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Investigating the Expanded Use of Modelling and Simulation for Evacuation Certifications Using the airEXODUS Aircraft Evacuation Simulation Software

Author(s):
Ed Galea
Peter Lawrence
Lazaros Filippidis,
David Cooney
Darren Blackshields

Fire Safety Engineering
Group. University of
Greenwich London SE10
9LS

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Ed R. Galea (ORCID 0000-0002-0001-6665) Peter J. Lawrence (ORCID 0000-0002-0269-0231) Lazaros Filippidis (ORCID 0000-0002-1852- 0042) David Cooney (ORCID 0000-0002-2341-0315) Darren Blackshields (ORCID 0000-0001-8940-0024)	DOT/FAA/AM-25/10

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12. Abstract

Before an airplane can be licensed to carry passengers on commercial flights, the manufacturer must demonstrate that their airplane design can meet the evacuation requirements, commonly referred to as the 90-second certification test. Since the certification requirements use a single test, parameters that could significantly affect evacuation time are not fully understood or fully captured. One proposed method of addressing these limitations is to include simulated evacuation data in the certification process. This report examines the impact different parameters have on simulated evacuation data, such as exit availability, crew assertiveness, and passenger exit-selection behaviour. Five separate evacuations were simulated looking at these parameters (or a combination of two) and compared to a baseline design. Several of these parameters had a significant impact on simulated evacuation performance. The results of these simulations were used to make recommendations for how modelling and simulation data can be incorporated into aviation evacuation certification. This paper also recommends best practices for creating and evaluating modelling and simulation data for industry and regulators.

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Prof Ed Galea, Peter Lawrence, Lazaros Filippidis,
David Cooney and Darren Blackshields.
Fire Safety Engineering Group.
University of Greenwich
London SE10 9LS.
for
Chickasaw Health Consulting LLC
FAA Civil Aerospace and Medical Institute (CAMI)

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Executive Summary

(1) CONTEXT (see report Sections 1-3)

This document represents the final report for the research project resulting from a request for proposal (RFP) from Chickasaw Health Consulting (CHC) on behalf of FAA CAMI concerning the expanded use of modelling and simulation for evacuation certification as described in the FAA statement of work (SOW). The research, undertaken by the Fire Safety Engineering Group (FSEG) of the University of Greenwich (UoG), commenced on 1 February 2024. The project consisted of two phases and involved an analysis, using the state-of-the-art airEXODUS evacuation simulation software, to:

(a) **Phase 1:** Undertake a sensitivity study examining the impact of various parameters on the rapid evacuation of a transport category aircraft. Based on findings from the sensitivity study, make recommendations on how to evaluate simulation data produced by aircraft evacuation simulation software.

(b) **Phase 2:** Make recommendations on how evacuation simulation data may be used to support and enhance the current evacuation certification process as described in 14 CFR 25.803(c).

Due to project timescales and budgetary constraints, it was not possible to explore multiple aircraft configurations and multiple evacuation scenarios, so a representative aircraft configuration and a reduced set of evacuation scenarios (five) were selected for analysis with CAMI agreement. The aircraft configuration consisted of a single-aisle narrow-body aircraft configuration typical of the popular B737/A320 models. The aircraft seats 180 passengers (PAXs), with three cabin crew (CC) and two flight deck crew (FDC), resulting in 185 people on board. The available exits on the aircraft consist of two pairs of Type C exits (one pair located forward and one pair located aft) and two pairs of Type-III (overwing) exits.

The five evacuation scenarios agreed for investigation were defined as follows:

(1) **Scenario 1, Base Case:** This consists of the certification configuration (50% of the available exits all on one side of aircraft), assertive behaviour of crew at exits, and certification-compliant exit opening times with optimal passenger exit-selection behaviour. The impact of 1000 different populations, satisfying the certification requirements, is explored.

(2) **Scenario 2, Sensitivity Case 1 - Exit availability:** This consists of two forward exits and two overwing exits on one side available (50% of the available exits and the same exit type mix as required by 14 CFR 25.803) and cabin crew and passenger behaviour as in Scenario 1 (Base Case). This scenario is repeated 1000 times with 1000 different populations, as in Scenario 1.

(3) **Scenario 3, Sensitivity Case 2 – Crew assertiveness at exits:** The scenario is configured as Scenario 1 (Base case) or Scenario 2, except for the crew assertiveness at the exits. This scenario is repeated 1000 times with 1000 different populations as in Scenarios 1 and 2. This scenario consists of two different cases, as follows:

   (a) Scenario 3a: 0% assertive crew, setup as Scenario 1: cabin crew at forward and aft Type C exits utilise the ‘in-between’ cabin crew assertive behaviour.

Scenario 3b: 0% assertive crew, setup as Scenario 2: cabin crew at the two forward Type C exits utilise the ‘in-between’ cabin crew assertiveness behaviour**.**

(4) **Scenario 4, Sensitivity Case 3 – Passenger exit-selection behaviour:** The scenario is configured as Scenario 1 (Base case) with the exception of the passenger exit-selection behaviour. In this case, passengers will select their nearest exit. This scenario is repeated 1000 times with 1000 different populations, as in Scenario 1.

Furthermore, an additional scenario is considered for the sensitivity analysis that was undertaken as part of an earlier modelling study to investigate the impact of passenger retrieval of cabin luggage on evacuation performance. This scenario is the equivalent of Scenario 2, but passengers attempt to utilise their nearest exit (as in Scenario 4), effectively not responding to cabin crew commands to redirect to optimally utilise available exits.

Based on findings from the sensitivity study conducted in Phase 1, Phase 2 explored and made recommendations concerning how evacuation simulation could be used to support and enhance the current evacuation certification process as described in 14 CFR 25.803.

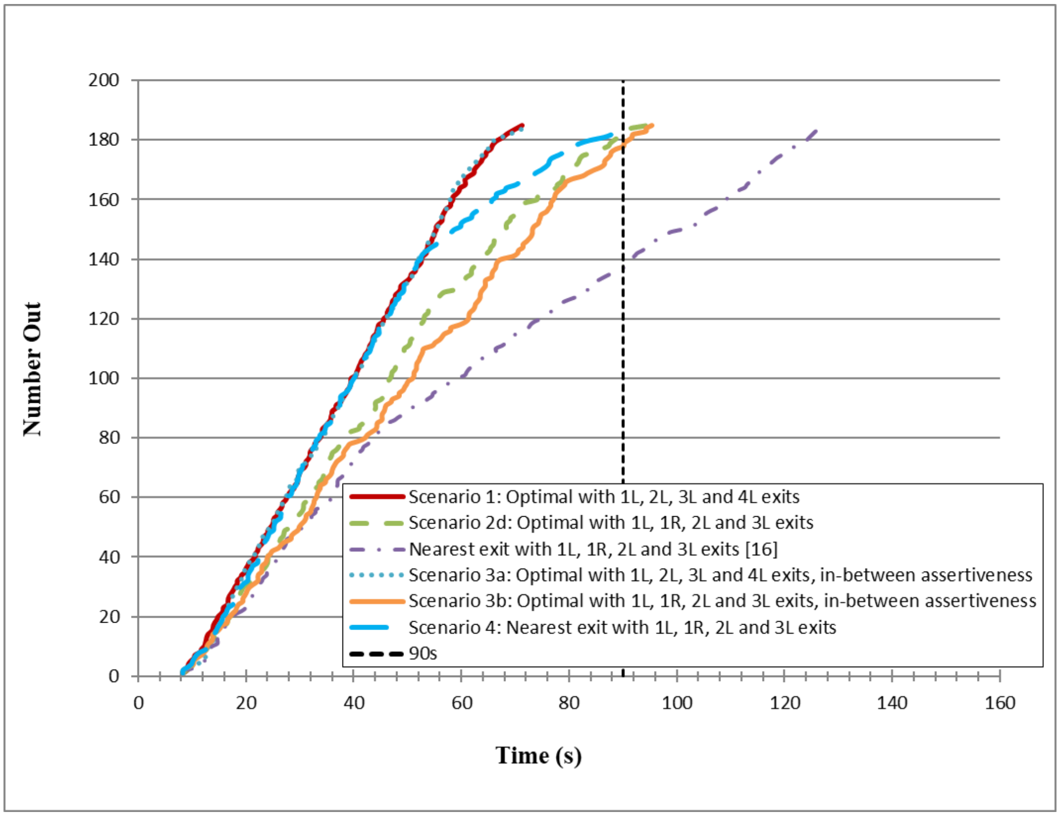
(2) INTERPRETATION OF PHASE 1 RESULTS (see report Sections 5-9)

Presented in Executive Figure 1 are the evacuation curves for the 95th percentile cases for six scenarios, the near-optimal evacuation performance achieved for the aircraft configuration in Scenario 1 (exits 1L, 2L, 3L and 4L) (see Section 5.2), Scenario 2d (exits 1L, 1R, 2L and 3L) (see Section 6.2), Scenario 3a (exits 1L, 2L, 3L and 4L, with CC with reduced assertiveness) (see Section 7.2.2), Scenario 3b (exits 1L, 1R, 2L and 2L, with CC with reduced assertiveness) (see Section 7.2.4), plus the evacuation results for the nearest-exit evacuation performance achieved for the aircraft configuration in Scenario 4 (exits 1L, 2L, 3L and 4L) (see Section 8.2) and the nearest-exit variant of Scenario 2d (from [16]). It is noted that four of the six scenarios (i.e., Scenario 2d, Scenario 3b, Scenario 4, and the equivalent nearest-exit case (from [16])) produce total evacuation times (TETs) in excess of 90 s.

As can be seen, even though similar populations are simulated, and in each case, 50% of the available exits are utilised (with the same mix of exit types), the 95th percentile TET can vary significantly. Across all five scenarios, the 95th percentile time varies from 71.3 s (Scenario 1) to 127.7 s (the nearest-exit variant of Scenario 2d [16]).

Executive Figure 1

Evacuation performance of the 95th percentile cases for Scenarios 1, 2d, 3a, and 3b optimal case; and nearest-exit cases Scenario 4 and Scenario 2d (nearest-exit variant from [16]).



