smaller than the evacuation time of the certification trial.

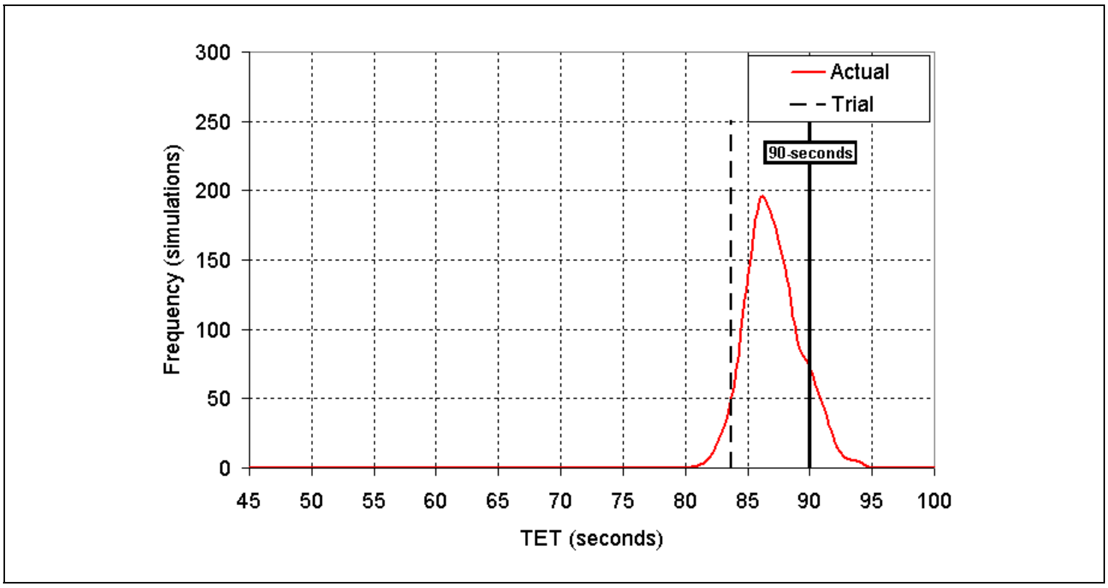


Figure 9 Frequency Distribution of TETs Generated by airEXODUS in Certification Trial Case 1 using the Actual Data

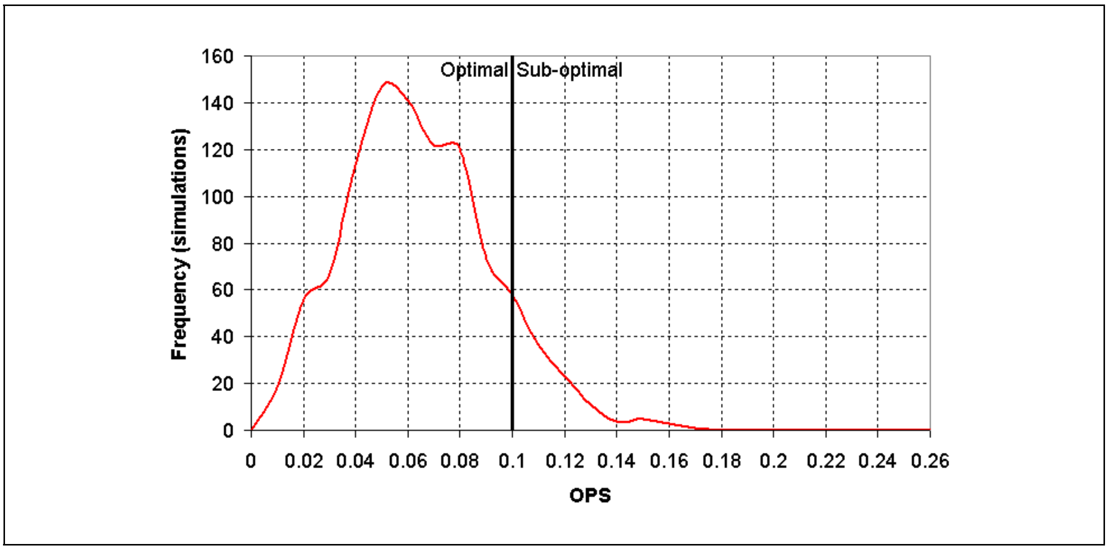


Figure 10 Frequency Distribution of OPS Generated by airEXODUS in Certification Trial Case 1 using the Actual Data

Thus, for this aircraft, the majority of airEXODUS simulations generate longer evacuation times than was achieved in the single certification trial. This however does not necessarily imply that airEXODUS is over-predicting the actual performance of the aircraft. Recall that the evacuation time measured from the certification trial is not a mean value, but simply represents the result from a single evacuation experiment. If the certification trial were repeated many times – as is the evacuation model – the measured TET's would also form a distribution. This distribution could then be compared with the model produced distribution. However, with data from only a single certification trial it is not possible to determine the nature of the likely experimental distribution and so it is difficult to comment on the level of agreement between model predictions and certification trial.

However, given the airEXODUS generated TET frequency distribution, we can say that the certification performance achieved by the aircraft on the day was generally better than would normally be expected for this aircraft. Furthermore, it can be seen in Figure 9 that a small portion (7.6%) of the TET frequency distribution generated by airEXODUS is in excess of 90 seconds. At this point, it is important to recall that the TETs of both airEXODUS and the evacuation time derived from the certification trial do not include off-times, i.e. the time taken to traverse and dismount exit slide. Thus, the probability of failure is likely to be increased if the off-times are included.

These results suggest that when dealing with a distribution of total evacuation times for certification trials that it will be necessary to come up with a consistent manner of dealing with occasional failures. In a later section of this report, we discuss a process for determining compliance with FAR 25.803 requirements.

The OPS measure gives an indication of how similar the airEXODUS simulations are to the actual certification trial in terms of a key performance criterion - namely the optimal balancing of passengers to exits. Returning to Table 5 we can examine the OPS values generated by airEXODUS during the simulations of Case 1 and thus gauge how closely the results of the model match those of the trial. Table 5 reveals that airEXODUS generated OPS values between 0.0 and 0.17 with a mean OPS score of 0.06. Figure 10 plots the frequency distribution of OPS scores generated by airEXODUS. It is apparent from Figure 10 that the majority (91.6%) of airEXODUS simulations are optimal and that a small portion (8.4%) of the airEXODUS simulations would be classed as sub-optimal. The OPS score of this certification trial was 0.1, which would be classified as optimal (see Section 3.3), albeit only just.

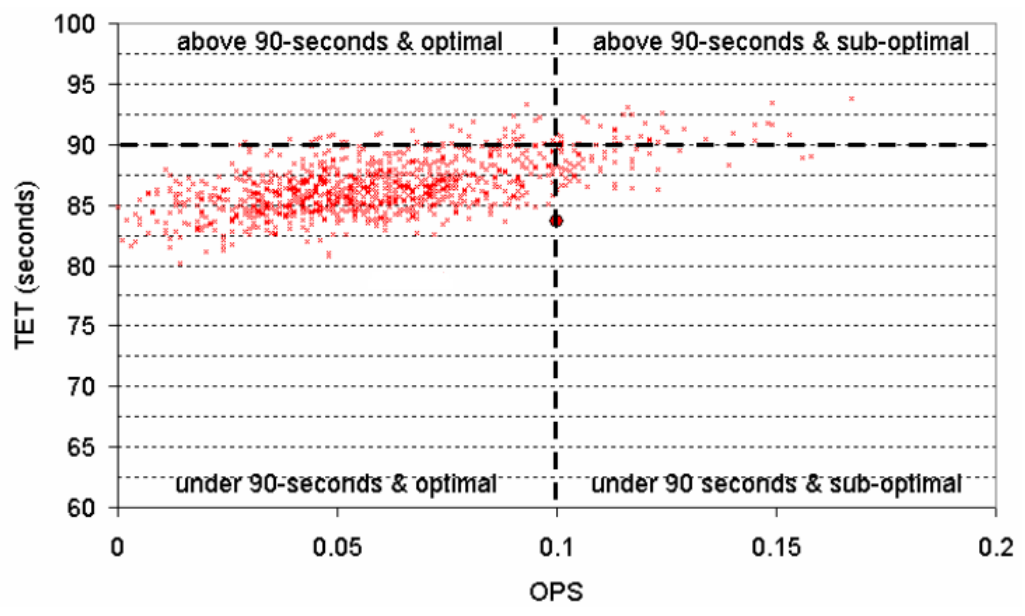


Figure 11 Scatter Diagram of TET and OPS Generated by airEXODUS (1000 data points) and the Result of the Certification Trial (1 data point) when using the Actual Data

Whilst the results of airEXODUS are comparable with the result of the actual certification trial - as both are optimal – the airEXODUS results were marginally more optimal than the certification trial. This can be more clearly seen by examining the scatter plot of OPS versus TETs generated by airEXODUS and the single data point generated by the trial (Figure 11). The small percentage of simulations (7.6%) that achieved evacuation times in excess of 90 seconds are split between Quadrant 2 and 3. The scatter plot also reveals that there is very small chance that the evacuation performance for this aircraft will stray into Quadrant 2. It should be recalled that aircraft with a substantial presence in Quadrant 2 potentially have a serious problem with regard to their configurational layout. However, the majority of data points for this aircraft fall into Quadrant 1 which are optimal and sub 90 seconds.

To summarise, airEXODUS is capable of reproducing the results of this certification trial. airEXODUS generated a range of TETs that includes the evacuation time of the certification trial. The TETs generated by airEXODUS were generally higher than the evacuation time of the certification trial. It was argued that this does not necessarily indicate that airEXODUS over-predicts trial results, as we only have one data point from the certification trial. If the airEXODUS reconstructions are considered representative, the model suggests that the evacuation time of the certification trial was comparatively good for this aircraft. Furthermore, the airEXODUS simulations suggest that if this aircraft's certification trial was repeated 1000 times it is likely that 7.6% of the cases would fail to meet the 90 second acceptance criteria.

5.1.2 Results and Discussion: Case 2 Generated using the Actual Data

The aircraft examined in Case 2 is the second of three aircraft belonging to the same family of wide-body aircraft to be studied in this report. The certification trial proceeded without any abnormal behaviour. The results of certification trial Case 2 are presented in Table 6.

It can be seen that airEXODUS generated TETs between 66.3 and 76.6 seconds with a mean TET of 70.4 seconds. The evacuation time achieved in the certification trial was 72.6 seconds. This falls within the range of TETs generated by airEXODUS. The airEXODUS mean TET is 3% (2.2 seconds) faster than the TET generated in the actual certification trial.

Table 6 Summary of airEXODUS Results from Certification Trial Case 2 using the Actual Data

	First out (secs)	TET (secs)	CWT (secs)	PET (secs)	OPS
Min	6.4	66.3	20.6	35.8	0.01
Mean	**7.3**	**70.4**	**22.1**	**37.4**	**0.05**
Max	8.8	76.6	23.8	39.2	0.15
STD	0.53	1.61	0.46	0.49	0.02

Figure 12 plots the TETs generated by airEXODUS in certification trial Case 2. It can be seen that the majority (89.7%) of TETs are marginally quicker than that generated in the actual certification trial. Again it should be noted that this result does not necessarily indicate the level of accuracy achieved by airEXODUS. The airEXODUS generated distribution suggests that the evacuation time achieved by the aircraft in the certification trial was comparatively slow for this aircraft. This is indicated by the fact that the frequency distribution of TETs generated by airEXODUS is offset to the left, i.e. towards quicker TETs than the time generated by the actual certification trial.

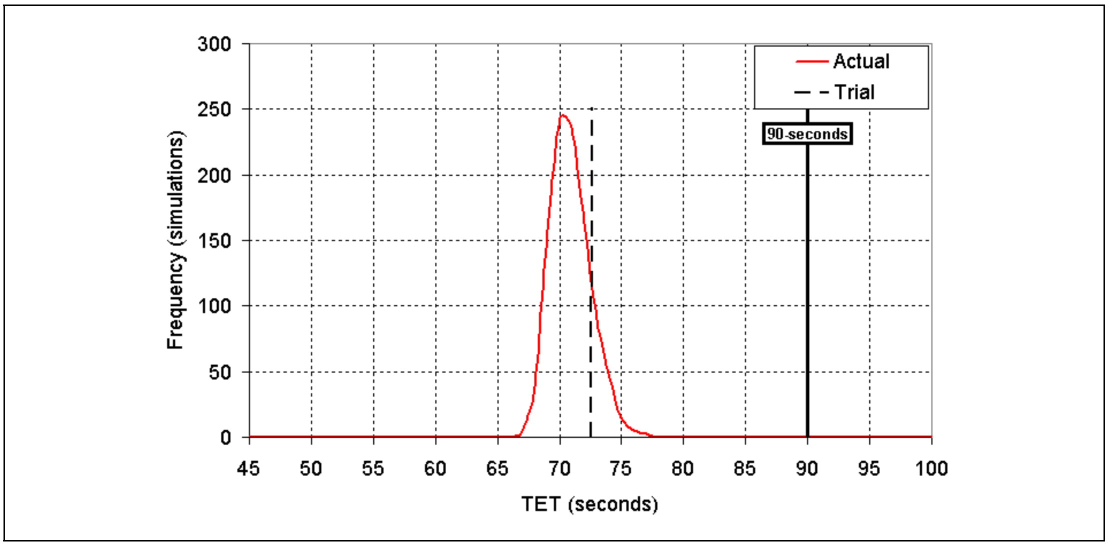


Figure 12 Frequency Distribution of TETs Generated by airEXODUS in Certification Trial Case 2 using the Actual Data

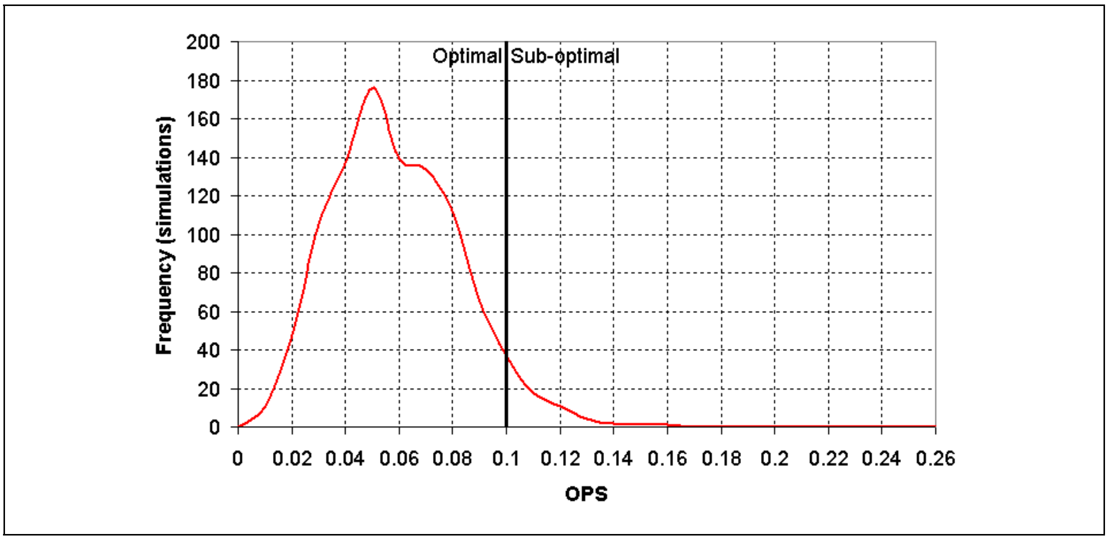


Figure 13 Frequency Distribution of OPS Generated by airEXODUS in Certification Trial Case 2 using the Actual Data

Table 6 shows the OPS scores generated by airEXODUS for Case 2. It can be seen that airEXODUS generated a range of OPS values between 0.01 and 0.15 with a mean OPS of 0.05. The OPS value calculated for the certification trial (see Section 3.3) was 0.06. This is similar to the mean OPS generated by airEXODUS. Examining the scatter plot of TET and OPS (see Figure 14) it can be seen that the model has generated many data points in the region of the certification trial. Thus, the scenario is a very close match to that of the certification trial. Also note that all the data points fall either in Quadrant 1 or Quadrant 4, with the majority of points falling in Quadrant 1. This suggests the aircraft has a well balanced configuration.

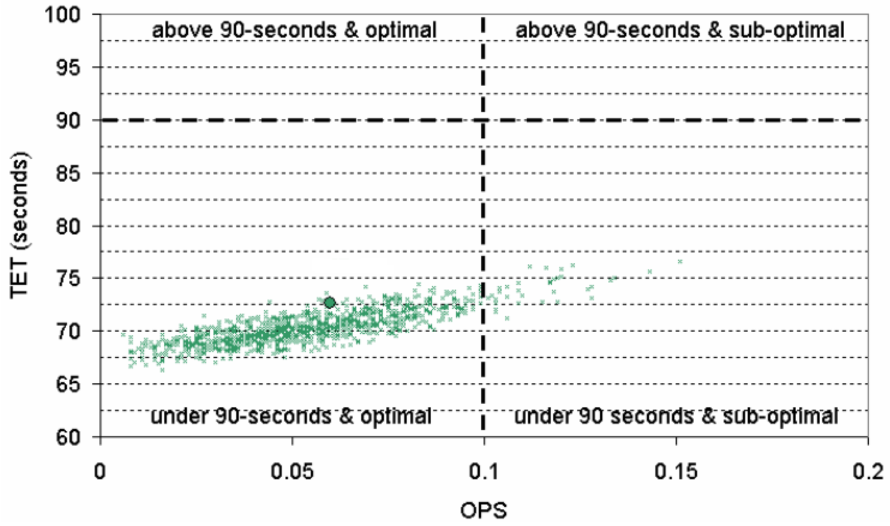


Figure 14 Scatter Diagram of TET and OPS Generated by airEXODUS (1000 data points) and the Result of the Certification Trial (1 data point) when using the Actual Data

Figure 13 shows the frequency distribution of OPS scores generated by airEXODUS for Case 2. It can be seen that the majority of OPS scores (96.3%) are optimal. Only a very small minority (3.7%) are sub-optimal. It can be concluded that both airEXODUS and the actual certification trial represent optimal evacuations of the aircraft in question. However, unlike the previous case, none of the predicted trial results exceeds the acceptance criteria of 90 seconds.

To summarise airEXODUS has reproduced the results of this certification trial. The evacuation time of the certification trial lies within the range of TETs generated by airEXODUS. Generally airEXODUS has generated a mean TET that is quicker (by on average 3% or 2.2 seconds) than the evacuation time achieved in the certification trial.

5.1.3 Results and Discussion: Case 3 Generated using the Actual Data

This aircraft was the third member of the three derivative aircraft family. The model predictions for certification trial Case 3 are presented in Table 7. It can be seen that airEXODUS generated TETs between 63.8 and 77.2 seconds with a mean TET of 68.2 seconds. The actual certification trial generated a TET of 71.7 seconds. This falls within the range of TETs predicted by airEXODUS. The mean TET generated by airEXODUS is 4.8% (3.5 seconds) lower than the evacuation time of the certification trial.

Table 7 Summary of airEXODUS Results from Certification Trial Case 3 using the Actual Data

	First out (secs)	TET (secs)	CWT (secs)	PET (secs)	OPS
Min	8.9	63.8	21.3	35.1	0.01
Mean	**9.2**	**68.2**	**22.8**	**36.7**	**0.07**
Max	9.7	77.2	24.5	38.5	0.17
STD	0.16	1.51	0.45	0.47	0.02

The frequency distribution of TETs generated by airEXODUS for Case 3 is shown in Figure 15. It can be seen that the majority (98.1%) of TETs generated by airEXODUS are smaller than the actual evacuation time achieved by the aircraft during the certification trial. The general trend of the airEXODUS simulations in Case 3 is towards lower TETs. Thus, from the airEXODUS generated distribution, the time achieved by the aircraft during the certification trial (i.e. 71.7 seconds) is longer than would normally be expected for this aircraft.

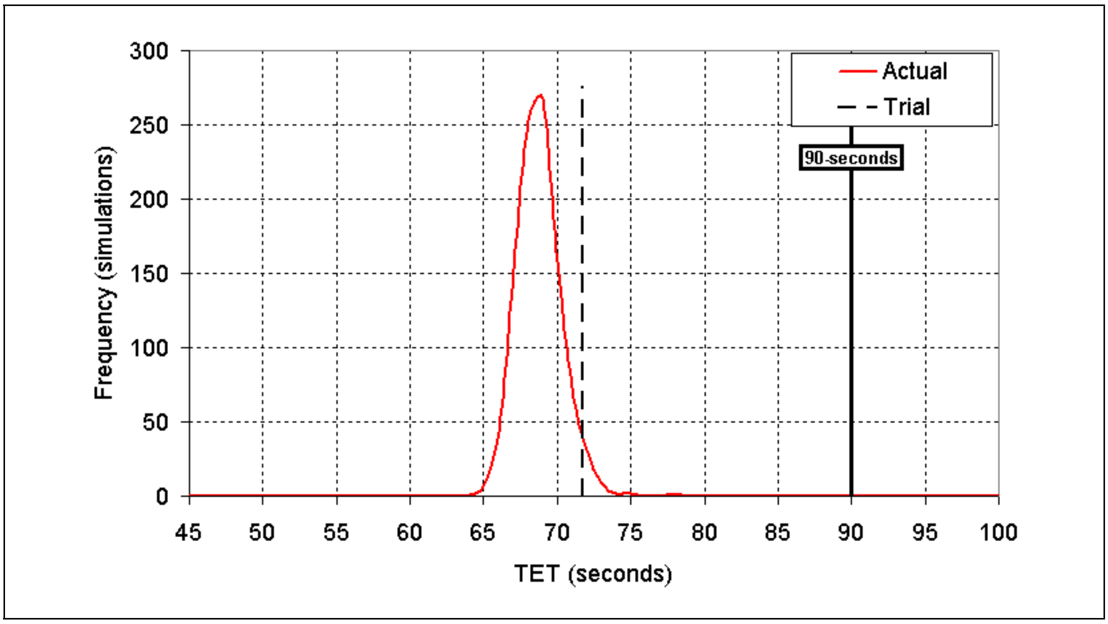


Figure 15 Frequency Distribution of TETs Generated by airEXODUS in Certification Trial Case 3 using the Actual Data

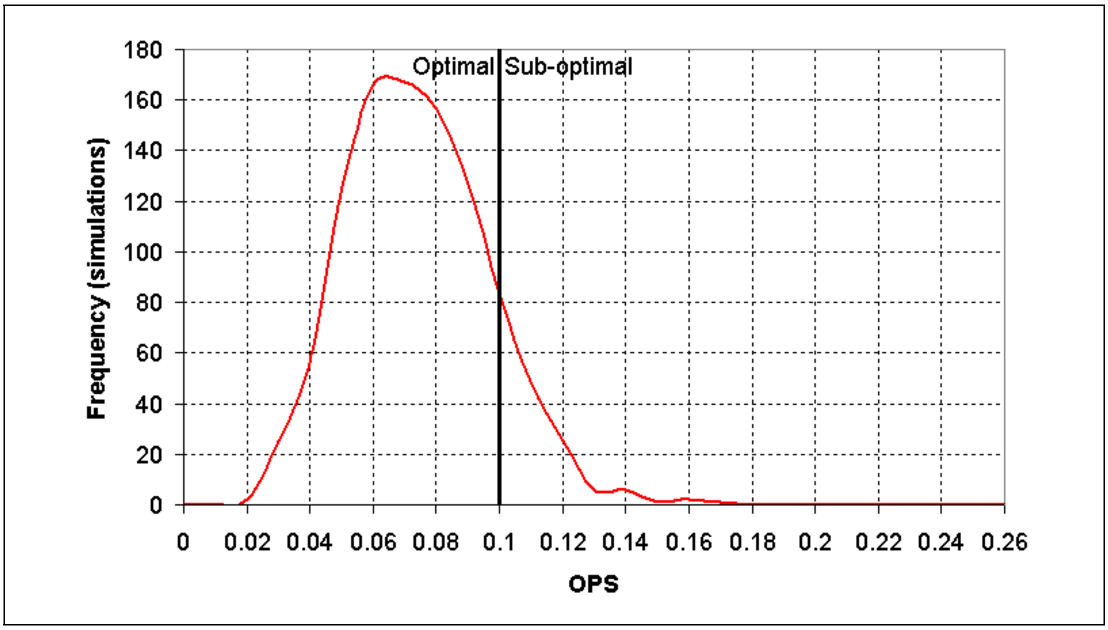


Figure 16 Frequency Distribution of OPS Generated by airEXODUS in Certification Trial Case 3 using the Actual Data

The airEXODUS generated OPS for this aircraft fall between 0.01 and 0.17 with a mean OPS score of 0.07 (see Table 7). From Section 3.3, we note that the actual certification trial generated an OPS score of 0.05. Examining the scatter of OPS and TETs it is apparent that the model generated a large number of simulations that had similar optimality to that of the certification trial. Thus, in this case the results of airEXODUS and the certification trial are very similar. Examination of Figure 16 shows that the majority (91%) of airEXODUS simulations for Case 3 were optimal and that 9% of simulations were sub-optimal. We can therefore conclude that in both the airEXODUS simulations and the actual certification trial represent optimal evacuations of this aircraft. Also note that all the data points fall either in Quadrant 1 or Quadrant 4, with the majority of points falling in Quadrant 1. This suggests the aircraft has a well balanced configuration.

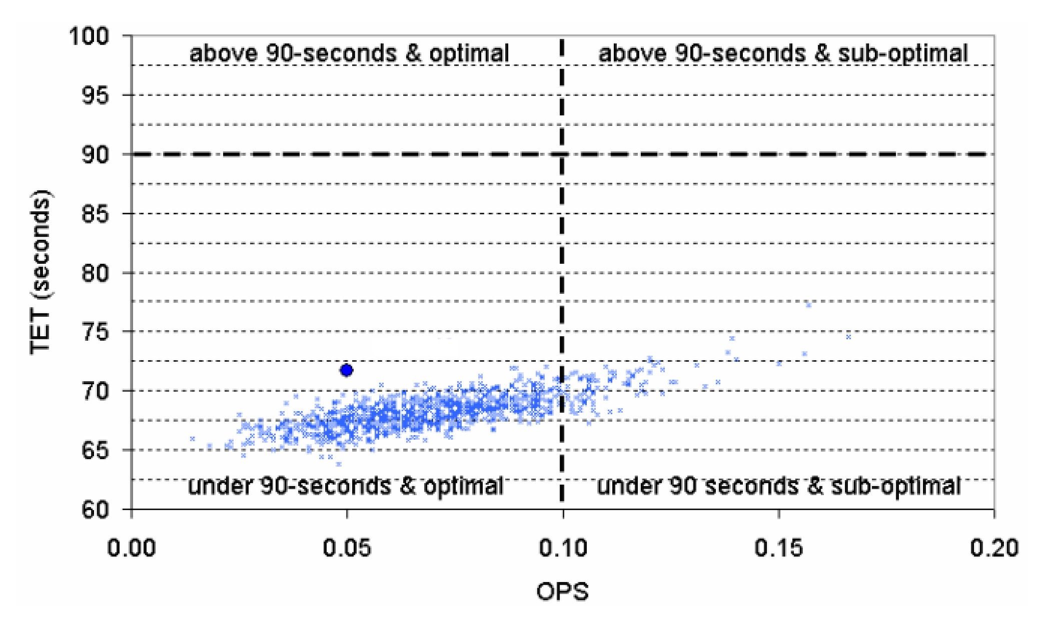


Figure 17 Scatter Diagram of TET and OPS Generated by airEXODUS (1000 data points) and the Result of the Certification Trial (1 data point) when using the Actual Data

To summarise, airEXODUS is capable of reproducing the result of this certification trial. The evacuation time generated by the certification trial falls within a range of TETs generated by airEXODUS. The general trend of airEXODUS for Case 3 is towards generating TETs that are shorter than the evacuation time achieved by the aircraft during the certification trial (by on average 4.8% or 3.5 seconds).

5.1.4 Results and Discussion: Case 4 Generated using the Actual Data

The aircraft studied in this trial did not belong to the family of derivative aircraft examined in Cases 1-3. The results of airEXODUS are presented in Table 8. It can be seen that airEXODUS generated TETs between 72.0 and 85.3 seconds with a mean TET of 76.9 seconds. The time at which the last passenger evacuated that aircraft in the certification trial was 74.4 seconds. This falls within the range predicted by airEXODUS. The mean TET generated by airEXODUS was 3.4% (2.5 seconds) longer than the time generated in the actual certification trial. There appears to be a tendency in this case for airEXODUS to generate slightly longer TETs than the evacuation time achieved in the actual certification trial (by on average 3.4% or 2.5 seconds).

Figure 18 shows the frequency distribution of TETs generated by airEXODUS. It is apparent that the evacuation time of the certification trial is situated towards the lower end of those TETs generated by airEXODUS. According to Figure 18, approximately 92.3% of airEXODUS simulations generated a longer TET than the certification trial. The general trend in this case is towards generating slightly longer TETs than that achieved in the certification trial.

Table 8 Summary of airEXODUS Results from Certification Trial Case 4 using the Actual Data

	First out (secs)	TET (secs)	CWT (secs)	PET (secs)	OPS
Min	11.2	72.0	25.0	40.1	0.00
Mean	**11.3**	**76.9**	**26.7**	**41.8**	**0.05**
Max	11.7	85.3	28.2	43.5	0.13
STD	0.08	1.81	0.47	0.49	0.02

Examination of Table 8 shows that airEXODUS generated OPS values between 0.0 and 0.13 with a mean of 0.05. The OPS score for certification trial was 0.05 (see Section 3.3). Figure 19 plots the frequency distribution of OPS. It is apparent that the majority (98.1%) of the results of airEXODUS meet our optimality criterion ($OPS \leq 0.1$). The result of the certification trial and airEXODUS are comparable in that they both generated optimal results.

In this scenario many of the simulations generated by airEXODUS shared the same OPS as that attained in the 90 second certification trial (see Figure 20). The mean OPS from the airEXODUS simulations is the same as the OPS generated in the certification trial. Also note that all the data points fall either in Quadrant 1 or Quadrant 4, with the majority of points falling in Quadrant 1. This suggests the aircraft has a well balanced configuration.

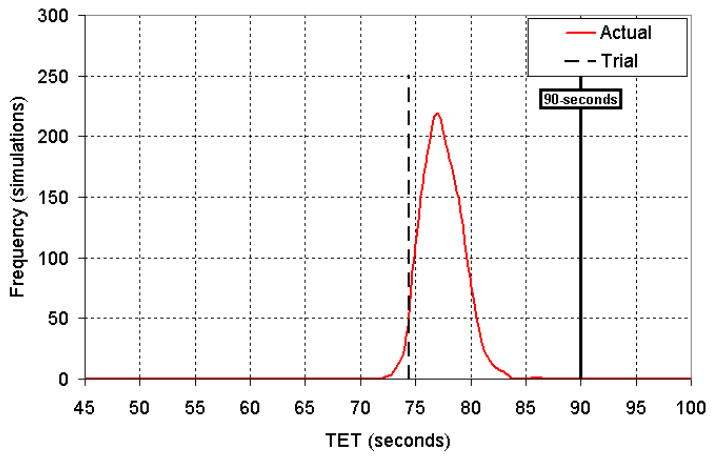


Figure 18 Frequency Distribution of TETs Generated by airEXODUS in Certification Trial Case 4 using the Actual Data

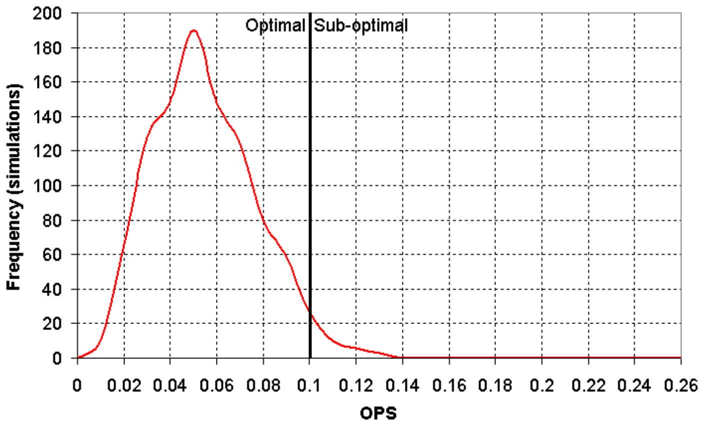


Figure 19 Frequency Distribution of OPS Generated by airEXODUS in Certification Trial Case 4 using the Actual Data

To summarise, airEXODUS is capable of reproducing the results of this certification trial. The evacuation time of the certification trial falls within the range of TETs generated by airEXODUS. Generally, airEXODUS generated higher TETs (by on average 3.4% or 2.5 seconds), than the evacuation time achieved by the aircraft in the certification trial.

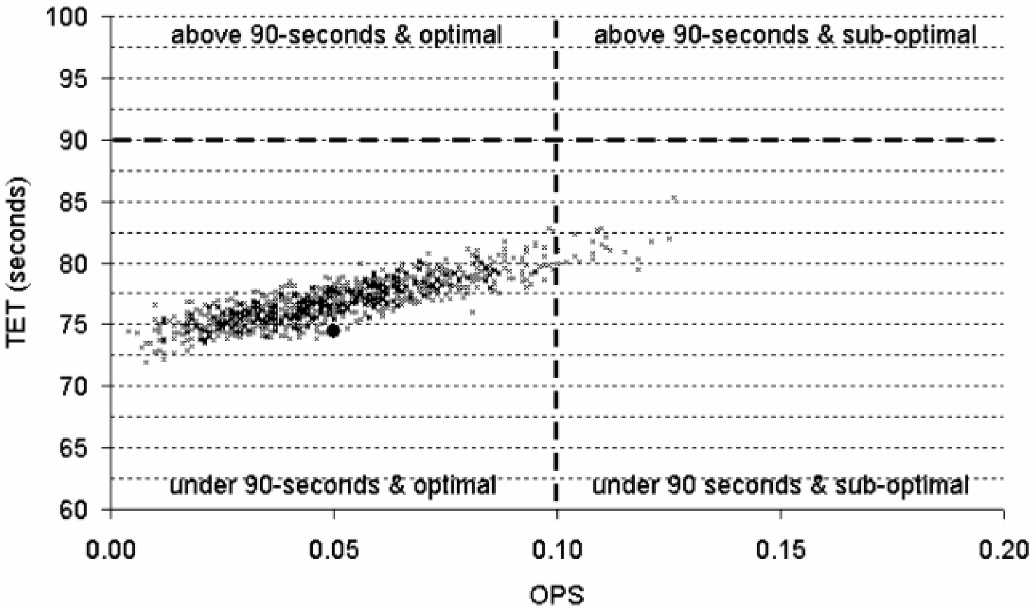


Figure 20 Scatter Diagram of TET and OPS Generated by airEXODUS (1000 data points) and the Result of the Certification Trial (1 data point) when using the Actual Data

5.1.5 General Discussion: Comparison of the airEXODUS Predictions of Certification Trial Cases 1-4 when using Actual Data

As the certification trial is a benchmark it provides us with a way of ranking aircraft evacuation performance. For the computer model to be considered representative of, or equivalent to the certification trial, the ranking of aircraft by the model should be broadly equivalent to that generated by the trial. In this section the ability of airEXODUS to rank aircraft will be examined.

A summary of the trial results and the model predictions can be found in Table 9 and Figure 21. For the family of derivative aircraft, the rank ordering of the certification trial results places Case 3 with the quickest evacuation time, followed by Case 2 and lastly Case 1. Examination of the data in Table 9 demonstrates that airEXODUS reproduces the same rank ordering when the mean time from the airEXODUS distribution is used to rank the aircraft.

Table 9 Trial and airEXODUS Results for Certification Trial Cases 1-4 using the Actual Data

Case / Aircraft	Trial Result (secs)	airEXODUS mean (secs)	Trial rank	airEXODUS rank
Case 1	83.7	86.6	4	4
Case 2	72.6	70.4	2	2
Case 3	71.7	68.2	1	1
Case 4	74.4	76.9	3	3

Furthermore, the relative differences between the various aircraft performances – as measured by the differences between the trial results and the airEXODUS mean results - generated by airEXODUS match those observed in the actual certification trials. Closer examination of Figure 21(a) reveals that the difference between the certification trials of Case 2 and Case 3 were only small, i.e. the dashed lines are close together, whereas the difference between certification trials of Case 2 and Case 1 was large. It can be seen in Figure 21(a) that airEXODUS broadly reproduces these features. The airEXODUS generated TET frequency distributions of Case 2 and Case 3 are relatively close together, whereas the airEXODUS generated TET frequency distributions of Case 2 and Case 1 are reasonably far apart.

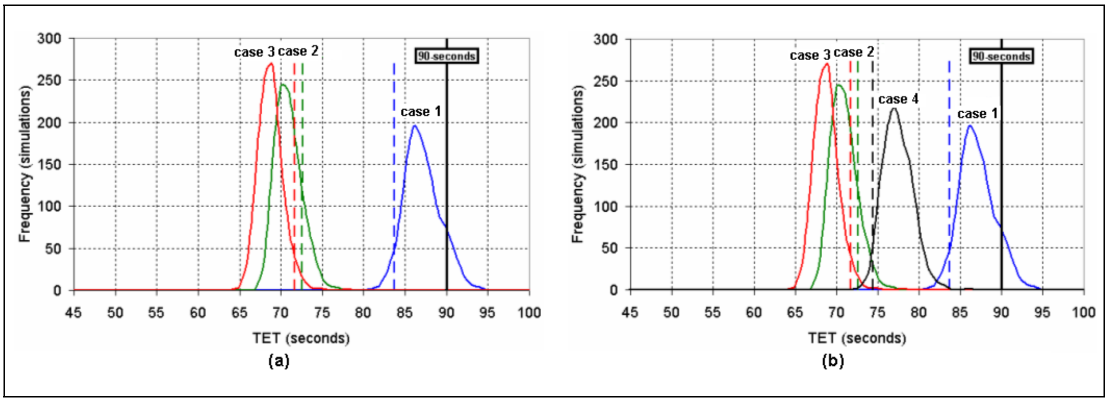
At this point it is important to raise a note of caution in the above analysis concerning the rank ordering of the aircraft. As the actual performance (and model simulated performance) of an aircraft is defined by a probability distribution, it is possible for the rank ordering of the aircraft - as gauged by a single data point - to change with repeated trials. Thus the rank ordering achieved by the certification trials single data point is not truly indicative of the rank ordering of the performance capabilities of the aircraft. This will be the case if the probability distributions for any two aircraft overlap.

To demonstrate this let us assume that the model generated probability distributions for each aircraft accurately represents the actual frequency distribution. We see from Figure 21b that these frequency distributions all overlap to a certain extent. Thus if we were to select one time at random from each distribution to represent that actual time achieved in the certification trial we would obtain a particular rank order. If we were to select a second point at random from each distribution it is possible that we would obtain a completely different rank ordering – due to the overlap. Thus the rank ordering achieved in the certification trials cannot be taken as a definitive measure of the relative ranking and hence relative performance of the aircraft. Thus, it may in fact be fortuitous that the rank ordering achieved by airEXODUS and the certification trials agree. This issue is further discussed in section 7.3.

To summarise, airEXODUS has demonstrated that it is was able to reproduce the rank order of each of the derivative aircraft. Furthermore airEXODUS is capable of capturing the relative differences in the performances of each of the derivative aircraft. However, the rank ordering produced by the certification trials is subject to variation due to the probabilistic nature of the trials.

The frequency distribution of TETs for Case 4 – which is not part of the family of aircraft examined in Cases 1-3 – is presented along with the results for the first three cases in Figure 21(b). Looking first at the times generated by the certification trials, it can be seen that the evacuation time measured in the certification trial of Case 4 is positioned between the times measured for Case 2 and Case 1.

It can be seen that the frequency distributions that were generated by airEXODUS demonstrate exactly the same ordering. In addition, the TET frequency distribution for Case 4 has been correctly placed in between the TET frequency distribution of Case 1 and Case 2. In other words, airEXODUS is able to correctly rank order all of the wide-bodied cases considered and in doing so capture the major quantitative differences between each of the cases.



(a)

(b)

Figure 21 Combination of Frequency Distributions Generated by airEXODUS using the Actual Data (a) the Derivative Cases 1- 3 and (b) all Cases 1-4

Having established that airEXODUS can reproduce the general trends of the certification trials we now examine the differences between airEXODUS predictions and the evacuation times of the certification trials.

Firstly, we note that in each case the evacuation time of the actual certification trial was within the range of values predicted by airEXODUS. In other words, airEXODUS is generating results that include the result of the certification trial.

Table 10 also reveals that the magnitude of the difference (in seconds) between the mean TET generated by airEXODUS and the evacuation time achieved in the certification trials. As shown, the differences range from 2.2 to 3.5 seconds with a mean absolute difference of 2.8 seconds. These results suggest that when using the actual data from the certification trial airEXODUS can produce a mean TET that is within 3.0% to 4.9% of the result of the actual certification trial (or 3.7% on average).

It can be seen that in two cases the airEXODUS mean was higher than the result of the certification trial and in two cases the airEXODUS mean was lower thus, airEXODUS is not consistently over- or under-predicting the certification results. Furthermore, the degree of over- or under-prediction is small, with an average absolute mean difference of 3.7% (2.8 seconds).

Table 10 Summary of the Comparisons between the Results of the Certification Trial Cases and the airExodus results when using the Actual Data from the Cerification Trials

	Case 1	Case 2	Case 3	Case 4	Mean of Absolute Difference
Difference between airEXODUS mean TET and trial TET (%)	3.5%	3%	4.9%	3.4%	3.7%
Difference between airEXODUS mean TET and trial TET (secs)	2.9	2.2	3.5	2.5	2.8
trial TET within bounds of airEXODUS TETs	YES	YES	YES	YES	N/A
Probability that the aircraft will fail (number of simulations)	76	0	0	0	N/A
Probability that the aircraft will fail (%)	7.6%	0	0	0	N/A
Distance between 90 second and airEXODUS mean (standard deviations)	1.6	0	0	0	N/A

As mentioned previously, the evacuation time generated in each of the certification trials represents only one data point from a hypothetical distribution of data points. It could be that a certification trial that generated an evacuation time that was higher than the airEXODUS mean performed worse than the average certification trial of the aircraft. Conversely a certification trial that generated an evacuation time that was lower than the airEXODUS mean could have performed better than the average certification trial of particular aircraft. It is most likely that the differences between the mean TETs of airEXODUS and the evacuation time of certification trials originate from a degree of airEXODUS error and the intrinsic unreliability associated with performing a single certification trial.

In conclusion, given the lack of multiple data points for each certification trial it is difficult to make definitive statements concerning how accurate airEXODUS reproduces the certification trials. However, we can improve our level of confidence through the number of certification trials with which airEXODUS is compared. airEXODUS has consistently shown that it is capable of producing a range of TETs that both: includes the evacuation time generated in the certification trial and produce a mean that is reasonably close to the evacuation time of the certification trial. More confidence can be derived from the fact that airEXODUS is reproducing the comparative trends, i.e. the correct rank order of the aircraft.

5.2 Predicting the Results of Wide-bodied Certification Trials using the Generalised Data

The previous section demonstrated that airEXODUS could reproduce the results of certification trials with reasonable accuracy when supplied with the actual data from the certification trial. In the absence of data from the actual certification trial, airEXODUS makes use of generalised data appropriate to the exit type. This generalised data is based upon numerous previous evacuation certification trials. If demonstrated as feasible, this approach allows a prediction based on a generalised data for the aircraft. In this section we re-evaluate the certification trials using the generalised data within airEXODUS.

Generalised data will be applied to both passenger exit delays and to the time required to ready an exit for use. In these cases cabin crew performance is uniformly fixed as assertive. The time required to ready an exit for use will be set to an average value that was derived from the analysis of certification trials (see Section 3.3). Apart from the aforementioned variables all of the parameters will remain identical to the previous section. This will enable a direct comparison with the results using the actual data.

5.2.1 Results and Discussion: Case 1 Generated using the Generalised Data

Table 11 summarises the results of the airEXODUS predictions for Case 1 using the generalised data. It can be seen that using the generalised data, the TETs lie between 76.2 and 93.8 seconds with a mean of 82.7 seconds. The evacuation time generated in the certification trial was 83.7 seconds. The evacuation time of the certification trial falls within the range of TETs generated by airEXODUS.

The mean TET that was generated by airEXODUS was 1.2% (1 second) less than the evacuation time achieved in the actual certification trial. It can be seen in Figure 22 that a small majority (68.3%) of the simulations generated TETs that were lower than the evacuation time of the certification trial, whilst a large minority of 31.7% were higher than the evacuation time of the certification trial. When using the generalised data in this case, the mean TET generated by airEXODUS is extremely close to the TET of the certification trial, exhibiting only a very minor trend towards under prediction.

Table 11 Summary of Results Generated by airEXODUS in Certification Trial Case 1 using Generalised Data

		First out (secs)	TET (secs)	CWT (secs)	PET (secs)	OPS
Generalised Data	**Min**	11.2	76.2	25.1	41.1	0.00
	Mean	**11.3**	**82.7**	**27.4**	**43.4**	**0.07**
	Max	12.1	93.8	30.4	46.4	0.19
	STD	0.11	2.26	0.83	0.85	0.03

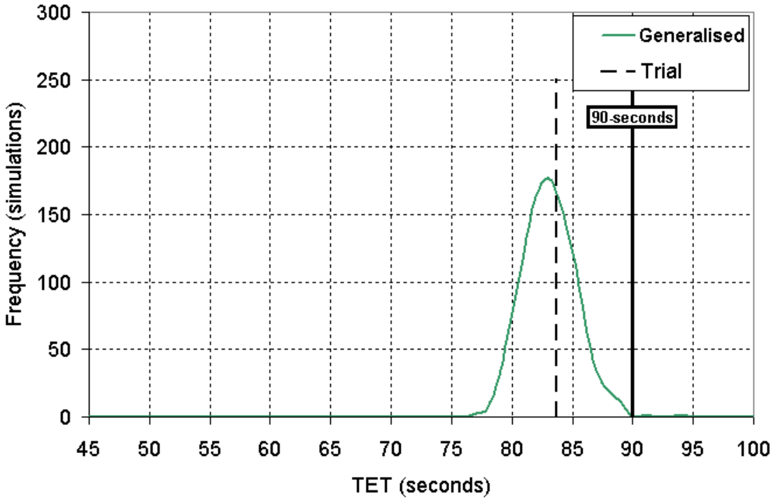


Figure 22 Frequency Distribution of TETs Generated by airEXODUS in Certification Trial Case 1 using the Generalised Data

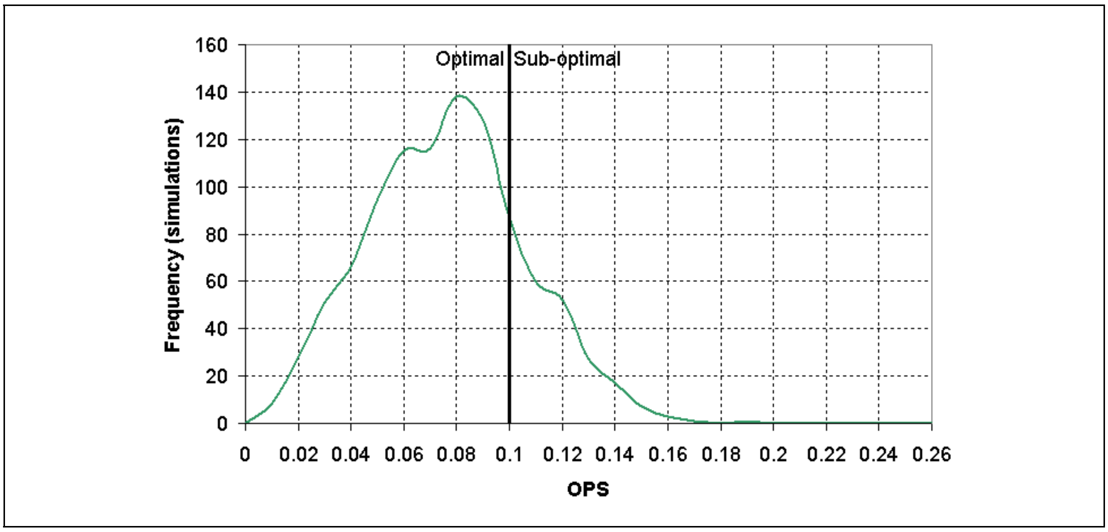


Figure 23 Frequency Distribution of OPS Generated by airEXODUS in Certification Trial Case 1 using the Generalised Data

As was the case when the actual data was used in the simulations, airEXODUS predicts that a small number (0.3%) of these trials will fail to satisfy the 90 second certification criteria. This number may well be increased if allowances are made for the extra time required to traverse and dismount the exit slides.