Furthermore, the best evacuation performance is for Scenario 1 (exits 1L, 2L, 3L, and 4L), which is a scenario equivalent of the certification demonstration trial protocol producing a 95th percentile TET of 71.3 s, while the worst performance is for the nearest-exit variant of Scenario 2d (exits 1L, 1R, 2L and 3L), which produces a 95th percentile TET of 127.7 s [16]. The significant differences between these two extremes of evacuation performance are the exit availability, i.e., which 50% of the available exits are used (while maintaining the mix of available exits, i.e., two Type C and two Type-III exits) and the passenger exit-selection behaviour. In Scenario 1, the passengers select their optimal exits, assuming that CC can direct passengers to their optimal exits (as usually occurs in the ideal conditions of a certification trial), while in the nearest-exit variant of Scenario 2d, passengers elect to use their nearest exit (as in accident scenarios). The small and relatively slow Type-III exits are the closest to the majority of passengers, so in the nearest-exit scenarios, these exits become overutilized.

(i) Repeating the evacuation with a different regulatory-compliant population

If a scenario is repeated using a different population satisfying the certification population requirements, a different TET is produced. Repeating this process 1000 times results in a significant variation in TETs (see Executive Table 1), with the distribution of TETs being near normal (see Executive Figure 2). For example, Scenario 1 is intended to be representative of the evacuation certification demonstration trial and produce results indicative of the expected ***optimal*** performance of the configuration in the evacuation certification demonstration scenario.

Of all the scenarios investigated, Scenario 1 is intended to be the closest modelling representation of the certification demonstration trial.

Executive Table 1

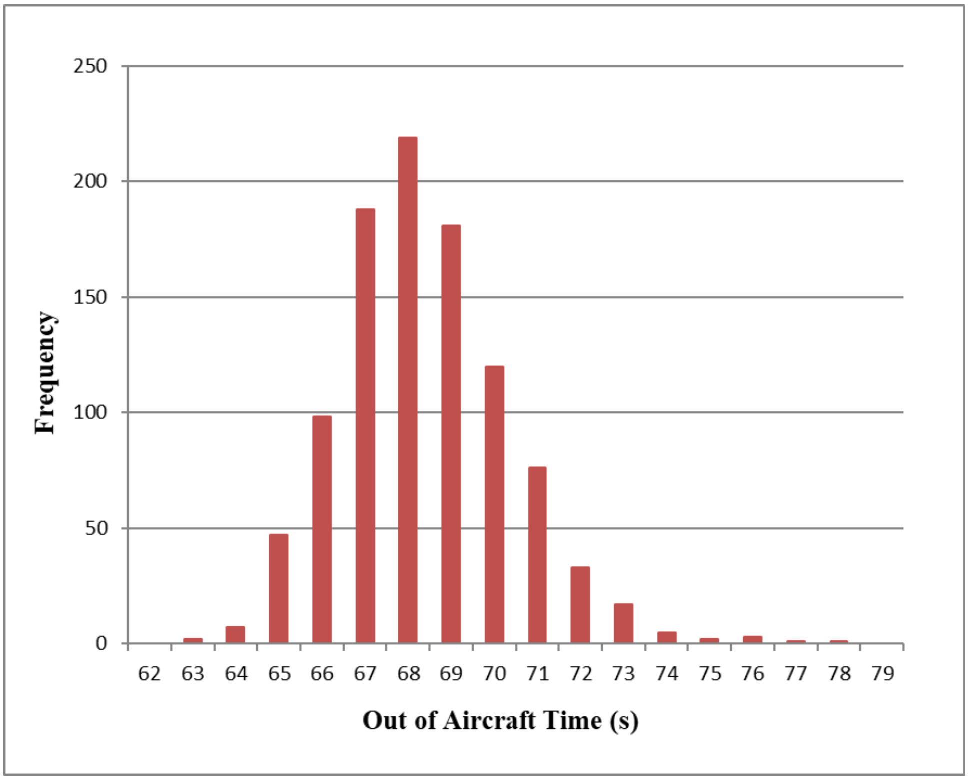
Range of TETs for Scenarios 1, 2, 3a, and 3b with optimal passenger exit selection and Scenario 4 and Scenario 2 with passenger nearest-exit selection (from [16]).

Scenario	Minimum TET (s)	Median TET (s)	Maximum TET (s)	95th % TET (s)
Scenario 1 (optimal-exit selection), exits 1L, 2L, 3L, and 4L	62.9 s	67.7 s	77.0 s	71.3 s
Scenario 2 (optimal-exit selection), exits 1L, 1R, 2L, 3L	80.3 s	88.6 s	102.7 s	94.7 s
Nearest-exit variant of Scenario 2 (from [16])	111.2 s	122.0 s	139.7 s	127.7 s
Scenario 3a (optimal-exit selection), exits 1L, 2L, 3L, and 4L 0% ‘assertive’ crew	63.5 s	68.4 s	76.6 s	72.3 s
Scenario 3b (optimal-exit selection), exits 1L, 1R, 2L, 3L 0% ‘assertive’ crew	79.7 s	88.9 s	103.2 s	95.3 s
Scenario 4 (nearest-exit selection), exits 1L, 2L, 3L, 4L	74.9 s	84.3 s	96.5 s	90.1 s

Scenario 1 produces **Out Of Aircraft (OOA) TETs** of between **62.9 s and 77.0 s** with a **median TET of 67.7 s** and a **95th percentile TET of 71.3 s**. By repeating the scenario 1000 times, with each simulation using a different representative population, the spread in OOA TETs is 14.1 s. This large variation in OOA TETs (i.e., 14.1 s) and the relatively high (compared to the median) 95th percentile OOA TET (71.3 s) is produced simply by repeating the certification demonstration trial with a different compliant population distribution. This predicted variation in evacuation performance cannot be captured by the current certification demonstration trial protocol, i.e., 14 CFR 25.803, as only a single demonstration trial is required. Furthermore, the interpolated certification demonstration trial OOA TET for the 185-person variant of the aircraft is estimated to be 76.9 s with an Optimal Performance Statistic (OPS) of 0.115. Thus, the estimated trial OOA TET falls within the range of simulated OOA TETs. This suggests that the predicted simulation results are a reasonable approximation of the likely certification performance for the aircraft.

Executive Figure 2

Distribution of TET for Scenario 1 produced from 1000 repeat simulations.



(ii) Exit Availability

With passengers exhibiting optimal exit-selection behaviour (Scenarios 1, 2d, 3a, and 3b) and assertive CC (Scenarios 1 and 2d), **simply selecting a different combination of 50% of the available exits (Scenarios 1 and 2d) can increase the 95th percentile TET from 71.3 s to 94.7 s, an increase in evacuation time of 23.4 s or 32.8%.** More significantly, this change in exit availability results in a different conclusion concerning the acceptability of evacuation performance, from a pass (in Scenario 1) to a failure (in Scenario 2d) in terms of satisfying the 90 s certification requirement.

The reason for this significant difference in evacuation performance is due to the two forward Type C exits in Scenario 2d not being able to achieve their maximum flow due to the inability of the narrow cabin aisle to supply a sufficient flow to the two exits. Furthermore, the evacuation performance in Scenario 2d is highly susceptible to slow-moving passengers (e.g., elderly or disabled—however, disabled passengers are not considered in the certification analysis), which can create momentary gaps in the supply of passengers to both Type C exits. While the same slow-moving passengers exist in Scenario 1, their impact is less noticeable, as their behaviour will only impact one of the two Type C exits at any one time.

(iii) Crew Assertiveness

If the assertiveness of the crew at the Type C exits is decreased only slightly, from ‘assertive’ to ‘in-between’, the TET is only increased marginally. Comparing Scenario 1 (exits 1L, 2L, 3L, and 4L with ‘assertive’ crew) and Scenario 3a (exits 1L, 2L, 3L, and 4L with ‘in-between’ crew), the TET increases from **71.3 s** (in Scenario 1, see Section 5.2) **to 72.3 s** (in Scenario 3a, see Section 7.2), an increase of only **1.4%.** Comparing Scenario 2d (exits 1L, 1R, 2L, and 3L with ‘assertive’ crew) and Scenario 3b (exits 1L, 1R, 2L, and 3L with ‘in-between’ crew), the TET increases from **94.7 s** (in Scenario 2d) **to 95.3 s** (in Scenario 3b), an increase of only **0.6%.**

This small increase in TET is the result of the small decrease in average exit flow resulting from the Passenger Exit Delay Time (PEDT) distribution associated with ‘in-between’ assertiveness (see Annex 3). While this is only a small increase in TET, it does not necessarily represent a true impact of the importance of CC assertiveness on evacuation performance. As noted in Section 2.5b, the impact of unassertive CC on evacuation performance could not be assessed in this study, as PEDT data associated with unassertive CC for Type C exits are not available. The use of unassertive CC operating the exits is likely to further reduce average flow rates achieved, thereby decreasing evacuation performance.

(iv) Passenger Exit Selection

If passenger exit-selection behaviour is changed from optimal (as in most certification demonstration trials) to nearest exit (as is likely to occur in real accidents), evacuation efficiency is significantly reduced, with a significant increase in TET. Comparing Scenario 1 (exits 1L, 2L, 3L, and 4L with optimal-exit selection) and Scenario 4 (exits 1L, 2L, 3L, and 4L with nearest-exit selection), the TET increases from **71.3 s** (in Scenario 1) **to 90.1 s** (in Scenario 4), an increase of **26%, and more significantly, results in a failure in terms of the certification demonstration trial performance.** Comparing Scenario 2d (exits 1L, 1R, 2L, and 3L with optimal-exit selection) and the nearest-exit selection variant of Scenario 2d (exits 1L, 1R, 2L, and 3L with nearest-exit selection) from [16], the TET increases from **94.7 s** (in Scenario 2d) **to 127.7 s** (in nearest-exit variant of Scenario 2d), an increase of **35%.**

Changing passenger exit-selection bias from optimal to nearest exit has a **significant** impact on evacuation performance.