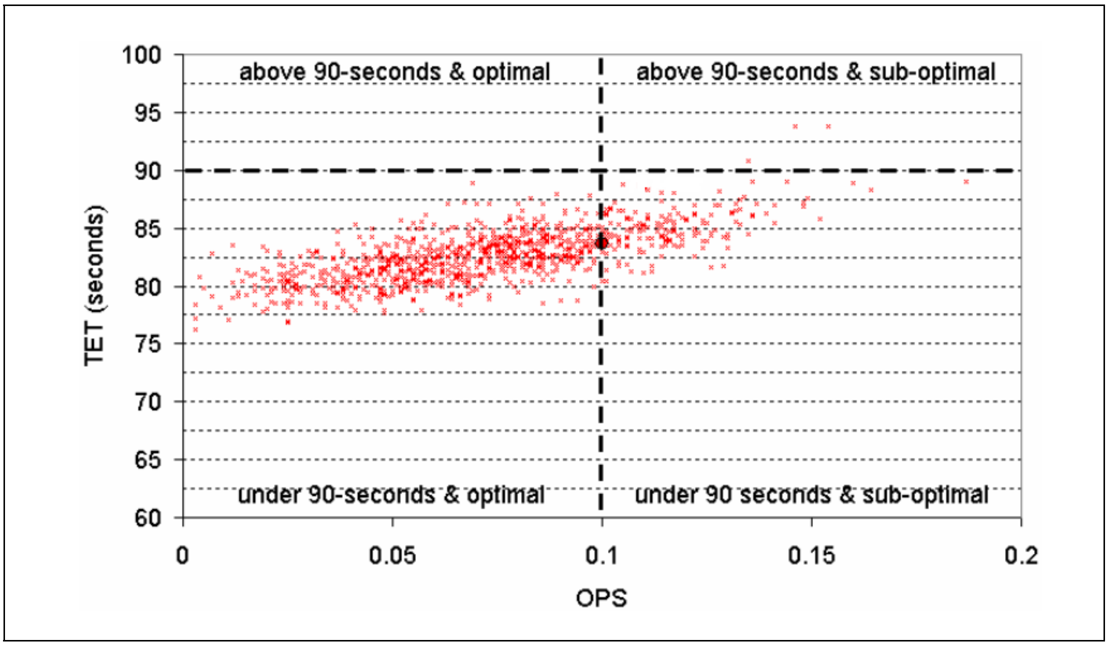


Figure 24 Scatter Diagram of TET and OPS Generated by airEXODUS (1000 data points) and the Result of the Certification Trial (1 data point) when using the Generalised Data

The OPS values generated using the generalised data were range between 0.0 and 0.19 with an average of 0.07 (see Table 11). The low mean OPS value indicates that in general these simulations are optimal. Recall that the OPS generated in the 90 second certification trial scenario was 0.1. Examination of the frequency distribution of OPS values in Figure 23 shows that the majority of the simulations (83.2%) are optimal and only a small minority of 16.8% are sub-optimal. Examination of the scatter plot for TET and OPS generated by airEXODUS (see Figure 24), suggests that whilst on average the simulations were more optimal than the certification trial, there were numerous simulations that shared a similar optimality to that of the certification trial. Also note that all the data points fall either in Quadrant 1, Quadrant 4 or Quadrant 3, with the majority of points falling in Quadrant 1. This suggests the aircraft has a well balanced configuration but at times the procedures may be improved. However, the majority of times in which the procedures fail to produce optimal results the evacuation time is still likely to be sub 90 seconds. In slight contrast to the case with the actual data, the generalised data produces no cases in Quadrant 2. However, recall that only a very small number of cases appeared in Quadrant 2 when the actual data was used.

These results have shown that in the absence of the actual data for this certification trial airEXODUS could predict the results using the generalised data. The evacuation time of the certification trial is positioned within the bounds predicted by airEXODUS. Furthermore when using the generalised data in this case, airEXODUS can predict the result of the certification trial with a high degree of accuracy, i.e. the airEXODUS mean is within 1.2% (1 second) of the evacuation time measured in the certification trial. Finally, as was found when the actual data was used, airEXODUS suggests that a small number of these trials are likely to fail to meet the certification criteria.

5.2.2 Results and Discussion: Case 2 Generated using the Generalised Data

The results of airEXODUS for Case 2 when using the generalised data are presented in Table 12. It can be seen that this case generated TETs between 68.6 and 79.5 seconds with a mean of 73.1 seconds. The evacuation time recorded in the certification trial was 72.6 seconds. This falls within the range of TETs generated by airEXODUS.

It can be seen that the mean TET generated by airEXODUS is 0.8% (0.5 seconds) higher than the evacuation time of the certification trial. Examination of the frequency distribution of TETs generated in Figure 25 highlights the fact that the evacuation time of the certification trial is positioned very close to the peak of the frequency distribution and therefore close to the mean. This fact is further substantiated by the large minority of 39.8% of simulations that were lower than the evacuation time of the certification trial and that a small majority of 60.2% that were higher.

Table 12 Summary of Results Generated by airEXODUS in Certification Trial Case 2 using Generalised Data

		First out (secs)	TET (secs)	CWT (secs)	PET (secs)	OPS
Generalised Data	**Min**	6.4	68.6	22.2	37.4	0.00
	Mean	**7.5**	**73.1**	**23.9**	**39.3**	**0.04**
	Max	9.2	79.5	26.0	41.4	0.13
	STD	0.52	1.64	0.60	0.63	0.02

From Table 12 we note that the when using the generalised data the OPS values range between 0.0 and 0.13 with a mean OPS of 0.04. Recall that the OPS generated by the certification trial was 0.06. In these simulations the optimality of the airEXODUS simulations were reasonably close to that attained in the certification trial (see Figure 26). Figure 27 shows the frequency distribution of OPS values generated by airEXODUS.

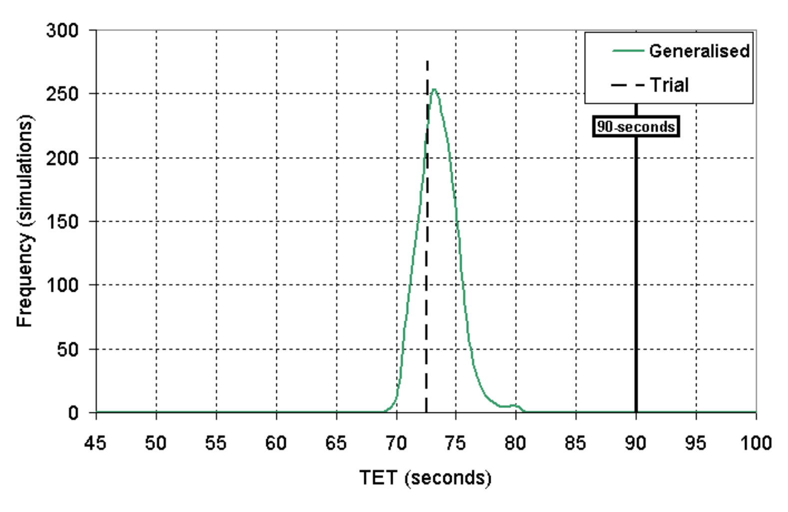


Figure 25 Frequency Distribution of TETs Generated by airEXODUS in Certification Trial Case 2 using the Generalised Data

It can be seen that the vast majority (98.6%) of OPS values generated are optimal and that only a small minority of 1.4% are sub-optimal. Also note that all the data points fall either in Quadrant 1 or Quadrant 4, with the majority of points falling in Quadrant 1. This suggests the aircraft has a well balanced configuration. The scatter plot is also similar to that generated using the actual data.

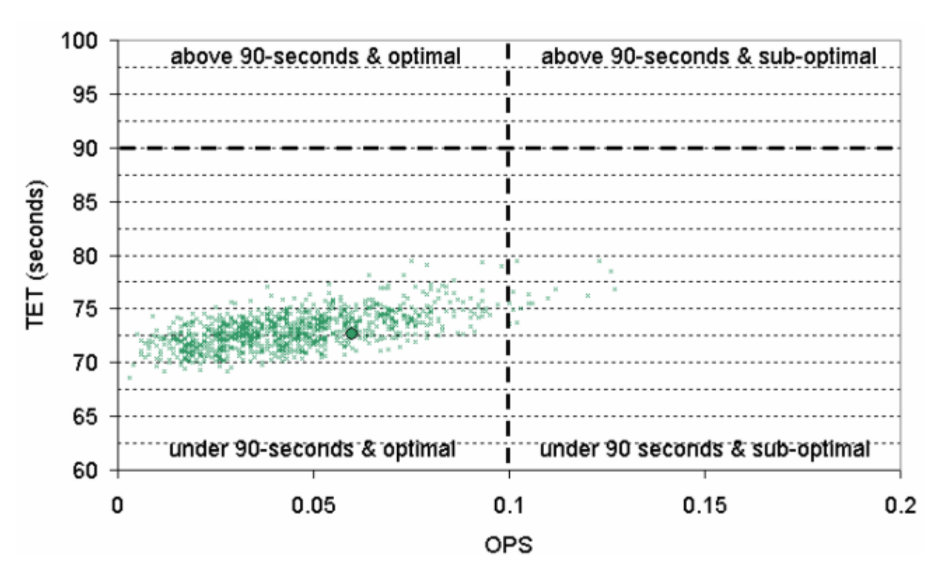


Figure 26 Scatter Diagram of TET and OPS Generated by airEXODUS (1000 data points) and the Result of the Certification Trial (1 data point) when using the Generalised Data

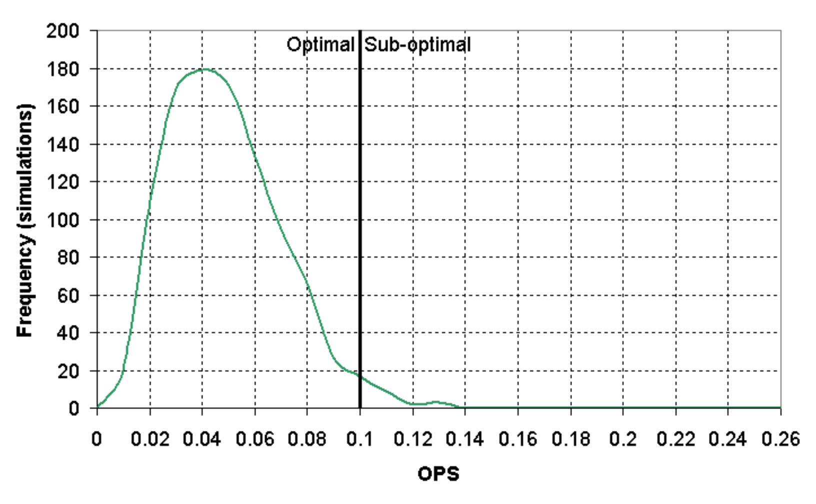


Figure 27 Frequency Distribution of OPS Generated by airEXODUS in Certification Trial Case 2 using the Generalised Data

To summarise, it has been shown that the evacuation time of the certification trial is positioned within the bounds predicted by airEXODUS in this case. In fact when using the generalised data airEXODUS predicts a mean TET that is close (within 0.8% or 0.5 seconds) of the evacuation time measured during the certification trial.

5.2.3 Results and Discussion: Case 3 Generated using the Generalised Data

The results of the airEXODUS predictions for the certification trial of Case 3 when using the generalised data are presented in Table 13. When using the generalised data, airEXODUS produces TETs between 64.2 and 74 seconds, with a mean of 68.3 seconds. The evacuation time generated by the certification trial was 71.7 seconds. This falls within the bounds of TETs generated by airEXODUS.

The mean TET generated by airEXODUS is 4.7% (3.4 seconds) lower than the evacuation time generated in the certification trial. The frequency distribution of TETs generated by airEXODUS is presented as Figure 28. It can be seen that the vast majority (97.7%) of TETs were shorter than the evacuation time of the certification trial and that a small portion (2.3%) of TETs were longer. The evacuation time of the certification trial is situated towards the upper tail of the frequency distribution of TETs generated by airEXODUS.

Table 13 Summary of Results Generated by airEXODUS in Certification Trial Case 3 using Generalised Data

		First out (secs)	TET (secs)	CWT (secs)	PET (secs)	OPS
Generalised Data	**Min**	8.9	64.2	21.6	35.4	0.01
	Mean	9.2	68.3	22.9	36.8	0.06
	Max	10.1	74.0	24.4	38.4	0.19
	STD	0.17	1.54	0.48	0.51	0.03

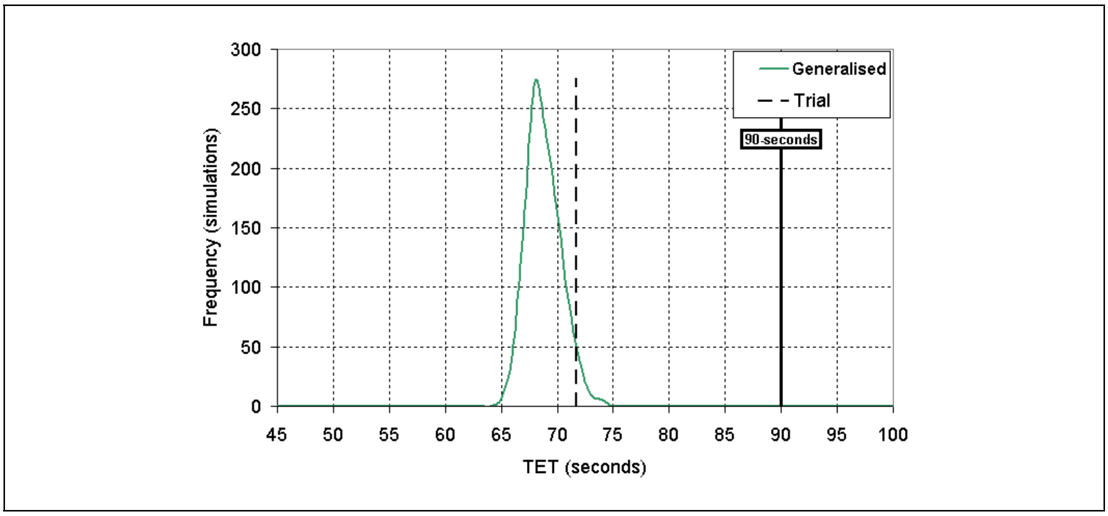


Figure 28 Frequency Distribution of TETs Generated by airEXODUS in Certification Trial Case 3 using the Generalised Data

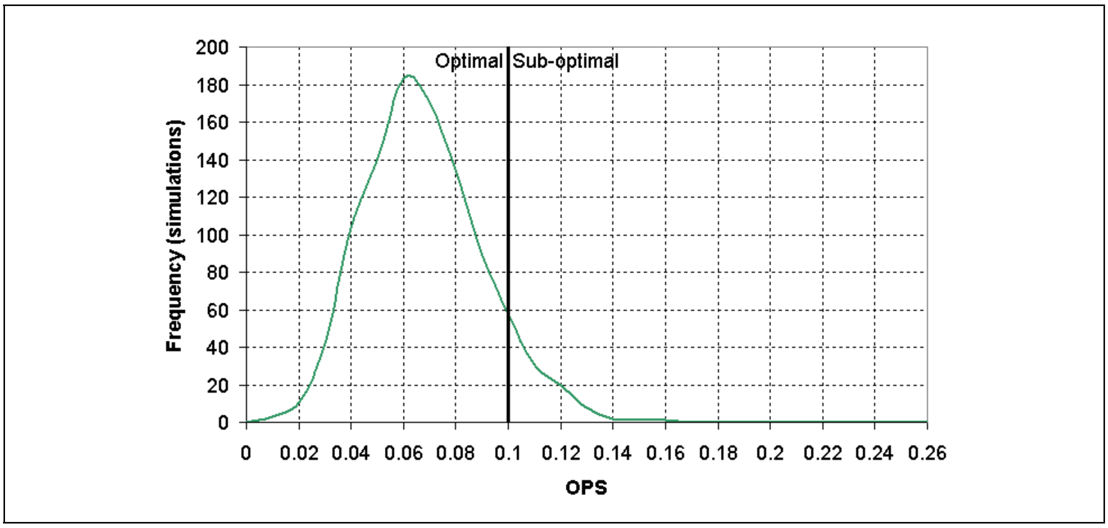


Figure 29 Frequency Distribution of OPS generated by airEXODUS in Certification Trial Case 3 using the Generalised Data

Examining the optimality of these simulations reveals that OPS values were generated between 0.01 and 0.19 with a mean of 0.06. The frequency distribution of OPS values is presented in Figure 29. It can be seen that the vast majority (93.6%) of simulations were optimal and that only a small minority of 6.4% of simulations were sub-optimal. Furthermore, the airEXODUS scenario closely matches that of the certification trial as numerous data points shared similar OPS to that of the certification trial (see Figure 30). Also note that all the data points fall either in Quadrant 1 or Quadrant 4 with the majority of points falling in Quadrant 1. This suggests the aircraft has a well balanced configuration. The scatter plot is also similar to that generated using the actual data.

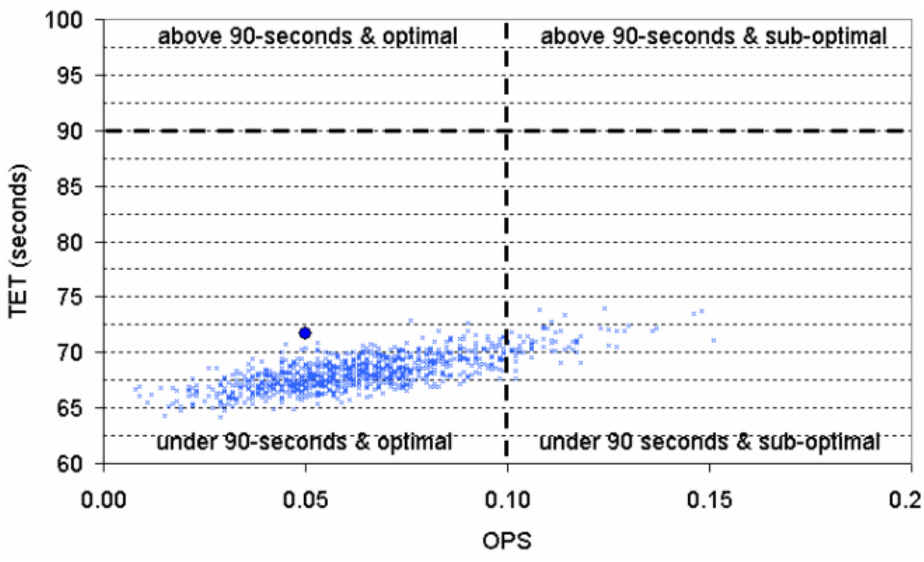


Figure 30 Scatter Diagram of TET and OPS Generated by airEXODUS (1000 data points) and the Result of the Certification Trial (1 data point) when using the Generalised Data

To summarise, the evacuation time of the certification trial falls within the range of TETs generated by airEXODUS. However, it is situated towards the upper tail of the frequency distribution of TETs. This has led to airEXODUS predicting generally shorter TETs (by on average 4.7% or 3.4 seconds).

5.2.4 Results and Discussion: Case 4 Generated using the Generalised Data

The results of the airEXODUS simulations of the certification trial of Case 4 when using the generalised data are presented in Table 14. It can be seen that airEXODUS generated TETs between 73.3 and 83.7 seconds with a mean of 77.9 seconds. The evacuation time of the certification trial was 74.4 seconds. This falls within the range of values predicted by airEXODUS. Whilst the evacuation time of the certification trial falls within the range of predicted values, the predicted mean TET of airEXODUS is 4.7% (3.5 seconds) higher than the TET generated in the actual certification trial.

Figure 31 shows the airEXODUS generated TET frequency distribution for this certification trial when using the generalised data. It can be seen that the evacuation time of the certification trial is positioned towards the extreme lower end of airEXODUS predictions. The vast majority (98.9%) of airEXODUS simulations generated a higher TET than the evacuation time of the certification trial.

Table 14 Summary of Results Generated by airEXODUS in Certification Trial Case 4 using Generalised Data

		First out (secs)	TET (secs)	CWT (secs)	PET (secs)	OPS
Generalised Data	**Min**	11.2	73.3	25.1	39.8	0.02
	Mean	**11.3**	**77.9**	**26.8**	**41.5**	**0.07**
	Max	12.1	83.7	29.3	44.3	0.15
	STD	0.11	1.64	0.56	0.58	0.02

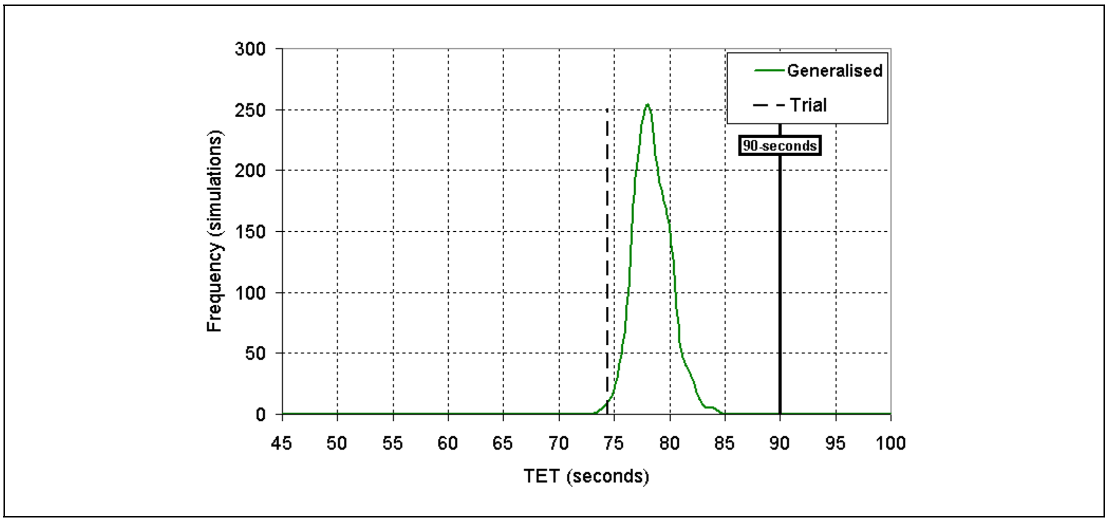


Figure 31 Frequency Distribution of TETs Generated by airEXODUS in Certification Trial Case 4 using the Generalised Data

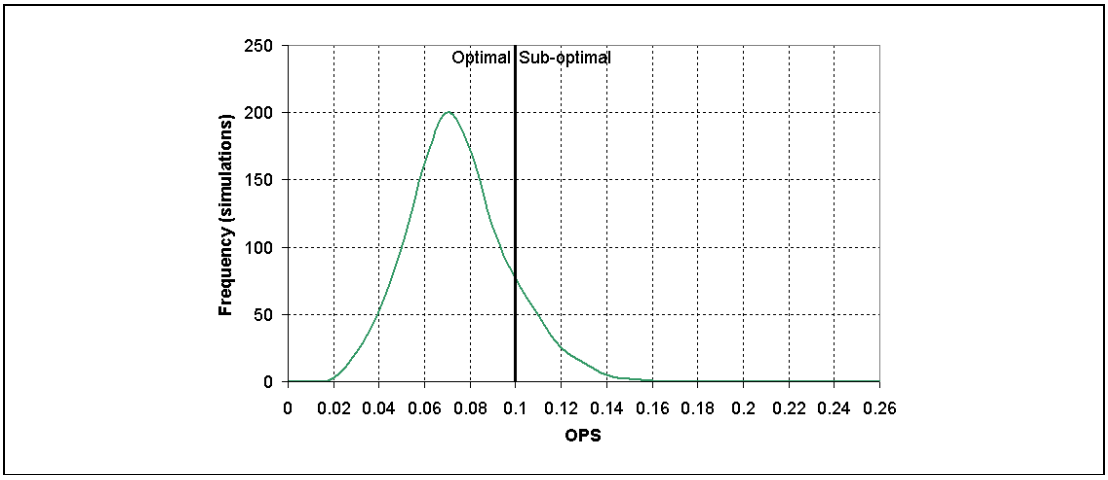


Figure 32 Frequency Distribution of OPS Generated by airEXODUS in Certification Trial Case 4 using the Generalised Data

Figure 32 shows the optimality of the airEXODUS simulations. It can be seen that the OPS values generated using the average data range from 0.02 to 0.15 with a mean of 0.07. Furthermore, the majority (90.4%) of simulations were optimal. In general the results of airEXODUS in this case are optimal. The OPS generated by the certification trial was 0.05. This is reasonably close to that attained in the model simulations (0.07). However, examination of the scatter plot reveals that more simulations generated higher OPS than that attained in the 90 second certification trial (see Figure 33). The higher level of OPS achieved in the simulations led to the generation of evacuation times that were on average larger than that of observed in the trial. Also note that all the data points fall either in Quadrant 1 or Quadrant 4 with the majority of points falling in Quadrant 1. This suggests the aircraft has a well balanced configuration. The scatter plot is also similar to that generated using the actual data.

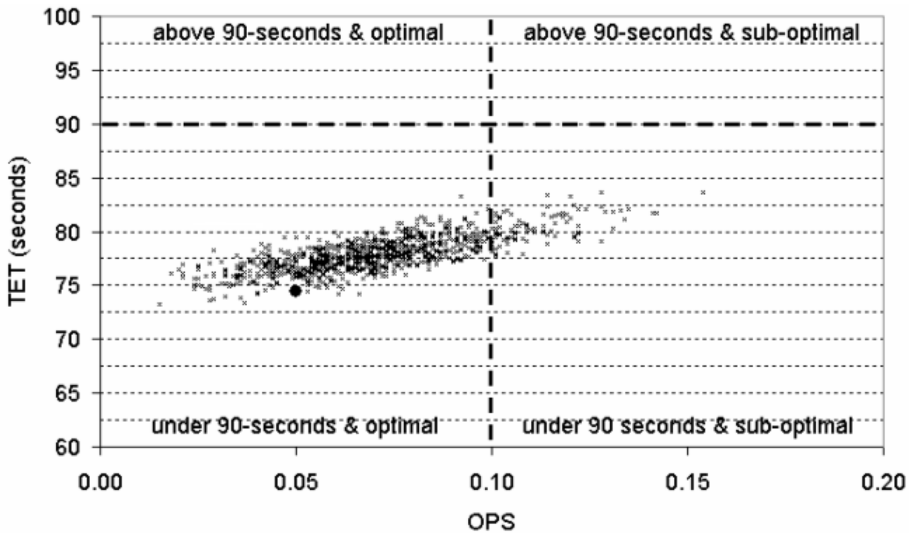


Figure 33 Scatter Diagram of TET and OPS Generated by airEXODUS (1000 data points) and the Result of the Certification Trial (1 data point) when using the Generalised Data

To summarise, when using the generalised data airEXODUS predicts a range of TETs which includes the evacuation time of the certification trial. However, the evacuation time of the certification trial is situated towards the lower end of the frequency distribution of TETs. This indicates that airEXODUS is generally predicting higher TETs (by on average 4.7% or 3.4 seconds) than the evacuation time achieved by this aircraft in the certification trial.

5.2.5 General Discussion: Comparison of the airEXODUS Predictions of Certification Trial Cases 1-4 using Generalised Data

The previous section has demonstrated that airEXODUS can predict the results of certification trials when using generalised data for the exit hesitation times and exit ready times. In this section we examine the ability of airEXODUS to predict the rank ordering of aircraft using generalised data.

A summary of the trial results and the model predictions can be found in Table 15 and Figure 34. Examination of the data in Table 15 demonstrates that, when using the generalised data, airEXODUS is still capable of reproducing the same rank ordering of aircraft performance as is achieved in the actual certification trials.

Table 15 Trial and airEXODUS Results and Rank Order for Certification Trial Cases 1-4 using the Generalised Data

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

Once again, it is important to note as in Section 5.1.5 that the rank ordering produced by the certification trials should not be taken to indicate a definitive rank ordering due to the probabilistic nature of evacuation performance. This issue is further discussed in section 7.3.

Having established that airEXODUS can predict the general trends, i.e. rank ordering, of the certification trials, we can now examine how the means of the TETs generated by airEXODUS compare with the measured evacuation time of the certification trials. Similarly to the reconstruction cases of the previous sections, confidence in the predictive ability of the model using generalised data can be derived from the fact that in every case the evacuation time of the certification trial was within the range of values predicted by airEXODUS. When using the generalised data airEXODUS predicts TETs that include the evacuation time of the certification trial.

The differences between the airEXODUS mean TET and the evacuation time of the certification trials is shown in Table 16. It can be seen that the difference between the airEXODUS mean TETs and the evacuation time measured in the actual certification trials range from 0.5 to 3.5 seconds (0.8% to 4.7%). 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. The mean absolute difference across all cases was 2.8% (2.1 seconds). Returning to the results from the reproduction cases (i.e. using the actual data), we note from Table 10 that the maximum difference between the airEXODUS mean and the actual evacuation time achieved in the certification trials was 4.9% (3.5 seconds) with an average variation between all of the actual cases of 3.7% (2.8 seconds). Contrasting the results of the actual and generalised cases reveals that the results have not greatly altered.

However, as is to be expected when using generalised data, there are some differences between the predicted and measured trends. For example, a feature of the certification trials was that the difference between the evacuation time of Case 3 and Case 2 was small (see the dashed lines on Figure 34(a)) while using the generalised data we predict a larger difference. The actual difference between the performance of these two aircraft was 0.9 seconds or 1.3%. Using the actual data, this difference was 2.2 seconds or 3.2% while using the generalised data the difference was 4.8 seconds or 7.0%. Thus, while the rank ordering of the two aircraft is correctly predicted using the model, when the generalised data is used we have a greater relative difference between the performance of these two aircraft.

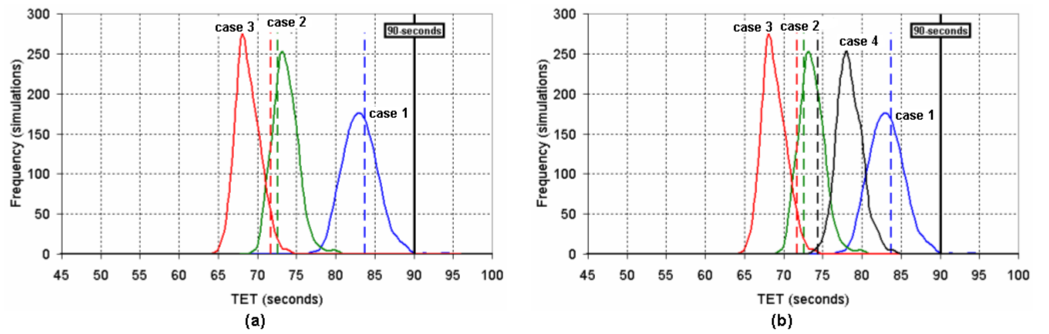


Figure 34 Combination of Frequency Distributions Generated by airEXODUS using the Generalised Data for (a) the Derivative Cases 1- 3 and (b) all Cases 1-4

Table 16 Summary of the Comparisons between the Results of the Certification Trial Cases and the airExodus results when using the Generalised Data

	Case 1	**Case 2**	**Case 3**	**Case 4**	**Mean of Absolute Difference**
Difference between airEXODUS mean and trial TET (%)	1.2%	0.8%	4.7%	4.7%	2.8%
Difference between airEXODUS mean and 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

This can again be seen by comparing the relative performance achieved in Case 3 and Case 1. The actual difference between the performance of these two aircraft was 12 seconds or 16.7%. Using the actual data, this difference was 18.4 seconds or 27.0% while using the generalised data the difference was 14.4 seconds or 21.1%. Once again, while the rank ordering of the two aircraft is correctly predicted using the model, when the generalised data is used we have a greater relative difference between the performance of these two aircraft.

Thus, while using the generalised data, the model has not been able to correctly predict the magnitude of the differences between the cases, the model has correctly predicted the trends in the differences, namely that the difference between Cases 3 and 2 will be “small” while the difference between Cases 3 and 1 will be “large”. Finally, it is worth recalling here that the trial results are only the result of a single experimental trial. Had more trial results been generated, the relative difference between the trial means could be very different.

To summarise, airEXODUS appears to be able to predict the results of the certification trial using the generalised data with at least as much accuracy as in the previous cases. In all of the wide-bodied cases the measured evacuation time of the certification trial is within the bounds of airEXODUS predictions. Additionally the difference between the airEXODUS generated means and the measured evacuation time of the certification trial is not significantly altered when using the generalised data compared with the actual data. While general trends in the results such as the rank ordering have been maintained, there are some differences in the nature of the frequency distributions produced by the generalised and actual data.

5.3 Examining the Predicted and Measured Evacuation Evolution of the Wide-bodied Certification Trials

The ability of airEXODUS to generate TETs that are reasonably close to the evacuation time of the certification trial is of major importance. However, simply predicting the total evacuation time is insufficient as this is simply a measure of the degree to which the model fits only a single measured quantity (i.e. the TET). It is possible to arrive at a good estimate of the end point for all the wrong reasons, thereby providing a misleading representation of the aircraft performance. It is therefore also essential that the model correctly predicts the evolution of the evacuation.

One measure of the evacuation evolution is provided by cumulative exit performance. This is a measure of the total number of passengers to exit the aircraft in each second of the evacuation. The cumulative number of passengers who have exited the aircraft at every second during the certification trial can be compared against the results generated by airEXODUS. In this way the airEXODUS predictions can be compared against the result of the certification trial at every second of the evacuation.

In airEXODUS the personal evacuation time (PET) of each passenger is recorded. From this the cumulative number of passengers who have exited the aircraft in each second of the evacuation can be determined. This process can be repeated for each of the repeat simulations. For the series of simulations a simulation envelope can be defined by taking the minimum and maximum number of passengers who have exited the aircraft in each second. For the simulations considered here, each case was repeated 1000 times. The simulation envelope for each scenario represents the minimum and maximum from 1000 simulations. Thus, each of the 1000 repeat simulations will produce a curve that falls within the envelope. In addition, the median of the 1000 airEXODUS simulations can be determined.

This predicted window of cumulative exit timings can be compared with the actual results derived from each certification trial. In order to construct the cumulative exit curve for the certification trial it is necessary to study the video recording of the actual certification trial. Video recordings of each certification trial were inspected and the time that each passenger exited the aircraft was noted. Using this data, the cumulative number of passengers who have exited can be determined at every second of the actual evacuation. These results were then plotted as a function of time and compared with the model generated curves.

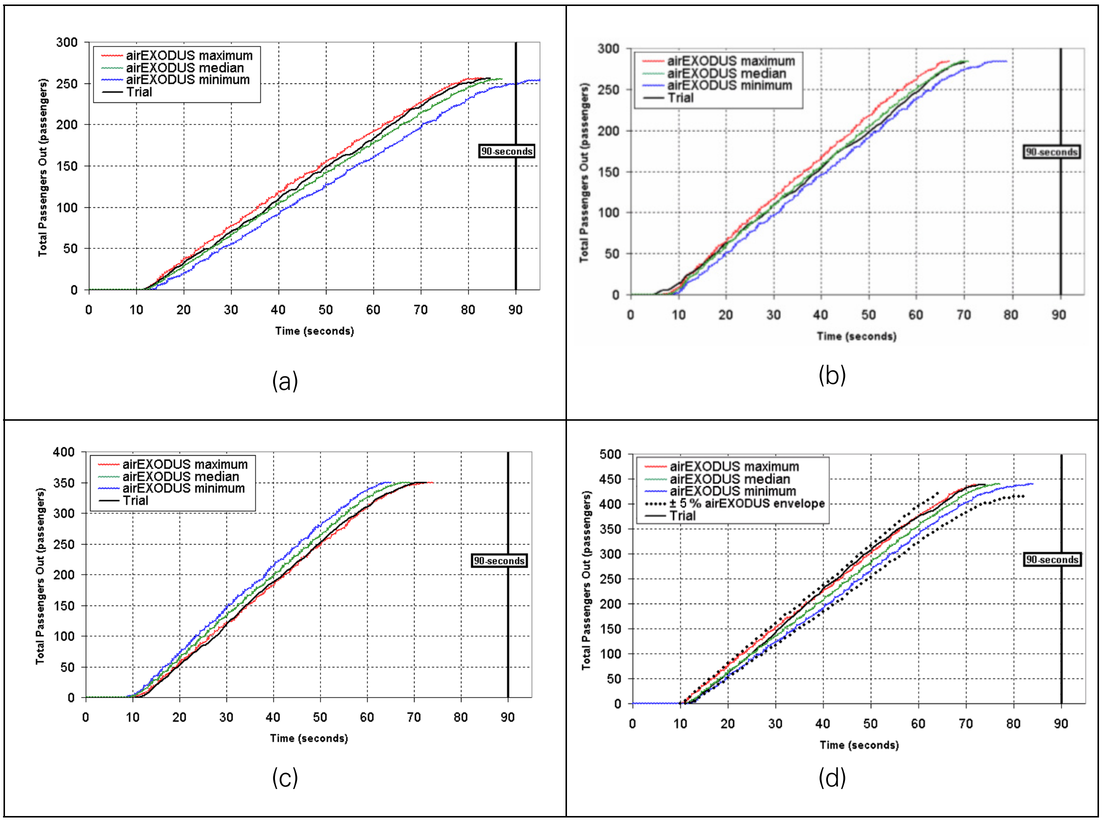
5.3.1 Validating the airEXODUS Prediction for the Evolution of Wide-bodied Certification Trials using the Actual Data

The airEXODUS cumulative exit envelope predicted using the actual data, together with the result of the certification trials for each of the four aircraft is shown in Figure 35. As can be seen from the curves, 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, indicated in Figure 35 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.

It can be seen that airEXODUS predictions produce similar structure to the certification trial. This indicates that airEXODUS is predicting a similar chain of events to that which occurred during the certification trial.

Furthermore, it can be seen that the results from the certification trials, denoted by the black lines in Figure 35, are totally within the airEXODUS simulation envelopes for Case 1, Case 2 and Case 3. This suggests that at each second of the evacuation airEXODUS is producing a similar set of events to that which occurred in the certification trial.

However, for Case 4 we note that between 35 and 60 seconds the certification trial curve crosses outside of the airEXODUS simulation envelope, but is within the +/-5% error band drawn around the minimum and maximum times. This minor departure from the simulation envelope indicates that the certification trial performed marginally better than airEXODUS during this period. This may result from an abnormally high exit flow rate during this period. Further examination reveals that it is a minor excursion from the airEXODUS envelope and that the results of the certification trial quickly return within the simulation envelope. In general it is apparent that at every second of the evacuation airEXODUS is generating similar results to the certification trials.



(a)

(b)

(c)

(d)

Figure 35 airEXODUS Simulation Envelope Generated using the Actual Data and Actual Trial Results for (a) Case 1, (b) Case 2, (c) Case 3 and (d) Case 4

5.3.2 Validating the airEXODUS Prediction for the Evolution for Wide-bodied Certification Trials using the Generalised Data

The airEXODUS simulation envelope generated using the generalised data can be seen in Figure 36. As described in the previous section, the curves generated by the generalised data follow the general trends observed in the trials. The envelopes are similar in shape to those generated using the actual data (see Figure 36). Furthermore, for each of the wide-bodied cases examined, for every second of the evacuation, the certification trial curve falls within the simulation envelope generated by airEXODUS.

As with the case for the actual data, we find that for Case 4 we note that between 40 and 55 seconds the certification trial curve crosses outside of the airEXODUS simulation envelope, but is within the +/-5% error band drawn around the minimum and maximum times. This minor departure from the simulation envelope indicates that the certification trial performed marginally better than airEXODUS during this period. In general it is apparent that at every second of the evacuation airEXODUS is generating similar results to the certification trials.

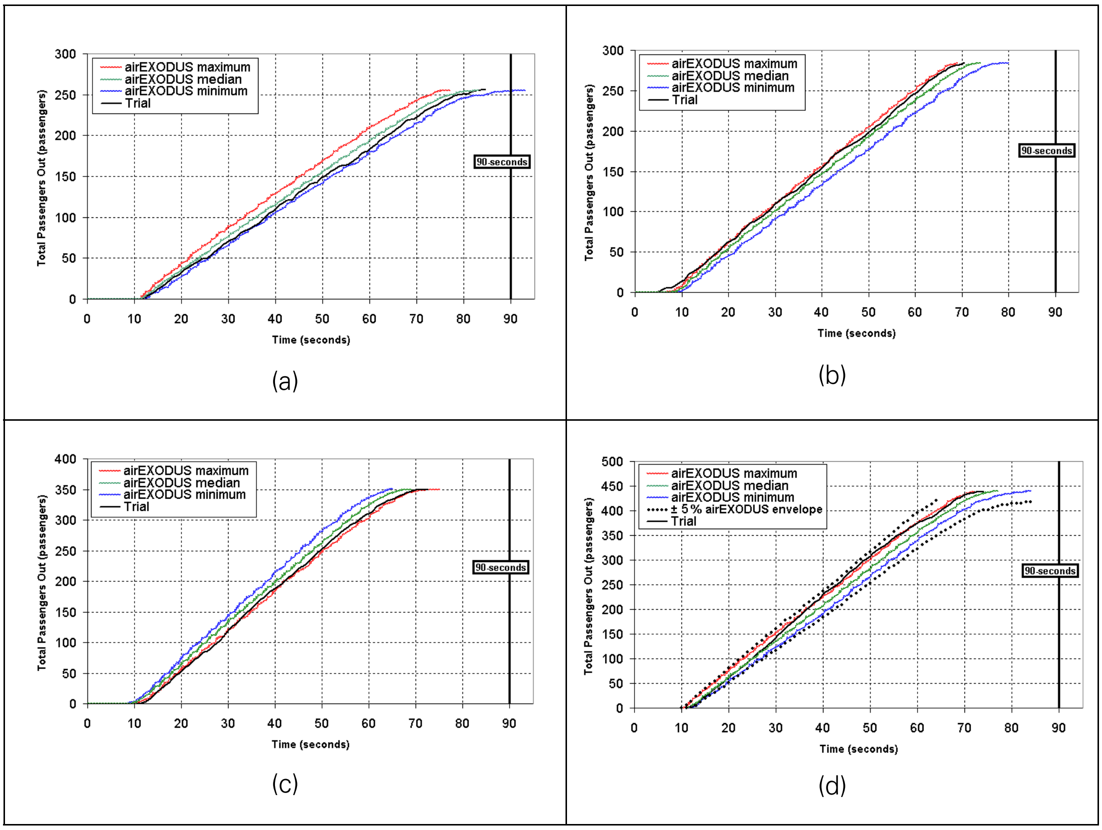


Figure 36 airEXODUS Simulation Envelope Generated using the Generalised Data for (a) Case 1, (b) Case 2, (c) Case 3 and (d) Case 4

5.4 Summarising the Outcome of the airEXODUS Reconstructions and Predictions for Wide-bodied Certification Trials

Several key points can be made from the analysis of the wide-bodied results:

1a) Using the actual data from specific certification trails, airEXODUS is able to produce distributions of Total Evacuation Times for each aircraft such that the actual trial data point is contained within the distribution.

1b) Using the generalised certification trial data, airEXODUS is able to predict distributions of Total Evacuation Times for each aircraft such that the actual trial data point is contained within the distribution.

2a) Using the actual data from the specific certification trials, airEXODUS was able to successfully rank three derivative aircraft in the identical order that was achieved in the certification trials. However, it should be noted that a ranking based on a single certification trial result for each aircraft may not be indicative of the actual ranking of the aircraft.

2b) Using the generalised certification data, airEXODUS was able to successfully rank three derivative aircraft in the identical order that was achieved in the certification trials.

3a) Using the actual data from the specific certification trials, airEXODUS was able to closely predict the relative and absolute differences between the rank ordering.

3b) Using the generalised certification data, airEXODUS was able to closely predict the relative differences between the rank ordering, while the absolute differences could not be predicted with a high degree of certainty due to the natural differences that occur in specific certification trials.

4a) Using the actual data from the specific certification trials, airEXODUS was able to successfully rank the performance of an additional aircraft not related to the original three derivative aircraft.

4b) Using the generalised certification data, airEXODUS was able to successfully rank the performance of an additional aircraft not related to the original three derivative aircraft.

5a) Using the actual data from specific certification trials, airEXODUS predicted that one of the four aircraft (one of the aircraft in the three aircraft derivative family), while having a strong possibility of passing the certification trial, has a small probability that it could fail the certification criterion.

5b) Using the generalised certification data, airEXODUS predicted that the same aircraft had a small probability of failing the certification criterion. However, the probability of failure was smaller using the generalised data.

6) The cumulative exit curves for each of the four aircraft examined fall within the numerical envelope predicted using airEXODUS and the generalised certification data. This suggests that airEXODUS is capable of predicting the time evolution of the evacuation using the generalised data.

Thus, whether the model makes use of the generalised or actual trial data, an engineer using the model would come to the same conclusions regarding the Total Evacuation Time of the aircraft and the evolution of the aircraft evacuation. Of more importance however, the mean TET predicted using the generalised data is a good indicator of the likely performance of the aircraft in the actual certification trial. In addition to predicting the mean TET and the evacuation evolution, the model can also estimate the likelihood of failure and identify potential problem areas with the cabin layout. This is an important conclusion as it suggests that airEXODUS has the capability of predicting the likely distribution of Total Evacuation Times under optimal certification conditions. Perhaps of greater interest, the model is also capable of examining the ramifications of sub-optimal conditions such as “what if exit 2L could not be opened”, “what if the crew behaved in an unassertive manner”, “what if the crew member at exit 2L required an additional 10 seconds to make the exit ready”, etc.