(v) Combining two parameters, Exit Availability and Passenger Exit Selection Behaviour

Combining the impact of two parameters, i.e., **exit availability and passenger exit selection** in the nearest-exit variant of Scenario 2d (exits 1L, 1R, 2L, 3L available) **significantly increases 95th percentile TET compared to Scenario 1** (exits 1L, 2L, 3L, 4L available and optimal passenger exit selection) **from 71.3 s to 127.7 s, an increase of 56.4 s or 79%.**

(3) PHASE 2, LIMITATIONS IN THE CURRENT 14 CFR 25.803 EVACUATION DEMONSTRATION PROTOCOL (see report Sections 10.1, 10.2)

A number of limitations in the current 14 CFR 25.803 certification protocol were identified, some of which were supported by evidence from the Phase 1 model sensitivity study. These limitations include:

(i) Only a single evacuation trial is performed, and only a single population mix is selected for testing.

The results from each of the five sensitivity scenarios simulated in Phase 1 clearly demonstrate that a significant variation in TET can be achieved simply by repeating the evacuation with a different population satisfying the regulatory-specified population demographics. Thus, the result from a single certification trial may not provide a true indication of the likely evacuation performance of the airplane.

(ii) Only a single exit availability is tested, and this assumes one exit from each exit pair.

The certification demonstration trial assumes that 50% of the exits are available and further assumes that one exit from each exit pair is available, as in Scenario 1, i.e., exits 1L, 2L, 3L, and 4L (see Appendix J to 14 CFR 25.803). This exit availability is conducive to producing short evacuation times. Other combinations of 50% of the available exits that have the same mix of exit types and are likely to occur in accidents (e.g., 1L, 1R, 2L, and 3L as in Scenario 2) will result in longer evacuation times. In the sensitivity analysis, the 95th percentile TET increased from 71.3 s in Scenario 1 (certification mix of exits) to 94.7 s in Scenario 2 (different mix of 50% of available exits), an increase of almost 33%. Furthermore, this change in exit availability results in a 95th percentile TET in excess of 90 s and so would be considered a certification failure. Thus, while allowing only 50% of the exits to be used in the certification demonstration trial is reasonable, the exit availability selected for testing is not representative of frequently occurring accident exit availability combinations and is the optimal combination of 50% of available exits to produce the minimum likely evacuation time.

(iii) Lack of realism.

Participant and cabin crew behaviour in certification trials is unlikely to reflect that in a real accident because the certification trial lacks the realism of a challenging emergency evacuation, in part to reduce the risk of injury to participants.

Scenario 4 was intended to investigate just one such aspect related to passengers selecting their nearest exit rather than the optimal exit as directed by CC. All other factors in Scenario 4 were similar to the requirements for the certification demonstration trial (and so were identical to Scenario 1). Thus, rather than passengers following the guidance of CC and utilising the optimal exits to minimise overall TET (as typically occurs in certification trials), passengers in Scenario 4 elect to utilise their nearest exits (as often occurs in accident situations).

Scenario 4 produced a **95th percentile time of 90.1 s**. Furthermore, 5.3% (53 simulations) of the 1000 simulations produce a TET of 90 s or greater. From a life safety viewpoint, this is clearly a concern, as the 95th percentile TET exceeds 90 s. Thus, if passenger exit-selection behaviour is changed from optimal (as in most certification demonstration trials) to nearest exit (as is likely to occur in real accidents), evacuation efficiency is significantly reduced, with the 95th percentile TET increasing from **71.3 s** (in Scenario 1) **to 90.1 s** (in Scenario 4), an increase of **26%, and more significantly, results in a fail in terms of the certification demonstration trial performance.**

Other issues that impact the realism of the certification trial that are not directly explored in the model sensitivity study but are also amenable to evacuation modelling were identified and discussed. For example, the impact of passenger luggage collection during evacuation. This was not selected as a sensitivity case for the current study as it was part of an earlier modelling study [16]. However, it is now well established that in real accidents, many passengers attempt to evacuate with their carry-on cabin luggage, and this may have a significant negative impact on the evacuation. The previous modelling study suggests that the combined impact of the three realistic adverse factors (i.e., luggage collection, adverse exit availability, and passengers selecting their nearest exits) compared to the standard certification scenario (i.e., Scenario 1) results in a doubling of the **median TET** in the case of just 25% of the passengers attempting to retrieve luggage, i.e., an increase from **67.7 s** to **135.0 s**.

(4) PHASE 2, THE PROPOSED USE OF EVACUATION MODELLING TO ENHANCE AIRPLANE EVACUATION CERTIFICATION (see report Sections 10.3 and 10.4)

When considering the limitations of the current 14 CFR 25.803 evacuation certification trial protocol, it is important to consider that its original intent was to provide an indicative measure of the performance of the airplane under an artificial benchmark evacuation scenario. It was not intended to be a predictor of airplane performance under plausible or realistic accident scenarios. Furthermore, in its current form, the certification trial provides a means of comparing the evacuation performance of different airplane configurations under a set of identical—if somewhat artificial—evacuation scenario conditions.

Four options are proposed to enhance airplane evacuation certification that are either informed by evacuation modelling (**Option 1**) or make use of evacuation modelling (**Options 2 and 3**). While Option 3 is the preferred option, Options 2 and 3 should be considered together, as Option 3 is an extension of Option 2. While not strictly within the scope of the current project, a fourth option is proposed to update the Available Safe Egress Time (ASET)currently imposed in the 14 CFR 25.803 evacuation protocol, i.e., the 90 s requirement (**Option 4**).

(i) Option 1: Improve the realism of the certification trial.

While increasing the realism of the certification trial may be desirable, clearly this should not be achieved at the cost of compromising participant safety and preferably not greatly increasing the cost of the certification analysis. These principles effectively preclude the adoption of many realistic features, such as repeated trials, adverse airplane orientation, passengers retrieving (heavy) carry-on luggage, introduction of (theatrical, i.e., non-toxic) smoke in the cabin, introducing more elderly or disabled passengers, etc. However, several of the identified certification trial limitations could be addressed within a modified trial protocol without compromising safety or increasing the costs of the trials. These include:

- **Exits used during the trial evacuation.** Rather than selecting one exit from each exit pair, as in the current certification demonstration trial, the exits selected for testing in the certification trial should be representative of frequently occurring accident exit combinations. This can be achieved while maintaining the use of 50% of the available exits and the mix of exit types that would be used under the current requirement.
- **Cabin Crew fatigue.** Accidents requiring rapid emergency evacuation can occur at times when CC are fatigued (or suffering from lack of sleep). An important issue not currently covered by quantitative research is whether CC fatigue (and sleepiness) may severely impact

CC abilities to efficiently manage an emergency evacuation. It is recommended that research is conducted into the impact of fatigue and sleepiness on CC abilities to manage a cabin evacuation. Furthermore, if research suggests that CC fatigue can have a significant negative impact on their ability to efficiently manage an evacuation, consideration should be given to modifying the certification trial protocol so that it utilises CC that have induced fatigue levels appropriate for an evacuation that may occur at the end of a typical duty cycle.

- **Cabin Crew experience.** The experience of CC (measured in terms of length of service) could potentially impact performance in evacuation management tasks, so it should be managed by the certification protocol. It is suggested that consideration should be given to modifying the certification trial protocol so that 50% of the CC are considered relatively inexperienced (e.g., less than 2 years of service) and that all CC should have completed their last recurrent training at least 6 months prior to taking part in the certification trial. This approach would prevent using the most experienced and highly trained CC in the certification demonstration trial, making the certification trial more representative of conditions that may occur in a real accident.

(ii) Option 2: Expand the scope of the evacuation certification protocol beyond the experimental trial with additional scenarios simulated using agent-based evacuation models.

The use of evacuation modelling that makes use of advanced and validated agent-based models could be considered as a means to address the identified limitations of the 14 CFR 25.803 airplane evacuation certification trial. The proposed use of agent-based evacuation models to enhance the current airplane evacuation certification protocol is informed by common practice in the building and maritime industries, which routinely use evacuation modelling as part of the regulatory certification process. In particular, the proposed approach follows the principles adopted by the maritime industry, as outlined in the International Maritime Organization's Maritime Safety Committee Circular IMO MSC.1/Cir. 1533 (2016) [44]. This involves specifying:

- **additional scenarios to be investigated using evacuation modelling,**
- **the quantification of the relevant parameters to be used in the modelling,**
- **the number of repeat simulations and how the evacuation time is selected from the distribution produced by the repeat simulations,**
- **the pass/fail acceptance criteria, and**
- **quality control requirements for the software, analysis, and reporting of results (see Section (5)).**

How each of these requirements could be applied to aviation applications was explored, and a way forward is proposed. Clearly, each aspect requires further discussion with stakeholders, including the regulatory authorities, the manufacturers, the airlines, unions, professional bodies, etc.

(a) Identification of appropriate additional candidate certification model scenarios.

The maritime industry evacuation certification guidelines include four core evacuation scenarios that must be analysed for passenger ship applications and six core evacuation scenarios for naval applications. In a similar manner, the aviation regulatory authorities could identify a range of certification model scenarios that could be included in the enhanced certification protocol. A Certification Model Scenario (CMS) selected for inclusion in the enhanced certification protocol should provide important additional information not currently captured by the current certification trial. In addition, the CMS should provide additional insight into how the airplane is likely to perform in scenarios that are more representative of accident situations than the current certification demonstration trial scenario. Based on the Phase 1 model sensitivity study, several suitable candidate CMSs are suggested for consideration.

- **CMS1 (one exit from each exit pair, optimal passenger exit selection):** This scenario expands on the experimental result derived from the certification trial due to the number of times the scenario is repeated and the use of different populations satisfying the current population demographics specified in 14 CFR 25.803.
- **CMS2 (accident exit availability, optimal passenger exit selection):** This scenario is intended to explore the impact of exit availability commonly occurring in accidents for the airplane type being certified while maintaining only 50% exit availability.
- **CMS3 (one exit from each exit pair, nearest-exit passenger exit selection):** This scenario is the equivalent of CMS1 but where passengers make use of their nearest exit rather than optimal exits. This scenario utilises passenger exit selection typical of behaviour observed in accidents.
- **CMS4 (accident exit availability, nearest-exit passenger exit selection):** This scenario is the equivalent of CMS2 but where passengers make use of their nearest exit rather than optimal exits. This utilises passenger exit selection typical of behaviour observed in accidents.

It is suggested that these four CMSs form the core scenarios that could be considered for inclusion in the enhanced certification protocol. Additional CMSs could be considered but may be challenging given that further model development (and validation/verification) may be required and additional data may be required to specify some of the necessary parameters. Three additional CMSs were suggested: CMS5 (luggage retrieval based on [16]), CMS6 (modified population demographic including disabled passengers), and CMS7 (adverse cabin orientation).