6 Validation of airEXODUS using Narrow-bodied Certification Trial Data

In this section we continue the validation of airEXODUS using data from narrow-body aircraft trials.

6.1 Reconstructing the Results of Narrow-bodied Certification Trials using the Actual Exit Hesitation Time Data

As in the wide-bodied aircraft analysis, the actual data will be utilised to establish how accurately airEXODUS can match the results of the actual certification trial.

The actual distribution of passenger exit delay times experienced at each exit was extracted from the video record for each of the exits used on each aircraft and used in the simulations. Similarly the actual time required to ready each exit for use was measured and assigned to each of the exits within airEXODUS.

6.1.1 Results and Discussion: Case 5 Generated using the Actual Data

The aircraft examined in Case 5 is the first of two aircraft belonging to the same family of narrow-body aircraft to be studied in this report. The measured evacuation time from the trial was 64.1 seconds with an OPS of 0.02. It should be noted here that in this case crew directed by-pass from the Type III exit to the forward Type I exit occurred.

The airEXODUS predictions for Case 5 are presented in Table 17. From Table 17 it can be seen that airEXODUS generated TETs range from 62.9 to 89.8 seconds with a mean TET of 70.5. The airEXODUS mean is 10% (6.4 seconds) longer than the single measured evacuation time and the mean OPS of 0.09 is considerably longer than that generated in the trial. The evacuation time measured during the certification trial is within the range of TETs generated by airEXODUS.

Table 17 Summary of airEXODUS Results from Certification Trial Case 5 using the Actual Data (measured evacuation time 64.1 seconds)

		First out (secs)	TET (secs)	CWT (secs)	PET (secs)	OPS
Simulation results using actual data	Min	7.6	62.9	22.0	35.0	0.00
	Mean	8.3	70.5	24.5	37.8	0.09
	Max	9.9	89.8	27.5	40.9	0.28
	STD	0.4	2.7	0.8	0.9	0.04
Simulation results using actual data excluding sub-optimal results	Min	7.6	62.9	22.2	35.3	0.00
	Mean	8.3	69.5	24.6	37.8	0.07
	Max	9.9	76.4	27.4	40.8	0.10
	STD	0.4	2.0	0.8	0.8	0.02

Examination of the airEXODUS generated TET frequency distribution demonstrates that the majority (98.8%) of simulations were longer than the evacuation time measured during the certification trial (see Figure 37). This suggests that the evacuation time measured during the certification trial is positioned towards the extreme low tail of TETs generated by airEXODUS. In virtually all of the airEXODUS simulations a longer TET is predicted than the single evacuation time recorded during the certification trial.

As described in the previous sections, some differences are to be expected between the mean TET generated by airEXODUS and the result of the certification trial as the certification result represents the outcome from only a single event. However, the differences in this case are larger (10%) than those observed in the previous wide-body cases. A possible reason for this larger discrepancy may lie in the level of optimality achieved in these simulations.

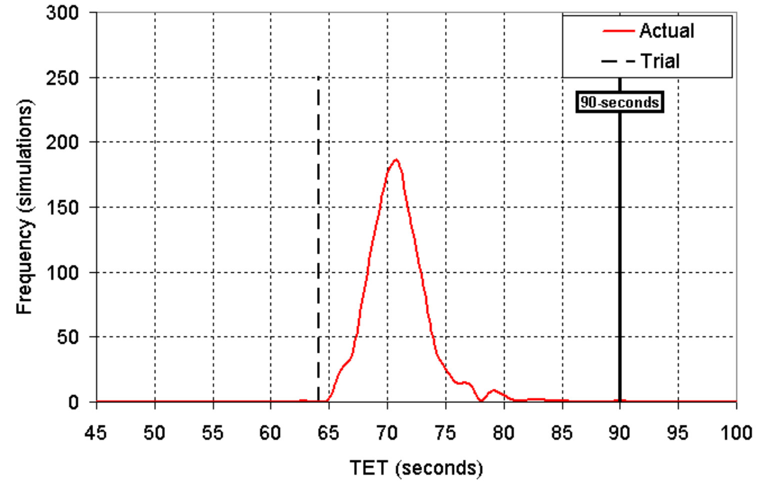


Figure 37 Frequency Distribution of TETs Generated by airEXODUS in Certification Trial Case 5 using the Actual Data

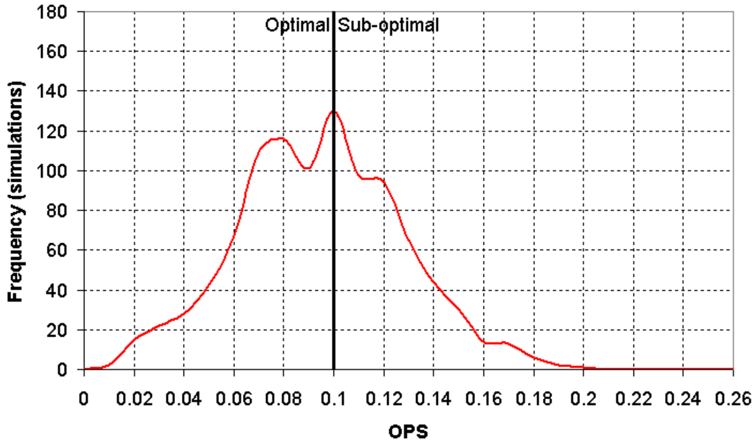


Figure 38 Frequency Distribution of OPS Generated by airEXODUS in Certification Trial Case 5 using the Actual Data

From Figure 38, it can be seen that only 61.6% of the results of airEXODUS were optimal. A significant proportion of the airEXODUS simulations (38.4%) did not meet the 0.1 optimality criteria i.e. OPS = 0.1. This suggests that it will be very difficult to achieve an optimal distribution of passengers between these exits. Furthermore, the optimality achieved in the trial was very good, with an OPS value of 0.02 being achieved.

This disparity between the optimality achieved in the airEXODUS simulations and that of the certification trial originates from the difficulty in achieving an optimal distribution of passengers between exits within airEXODUS. This indicates a need for crew directed bypass in some simulations. Indeed, cabin crew directed bypass proved necessary during the certification trial where it was observed that 5% of those passengers that evacuated via the R1 exit were bypassed from the R2 exit (see Section 3.3).

If some of the passengers were bypassed to the R1 exit it is likely that both the overall TETs generated by airEXODUS and the OPS scores would be reduced. This would have the effect of bringing the TET frequency distribution generated by airEXODUS closer to the evacuation time measured during the certification trial.

The current version of airEXODUS (i.e. airEXODUS V3.0 beta) has limited cabin crew bypass capabilities. Indeed, in the current version, cabin crew are only represented implicitly and so bypass is achieved implicitly through the selection of model parameters. In the current simulations, exit bypass would be extremely unlikely. This lack of a significant by-pass component within the simulations results in the large number of sub-optimal OPS scores generated and possibly the longer evacuation times generated.

It could be argued that the result achieved in the trial was indeed better than could normally be expected as the modelling results suggest that it will be extremely difficult to achieve a well-balanced distribution of passengers without significant crew intervention.

As already stated, the OPS score achieved in the trial was extremely good, being 0.02 whereas the airEXODUS simulations produced a significant number (38.4%) of sub-optimal results i.e. simulations with OPS > 0.1. Thus 38.4% of the simulations used in the comparison where not representative of the actual trial conditions.

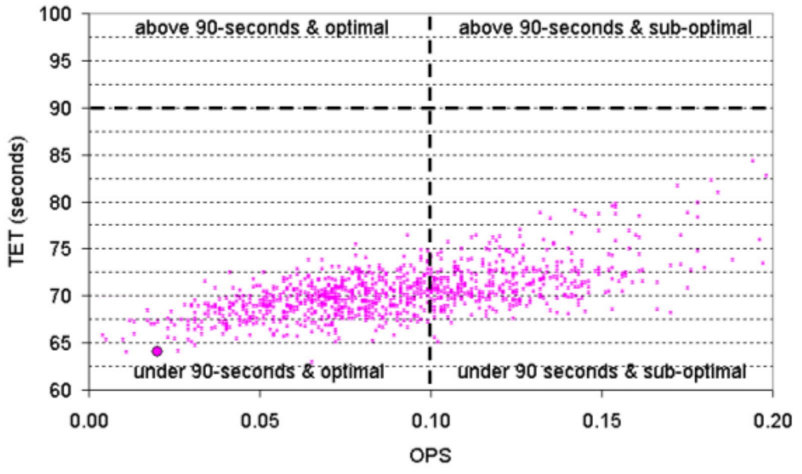


Figure 39 Scatter Diagram of TET and OPS Generated by airEXODUS (1000 data points) and the Result of the Certification Trial (1 data point) when using the Actual Data

Examination of the TET/OPS scatter diagram generated by airEXODUS (see Figure 39), clearly shows just how infrequently airEXODUS generated simulations with the OPS attained in the certification trial. However, it is apparent that when airEXODUS did generate a case in which the OPS was similar to that of the trial, the TET more closely matched that achieved in the trial. This suggests that if it were possible to generate simulations that shared the same OPS as the certification trial then the mean OPS of airEXODUS would have been much closer (within 2-3 seconds) of that achieved in the certification trial.

To achieve a more representative comparison with this particular trial, we can exclude the simulation results that failed to meet our optimality requirement of OPS < 0.1. It should be noted that excluding the sub-optimal results does not necessarily exclude the longer TET cases, but those cases in which there is a large in-balance in the exit finishing times.

If we consider only the optimal airEXODUS results (i.e. 616 out of 1000 simulations), the mean TET becomes 69.5 seconds. Thus, the predicted mean TET is 8.4% larger than the time actually achieved in the certification trial (64.1 seconds).

Also note that all the data points fall either in Quadrant 1 or Quadrant 4 with approximately half the points falling in Quadrant 1. This suggests the aircraft requires considerable procedural intervention in order to improve the evacuation effectiveness.

To summarise, airEXODUS is capable of generating a range of TETs that include the single evacuation time measured during the certification trial. However, the majority of airEXODUS simulations had longer TETs than the single evacuation time from the certification trial. It was noted that many of the airEXODUS simulations were sub-optimal. This results from the aircraft configuration requiring cabin crew procedures (such as by-pass) in order to generate an optimal distribution of passengers to exits. The mean airEXODUS prediction would be within 8.4% of the certification trial result if the sub-optimal cases were ignored.

6.1.2 Results and Discussion: Case 6 Generated using the Actual Data

The aircraft examined in Case 6 is the second of two aircraft belonging to the same family of narrow-body aircraft to be studied in this report. The airEXODUS predictions for Case 6 are presented in Table 18. From Table 18 it can be seen that airEXODUS generated TETs range from 67.9 to 81.1 seconds with a mean TET of 73.0. The airEXODUS mean is 7% (5.5 seconds) shorter than the single evacuation time of 78.5 seconds measured during the certification trial evacuation. The evacuation time measured during the certification trial is within the range of TETs generated by airEXODUS.

Table 18 Summary of airEXODUS Results from Certification Trial Case 6 using the Actual Data (measured evacuation time 78.5 seconds)

		First out (secs)	TET (secs)	CWT (secs)	PET (secs)	OPS
Actual Data	Min	7.7	67.9	24.7	37.5	0.00
	Mean	7.9	73.0	26.5	39.3	0.05
	Max	8.4	81.1	28.2	41.1	0.14
	STD	0.1	1.7	0.6	0.6	0.02

From Figure 40 it can be seen that nearly all (99.9%) of the TETs generated by airEXODUS were faster than the evacuation time measured during the certification trial. This suggests that in this case airEXODUS is predicting evacuation times that are quicker than the result of the certification trial.

While it is difficult to compare the results from a single trial with that of a distribution, the fact that the vast majority of airEXODUS results (99.9%) are quicker than that measured on the day must be explained. As noted in the previous case, one potential source for this discrepancy is the level of optimality achieved during the certification trial and the airEXODUS simulations. Unlike in the previous case the majority (98.7%) of airEXODUS simulations were optimal (see Figure 41), with a mean OPS of 0.05. However, the OPS achieved during the actual certification trial was precisely 0.1, making it a borderline case.

In the certification trial the R1 exit finished before any other exits. This was a result of the cabin crew being unable to enforce an optimal distribution of passengers between the exits. The failure of procedures is indicated by the protracted period of exit inactivity towards the end of the evacuation. As a result, the certification trial performed worse than could be expected had the crew been more effective at balancing passengers to exits.

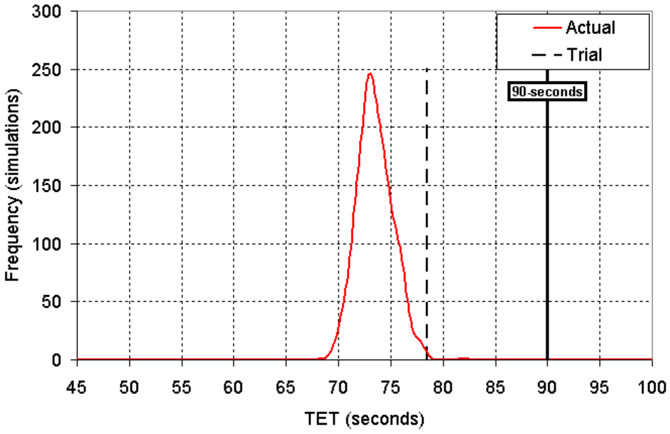


Figure 40 Frequency Distribution of TETs Generated by airEXODUS in Certification Trial Case 6 using the Actual Data

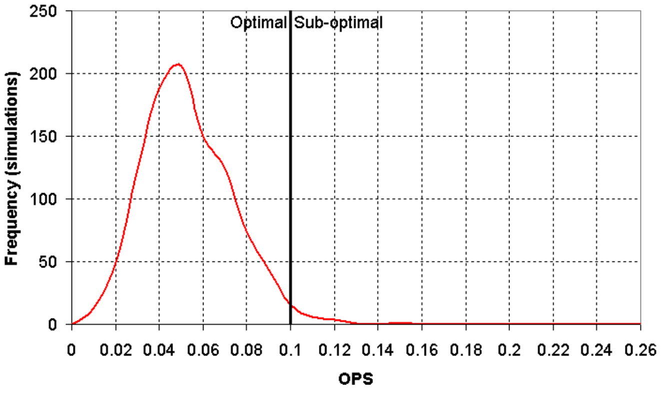


Figure 41 Frequency Distribution of OPS generated by airEXODUS in Certification Trial Case 6 using the Actual Data

From the OPS/TET scatter diagram (see Figure 42) we again note that the vast majority of model results are more optimal than the certification trial result. Also note that all the data points fall either in Quadrant 1 or Quadrant 4 with the vast majority of points falling in Quadrant 1. This suggests that if an optimal distribution of passengers is achieved, the TET will be sub 90 seconds.

By contrast, airEXODUS was configured such that an optimal distribution of passengers to the exits was achieved (98.7% of simulations were optimal). This was mainly due to an extra 7 passengers utilising the R1 exit in the airEXODUS simulations than did so during the certification trial. As a result, the airEXODUS simulations were generally more optimal than the result of the certification trial. The disparity in optimality could account for the reason that airEXODUS generates faster evacuation times than that achieved in the certification trial. It is clear that the results from a simulation that is configured to produce an "optimal" simulation will not agree very closely with the result from a trial that is sub-optimal. However, how would the model results compare with the trial result if the model were configured to produce a sub-optimal result?

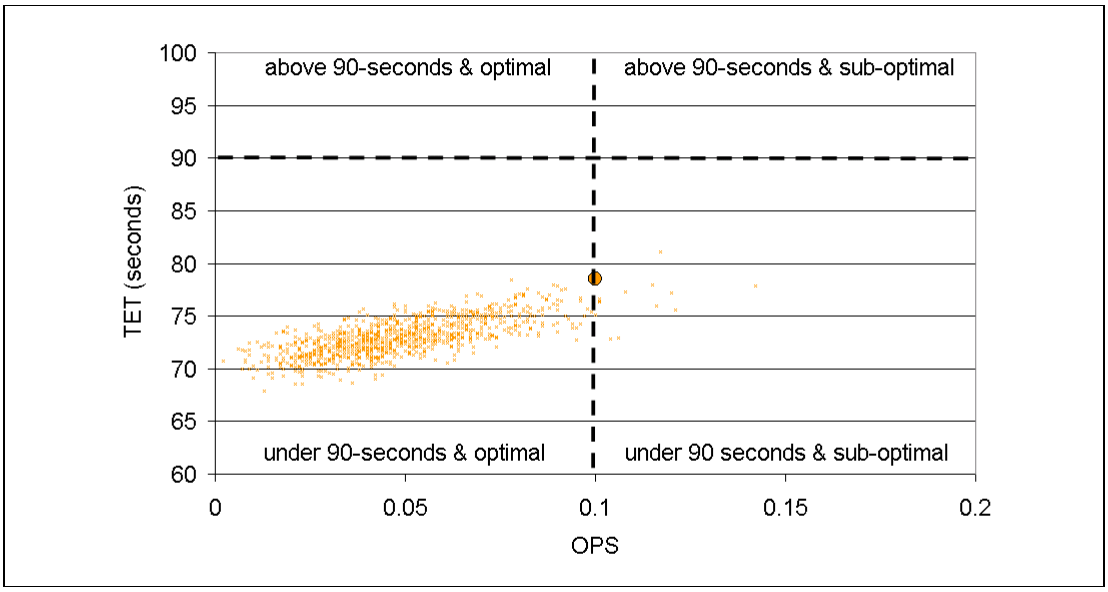


Figure 42 Scatter Diagram of TET and OPS Generated by airEXODUS (1000 data points) and the Result of the Certification Trial (1 data point) when using the Actual Data and with the Model in an OPTIMAL Configuration

To test this hypothesis it is possible to configure airEXODUS to generate results that are sub-optimal and thus more akin to the result of the certification trial. This can be achieved through configuring airEXODUS to model a similar passenger distribution to that of the certification trial. During the certification trial the passenger distribution resulted in the R1 exit being idle for some time during the final stages of the evacuations. airEXODUS was configured so that the average time that the last passenger evacuated through the R1 exit was shorter than other exits. An exact clone of the previous model was created. Then the attractiveness of the exits was altered so that less passengers utilised the R1 exit. The revised model was then run 1000 times in order to capture stochastic variations. The results are shown in Figure 43.

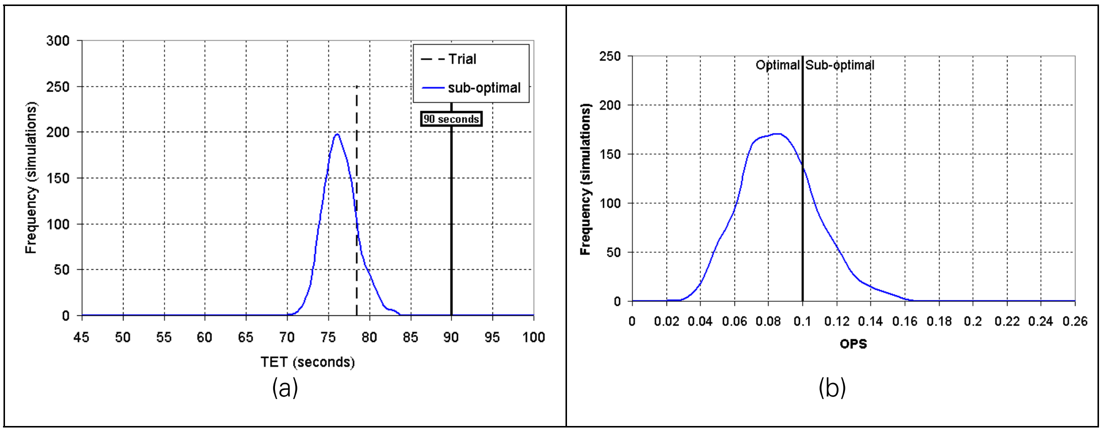


Figure 43 Frequency Distribution of (a) TETs and (b) OPS, both Generated by airEXODUS in Certification Trial Case 6 using the Actual and with the Aircraft in a SUB-OPTIMAL Configuration

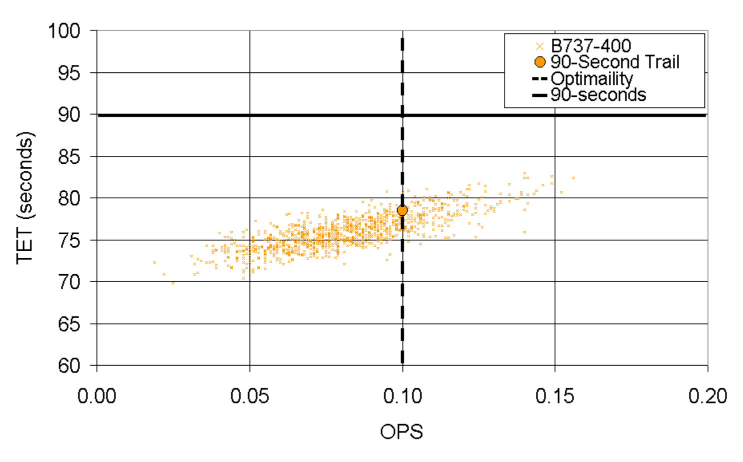


Figure 44 Scatter Diagram of TET and OPS Generated by airEXODUS (1000 data points) and the Result of the Certification Trial (1 data point) when using the Actual Data and with the Model in an SUB-OPTIMAL Configuration

From Figure 43 and Figure 44 it can be seen that when the level of optimality achieved in the airEXODUS simulations is more similar to that achieved in the trial, the result of the certification trial is more centrally positioned within the frequency distribution of TETs generated by airEXODUS. In addition, the mean TET generated (76.0 seconds) is within 3.2% (2.5 seconds) of the evacuation time recorded during the certification trial.

Thus there are two possible interpretations of these results. If the model is run in an optimal mode, then the observed result would be consistent with a low probability outlier event. If the model is configured to produce an equivalent sub-optimal distribution of passengers, then the observed result would be consistent with a high probability normal event.

To summarise, when airEXODUS is configured in an optimal manner in this case, a range of TETs is generated that only just includes the single evacuation time of the certification trial. In this case airEXODUS tends to generate shorter TETs (by on average 7% or 5.5 seconds). This difference may be accounted for by a disparity in optimality achieved. During the certification trial the R1 exit was idle for many seconds during the final stages of the evacuation. However, within airEXODUS a balance of passengers was achieved that utilised each of the exits for the entire duration of the evacuation. Thus, the results of airEXODUS were more optimal than the certification trial evacuation.

6.1.3 General Discussion: Comparison of the airEXODUS Predictions of Certification Trial Cases 5 and 6 when using Actual Data

In this section the ability of airEXODUS to rank aircraft performance under certification conditions will be examined.

It can be seen that the rank ordering of the derivative narrow-bodied aircraft during their respective certification trials shows that Case 5 was the fastest and that Case 6 was slowest (see Table 19). The mean TETs and rank ordering generated by airEXODUS can be seen in Table 19. It is apparent that when using the actual data airEXODUS ranks the aircraft in the same order as the certification trial.

Once again, it is important to note as in Section 5.1.5 that the rank ordering produced by the certification trials should not be taken to indicate a definitive rank ordering due to the probabilistic nature of evacuation performance. This issue is further discussed in section 7.3.

Table 19 Trial and airEXODUS Results and Rank Order for Certification Trial Cases 5-6 using the Actual Data

Case / Aircraft	Trial Result (secs)	airEXODUS Prediction (secs)	Trial Rank	airEXODUS Rank
Case 5	64.1	70.5[1]	1	1[1]
Case 6	78.5	73.0	2	2

1. More than 25% of these airEXODUS results were sub-optimal

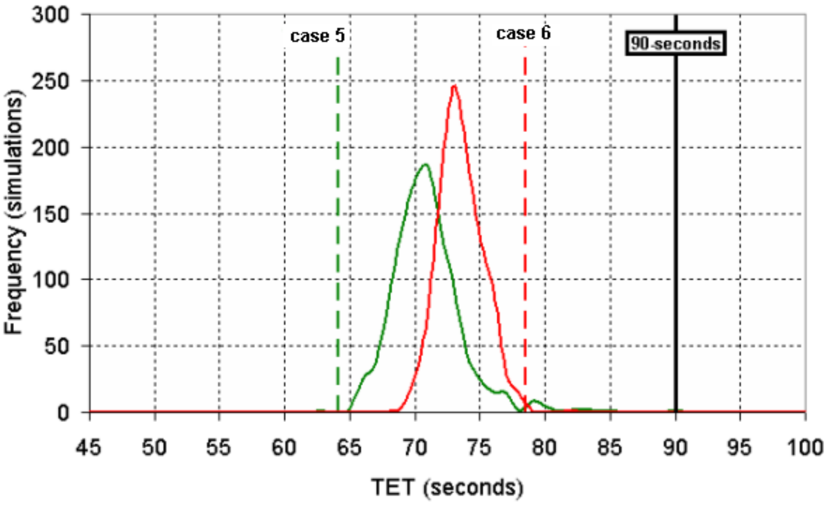


Figure 45 Combination of Frequency Distributions Generated by airEXODUS using the Actual Data for the Narrow-bodied Derivative Cases 5-6

The airEXODUS generated frequency distribution for these aircraft can be seen in Figure 45. From the TET frequency distribution it is apparent that the relative differences between the two derivative narrow-bodied aircraft was greater in the certification trials (indicated by dashed lines) than predicted by airEXODUS.

The relative difference between the certification trial results for these two aircraft is 14.4 seconds (see Table 19). However, the difference between the airEXODUS generated means for these two cases was only 2.5 seconds. Thus, while the airEXODUS simulations have correctly predicted the performance rank ordering of these two aircraft, the relative difference between the two aircraft has not been correctly predicted. airEXODUS predicts that the differences between the two aircraft are small while the trial results suggest that there is a more significant difference.

Table 20 Summary of Comparison between the Results of the Certification Trial Cases and the airEXODUS Predictions when using the Actual Data

	Case 5	**Case 6**	**Mean of Absolute Difference**
Difference between airEXODUS mean and trial TET (%)	10.0% (8.4%)[1]	7.0%	8.5% (7.7%)[1]
Difference between airEXODUS mean and trial TET (secs)	6.4 (5.4)[1]	5.5	5.9 (5.5)[1]
Trial TET within bounds of airEXODUS TETs	YES	YES	N/A
Number of simulations in excess of 90 seconds (simulations)	0	0	N/A
Number of simulations in excess of 90 seconds (%)	0	0	N/A
Distance between 90 second and airEXODUS mean (standard deviations)	N/A	N/A	N/A

1. airEXODUS results with an OPS > 0.1 are excluded

However, the discrepancies that were noted in each case act so as to compound the differences between the two aircraft.

Recall from the results of Case 5 that airEXODUS generated a significant number of sub-optimal cases (38.4% were sub-optimal) which effectively increased the mean TET for these predictions. This had the effect of moving the TET frequency distribution towards longer evacuation times. It was demonstrated that if the sub-optimal cases were removed from the analysis - thereby bringing the simulations into line with the observed trial - the mean TET would be reduced from 70.5 seconds to 69.5 seconds.

In Case 6, effectively the opposite problem occurred. In this case, the trial achieved a relatively poor level of optimality, producing an OPS = 0.1, compared with a predicted mean OPS of 0.05. This had the effect of pushing the predicted TET frequency distribution towards shorter evacuation times. Had a more optimal distribution of passengers been achieved during the trial, it is possible that the measured TET would have been reduced, bringing it closer to the predicted mean TET. When airEXODUS is configured to provide a similar level of OPS to that achieved in the trial the predicted mean TET is increased from 73.0 seconds to 76.0 seconds.

Taking these two factors into account, the difference between the predicted TETs for the two cases increases to 6.5 seconds, which is more inline with the observed difference. These two factors in conjunction with the limitations of having only a single trial data point for each case explain the variation in the relative differences.

To summarise, when using the actual data airEXODUS is able to successfully rank both of the narrow-bodied derivative aircraft. The mean absolute difference between the certification trial results and the mean TET generated by airEXODUS was 8.5%. This relatively large difference results from disparities in the levels of optimality achieved in the airEXODUS simulations and during the actual certification trials. Should optimality in all of the cases have been low then the mean absolute difference would have been reduced.

6.2 Predicting the Results of Narrow-bodied Certification Trials using the Generalised Data

The previous section demonstrated that airEXODUS could reproduce the results of certification trials with reasonable accuracy when supplied with the actual data from the certification trial. In the absence of data from the actual certification trial, airEXODUS makes use of generalised data appropriate to the exit type. This generalised data is based upon numerous previous evacuation certification trials. If demonstrated as feasible, this approach allows a prediction based on a generalised data for the aircraft. In this section we re-evaluate the certification trials using the generalised data within airEXODUS.

Similar to the analysis of the wide-bodied aircraft, the generalised data will be applied to both passenger exit delays and to the time required to ready an exit for use. In these cases cabin crew performance is uniformly fixed as assertive. The time required to ready an exit for use will be set to an average value that was derived from the analysis of certification trials (see Section 3.3). Apart from the aforementioned variables all of the parameters will remain identical to the previous section. This will enable a direct comparison with the results using the actual data later in this report.

6.2.1 Results and Discussion: Case 5 Generated using the Generalised Data

When using the generalised data for Case 5, airEXODUS generates a range of TETs between 59.8 and 77.4 seconds with a mean of 65 seconds. The range predicted by airEXODUS includes the result of the certification trial. The mean TET generated by airEXODUS is 1.4% (0.9 seconds) longer than the evacuation time recorded during the certification trial.

As in the simulations where the actual data was used, the airEXODUS generated TET frequency distribution (Figure 47) reveals that the majority (84.1%) of simulations generated longer TETs than the result from the certification trial. However, unlike the previous case, a good level of optimality was achieved during the airEXODUS simulations (see Figure 48). The majority (94.5%) of the simulations achieved an OPS < 0.1 with the mean OPS being 0.05. The actual certification trial also achieved an optimal evacuation, scoring an OPS of 0.02. Examination of the scatter diagram of TET and OPS indicates that the results of airEXODUS are close to that of the certification trial and when a similar optimality is achieved (see Figure 48).

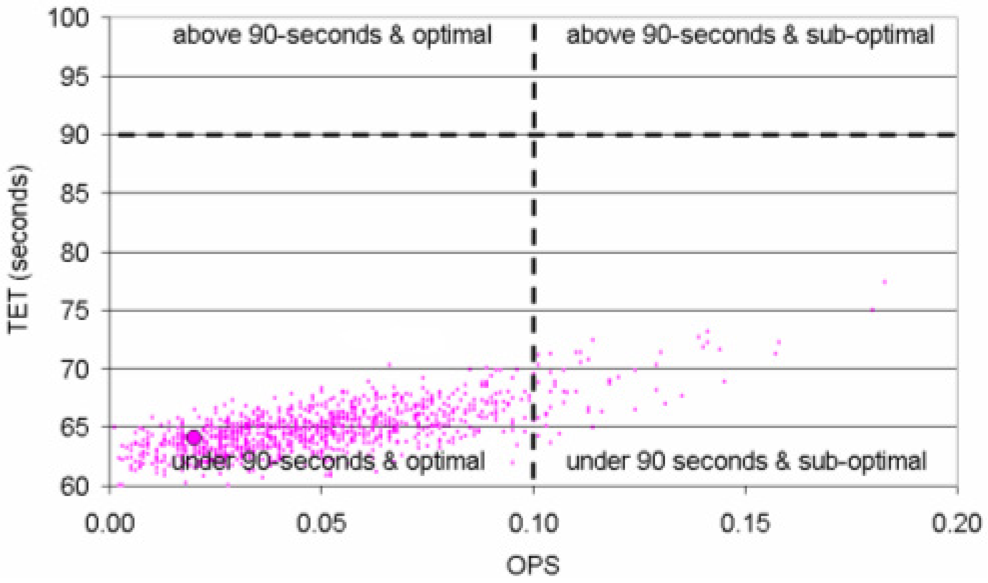


Figure 46 Scatter Diagram of TET and OPS Generated by airEXODUS (1000 data points) and the Result of the Certification Trial (1 data point) when using the Generalised Data

Table 21 Summary of airEXODUS Results from Certification Trial Case 5 using the Generalised Data (measured evacuation time 64.1 seconds)

		First out (secs)	TET (secs)	CWT (secs)	PET (secs)	OPS
Generalised Data	**Min**	7.5	59.8	20.4	33.3	0.00
	Mean	**7.7**	**65.0**	**22.6**	**35.7**	**0.05**
	Max	8.9	77.4	24.7	37.8	0.18
	STD	0.2	2.1	0.7	0.7	0.03

The results from these trials using the generalised data are consistent with the conclusion made in the previous section (based on the actual data) that the result from this trial was better than what would normally be expected. What has changed in using the generalised data is the degree to which this is the case. Using the generalised data, the certification trial result can be seen to be marginally better than would normally be expected. However, using the actual data, the difference is more pronounced.

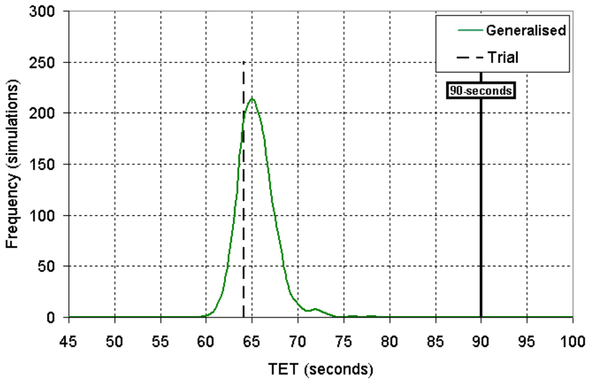


Figure 47 Frequency Distribution of TETs Generated by airEXODUS in Certification Trial Case 5 using the Generalised Data

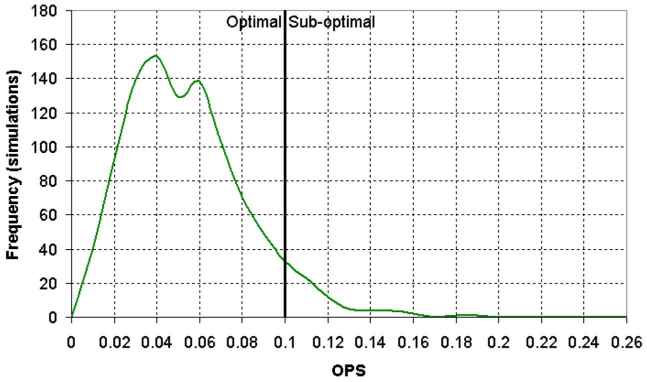


Figure 48 Frequency Distribution of OPS Generated by airEXODUS in Certification Trial Case 5 using the Generalised Data

6.2.2 Results and Discussion: Case 6 Generated using the Generalised Data

When using the generalised data in Case 6 airEXODUS generates a range of TETs between 64.1 and 74.8 seconds with a mean of 69.4 seconds (see Table 22). The mean TET generated by airEXODUS is 11.6% (9 seconds) quicker than the evacuation time recorded during the certification trial (78.5 seconds). However, this is the only case examined in which the range of TETs generated by airEXODUS does not include the single evacuation time measured during the certification trial.

Figure 49 shows the TET frequency distribution generated by airEXODUS for this case. It can be seen that the time recorded during the certification trial falls outside of the range of TETs generated by airEXODUS. All of the TETs generated by airEXODUS are shorter than the measured evacuation time for the certification trial. When using the generalised data in Case 6 the majority (92.6%) of the airEXODUS simulations were optimal (see Figure 50).

Recall from Section 3.3 that this certification trial was only just categorised as optimal. During the certification trial of Case 6 there was a significant period of inactivity at the R1 exit. In this case airEXODUS this was not configured to model this exit inactivity. Instead an optimal distribution of passengers to exits was achieved.

During the discussion of the results of Case 6 when using the actual data it was asserted that the disparity in the levels of optimality might account for the differences between the TETs generated by airEXODUS and the result of the certification trial. Since these airEXODUS simulations were also optimal, it is likely that a similar effect would occur in this case when using the generalised data.

Table 22 Summary of airEXODUS Results from Certification Trial Case 6 using the Generalised Data (measured evacuation time 78.5 seconds)

		First out (secs)	TET (secs)	CWT (secs)	PET (secs)	OPS
Generalised Data	**Min**	7.5	64.1	22.7	35.1	0.01
	Mean	**7.7**	**69.4**	**24.6**	**37.2**	**0.06**
	Max	8.7	74.8	26.5	39.2	0.14
	STD	0.1	1.7	0.7	0.7	0.03
Generalised Data (sub-optimal configuration)	**Min**	7.5	66.2	22.8	35.4	0.02
	Mean	**7.7**	**72.3**	**24.7**	**37.4**	**0.13**
	Max	8.6	78.7	26.6	39.4	0.22
	STD	0.1	1.9	0.7	0.7	0.03

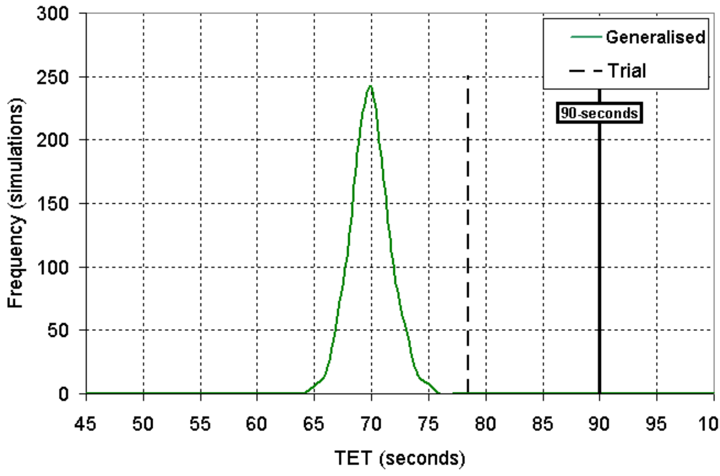


Figure 49 Frequency Distribution of TETs Generated by airEXODUS in Certification Trial Case 6 using the Generalised Data

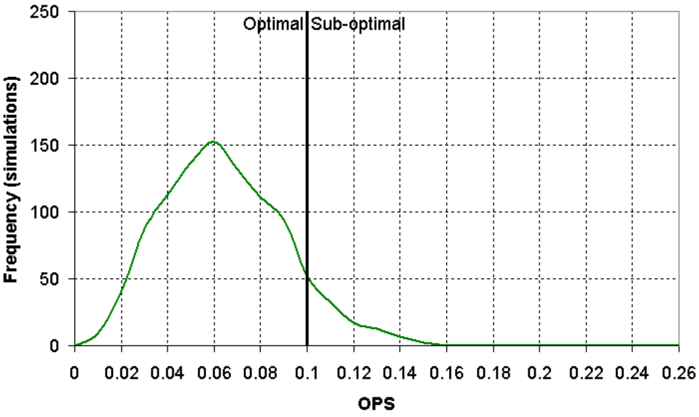


Figure 50 Frequency Distribution of OPS Generated by airEXODUS in Certification Trial Case 6 using the Generalised Data

To demonstrate this, the model was re-configured in a sub-optimal manner so as to generate average OPS similar to that attained in the certification trial (e.g. OPS=0.1). This involved generating a sub-optimal passenger split, in which slightly too many passengers used the over-wing exits and not enough used the forward and aft Type-C exit.

When the optimality of the simulations is reduced the average TET is increased from 69.4 seconds to 72.3 seconds and the range of model generated TET also now includes the trial point (see Table 22 and Figure 52). In the scatter diagrams we see more airEXODUS data-points in the vicinity of the certification trial data-point (Figure 51). We also note that TETs are generally increased.

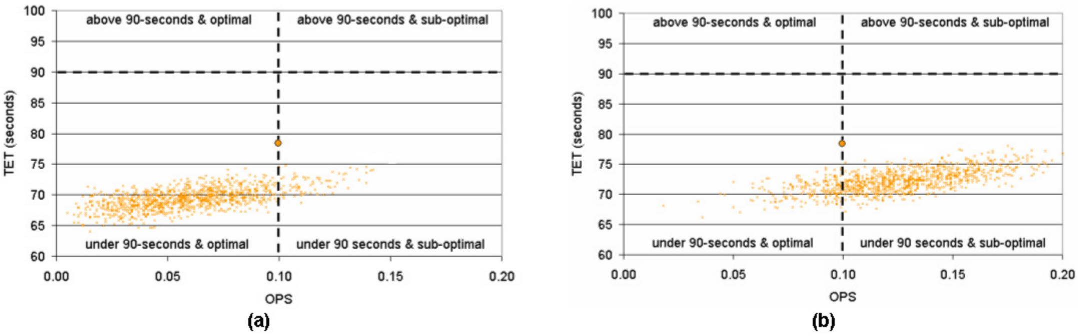
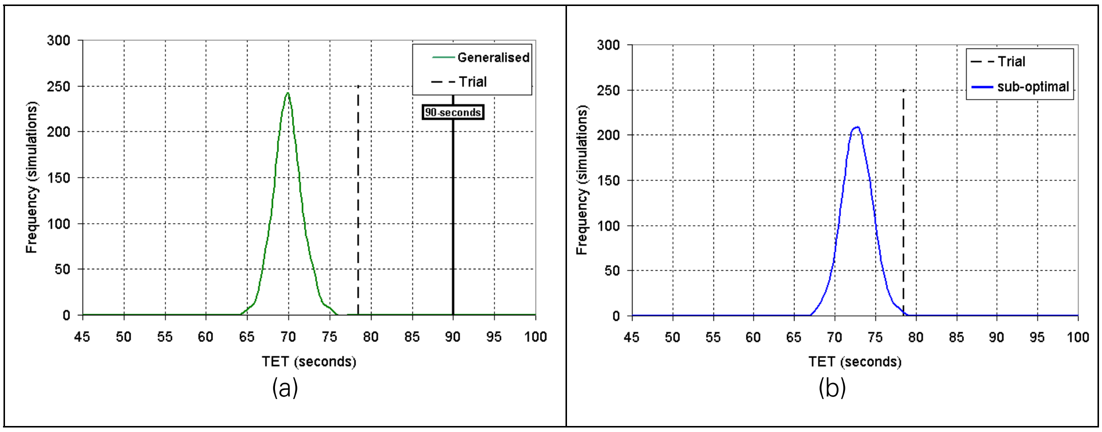


Figure 51 Scatter Plot Of TET and OPS for Case 6 in (a) an OPTIMAL Configuration and (b) in a SUB-OPTIMAL Configuration, both using the Generalised Data



(a) (b)

Figure 52 airEXODUS Generated Frequency Distributions of TET Generated using the Generalised Data with the Model in (a) an OPTIMAL Configuration and (b) a SUB-OPTIMAL Configuration

The results from these trials using the generalised data are consistent with the conclusion made in the previous section (based on the actual data) that the result from this trial was worse than what would normally be expected.

To summarise, with airEXODUS configured in an OPTIMAL manner it does not generate a range of TETs that include the evacuation time recorded during the certification trial of this aircraft. Furthermore, all of the TETs generated by airEXODUS are shorter (by on average 11.6%) than the evacuation time achieved during the certification trial. In part, this may result from the disparity in the level of optimality achieved during the certification trial (OPS of 0.1) and by airEXODUS (average OPS of 0.06). When the model was configured in a SUB-OPTIMAL manner - i.e. a manner more akin to the actual certification trial - the results of the model are closer to that of the certification trial. Indeed, when configured in a SUB-OPTIMAL manner the certification trial result falls within the predicted envelope of TETs generated by airEXODUS.

6.2.3 General Discussion: Comparison of the airEXODUS Predictions of Certification Trial Cases 5 and 6 when using Generalised Data

In this section the ability of airEXODUS to rank aircraft performance under certification conditions using the generalised data will be examined.

Table 23 shows the results of the certification trial evacuations and the mean TETs generated by airEXODUS when using the generalised data. As can be seen, the airEXODUS predictions generated using the generalised data rank the aircraft in the same order as was achieved in the actual certification trials i.e. the evacuation performance of Case 5 is better than the evacuation performance of Case 6.

Once again, it is important to note as in Section 5.1.5 that the rank ordering produced by the certification trials should not be taken to indicate a definitive rank ordering due to the probabilistic nature of evacuation performance. This issue is further discussed in section 7.3.

Examination of the TET frequency distribution generated by airEXODUS when using the generalised data is shown as Figure 53. It can be seen that the relative difference between the evacuation times of the certification trial (indicated by the dashed lines) is greater than the relative difference between the maximum frequencies of the airEXODUS curves.

The relative difference between the certification trial results for these two aircraft is 14.4 seconds (see Table 23). However, the difference between the airEXODUS generated means for these two cases is 4.4 seconds. Thus, while the airEXODUS simulations have correctly predicted the performance rank ordering of these two aircraft, the relative difference between the two aircraft has not been correctly predicted. airEXODUS predicts that the differences between the two aircraft are small while the trial results that there is a more significant difference.

Table 23 Trial, airEXODUS Results and Rank Order for Certification Trial Cases 5-6 using the Generalised Data

Case / Aircraft	Trial Result (secs)	airEXODUS prediction (secs)	Trial rank	airEXODUS rank
Case 5	64.1	65	1	1
Case 6	78.5	69.4	2	2

Table 24 Summary of the Comparisons between the results of the Certification Trial Cases and the airEXODUS Results when using the Generalised Data

	Case 5	Case 6	Mean of absolute difference
Difference between airEXODUS means and trial TET (%)	1.4	11.6	6.5
Difference between airEXODUS means and trial TET (secs)	0.9	9.1	5.0
trial TET within bounds of airEXODUS TETs	YES	NO	N/A
Number of simulations in excess of 90 seconds (simulations)	0	0	N/A
Number of simulations in excess of 90 seconds (%)	0	0	N/A
Distance between 90 second and airEXODUS mean (standard deviations)	N/A	N/A	N/A

The difference between the airEXODUS mean TET and the certification results in each case is shown in Table 24. It can be seen that the mean TET generated by airEXODUS is relatively close (within 1.4% or 0.9 seconds) to the time recorded during the certification trial evacuation of Case 5. However the mean TET generated by airEXODUS in Case 6 is 11.6% (9.6 seconds) from the time recorded during the certification trial evacuation. The mean absolute difference between the airEXODUS means and the results of the certification trial is 6.5% (5.0 seconds). Whilst in Case 5 the result of the certification trial falls within the range of TETs generated by airEXODUS, in Case 6 the result of the certification trial does not fall within the range of TETs generated by airEXODUS.

It is important to recall the disparity in the level of optimality achieved in airEXODUS and during the certification trial of Case 6. In addition to this, differences are expected to result when comparing an average performance of passengers and crew - the generalised data - against a single performance during a single evacuation.

This is to be expected, as has already been discussed, the certification performance of Case 5 was better than would normally be expected while the certification performance of Case 6 was considerably worse than would normally be expected, thus compounding the measured difference between the two aircraft.