The number and type of CMSs eventually included in the proposed enhanced certification protocol should ideally be decided by the regulator in consultation with stakeholders. Furthermore, the number of CMSs introduced into the enhanced certification process may be small initially, with the number and scope of CMSs introduced expanded as confidence in the proposed enhanced protocol is established. For example, initially, only one CMS may be adopted, for which there is the greatest confidence in the veracity of the modelling predictions and similarity to the current demonstration certification scenario, i.e., CMS1. As confidence in the enhanced certification protocol grows, additional CMSs could be introduced into the analysis, as in the maritime evacuation certification protocols.

(b) Specification of the relevant parameters to be used in certification modelling.
Within the maritime industry regulatory guidelines for the use of evacuation modelling to demonstrate compliance with evacuation requirements [44,45], all the data required to define

the scenarios are provided within the regulatory guidance documents. Engineers wishing to demonstrate that their vessel meets the regulatory guidance must utilise the data provided in the documentation. A similar approach is suggested for aviation applications, with the data required to define the modelling parameters for each of the suggested seven CMSs provided in the proposed certification protocol.

(c) Specification of the number of repeat simulations and selection of the representative TET.

Within the maritime industry regulatory guidelines for the use of evacuation modelling [44, 45], the number of repeat simulations that must be performed for each scenario is specified as 500 repeat simulations. Furthermore, a statistical method has been developed using the concept of confidence intervals to test if 500 repeat simulations are sufficient or necessary to meet the intended requirement [67]. A similar approach is suggested for aviation applications. However, the critical number of repeat simulations that is required is likely to be dependent on the nature of software used to perform the evacuation simulations. For the airEXODUS software, a total of 1000 repeat simulations are considered appropriate. Nevertheless, whatever the number of repeat simulations specified, it should be described as a minimum value with the actual number of repeat simulations required being determined by the nature of the software tool used for the analysis.

In addition, given that a distribution of predicted TETs is generated for each scenario, a method for identifying the representative TET for the scenario must be specified. As the evacuation analysis forms part of a safety case, it is reasonable to adopt the plausible worst-case result from the TET distribution. This approach has been adopted within the maritime guidelines, where the 95th percentile time from the distribution of predicted evacuation times is considered the representative time for the scenario [44, 45]. It is therefore recommended that a similar approach is adopted in the aviation application, and the 95th percentile TET is adopted as the representative evacuation time for the scenario.

(d) Pass/Fail criteria

Within the proposed enhanced certification protocol Option 2, there are at least two and possibly up to eight certification TETs for the airplane configuration being certified. This includes one result from the experimental certification demonstration trial and between one and seven model-predicted results, one for each of the Certification Model Scenarios included, i.e., CMS1 to CMS7.

As there is now more than one certification TET for consideration, the challenge is how to determine if the airplane configuration has satisfied the evacuation certification requirement. If the process employed by the maritime industry in their evacuation certification protocol [44, 45] is adopted, then all scenarios must produce a TET of less than 90 s for the airplane configuration to be considered acceptable. It is important to note that in the maritime case, all the evacuation times are produced by model simulations, whereas in the aviation case, one of the evacuation times is generated from the real-world evacuation certification demonstration trial. This is an important distinction between the maritime and aviation cases, even though the aviation evacuation demonstration trial is for a somewhat unrepresentative scenario and results from only a single trial. It could be argued that the real-world result based on the certification trial should have greater importance than the CMSs in determining the pass/fail status for the airplane configuration. Furthermore, given the uncertainty associated with model predictions for some of the CMSs, it is also questionable as to whether each CMS should be considered of equal importance in determining the pass/fail status. Given these complicating issues, the simple approach adopted by the maritime industry to determine pass/fail status is not considered appropriate.

(iii) Option 3: Weighted sum of certification trial time and simulated certification model scenario times.

Option 2 introduced a methodology for identifying additional CMSs to be considered as part of the enhanced certification protocol, specified the data required for the simulation of the CMSs, identified the number of required repeat simulations to be performed for each CMS, and provided a means of selecting the representative TET from the distribution. Furthermore, it suggested a means of determining pass/fail criteria for the airplane configuration.

However, the suggested pass/fail criterion was not considered appropriate, primarily because it considered the certification demonstration trial result and each of the modelling results from the CMSs to be of equal importance. Given that some of the CMSs may be considered less likely events and that the modelling of these events may be less reliable due to less reliable datasets to characterise passenger behaviour, different levels of importance should be allocated to the certification trial and the various CMS results.

Using this approach, a weighted sum methodology was proposed to characterise the definitive certification evacuation performance of the airplane configuration, i.e., TET_{cert}. In this approach, two sets of weights are required: one set to distinguish between the relative importance of the certification demonstration trial result (i.e., W1) and the TET determined from the combined CMSs (i.e., W2). Another set of weights is required to rank the importance of each of the proposed CMSs, i.e., the weight associated with CMS1 is MW1, CMS2 is MW2, etc.

In both cases, the larger the weight, the greater the relative importance of the TET associated with the weight. Furthermore, so that the combined TET used to characterise TET_{cert} is representative of the individual component TETs—i.e., the TET associated with the trial, TET_{trial}; the TET associated with CMS1, TET_{CMS1}; the TET associated with CMS2, TET_{CMS2}, etc.—the sum of each set of weights should be 1.0 (see Equation 1).

$$W1 + W2 = 1.0, \text{ and } MW1 + MW2 + MW3 + \ldots\ldots = 1.0 \quad (1)$$

Using this two-layered weighted sum approach, the combined TET representing the definitive TET for the airplane, i.e., TET_{cert}, is given by Equation (2).

$$TET_{cert} = W1 * TET_{trial} + W2 * TET_{CMS} \quad (2)$$

where TET_{CMS} is given by Equation (3).

$$TET_{CMS} = MW1 * TET_{CMS1} + MW2 * TET_{CMS2} + MW3 * TET_{CMS3} + \ldots\ldots\ldots \quad (3)$$

For the airplane configuration to be considered to have satisfied the certification requirement, not every CMS would need to satisfy the requirement, but it would be necessary to demonstrate that

$$TET_{trial} < 90 \text{ s, and } TET_{cert} < 90 \text{ s} \quad (4)$$

It is proposed that the regulatory authority would define a set of definitive weights reflecting the importance and confidence the industry has in the model predictions for the various CMSs. In addition, the weights would be defined and specified as part of the certification protocol. Furthermore, the weights could be modified by the regulatory authority as confidence in the approach is established, additional data are made available to more reliably set model parameters, and additional CMSs are introduced.

The challenge in the weighted sum approach is to select a meaningful distribution of weights that reflects the importance of the CMS to the certification process and regulator and stakeholder confidence in the ability of the airplane evacuation models to accurately simulate airplane evacuation in the identified scenarios. To a certain extent, the selected weight distribution will be a measure of the regulator’s confidence in the quality of the model validation presented and the relevance of the verification test cases. A rationale is presented to guide the setting of the weights.

Enhancing the certification process through evacuation modelling using the weighted sum approach addresses a number of challenging issues:

1) It maintains the importance and influence of the standard demonstration certification trial to the certification process. This provides the regulatory community and the aviation industry with consistency to the previous protocol while enabling the potential of introducing new and relevant scenarios that enable safer airplane designs.

2) It provides a means of introducing into the certification process additional challenging and relevant accident scenarios without increasing the risk to participants through the use of evacuation modelling.

3) It provides the regulatory authorities with a means of gradually phasing in the use of evacuation modelling into the certification process by controlling (a) the number and type of certification modelling scenarios included in the certification process and (b) the relative importance of the certification trial and the model predictions through a series of weights.

4) The specific modelling scenarios and associated weights used in the enhanced evacuation protocol can be reviewed by the regulatory authority when deemed appropriate to determine if they can be updated as the evacuation modelling tools mature and more data to define the important modelling parameters become available.

5) It continues to provide a consistent means to compare the performance of one airplane configuration with another.

6) As the certification modelling scenarios and associated weights will be part of the defined regulatory process, they will be known by the airplane manufacturers well in advance of certification testing of the proposed new airplane configuration. As a result, they can be incorporated into the initial design process to derisk proposed airplane designs by ensuring that they are able to satisfy the modelling component of the enhanced evacuation certification protocol at the early design stage.

(iv) Option 4: Adopt fire modelling to identify a relevant ASET for airplane evacuation scenarios rather than continue to use the prescriptive 90 s.

While not strictly within the scope of the current project, a methodology was suggested to update the key component of 14 CFR 25.803 associated with the prescriptive evacuation performance requirement of 90 s. The proposed approach utilised CFD fire modelling to define the ASET based on a series of relevant fire scenarios. This approach is like that adopted by the building and maritime industries.

(5) PHASE 2, QUALITY CONTROL (see report Section 10.5)

As part of the proposed enhanced evacuation certification protocol outlined in (ii) and (iii), it is essential that measures are put in place to ensure the quality of the evacuation modelling analysis and the presentation of the results of the analysis. A suggested process is discussed in the report and summarised as follows:

- **Evacuation Models.**

It is important that appropriate evacuation models are used that can address the specific issues associated with airplane evacuation. While there are many evacuation models that are routinely used for building applications, there are fewer evacuation models that have been developed specifically for airplane evacuation. Given the small number of aircraft-specific evacuation models available, building-specific evacuation models are sometimes used for airplane evacuation applications. However, airplane evacuation differs from building evacuation in a number of significant ways, so it may not be appropriate to use a model developed for building applications for airplane evacuation certification applications. Given the range of evacuation models that could be used for airplane applications, it is essential that as part of the enhanced evacuation certification process, the models used are thoroughly described with appropriate evidence provided to demonstrate that they are capable of reliably simulating the proposed CMSs and supporting evidence provided of relevant validation and verification.