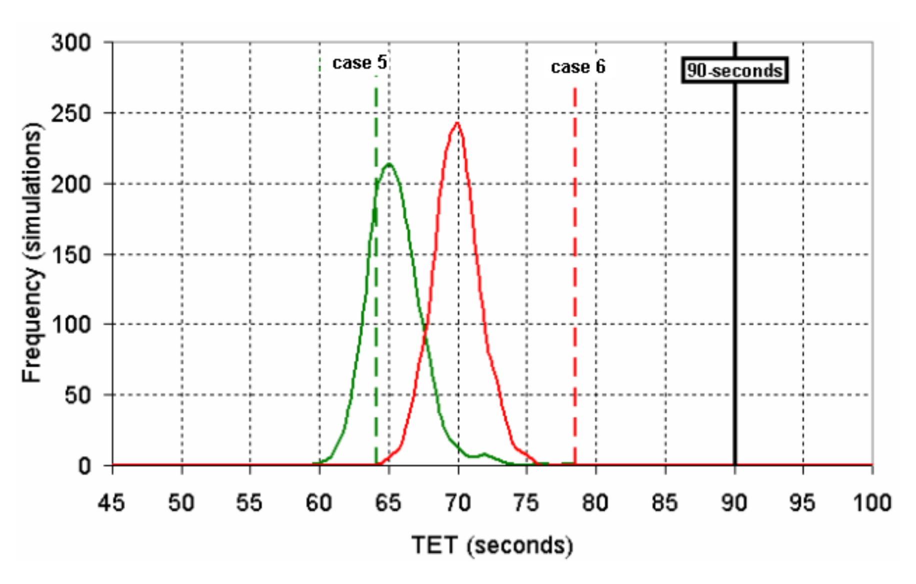


Figure 53 Combination of Frequency Distributions Generated by airEXODUS using the Generalised Data for the Narrow-bodied Derivative Cases 5-6

To summarise, when using the generalised data airEXODUS is able to rank the derivative narrow-bodied aircraft in the same order as the certification trials. The relative difference between the aircraft is not as pronounced as is suggested by the certification trial. This results in part from the relative sub-optimality of the certification trial evacuation for Case 6. The modelling results also suggest that both aircraft did not perform as would normally be expected, with Case 5 performing better than expected and Case 6 performing considerably worse than expected. This highlights the difficulties in making comparisons based on only two data points from single evacuations.

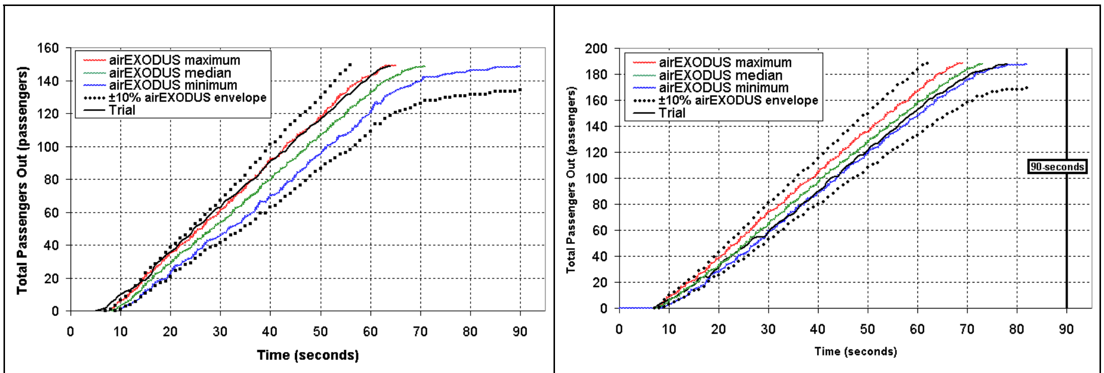
6.3 Examining the Predicted and Measured Evacuation Evolution of the Narrow-bodied Certification Trials

In this section we examine the ability of airEXODUS to predict the evolution of the narrow-bodied aircraft evacuation. Recall from Section 5.3 that a simulation envelope can be determined from the results of airEXODUS. The results from the certification trial is then compared with the airEXODUS generated simulation envelope at every second of the evacuation.

6.3.1 Validating the airEXODUS Prediction for the Evolution of Narrow-bodied Certification Trials using the Actual Data

The airEXODUS cumulative exit envelope predicted using the actual data, together with the result of the certification trials for each of the four wide-body aircraft is shown in Figure 35. As can be seen from the curves, 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, indicated in Figure 35 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.

The airEXODUS cumulative exit envelope predicted using the actual data, together with the result of the certification trials for each of the narrow-body aircraft is shown in Figure 54. In Case 6, it can be seen that the result of the certification trial is within the bounds of the simulation envelope. However, Case 5 falls outside the bounds of the envelope initially and remains marginally outside the envelope for the first 35 seconds. This suggests that in Case 5, the model was initially under-predicting the speed at which the passengers were exiting the aircraft.



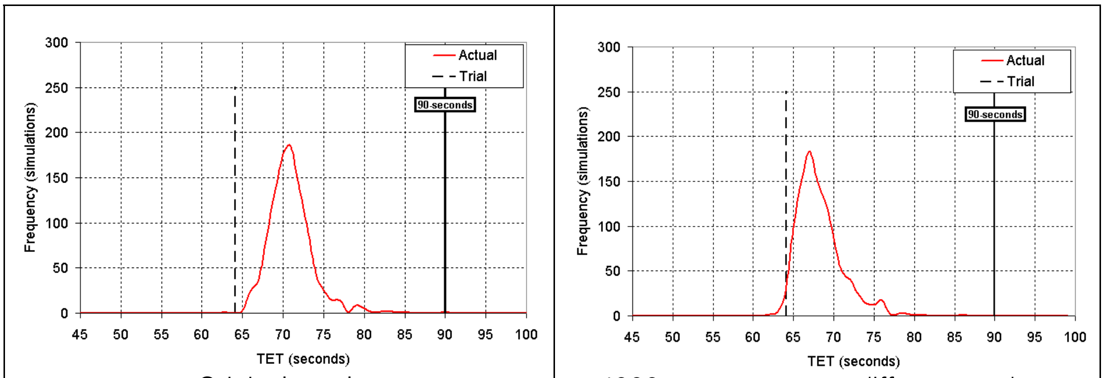
(a) (b)

Figure 54 The airEXODUS Simulation Envelopes Generated using the Actual Data for (a) Case 5 and (b) Case 6

This discrepancy is quite small and is within the +/-10% error bands defined around the model window. A possible explanation for this initial discrepancy could be due to the nature of the population distribution generated by airEXODUS.

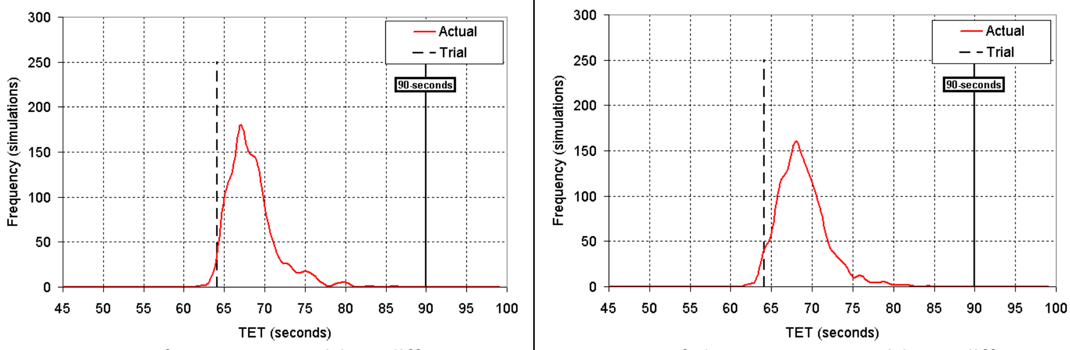
Table 25 Results from an airEXODUS Sensitivity Analysis for Case 5 of Passenger Seat Allocations using the Actual Data

		First out (secs)	TET (secs)	CWT (secs)	PET (secs)	OPS
Actual Data (Original) 61.6% OPS <0.1	**Min**	7.6	62.9	22.0	35.0	0.00
	Mean	**8.3**	**70.5**	**24.5**	**37.8**	**0.09**
	Max	9.9	89.8	27.5	40.9	0.28
	STD	0.4	2.7	0.8	0.9	0.04
Actual Data (single randomised seat allocation) 85.9% OPS <0.1	**Min**	6.9	62.6	21.7	34.9	0.00
	Mean	**7.1**	**68.8**	**23.9**	**37.1**	**0.06**
	Max	8.1	86.6	26.8	40.2	0.25
	STD	0.2	2.8	0.8	0.8	0.03
Actual Data (3 randomised seat allocations) 84.7% OPS <0.1	**Min**	6.9	62.6	21.3	34.5	0.00
	Mean	**7.1**	**68.9**	**23.7**	**37.0**	**0.06**
	Max	8.1	86.3	26.8	40.2	0.25
	STD	0.2	3.0	0.8	0.8	0.04
Actual Data (10 randomised seat allocations) 69.3% OPS <0.1	**Min**	**6.9**	**62.8**	**21.1**	**34.4**	**0.00**
	Mean	7.1	69.3	23.6	36.8	0.08
	Max	8.6	84.9	26.9	40.2	0.25
	STD	0.3	3.0	0.9	0.9	0.04



Original result

1000 runs, same pop different random seat allocations



333 runs of same pop with 3 different random seat allocations

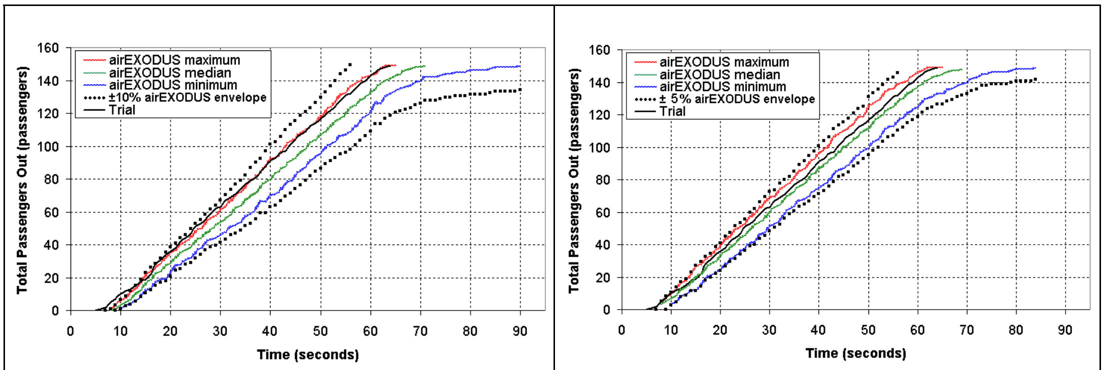
100 runs of the same pop with 10 different random seat allocations

Figure 55 Results of airEXODUS when Randomising Passenger Seating Allocations for Case 5 using the Actual Data

For each of the 1000 repeat simulations each of the passengers had the same seating allocation. Thus if slow passengers were seated in crucial positions they would always be in those positions and thus could adversely affect the result of the simulation. After examining Case 5 it was found that this was indeed the situation. In this case, slow passengers with relatively long response times were situated in the front rows on the aisle seats. Thus they delayed the start up of the evacuation process and thus may have caused the initial discrepancy in the results. This is an important observation and has a bearing on the nature in which certification simulation cases should be run.

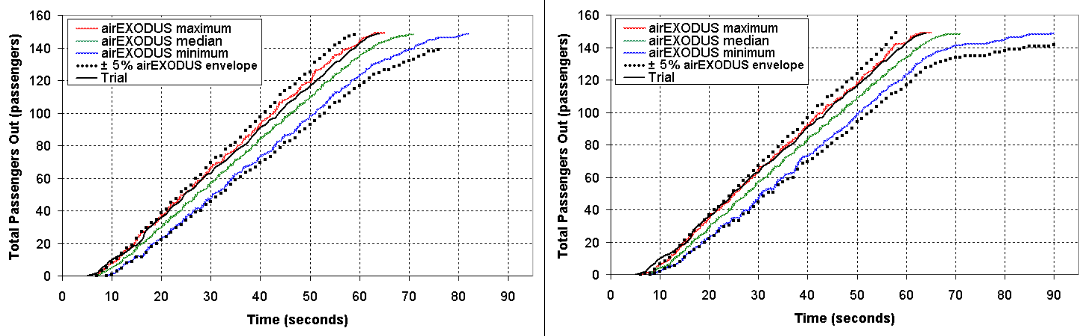
To investigate this possibility the simulations were repeated - with the same population as was used in Case 5 - but several different approaches were tried to randomise the population. In the first approach a single randomisation of the seating allocation was generated and the simulation repeated 1000 times. This generated a distribution with a mean TET of 68.8 seconds (see Table 25). This represents a reduction in TET of 1.7 seconds or 2.4%. The second approach consisted of three randomised seat allocations each run 333 times and the third case consisted of 10 randomised seat allocations each run 100 times. As can be seen from Table 25 and Figure 55, each of the different randomised selections produced similar results and all of them are different to the original single randomised selection.

Furthermore, as can be seen from Figure 56, the numerical window of results better captures the trial curve when a randomisation of seating allocations is used.



Original result

1000 runs, same pop different random seat allocations



333 runs of same pop with 3 different random seat allocations

100 runs of the same pop with 10 different random seat allocations

Figure 56 Results of airEXODUS when Randomising Passenger Seating Allocations for Case 5 using the Actual Data

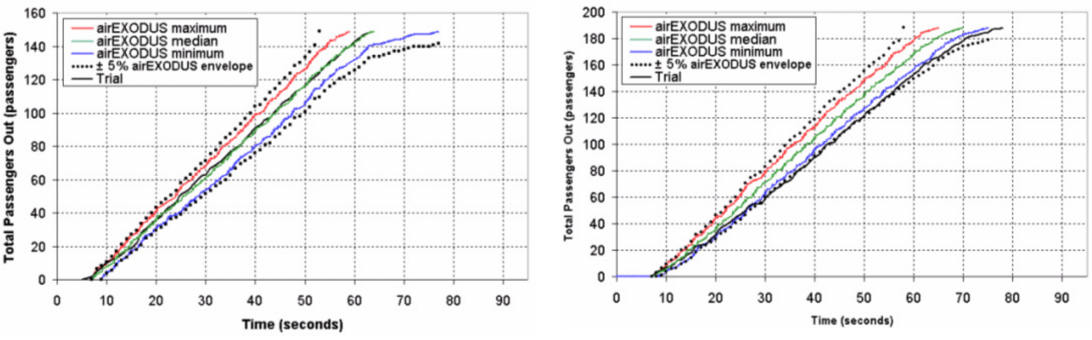
6.3.2 Validating the airEXODUS Prediction for the Evolution of Narrow-bodied Certification Trials using the Generalised Data

The simulation envelopes generated by airEXODUS for the narrow-body aircraft using the generalised data are depicted in Figure 57. It can be seen that in Case 5 the result of the certification trial is within the airEXODUS generated simulation envelope (see Figure 57 (a)) for practically the entire certification trial with the exception of the first few seconds of the evacuation. Thus, when using the generalised data in Case 5 airEXODUS predicts a similar number of evacuees to the certification trial at every second of the evacuation.

The results for the Case 6 certification trial marginally fall outside of the airEXODUS generated simulation envelope after approximately 30 seconds, but remain within or just exceeds the +/-5% tolerance window (see Figure 57 (b)). This is consistent with the observation made earlier that this trial was considerably slower than would normally be expected for this type of aircraft configuration. Thus the results of airEXODUS are expected to be better than the results of the single certification trial.

Table 26 Summary of the Result of an airEXODUS Sensitivity Analysis of Case 5 to Passenger Seat Location when using the Generalised Data

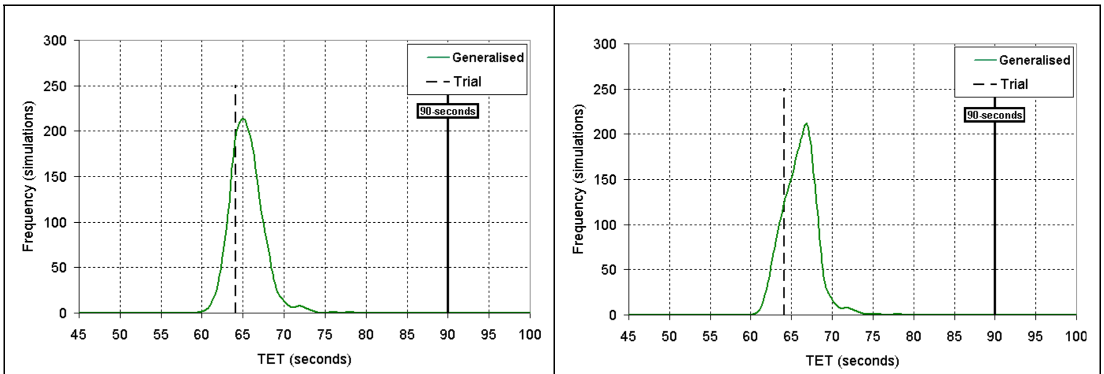
		First out (secs)	TET (secs)	CWT (secs)	PET (secs)	OPS
Generalised Data	**Min**	7.5	59.8	20.4	33.3	0.00
	Mean	**7.7**	**65.0**	**22.6**	**35.7**	**0.05**
	Max	8.9	77.4	24.7	37.8	0.18
	STD	0.2	2.1	0.7	0.7	0.03
Generalised Data (3 random seat locations)	**Min**	7.5	60.2	20.0	33.0	0.00
	Mean	**7.7**	**65.5**	**22.3**	**35.4**	**0.07**
	Max	8.8	77.4	24.7	37.8	0.18
	STD	0.1	2.1	0.9	0.9	0.03



(a) (b)

Figure 57 The airEXODUS Simulation Envelopes Generated using the Generalised Data for (a) Case 5 and (b) Case 6

In order to be consistent with the situation with the analysis using the actual data, Case 5 was run with several randomisations of the passenger seating allocation. The results are shown in Table 26 and Figure 58.



Original result

333 runs same pop. with 3 different random seat locations

Figure 58 Results of airEXODUS when Randomising Passenger Seating Locations for Case 5 using the Generalised Data

6.4 Summarising the Outcome of the airEXODUS Reconstructions and Predictions for Narrow-bodied Certification Trials

Several key points can be made from the analysis of the two narrow-bodied aircraft validation cases:

1a) Using the actual data from specific certification trails, airEXODUS is able to produce distributions of Total Evacuation Times for each aircraft such that the actual trial data point is contained within the distribution.

1b) Using the generalised certification trial data, airEXODUS was able to predict the distribution of Total Evacuation Times for one of the two aircraft such that the actual trial data point is contained within the distribution. However, the level of optimality as measured by the OPS for the simulation and the trial should be broadly in agreement.

2a) Using the actual data from the specific certification trials, airEXODUS was able to successfully rank the two derivative aircraft in the identical order that was achieved in the certification trials. However, it should be noted that a ranking based on a single certification trial result for each aircraft may not be indicative of the actual ranking of the aircraft.

2b) Using the generalised certification data, airEXODUS was able to successfully rank the two derivative aircraft in the identical order that was achieved in the certification trials.

3a) Using the actual data from the specific certification trials, airEXODUS did not predict the relative and absolute differences between the rank ordering. However, it should be noted that the relative differences between aircraft, like the ranking, based on a single certification trial result for each aircraft may not be indicative of the actual differences between the aircraft.

3b) Using the generalised certification data, airEXODUS did not predict the relative and absolute differences between the rank ordering.

4a) Using the actual data from specific certification trials, airEXODUS predicted that both of the aircraft would pass the certification criterion.

4b) Using the generalised certification data, airEXODUS predicted that both of the aircraft would pass the certification criterion.

5) The cumulative exit curves for each of the two aircraft examined fell within the numerical envelope predicted using airEXODUS and the generalised certification data or only marginally exceeded the envelope (within +/-5%). This suggests that airEXODUS is capable of predicting the time evolution of the evacuation using the generalised data.

6) The observed differences between the simulation predictions and the actual data are thought to be due to the natural variations that occur in specific certification trials. Indeed the two trials that were investigated are believed to be quicker than would normally be expected - for Case 5 - and slower than would be expected - for Case 6 - thus compounding the differences between the model predictions and actual data. However, two points have been noted concerning the use of and further development of the model. In terms of model use, it is important to generate randomisations of the seating allocations of passengers within the sequence of 1000 repeat simulations. In terms of model development, it would be desirable to develop an explicit capability to simulate crew instigated passenger by-pass.

7) For direct comparisons to be made between model predictions and trial results, similar levels of optimality must exist between the model and trial results. When quoting numerical results it is essential to not only quote the times achieved but also the levels of optimality achieved.

Finally, the general conclusions made for the wide-body aircraft apply equally well to the narrow-body aircraft.

7 Interpretation of Model Performance

7.1 Use of Generalised and Actual Data

It has been shown that the same broad conclusions concerning aircraft performance can be derived from simulations utilising the generalised data for exit hesitation times and exit opening times as simulations using the actual data. This suggests that the generalised data represents a good approximation for how key aircraft components will perform under certification applications. This provides the modelling and regulatory community with strong evidence to support the use of the generalised data for aircraft certification applications in which the standard configurations and components are being considered.

This general approach can be extended to situations in which the generalised data is not applicable, for example, when a new or significantly modified aircraft exit type is being used. In this situation, rigorous testing of the exit component is necessary in order to generate the appropriate data to use in the model. This testing should be sufficient to provide data of similar quality to that used to generate the existing generalised data.

7.2 Predicted Evacuation Times

It should be recalled here that in comparing the model predictions with the trial performance, we are attempting to compare a single experimental data point of a variable known to be defined by a probability distribution i.e. TET, with a predicted probability distribution for the TET. In reality, the TET from the trial could be any point on the probability distribution. In this analysis, we have chosen to compare the trial data point with the mean from the predicted distribution of TETs.

Across the six aircraft studied, using the generalised data, airEXODUS was able to predict the TET on average to within 3.8% (variation of 0.8 – 11.6 %) or 2.8 seconds (variation of 0.5 – 11.6 seconds) (see Table 27). When using the actual data, airEXODUS was able to predict the TET on average to within 5.3% (variation of 3.0 – 10.0 %) or 3.8 seconds (variation of 2.2 – 6.4 seconds) (see Table 28).

Situations that created the largest error involved cases in which the level of optimality of the trial did not sufficiently match that of the simulation. In these cases larger errors are to be expected as strictly speaking, like is not being compared with like. Effectively, differing levels of optimality should be represented as different scenario specifications. It was also demonstrated that airEXODUS was correctly able to predict the evolution of the evacuation in virtually every case and only in cases where the optimality was suspect was there a slight divergence between measured and model predictions.

Table 27 Summary of Trial and airEXODUS Predictions using the Generalised Data

	Trial evacuation time (Secs)	AirEXODUS mean TET (Secs)	Number of simulations with a similar OPS (Simulations)	airEXODUS mean from trial TET (%)	airEXODUS mean from trial TET (secs)
Case 1	83.7	82.7	1000	1.2	1.0
Case 2	72.6	73.1	1000	0.8	0.5
Case 3	71.7	68.3	1000	4.7	3.4
Case 4	74.4	77.9	1000	2.8	2.1
Case 5	64.1	65.0	1000	1.4	0.9
Case 6	78.5	69.4	1000	11.6	9.1
Average Absolute Error				3.8%	2.8 s

Table 28 Summary of Trial and airEXODUS Predictions using the Actual Data

	Trial evacuation time (Secs)	AirEXODUS mean TET (Secs)	Number of simulations with a similar OPS (Simulations)	airEXODUS mean from trial TET (%)	airEXODUS mean from trial TET (secs)
Case 1	83.7	86.6	1000	3.5	-2.9
Case 2	72.6	70.4	1000	3	2.2
Case 3	71.7	68.2	1000	4.9	3.5
Case 4	74.4	76.9	1000	3.4	-2.5
Case 5	64.1	70.5	1000	10	-6.4
Case 6	78.5	73.0	1000	7	5.5
Average Absolute Error				5.3%	3.8 s

It is recommended that as an indication of the likely error in predicted results, the errors associated with the actual data should be taken as this represents a true indication of the predictive capability of the model.

7.3 Ranking Aircraft Performance

Using the mean TET from the predicted distribution, it has been shown that airEXODUS was able to correctly rank the performance of the four wide-body aircraft and the two narrow-body aircraft (see Table 29). However, when the narrow and wide-body aircraft and put together and the six aircraft are ranked, we no longer find that the predicted ranking of the aircraft match the ranking observed on the basis of the single certification trial (see Table 29). This is true whether we make use of the actual or generalised data.

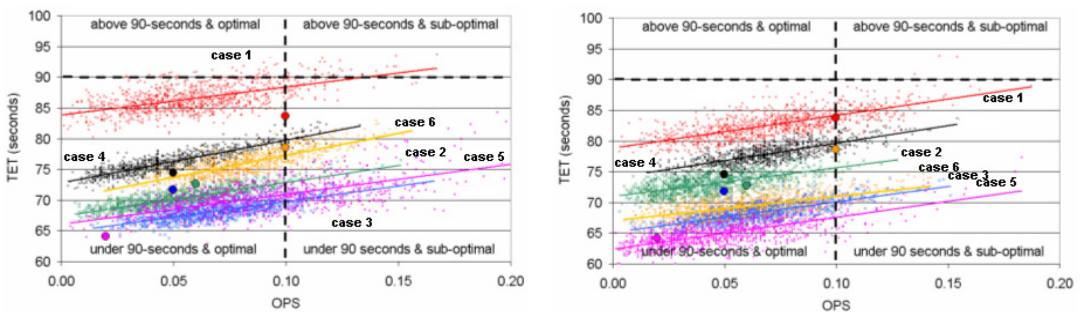
As mentioned earlier, it is not meaningful to attempt an absolute or even relative rank ordering of aircraft performance based on the performance of a single certification trial (or model result). This is because the performance of the aircraft is defined by a probability distribution of which the single data point is not a characteristic measure.

Thus there is no guarantee that the ranking derived from the certification trials are typical or indicative of actual relative or absolute performance.

Table 29 Rank Ordering of Aircraft Evacuation Performance using the Trial Data and airEXODUS Generated TET using the Actual and Generalised Data

Actual Data	**Trial Evacuation Time (Secs)**	**airEXODUS Mean TET (Secs)**	**Trial Wide-body Rank**	**airEXODUS Wide-body Rank**	**Trial Narrow-body Rank**	**airEXODUS Narrow-body Rank**	**Overall Trial Rank**	**Overall airEXODUS Rank**
Case 1	83.7	86.6	4	4	–	–	6	6
Case 2	72.6	70.4	2	2	–	–	3	2
Case 3	71.7	68.2	1	1	–	–	2	1
Case 4	74.4	76.9	3	3	–	–	4	5
Case 5	64.1	70.5	–	–	1	1	1	3
Case 6	78.5	73	—	–	2	2	5	4
Generalised Data	**Trial Evacuation Time (Secs)**	**airEXODUS Mean TET (Secs)**	**Trial Wide-body Rank**	**airEXODUS Wide-body Rank**	**Trial Narrow-body Rank**	**airEXODUS Narrow-body Rank**	**Overall Trial Rank**	**Overall airEXODUS Rank**
Case 1	83.7	82.7	4	4	–	–	6	6
Case 2	72.6	73.1	2	2	–	–	3	4
Case 3	71.7	68.3	1	1	–	–	2	2
Case 4	74.4	77.9	3	3	–	–	4	5
Case 5	64.1	65.0	–	–	1	1	1	1
Case 6	78.5	69.4	—	–	2	2	5	3

As can be seen from Figure 59 if the trials are repeated a sufficient number of times, the TET can be distributed with a large scatter and it is possible for data points for different aircraft to become mixed. In this overlap region it is possible for the rank ordering of aircraft to be altered, depending on which data points are selected at random to represent the aircraft. This can be more clearly seen in Figure 60 that shows the range of TETs generated by airEXODUS for each aircraft.



(a) (b)

Figure 59 airEXODUS Produced Scatter Plots of TET Vs OPS for the Six Aircraft Generated using (a) Actual Data and (b) Generalised Data

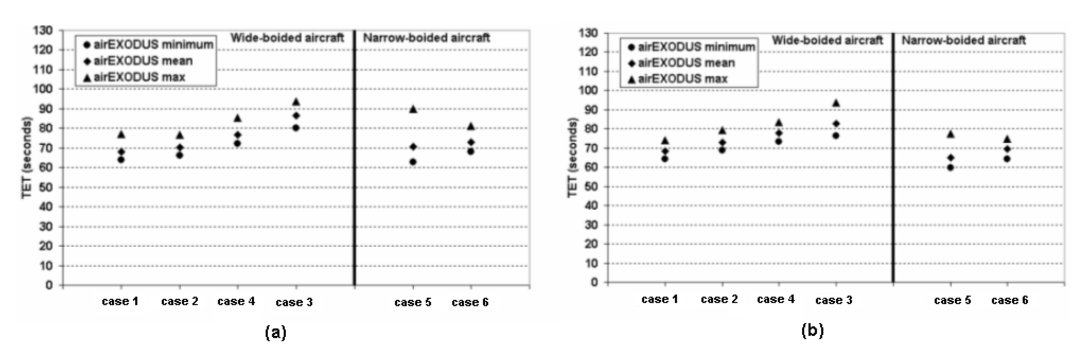


Figure 60 airEXODUS Produced TETs Generated using (a) the Actual Data (b) the Generalised Data

As can be seen from Figure 59 and Figure 60, in the majority of cases the frequency distribution curves for the various aircraft show some degree of overlap. In cases where overlap occurs it is possible for the ranking of the aircraft to be altered if only a single data point is selected to represent the performance of the aircraft – as is the case in the certification trials. Similarly, in cases where there is no overlap, it is possible to define a definitive ranking.

To demonstrate this let us assume the model generated probability distributions for the TET to accurately represent the actual frequency distribution for these aircraft. Consider the performance of Case 3 and Case 1 (see Figure 61(a)). It is apparent from these distributions that there is no overlap and as such, Case 3 will always be ranked ahead of the Case 1. If we were to assume the methodology of the 90 second certification trial and randomly select a single TET from each distribution it is apparent that the rank ordering will always be the same – the Case 3 will always come out quicker than the Case 1.

In contrast, the distribution of TETs generated by airEXODUS for Case 2 and Case 4 demonstrate a situation where there is a definite overlap (see Figure 61(b)). Based on the means of the two distributions, Case 2 will be ranked faster than Case 4. However, if a data point is selected at random from each distribution, to represent the performance of a single certification trial, there is a finite probability that the rank ordering of these aircraft will be reversed. In this case, given a single certification trial for each aircraft there is a 34% chance that we cannot say with certainty what the rank ordering will be.

This has important implications for the certification trial methodology. Since only a single data-point is every generated it is possible that the rank ordering that is generated is not reflective of the aircraft's true evacuation capabilities. As such, the rank ordering generated by the certification trial is of little meaning and is an unreliable measure of the relative performance of the aircraft. Indeed, the more aircraft that are considered in this manner, the less reliable the rank ordering becomes as the number of possible permutations resulting from overlaps potentially increases.

A more meaningful ranking can be made by comparing the means of the distributions as this represents a result of known likelihood. However, to do this it is necessary to have knowledge of the nature of the probability distribution and this can only be generated from repeated experimental trials or through reliable computer simulation.

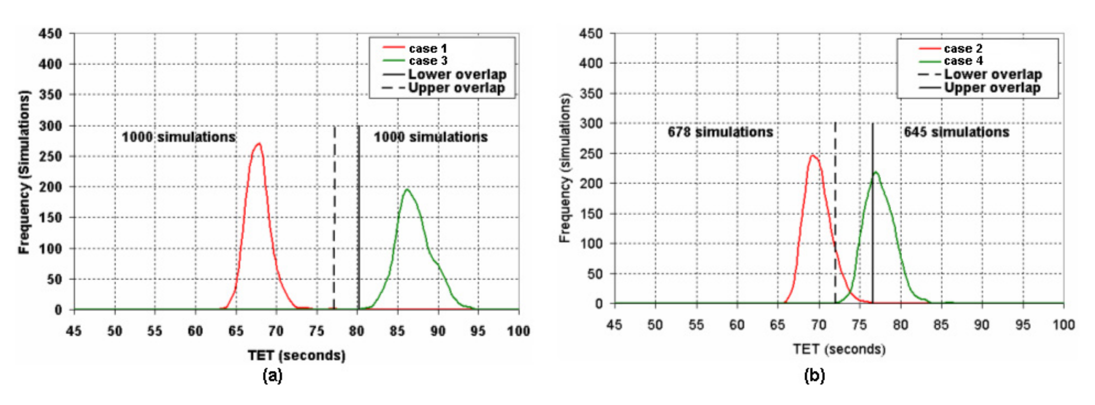


Figure 61 airEXODUS TET Distributions Generated using the Actual Data for (a) Case 1 and Case 3 Demonstrating a Situation of no over-lap and (b) the Case 2 and Case 4 Demonstrating an Overlap Situation.

7.4 Important Model Parameters

In using airEXODUS to undertake these validation simulations a number of important observations can be made as to the correct use of airEXODUS, which are particularly important when using the model to undertake certification applications.

7.4.1 Number of Repeat Simulations

The first concerns the number of simulations necessary to achieve a good representation of the natural variation in model performance. In each of the cases studied in this report, 1000 repeat simulations were used. The number of repeat simulations is driven by a number of factors inherent in the make up of the model, but the most significant is the nature of the probability distribution used to represent the passenger exit hesitation time distribution. Analysis of the generalised data suggests that for some exits some hundred odd passenger exiting events is necessary to capture the nature of the distribution. The number of simulations necessary to capture this data may be as few as 10 or as many as 100 depending on the particular exit, how many exits of that type are present on the aircraft and how many people use the exit. Thus utilising 1000 repeat simulations may be considered over-kill, however it ensures that the randomness element has been sufficiently catered for. As can be seen from the graphics produced in this report, it also produces sufficient data points on which to base a good plot of the probability distribution for TETs.

7.4.2 Population Randomisation

The second concerns the nature of the population utilised in the simulations. The standard 90 second population used within airEXODUS has been shown to be a good representation of the typical population used in actual 90 second certification trials. However, how the population is used when 1000 repeat simulations are run is of paramount importance. As was shown in the simulation of Case 5 a particular seating allocation could result in ‘unusually’ slow performance due to the unfortunate seating of a particular passenger in a particularly important location. It was shown that randomising the seating allocation several times produced the best results and that these results were consistent with each other. It is suggested that three randomised seating allocations should be performed within the 1000 simulations for the single certification population. This would result in 333 simulations for each randomised seating allocation.

7.4.3 Scenario Specification

The third point concerns the nature of the scenario or scenarios considered. An aircraft evacuation simulation scenario is made up of the following six key components:

- **Aircraft Configuration Specification:** consisting of cabin layout, exit configuration and exit availability.
- **Aircraft Environmental Specification:** consisting of the orientation of the aircraft and the nature of the cabin atmosphere with regard to heat, smoke and toxic gases.
- **Crew Behaviour:** consisting of the number and role of cabin crew, level of assertiveness displayed by the crew at exits and the exit ready times.
- **Passenger Population Distribution:** consisting of the nature of the population used in the simulation, either a standard 90 second population or other mix of passengers including for example disabled passengers.
- **Passenger Behaviour:** consisting of standard 90 second type non-competitive behaviour or accident specific competitive behaviour (e.g. seat jumping, aisle swapping, etc).
- **Passenger Exit Selection:** consisting of which exits the passengers will attempt to utilise during the evacuation, this is essentially one of three basic types, optimal exit, nearest exit, or case specific sub-optimal exit selection.

Changing the selection of any of these parameters will change the outcome of the simulation. In effect, changing these parameters is equivalent to changing the nature of the question that is being posed. Throughout this report a single main scenario was studied. This consisted of:

- **Aircraft Configuration Specification:** cabin layout and exit specification given by aircraft drawings exit availability determined by standard 90 second protocol.
- **Aircraft Environmental Specification:** standard 90 second protocol used, normal orientation and no fire products.
- **Crew Behaviour:** for the simulations using the actual data: actual crew assertiveness at each exit and actual exit ready times; for the simulations using the generalised data: assertive crew and generalised exit ready times.
- **Passenger Population Distribution:** standard 90 second population distribution.
- **Passenger Behaviour:** standard 90 second type non-competitive behaviour.
- **Passenger Exit Selection:** optimal exit selection.

If the model is being used for certification applications, the standard settings can be used for all the parameters as shown above. However, in addition, it is suggested that consideration of likely failure modes should also be considered. In addition to simulating the "optimal" scenario it is important to simulate likely "what if" scenarios that may occur. These are likely to be aircraft specific and depend on the nature of the aircraft geometry. Indeed this type of analysis was performed on Case 6 where the Passenger Exit Selection was altered from the standard optimal configuration to a likely sub-optimal simulation where more passengers choose to use the Type-III exits. This particular scenario was a predictable sub-optimal (or failure mode) for this aircraft due to the proximity of the exit to a large number of passengers – in effect, this exit was the nearest exit for a large number of passengers - and so is a reasonable alternative scenario to consider.

8 The Use of Evacuation Models for Certification Applications

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, computer modelling should also improve the certification process i.e. provide the aviation community and the passengers that use the aircraft something more than the simple one-off testing provides. If we are to rise to this challenge it is essential that we begin to question some of our current preconceptions concerning certification.

8.1 Certification Scenarios

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 – from for example one of the several accident databases that have been developed. 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. 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. In this way evacuation simulation provides better insight to the performance capability of the aircraft under a range of scenarios.

8.2 Acceptance Criteria

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? In the hypothetical example provided (see Figure 52), 950 of the 1000 simulations (i.e. 95%) produced an evacuation time less than 90 seconds. Should this aircraft configuration be deemed to pass or fail the certification criteria?

An interesting example of this dilemma was shown through Case 1 examined in this document. In this example, the aircraft achieved an actual certification performance of 83.7 seconds with a mean airEXODUS predicted evacuation time of 82.7 seconds. 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, the airEXODUS analysis suggests that of the 1000 simulations, three or 0.3% are predicted to marginally fail the certification requirement. If the mean 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 0.3%? If this general approach were considered viable, the logical extension would require that all of the past aircraft that have undergone the certification process would need 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 certification maximum of 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. This provides a better indication of the performance capability of the aircraft.

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.

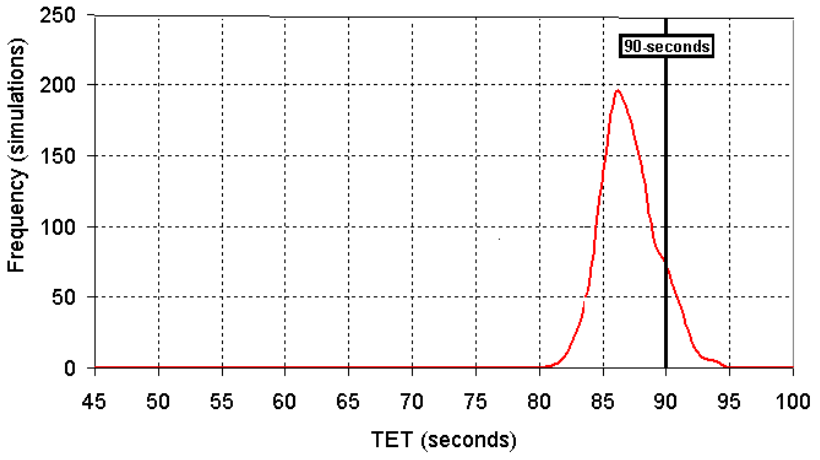


Figure 62 Numerically Generated Evacuation Time Distribution (frequency Vs evacuation time) for a Particular Scenario for an Aircraft Configuration.

This 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 [19, 8].

Recently in the marine industry a half way house approach has been adopted. Rather than use the building industries ASET/RSET approach, IMO have adopted as draft guidelines a methodology where the ASET is set by a prescriptive limit, similar in concept to the 90 second "magic number" used in the aviation industry while the RSET can be determined by computer simulation [20]. To determine the RSET the submitted design is subjected to four benchmark scenarios each evaluated by computer simulation. The precise nature of the benchmark scenarios are prescribed in a similar way to the current 90 second certification trial. The ship design must pass all four benchmark scenarios in order to be deemed to satisfy the requirement. Furthermore, IMO have acknowledged that a distribution of evacuation times will be produced for any single evacuation scenario. As a result, they have adopted the 95% rule described above.

A similar methodological approach to either the building or maritime industries should be considered for aviation.

Other disciplines such as the building and maritime industries accept computer based simulations as part of the certification process. These have adopted a common approach to the validation and verification of evacuation models that could easily be adapted for aviation applications. Furthermore, in the marine industry, specific documentation is required to be submitted along with the simulation results. This documentation is intended to demonstrate the credibility and appropriateness of the approach adopted and furthermore allow easy verification and reproduction of the submitted results [20]. These requirements include the specification of:

- the variables used in the model to describe the dynamics, e.g. walking speed of each person;
- the functional relation between the parameters and the variables;
- the type of update used within the model;

- the representation of stairs, doors, … and other special geometrical elements and their influence on the variables during the simulation and the respective parameters quantifying this influence;
- a detailed user guide/manual specifying the nature of the model and its assumptions and guidelines for the correct use of the model and interpretation of results should be readily available.

Certification analysis performed for the aviation industry using computer simulation should require a similar level of documentation.

8.3 Suggested Certification Methodology

As in the marine and building industries, it is essential that a protocol be developed for the acceptable use of computer simulations for aircraft certification applications. However, it is essential to note that such a methodology is not intended to replace the entire certification process. Existing testing such as slide inflation testing, door opening times, etc would still be required as would compliance with prescriptive rules. The protocol is only intended as an alternative to the current full-scale evacuation demonstration.

Such a protocol should address the following five key issues:

i) **Model Validation and Demonstration Requirements**

Before a model is used for a certification application it must be demonstrated that the model is capable of simulating the certification test with a specified degree of accuracy. The cases examined in this report could form the basis of such validation/demonstration cases.

ii) **Simulation Protocols**

It is necessary to specify the manner in which the simulations are to be run and the nature of the core results must be presented. This should include for instance the number of repeat simulations required, the nature of the data used in the simulations, the nature of the population to be used, etc.

iii) **The Scenarios to be Investigated**

A range of scenarios should be considered by the analysis which includes the standard 90 second scenario as a base case and additional scenarios drawn from accident analysis as suggested in section 8.1. The scenario specification should specify the six key components as identified in section 7.4.3.

iv) **The Acceptance Criteria**

Due to the probabilistic nature of the results produced from repeated simulations, it is essential that a rational acceptance criteria be developed. This should be based on meaningful statistical analysis as outlined in section 8.2.

v) **Supporting Documentation**

The evacuation analysis must be supported by appropriate documentary evidence. This should provide a thorough justification for the analysis presented – covering both the numerical technique and data used - and provide a means of reproducing the analysis in some way. The approach adopted by International Maritime Organisation discussed in section 8.2 provides the basis for developing such a system for aviation applications.

Until such protocols are in place, it is unlikely that the aviation industry will adopt the use of computer simulation for evacuation certification analysis.

9 Conclusions

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 model's predictive capabilities will be improved the more often it is shown to produce reliable predictions.

A key component of the airEXODUS evacuation model is the use of the generalised passenger exit hesitation time data and exit ready times. The generalised data is a statistical composite of all available data from previous certification trials. The results from the six test cases considered has shown that the same broad conclusions concerning aircraft performance can be derived from simulations utilising the generalised data for exit hesitation times and exit opening times as simulations using the actual data. This suggests that the generalised data represents a good approximation for how key aircraft components will perform under certification applications. This provides the modelling and regulatory community with strong evidence to support the use of the generalised data for aircraft certification applications in which the standard configurations and components are being considered.

This general approach can be extended to situations in which the generalised data is not applicable, for example, when a new or significantly modified aircraft exit type is being used. In this situation, rigorous testing of the exit component under certification conditions is necessary in order to generate the appropriate data to use in the model. This testing should be sufficient to provide data of similar quality to that used to generate the existing generalised data. This approach is identical to that used in those simulations that made use of the actual data rather than the generalised data.

This project has added an additional six test cases to the list of validation already undertaken by airEXODUS. These cases have shown that the model is capable of successfully reproducing the overall evacuation performance of both wide-body and narrow-body aircraft under certification conditions. Using the mean of the airEXODUS generated total evacuation time distribution for each aircraft and the single time achieved by the aircraft in each of the trials to represent the typical evacuation performance, airEXODUS is capable of predicting the total evacuation time to within 5.3% or 3.8 seconds on average. It was also shown that the model is able to reliably predict the likely evolution of the evacuation from its start to its completion.

The analysis has also highlighted the inability of the current certification process to meaningfully rank aircraft performance, on the basis of a single trial result due to the probabilistic nature of the evacuation process. In order to rank aircraft performance it is necessary to undertake repeated evacuation trials. Alternatively, computer simulation could be used to generate the total evacuation time probability distribution and base a ranking system on the statistical information provided by such a distribution.

The analysis has also shown that even though an aircraft may pass a single one-off certification trial, there may be a finite chance that the aircraft will fail to meet the requirements of the certification process if the trial were repeated a number of times. This information is invaluable when attempting to assess the true evacuation performance of the aircraft. It provides insight into the design of the aircraft that can only be practically provided through evacuation simulation.

Finally, the success of airEXODUS in predicting the outcome of previous 90 second certification trials is a compelling argument of the suitability of this 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.

Thus, aircraft evacuation modelling has been shown to:

- be capable of reproducing the evacuation performance of aircraft, passengers and crew in full-scale certification trials;
- be a safer and more efficient process than full-scale evacuation trials;
- provide better insight into the actual performance capabilities of the aircraft by generating a performance probability distribution or performance envelope rather than a single datum; and
- be capable of easily and efficiently investigating a range of relevant certification scenarios rather than a single scenario.

These capabilities provide the aviation community (passengers, crew, manufacturers, airlines, regulators) significantly more than the current simple one-off testing procedure provides.

Future effort should be directed towards two goals, producing a framework for the application of aircraft evacuation models to the regulatory environment and the continued development of aircraft evacuation modelling technology to include additional behavioural features common in real accident scenarios.

As in the marine and building industries, it is essential that a suggested protocol be developed for the acceptable use of computer simulations for aircraft certification applications. Until such protocols are in place, it is unlikely that the aviation industry will adopt the use of computer simulation for evacuation certification analysis. An outline of such a protocol has been suggested in this document.

With regard to model development, it is suggested that additional capabilities to explicitly represent the crew and their interactions with passengers should be developed. This should include the ability to simulate crew directed by-pass. Wherever possible these developments should be guided by evidence available from actual accidents. Additional capabilities relating to behaviours noted in actual accidents such as the ability for passengers to jump over seats and switch aisles should also be developed and where possible this development should be guided by actual accident analysis.

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