- **Validation.**

Before airplane evacuation models can reliably be used for certification applications, it is essential that they undergo a range of relevant and appropriate validation demonstrations. Reliable and thorough datasets to validate evacuation models are extremely challenging to collect, as they require the collection of a vast amount of data. As a result, there are few datasets that possess sufficient information for thorough validation. For airplane evacuation, data from experimental trials are typically used for validation purposes. Generally, these fall into one of two categories: they are either laboratory-based trials designed to address a particular research question, such as the impact of seat pitch on overall evacuation time, or they are full-scale evacuation trials designed to measure the evacuation performance of an aircraft, e.g., the 14 CFR 25.803 certification evacuation demonstration. Data from the 14 CFR 25.803 demonstration certification trials, if available, are a good source of validation data for aircraft evacuation models. Another potential source of data for aircraft model validation is real accidents if sufficient detailed information has been collected from the incident. As part of the proposed enhanced certification process, it is recommended that aviation regulators develop a database of appropriate airplane validation test cases, preferably based on previous actual 14 CFR 25.803 demonstration trials.

- **Verification.**

Given that validation data for airplane evacuation models is not readily available, in addition to providing evidence of validation, it is recommended that a series of verification cases be defined as part of the enhanced evacuation certification protocol. This is similar to the requirements set out in the International Maritime Organziation (IMO) evacuation protocol guidance [44]. In the maritime guidance, some 12 'simple' verification test cases are specified to demonstrate that the evacuation simulation software used in the certification analysis is capable of representing the basic functionality required for a ship evacuation model. It is noted that the verification cases are intended to demonstrate both qualitative and quantitative agreement with informed expectations. A series of eight potential verification cases is suggested for consideration as part of the enhanced evacuation certification protocol.

- **Documentation.**

It is recommended that the documentation supporting a modelling evacuation analysis should include the following:

(1) Certification Analysis Report: A report describing the analysis for the airplane configuration undergoing the certification process should be submitted to the regulatory authority following the live full-scale certification trial. The numerical results for the CMSs should be provided in a detailed report that describes the model, any assumptions imposed on the simulations, and the data used to specify the scenarios. In addition, the exit curves for each CMS should be provided, along with the exit curve for the certification demonstration trial. The trial exit curve should be compared with the exit curves produced by the CMS most closely resembling the certification demonstration trial (see, for example, the analysis presented in [14]) as a form of validation. The calculations to determine TET_{CERT} and TET_{CMS} should be provided. The input and output files for each of the CMSs should be provided and available for independent verification.

(2) Results of the Verification Cases: The results for the verification test cases could be provided as an appendix to the Certification Analysis Report or as an appendix in the user guide of the airplane evacuation simulation software. In addition to the written report describing the results of the verification cases, the input files required to generate the verification cases and the associated output files should be provided and available for independent verification.

Evidence of Validation: Until the regulatory community develops an appropriate dataset of airplane validation test cases, evidence of relevant rigorous validation of the airplane evacuation modelling software should be provided to support its use in airplane evacuation certification applications. This could include peer-reviewed publications or project reports describing the validation test cases. The documentation should describe the validation cases (including how the data were collected), the nature of the validation cases, including the airplane configuration, the nature of the validation comparison (what experimental data are used for comparison purposes), and an assessment of how well the model predictions match the experimental data.

(3) Software User Guide: 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.

(6) PROJECT LIMITATIONS (see report Section 11)

It is accepted that any modelling exercise approximates reality, so modelling incorporates a range of assumptions and, hence, limitations that need to be considered when reviewing and interpreting modelling results. This work is no exception. The modelling work presented in this report incorporates a range of limitations in terms of the data used in the modelling, the nature of the scenarios implemented, and the capabilities of the modelling tool. These are discussed in Section 11 of the report.

(7) RECOMMENDATIONS FOR ADDITIONAL ANALYSIS AND DATA TO ASSIST THE REGULATORY PROCESS (see report Section 12)

While this work has addressed the key project questions concerning evacuation model sensitivity and suggested how evacuation simulation could be used to enhance the regulatory process, it is recommended that additional analysis be undertaken to better understand model sensitivities and to further refine the suggested enhanced modelling certification protocol. Furthermore, additional experimental data are required to assist in both model development and to support the reliable use of evacuation models in certification applications. Finally, while not strictly within the remit of this project, a recommendation concerning fire data is suggested to assist in updating the ASET currently imposed in the 14 CFR 25.803 evacuation protocol, i.e., the 90 s requirement. The recommendations are discussed in full in Section 12 and are summarised as follows:

(1) Characterisation of the demographics of the travelling public.
(2) Experimental campaign to collect data on movement capabilities of disabled passengers.
(3) Experimental campaign to collect data on the impact of cabin orientation on movement speeds and behaviour.
(4) Experimental campaign to collect data on the impact of CC fatigue on evacuation performance.
(5) Experimental campaign to collect data on the impact of CC experience on evacuation performance.
(6) Extend the model sensitivity analysis to include wide-body aircraft.
(7) Extend the model sensitivity analysis to consider the impact of passengers with movement disabilities, a greater number of elderly passengers, group dynamics, and adverse cabin orientation.
(8) Extend the scope of the suggested CMSs, as in (7).
(9) Demonstrate the suggested 'weighted sum' approach for the enhanced evacuation certification process to both narrow- and wide-body airplanes that have available 14 CFR 25.803 certification data.
(10) Develop and demonstrate an appropriate set of evacuation model validation and verification cases.
(11) Experimental campaign to collect fire data to characterise the performance of new fuselage and cabin materials and establish an appropriate ASET.

Key Takeaways

1) Phase 1 Model Sensitivity Study
As part of the model sensitivity analysis, five key scenarios were investigated.

a. Scenario 1: Certification trial scenario, with multiple different populations satisfying the certification demographic.

b. Scenario 2: As Scenario 1, but with an exit availability typical of that frequently occurring in accidents, while satisfying the certification requirement of involving 50% of the available exits and including a mix of exit types equivalent to that resulting from the certification requirements.

c. Scenario 3a: As Scenario 1, but with the assertiveness of the cabin crew at the Type C exits slightly reduced (set to 'in-between'), so that the cabin crew behave assertively but on occasion they behave unassertively during the evacuation.

d. Scenario 3b: As Scenario 2, but with the assertiveness of the cabin crew at the Type C exits slightly reduced (set to 'in-between'), so that the cabin crew behave assertively but on occasion they behave unassertively during the evacuation.

e. Scenario 4: As Scenario 1, but passengers attempt to utilise their nearest exit, effectively not responding to cabin crew commands to redirect to optimally utilise available exits. The passenger exit selection behaviour is representative of observed passenger behaviour in accidents.

Two additional scenarios that were undertaken as part of an earlier modelling study to investigate the impact of passenger retrieval of cabin luggage on evacuation performance [16] can be considered as part of the model sensitivity analysis.

f. Scenario 5: Equivalent to Scenario 2, but passengers attempt to utilise their nearest exit, effectively not responding to cabin crew commands to redirect to optimally utilise available exits. The passenger exit selection behaviour is representative of observed passenger behaviour in accidents.

g. Scenario 6: Equivalent to Scenario 5, but with 25% of the passengers attempting to retrieve cabin luggage during evacuation.

2) Key findings of the Phase 1 Model Sensitivity study.

a. Model predicted evacuation performance is sensitive to the precise mix of passengers. When each of the scenarios is repeated 1000 times (with a different population satisfying the certification demographics) the predicted total evacuation time (TET) can vary significantly. For example, in Scenario 1 (certification trial configuration), the TET varies from 62.9 s to 77.0 s, with a median of 67.7 s and a 95th percentile time of 71.3 s.

b. It is noted that the estimated 14 CFR 25.803 performance for the aircraft (interpolated result based on the certification trial performance of a similar aircraft with nine more persons onboard) is 76.9 s which falls within the predicted range of evacuation times for Scenario 1, suggesting that the model predictions are a reasonable approximation to the likely performance for the aircraft.

c. Population effects can be more apparent in scenarios with adverse exit availability (two exits in one pair available e.g., Scenarios 2, 3b, 5 and 6) as the supply flow to two exits can be impacted by individual slow passengers

d. Exit availability can have a profound impact on evacuation performance. Simply selecting a different combination of 50% of the available exits, can increase the 95th percentile TET from 71.3 s (Scenario 1, the certification case, exits 1L, 2L, 3L, 4L) to 94.7 s (Scenario 2 – exits 1L, 1R, 2L, 3L), an increase in TET of 23.4 s or 32.8%. Furthermore, this change in exit availability results in a TET more than 90 s and so would be considered a certification fail.

e. If the assertiveness of the crew at the Type C exits is decreased only slightly, from 'assertive' to 'in-between', the TET is only increased marginally (increase of 1.4% in Scenario 3a compared with Scenario 1 and 0.6% in Scenario 3b compared with Scenario 2). While this is only a small increase in TET it does not necessarily represent a true impact of the importance of CC assertiveness on evacuation performance as the impact of fully unassertive CC was not assessed.

f. If passenger exit selection behaviour is changed from optimal (as in most certification demonstration trials) to nearest exit (as is likely to occur in real accidents), evacuation efficiency is significantly reduced, with a significant increase in TET. Comparing Scenario 1 (exits 1L, 2L, 3L and 4L, with optimal exit selection) and Scenario 4 (exits 1L, 2L, 3L and 4L, with nearest exit selection), the TET increases from 71.3 s (in Scenario 1) to 90.1 s (in Scenario 4), an increase of 26%, and more significantly results in a failure in terms of the certification demonstration trial performance.

g. If three adverse factors are considered i.e., 25% of passengers retrieve luggage, adverse exit availability and passengers selecting their nearest exit (i.e., Scenario 6), evacuation efficiency is significantly reduced, with a large increase in TET. Comparing Scenario 1 with Scenario 6, the median TET increases from 67.7 s (in Scenario 1) to 135.5 s (in Scenario 6), a doubling of the TET compared to the expected certification trial performance and results in a significant failure.

3) Implications of the Phase 1 model sensitivity study to the certification trial protocol.

a. The use of a single evacuation trial, as required in the current evacuation certification protocol, is unlikely to be sufficient to characterise the airplane evacuation performance.

b. The use of a single population satisfying the current demographic, is unlikely to be sufficient to characterise the airplane evacuation performance.

c. The exit availability currently used in the evacuation certification protocol (one exit from each exit pair, e.g., 1L, 2L, 3L and 4L), is the most conducive to producing short evacuation times. Other combinations of 50% of the available exits, that result in the same mix of exit types, and are likely to occur in accidents, will result in longer evacuation times.

d. If passengers select their nearest exit, as is typical in accident scenarios, this will result in longer evacuation times than will be achieved if passengers utilise optimal exits under the guidance of cabin crew direction.

4) Other factors that could impact evacuation performance in the certification trial protocol, but not explicitly examined in Phase 1.

a. Including additional elderly passengers and/or disabled passengers who can move unaided.

b. Adverse cabin orientation due to partial collapse of landing gear.

c. Cabin crew fatigue (or sleepiness) during emergency evacuation.

d. Number of years of experience of cabin crew and the duration of time between the certification demonstration trial and the last recurrent training event for the crew.

e. Presence of social groupings amongst passengers.

These factors could potentially be included in evacuation modelling analysis, but additional data is required to quantify behaviours associated with each factor.

5) Phase 2: The proposed use of evacuation modelling to enhance airplane evacuation certification

Four options were proposed to enhance airplane evacuation certification. The first option proposed updating the nature of the certification demonstration trial so that it more closely reflects relevant accident scenarios without increasing the risk to trial participants or the cost of the trial (**Option 1**). The second option includes a number of additional evacuation scenarios to the certification requirement that could be explored using appropriate aircraft evacuation models. The proposed approach is similar in concept to the approach adopted by the IMO for the evacuation certification of passenger ships sailing in international waters. Using this approach, each of the proposed certification scenarios (i.e., certification demonstration trial and simulation scenarios) would need to satisfy the 90 s requirement (**Option 2**). The third option provides a means of assessing the evacuation performance of the airplane using a weighted sum of certification demonstration trials and model-based certification scenarios (**Option 3).** While not strictly within the scope of the current project, a fourth option was proposed to update the ASET currently imposed in the 14 CFR 25.803 evacuation protocol, i.e., the 90 s requirement (**Option 4**).

6) Option 2: Examples of proposed additional Certification Model Scenarios (CMSs).
A Certification Model Scenario (CMS) selected for inclusion in the enhanced certification protocol should provide important additional information not currently captured by the current certification trial. In addition, the CMS should provide additional insight into how the airplane is likely to perform in scenarios that are more representative of accident situations than the current certification demonstration trial scenario. Based on the Phase 1 model sensitivity study, several suitable candidate CMSs are suggested for consideration:

- **CMS1 (one exit from each exit pair, optimal passenger exit selection):** This scenario expands on the certification demonstration trial result due to the number of times the scenario is repeated and the use of different populations satisfying the current population demographics specified in 14 CFR 25.803.
- **CMS2 (accident exit availability, optimal passenger exit selection):** This scenario is intended to explore the impact of exit availability commonly occurring in accidents for the airplane type being certified while maintaining only 50% exit availability.
- **CMS3 (one exit from each exit pair, nearest-exit passenger exit selection):** This scenario is the equivalent of CMS1 but where passengers make use of their nearest exit, rather than optimal exits. This scenario utilises passenger exit selection typical of behaviour observed in accidents.
- **CMS4 (accident exit availability, nearest-exit passenger exit selection):** This scenario is the equivalent of CMS2 but where passengers make use of their nearest exit, rather than optimal exits. This utilises passenger exit selection typical of behaviour observed in accidents.

It is suggested that these four CMSs form the core scenarios that could be considered for inclusion in the enhanced certification protocol. Additional CMSs that could be considered but may be challenging given that further model development (and validation/verification) may be required, and additional data may be required to specify some of the necessary parameters. Three additional CMSs were suggested: CMS5 (luggage retrieval based on [16]), CMS6 (modified population demographic, including disabled passengers), and CMS7 (adverse cabin orientation).

The number and type of CMSs eventually included in the proposed enhanced certification protocol should ideally be decided by the regulator in consultation with stakeholders. Furthermore, the number of CMSs introduced into the enhanced certification process may be small initially, with the number and scope of CMSs introduced being expanded as confidence in the proposed enhanced protocol is established. For example, initially, only one CMS may be adopted, for which there is the greatest confidence in the veracity of the modelling predictions and similarity to the current demonstration certification scenario, e.g., CMS1. As confidence in the enhanced certification protocol grows, additional CMSs could be introduced into the analysis.

7) Option 3: The proposed weighted sum approach
The weighted sum approach enables the regulator to weight the relative importance of the traditional certification demonstration trial result (TET_{trial}) compared to the result derived from the modelling analysis (TET_{CMS}) and furthermore, weight the relative importance of the results from the

individual CMSs (TET_{CMS1}, TET_{CMS2}, TET_{CMS3}, ….) in determining the overall result from the modelling analysis (TET_{CMS}).

In this approach, two sets of weights are required: one set to distinguish between the relative importance of the experimental trial result (i.e. W1) and the TET determined from the CMSs (i.e., W2). Another set of weights is required to rank the importance of each of the proposed CMSs, i.e., the weight associated with CMS1 is MW1, CMS2 is MW2, etc. In both cases, the larger the weight, the greater the relative importance of the TET associated with the weight. Furthermore, so that the definitive certification TET for the airplane, i.e., TET_{cert}, is representative of the individual component TETs, i.e., TET_{trial}, TET_{CMS1}, TET_{CMS2}, etc., the sum of each set of weights should be 1.0 (see Equation 1).

$$W1 + W2 = 1.0, \text{ and } MW1 + MW2 + MW3 + \ldots\ldots = 1.0 \tag{1}$$

Using this two-layered weighted sum approach, the combined TET representing the definitive TET for the airplane, i.e., TET_{cert}, is given by Equation (2).

$$TET_{cert} = W1 * TET_{trial} + W2 * TET_{CMS} \tag{2}$$

where TET_{CMS} is given by Equation (3).

$$TET_{CMS} = MW1 * TET_{CMS1} + MW2 * TET_{CMS2} + MW3 * TET_{CMS3} + \ldots\ldots\ldots \tag{3}$$

For the airplane configuration to be considered to have satisfied the certification requirement, not every CMS would need to satisfy the requirement, but it would be necessary to demonstrate that

$$TET_{trial} < 90 \text{ s, and } TET_{cert} < 90 \text{ s} \tag{4}$$

It is proposed that the regulatory authority would define a set of definitive weights reflecting the importance and confidence the industry has in the model predictions for the various CMSs and would be specified as part of the certification protocol.

The challenge in the weighted sum approach is to select a meaningful distribution of weights that reflects the importance of the CMS to the certification process and regulator and stakeholder confidence in the ability of the airplane evacuation models to accurately simulate airplane evacuation in the identified scenarios. To a certain extent, the selected weight distribution will be a measure of the regulator's confidence in the quality of the model validation presented and the relevance of the verification test cases. A rationale is presented to guide the setting of the weights.

Enhancing the certification process through evacuation modelling using the weighted sum approach addresses several challenging issues:
1) It maintains the importance and influence of the standard demonstration certification trial.
2) It provides a means of introducing additional challenging and relevant accident scenarios into the certification process without increasing the risk to participants.
3) It provides the regulatory authorities with a means of gradually phasing in the use of evacuation modelling into certification.
4) The specific modelling scenarios and associated weights used in the enhanced evacuation protocol can be reviewed by the regulatory authority and updated as appropriate.
5) It continues to provide a consistent means to compare the performance of one airplane configuration with another.

6) The certification modelling scenarios can be used by airplane manufacturers as part of the design process to derisk proposed airplane designs by ensuring that they are able to satisfy the modelling component of the enhanced evacuation certification protocol at the early design stage.

8) Other aspects related to the proposed enhanced evacuation certification protocol
The proposed use of agent-based evacuation models to enhance the current airplane evacuation certification protocol will require additional processes and parameters to be set by the regulator. These are necessary to ensure a consistent application of the proposed protocol and to ensure the quality of the required analysis. The specification of these requirements is informed by common practice in the building and maritime industries, which routinely use evacuation modelling as part of the regulatory certification process. In particular, the proposed approach follows the principles adopted by the maritime industry, as outlined in IMO MSC.1/Cir. 1533 (2016). In addition to specifying the CMSs that need to be simulated (see (6), as well as the pass/fail criteria (see (7)), this involves specifying:

- the quantification of the relevant parameters to be used in the modelling,
- the number of repeat simulations and how the evacuation time is selected from the distribution produced by the repeat simulations, and
- quality control requirements for the software and analysis and reporting of results.

How each of these requirements could be applied to aviation applications was explored, and a way forward is proposed. Clearly, each aspect requires further discussion with stakeholders, including the regulatory authorities, the manufacturers, the airlines, unions, professional bodies, etc.

9) Quality Control
As part of the proposed enhanced evacuation certification protocol, it is essential that measures are put in place to ensure the quality of the evacuation modelling analysis and the presentation of the results of the analysis. A suggested process is discussed in the report and summarised as follows:

- **Evacuation Models.**

It is important that appropriate evacuation models are used that can address the specific issues associated with airplane evacuation. Given the range of evacuation models available, it is essential that as part of the enhanced evacuation certification process, the models used are thoroughly described with appropriate evidence provided to demonstrate that they are capable of reliably simulating the proposed CMSs and supporting the evidence provided of relevant validation and verification.

- **Validation.**

Before airplane evacuation models can reliably be used for certification applications, it is essential that they undergo a range of validation demonstrations. Data from the 14 CFR 25.803 demonstration certification trials, if available, are a good source of validation data for aircraft evacuation models. Another potential source of data for aircraft model validation is real accidents, if sufficient detailed information has been collected from the incident. As part of the proposed enhanced certification process, it is recommended that aviation regulators develop a database of appropriate airplane validation test cases, preferably based on previous actual 14 CFR 25.803 demonstration trials.

- **Verification.**

Given that validation data for airplane evacuation models are not readily available, in addition to providing evidence of validation, it is recommended that a series of verification cases be defined as part of the enhanced evacuation certification protocol. This is similar to the requirements set out in the IMO evacuation protocol guidance [44]. A series of eight potential verification cases is suggested for consideration as part of the enhanced evacuation certification protocol.

- **Documentation.**

It is recommended that the documentation supporting a modelling evacuation analysis should include the following documents:

(1) **Certification Analysis Report:** A report describing the analysis for the airplane configuration undergoing the certification process should be submitted to the regulatory authority. The results for the CMSs should be provided, including a detailed description of the model, assumptions imposed on the simulations, and the data used to specify the scenarios. In addition, the exit curves for each CMS should be provided, along with the exit curve for the certification demonstration trial. The trial exit curve should be compared with the exit curves produced by the CMS most closely resembling the certification demonstration trial (see, for example, the analysis presented in [14]) as a form of validation. The calculations to determine TET_{CERT} and TET_{CMS} should be provided. The input and output files for each of the CMSs should be provided and available for independent verification.

(2) **Results of the Verification Cases:** The results for the verification test cases should be provided as an appendix to the Certification Analysis Report or as an appendix in the user guide of the airplane evacuation simulation software. The input files required to generate the verification cases and the associated output files should be provided and available for independent verification.

(3) **Evidence of Validation:** Evidence of relevant rigorous software validation should be provided, such as peer-reviewed publications or project reports.

(4) **Software User Guide:** 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.

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List of Abbreviations

Acronym	Abbreviation Explained
ASET (s)	Available Safe Egress Time, measured in seconds
BWB	Blended Wing Body
CAMI	Civil Aerospace Medical Institute
CC	Cabin Crew (also known as Flight Attendants)
CFD	Computational Fluid Dynamics
CFRP	Carbon fibre-reinforced polymer
CMS	Certification Modelling Scenario
CO	Chemical composition of Carbon Monoxide
CWT (s)	airEXODUS predicted parameter, Cumulative Wait Time incurred by an agent, measured in seconds
CHC	Chickasaw Health Consulting
DT (m)	airEXODUS predicted parameter, Distance Travelled by an agent from seat to exit point, measured in meters
FAA	Federal Aviation Administration
FDC	Flight Deck Crew
FED	Fractional Effective Dose
FSEG	Fire Safety Engineering Group
HCL	Chemical composition of Hydrogen Chloride
HCN	Chemical composition of Hydrogen Cyanide
IMO	International Maritime Organization
LOPA	Layout of Passenger Accommodation, An engineering diagram (CAD) of the aircraft's cabin interior that includes, locations of PAX and CC seats, emergency equipment, exits, lavatories, and galleys
MCA	Marine and Coastguard Agency
MWi	Weight associated with the importance of the TET derived from CMSi
NYC	New York City
OG	On Ground
OPS	airEXODUS parameter, Optimal Performance Statistic, measure of evacuation efficiency, dimensionless parameter (see Equation 1)

OOA	Out Of Aircraft
PAX	Passenger
PEDT (s)	airEXODUS parameter, Passenger Exit Delay Time, measured in seconds
PET (s)	airEXODUS predicted parameter, Personal Evacuation Time, time for agent to exit the aircraft, measured from start of the simulation to the time they exit, measured in seconds
PPM	People Per Minute
RSET (s)	Required Safe Egress Time
TET (s)	airEXODUS predicted parameter, Total Evacuation Time, time for the last agent to exit the aircraft, measured in seconds
UOG	University of Greenwich
W1	Weight associated with the importance of the TET derived from the certification demonstration trial
W2	Weight associated with the importance of the TET derived from the combined CMSs

1. Motivation

The Federal Aviation Administration (FAA) Policy and Standards Division (AIR-600) needs to address limitations in existing policy and guidance so the FAA and industry can more efficiently certify aircraft components.

One area of focus is aircraft evacuation certification. Before an airplane can be licensed to carry passengers on commercial flights, the manufacturer must demonstrate that their airplane design can meet the evacuation requirements of 14 CFR 25.803, commonly referred to as the 90-second certification test. Since the certification requirements use a single test, parameters that could significantly affect evacuation time are not fully understood or fully captured. One proposed method of addressing these limitations is to include simulated evacuation data in the certification process.

This research will support the FAA and industry in making informed aircraft certification decisions for evacuations when modelling and simulation data are submitted. This research report can be used to support the development of an FAA framework that allows analysis to be directly used in certifying new products.

This research report examines the effect of three different parameters (exit availability, crew assertiveness at exits, and passenger exit-selection behaviour) on evacuation performance for a baseline fuselage design. This research report also discusses best practices for developing models and simulating aircraft evacuation and outlines procedures that regulators could adopt to improve evacuation certification efficiency and accuracy.

2. Introduction

This document represents the final report for the research project [1] resulting from a request for proposal (RFP) from Chickasaw Health Consulting (CHC) on behalf of FAA CAMI [2] concerning the expanded use of modelling and simulation for evacuation certification as described in the FAA statement of work (SOW) [3]. The research, undertaken by the Fire Safety Engineering Group (FSEG) of the University of Greenwich (UoG), commenced on 1 February 2024. The project consisted of two phases and involved an analysis, using the state-of-the-art airEXODUS evacuation simulation software [4-16], to:

(a) **Phase 1:** Undertake a sensitivity study examining the impact of various parameters on the rapid evacuation of a transport category aircraft. Based on findings from the sensitivity study, make recommendations on how to evaluate simulation data produced by aircraft evacuation simulation software.
(b) **Phase 2:** Make recommendations on how evacuation simulation data may be used to support and enhance the current evacuation certification process as described in 14 CFR 25.803(c) [23].

Due to project timescales and budgetary constraints, it was not possible to explore multiple aircraft configurations and multiple evacuation scenarios, so a representative aircraft configuration and a reduced set of evacuation scenarios (five) were selected for analysis with CAMI agreement [1]. The aircraft configuration consisted of a single-aisle narrow-body aircraft configuration typical of the popular B737/A320 models, which was also used in the earlier analysis conducted for CAMI concerning the impact of passenger luggage retrieval during evacuation [16]. The aircraft seats 180 passengers (PAXs), with three cabin crew (CC) and two flight deck crew (FDC), resulting in 185 people on board. The available exits on the aircraft consist of two pairs of Type C exits (one pair located forward and one pair located aft) and two pairs of Type-III (overwing) exits [1,16]. The evacuation scenarios that were agreed upon for investigation involved variations in passenger population, exit availability, passenger exit-selection behaviour (i.e., nearest exit or optimal exit), and assertiveness of crew at exits [1].

As part of Phase 1, a total of five evacuation scenarios were examined as described in the research proposal [1]:

(1) **Scenario 1, Base Case:** This consists of the certification configuration (50% of the available exits all on one side of the aircraft), assertive behaviour of crew at exits, and certification-compliant exit opening times with optimal passenger exit-selection behaviour. The impact of 1000 different populations, satisfying the certification requirements, is explored.
(2) **Scenario 2, Sensitivity Case 1 – Exit availability:** This consists of two forward exits and two overwing exits on one side available, cabin crew and passenger behaviour as in Scenario 1 (Base Case). This scenario is repeated 1000 times with 1000 different populations, as in Scenario 1.
(3) **Scenario 3, Sensitivity Case 2 –** Crew assertiveness at exits: The scenario is configured as Scenario 1 (Base Case) or Scenario 2 with the exception of the crew assertiveness at the exits. This scenario is repeated 1000 times with 1000 different populations, as in Scenario 1 and Scenario 2. This scenario consists of two different cases, as follows:

(a) **Scenario 3a:** 0% assertive crew, setup as in Scenario 1: cabin crew at forward and aft Type C exits utilise the ‘in-between’ cabin crew assertive behaviour.
(b) **Scenario 3b:** 0% assertive crew, setup as in Scenario 2: cabin crew at the two forward Type C exits utilise the ‘in-between’ cabin crew assertiveness behaviour.
(4) **Scenario 4, Sensitivity Case 3 – Passenger exit-selection behaviour:** The scenario is configured as Scenario 1 (Base Case) with the exception of the passenger exit-selection behaviour. In this case, passengers will select their nearest exit. This scenario is repeated 1000 times with 1000 different populations, as in Scenario 1.

Furthermore, an additional scenario is considered for the sensitivity analysis that was undertaken as part of an earlier modelling study to investigate the impact of passenger retrieval of cabin luggage on evacuation performance [16]. This scenario is the equivalent of Scenario 2, but passengers attempt to utilise their nearest exit (as in Scenario 4), effectively not responding to cabin crew commands to redirect to optimally utilise available exits.

Based on findings from the sensitivity study conducted in Phase 1, Phase 2 will explore and recommend how evacuation simulations may be used to support and enhance the current evacuation certification process as described in 14 CFR 25.803 [23].

The structure of this report consists of the following sections:

- **Section 2, Project Assumptions:** the key project assumptions, including the nature of the inherent airEXODUS modelling assumptions, are presented.
- **Section 3, Phase 1, Evacuation Scenarios:** the evacuation scenarios explored as part of Phase 1 are described.
- **Section 4, Phase 1, Interpreting Simulation Results:** key simulation parameters are identified and described.
- **Section 5, Phase 1, Scenario 1, Base Case, Results, and Analysis:** the aircraft configuration employed in the analysis, along with modelling parameters used to represent the geometry, including results for the Base Case scenario.
- **Section 6, Phase 1, Scenario 2, Sensitivity Case 1 – Exit Availability, Results, and Analysis:** The results and analysis for Scenario 2 are presented and discussed.
- **Section 7, Phase 1, Scenario 3, Sensitivity Case 2 – Crew Assertiveness, Results, and Analysis:** The results and analysis for Scenarios 3a and 3b are presented and discussed.
- **Section 8, Phase 1, Scenario 4, Sensitivity Case 3 – Passenger Exit Selection Behaviour, Results, and Analysis:** The results and analysis for Scenario 4 are presented and discussed.
- **Section 9, Phase 1, Discussion:** The results from all five scenarios are reviewed, and key findings are discussed.
- **Section 10, Phase 2, Use of Evacuation Modelling to Enhance Certification:** A methodology describing the combined use of data from the current evacuation demonstration certification trial and evacuation modelling to enhance the certification process are presented.
- **Section 11, Project Limitations:** Key limitations in the modelling are presented and discussed.

- **Section 12, Recommendations for Additional Analysis and Data to Assist the Regulatory Process:** Recommendations for data and additional model analysis are presented.
- **Section 13, Concluding Comments:** The key findings are summarised.
- **Section 14, References:** References cited in the work are presented.
- **Annexes:** Annexes referenced in the main report are presented.

3. Project Assumptions

Many of the key project assumptions and simplifications are related to assumptions inherent in the airEXODUS software and are associated with how human behaviour during aircraft evacuation is represented within the modelling environment. Thus, in this section, the airEXODUS software is briefly described, along with the inherent assumptions incorporated into the software, together with key project assumptions related to the project proposal and SOW [1,2,3].

3.1. The Evacuation Simulation Software

The simulations were undertaken using the agent-based aircraft evacuation simulation software airEXODUS [4-17]. EXODUS is a suite of software tools developed by FSEG and designed to simulate the evacuation of large numbers of individuals from complex spaces. The EXODUS family of evacuation models currently consists of airEXODUS, maritimeEXODUS, buildingEXODUS, railEXODUS, matEXODUS, and urbanEXODUS. The airEXODUS variant is designed for applications in the aviation industry, including aircraft design, assessment of aircraft evacuation capabilities, compliance with evacuation certification requirements, crew training, development of crew procedures, resolution of operational issues and accident investigation. This state-of-the-art software was developed with support from the UK CAA and has undergone a number of validation exercises to demonstrate its ability to reproduce certification evacuation trials [14] and verification demonstrations to forensically explore real accident scenarios, such as the analysis of the Manchester Airport B737 fatal fire [4].

Application projects include design applications for aircraft manufacturers of large passenger aircraft such as the A380, A340-600, and JetZero BWB; concept projects for manufacturers, e.g., Airbus BWB [5,7]; projects for operators assessing modifications to cabin layout, such as B777 variants; design of regional aircraft for Bombardier and Mitsubishi, e.g., Dash 8-400, RJ, and MRJ; and specialist evacuation analysis projects for aviation companies, such as Jet Aviation, Zodiac, PEMCO, and Pt21, on aircraft ranging from B737 to VIP B747.

The software has been described many times in the literature, so it is only briefly described here, with further details presented in Annex 1.

The EXODUS suite of software takes into consideration people–people, people–fire, and people–structure interactions. It comprises five core interacting sub-models: the **Passenger, Movement, Behaviour, Toxicity, and Hazard** sub-models (see Annex 1 Figure 27). The software describing these sub-models is rule-based, with the progressive motion and behaviour of each individual being determined by a set of heuristics or rules. These sub-models operate on a region of space defined by the **GEOMETRY** of the enclosure. The model tracks the trajectory of each individual as they make their way out through the geometry or are overcome by fire hazards such as heat, smoke, and toxic gases.

The airEXODUS software is stochastic in nature, as certain behaviour rules, e.g., conflict resolution, personal attributes, e.g., response time, and model parameters, e.g., passenger exit delay times (PEDT), are probabilistic in nature. Thus, the model will not produce identical results if a simulation is repeated. Furthermore, if the population demographics are modified or a specific population is given a different seating allocation, the simulation will produce different results. In studying a particular evacuation scenario, it is thus necessary to repeat the simulation a number of times in order to produce a distribution of results. As a result, each scenario investigated is repeated 1000 times, resulting in the distribution of evacuation times and evacuation performance results. Each repeat simulation is performed with a different population, satisfying the requirements of the specified population distribution.

The simulations were performed and analysed following standard workflow procedures developed by FSEG for the analysis of simulation results [18]. As a scenario is repeated 1000 times, key simulation data relate to the simulations producing the minimum, maximum, median, and 95th percentile total evacuation times (TETs) for a scenario. The interpretation of model parameters and model results is further described in Section 4.

3.2. Aircraft Configuration

The aircraft configuration consisted of a single-aisle narrow-body aircraft configuration typical of the popular B737/A320 models, which was also used in the earlier analysis conducted for CAMI concerning the impact of passenger luggage retrieval during evacuation [16]. The aircraft seats 180 PAXs, with three CC and two FDC, resulting in 185 people on board. The available exits on the aircraft consist of two pairs of Type C exits (one pair located forward and one pair located aft) and two pairs of Type-III (overwing) exits [1,16]. As FSEG already possessed this aircraft from the previous project [16], the DXF file defining the structure of the aircraft had already been imported into airEXODUS, and the overall nodal structure was fully built and tested. The basic model geometry was constructed following standard workflow procedures developed by FSEG for the construction of aircraft models [18].

Presented in Figure 1 is the cabin layout constructed in the airEXODUS software. The geometry consists of two pairs of Type C exits (i.e., 1L/1R and 4L/4R) and two pairs of overwing Type-III exits (i.e., 2L/2R and 3L/3R).

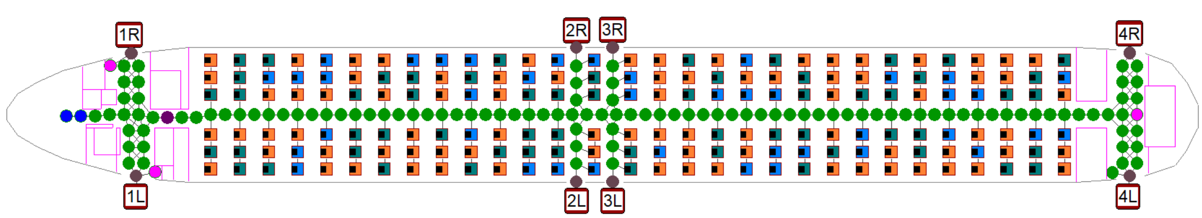


Figure 1
Cabin layout of the aircraft depicting passenger cabin as represented within airEXODUS showing the passenger seat locations, nodal structure throughout the cabin, and location of the eight exits.

.

= cabin crew seating location, = flight crew starting location, = passenger seats

The initial seating location for the CC is assumed to be beside the Type C exits, with two CC located at the front and one at the rear of the cabin. The FDC are also included in the analysis and are assumed to evacuate the aircraft as passengers.

3.3. Passenger Population

The passenger population is constructed by airEXODUS and complies with the population distribution typically used in the industry standard 90-second population distribution as specified in 14 CFR 25.803 [23] (referred to as target population). See Table 1 for gender and age breakdown and response time range.

(a) A single target population is used for all simulations.
(b) The target population begins each simulation from within the configuration specified in Figure 1. Each member of the population initially occupies a seat.
(c) The target population consists entirely of non-connected individuals (i.e., family groups are not considered).
(d) The population consists of agents with differing movement capabilities to reflect differing age groupings, ability levels, and response times.
(e) A different population mix (satisfying the description of the target population) is generated for each of the 1000 repeat simulations.

Table 1
Gender, age distribution, and response time for the 90-second population used in simulations.

Group (ages)	%	Response Time Range Min – Max (s)
Males 18-50	40	0.0 – 5.0
Males 50-60	20	4.0 – 7.0
Females 18-50	25	0.0 – 6.0
Females 50-60	15	5.0 – 8.0

3.4. Hazard Analysis

The simulations do not involve the airEXODUS capabilities to represent smoke, toxic gases, and heat. Furthermore, it is assumed that the orientation of the aircraft will not impact the movement or behaviour of the passengers. Thus, the simulations do not take into consideration the impact of adverse orientation or the potential impact of dynamic motion (in a ditching). The simulation thus represents ideal evacuation conditions assuming the aircraft is stationary and on its landing gear. The simulations also do not take into consideration cabin debris.

3.5. airEXODUS Simulation Parameters

To perform each simulation, a variety of data is required. This includes (a) exit ready times, (b) passenger exit delay times, (c) off-times, (d) passenger response times, and (d) passenger exit-selection behaviour.

(a) Exit Ready Times: This is a non-predicted parameter specified by the user as part of the scenario specification for each exit used during the evacuation. It is a measure of the time required to make the exit ready for evacuation use and is measured from the start of the evacuation process (and so incorporates CC response time) to the endpoint where the exit is made ready for use. For crew-operated exits, it represents the time from the start of the evacuation process to the point where the crew has opened the exit and made ready any evacuation assist means, e.g., a slide. For passenger-operated exits, it represents the time from the start of the evacuation process to the point where the passenger has opened the exit and made the exit ready, usually by discarding the exit for Type-III exits (for older-design Type-III exits).

The exit ready times for all the exits are the times derived from the FSEG analysis of previous certification trials [17, 19]. This represents the time from the start of the trial to the point where the exit is opened and ready for use. For the Type C exits, the exit ready time is set to 8.1 s. This value corresponds to the mean exit ready time of Type C exits derived from the certification trials for the B737-300 (2 exits), B737-400 (2 exits), B757 (2 exits), and B757-OW (2 exits). For the Type-III exits, the exit ready time is set to 11.6 s. This value corresponds to the mean exit ready time of Type C exits derived from the certification trials for the A320 (2 exits), B757-OW (2 exits), B767-200 (1 exit), B767-346 (2 exits), DC9-50 (2 exits), and DC9-80 (1 exit). The characteristics of the exits are summarised in Table 2.

Table 2
Exit Characteristics

Location	Type	Width	Passenger Exit Hesitation Time	Exit Ready Times (s)
L1	Type C FWRD Entry	0.86m (34”)	Assume Assertive/In-between Crew: Distribution from certification data for Type C assertive/in-between.	Time selected from certification data for Type C exits. 8.1 s
R1, L4, R4	Type C Galley SVC	0.76m (30”)	Assume Assertive/In-between Crew: Distribution from certification data for Type C assertive/in-between.	Time selected from certification data for Type C exits. 8.1 s
L2, R2, L3, R3	Type-III	0.52m (20”)	Unstaffed exit: Distribution from certification data for Type-III unstaffed.	Time selected from certification data for Type-III exits. 11.6 s

(b) Passenger Exit Delay Times: This is a non-predicted parameter specified by the user as part of the scenario specification for each exit used during the evacuation. The Passenger Exit Delay

Time (PEDT) is one the most important parameters in airEXODUS, as it makes a significant contribution to the flow performance for the exit. 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 the exit. Typically, this starts when an outstretched hand first touches the exit. The exit negotiation time represents the amount of time taken to pass through the exit. Within airEXODUS, each passenger is randomly assigned a delay time as they pass through the exit. The delay time is assigned using a frequency distribution the values of which are specified from analysis of actual evacuation certification demonstrations or full-scale experimentation. The delay time is dependent upon a number of factors. The following list represents the most prevalent of these factors:

(1) exit type – the exit type (thus size) causes different kinds of exiting techniques for each exit type; for example, passengers tend to crouch and climb out of Type-III exits and jump out of Type C exits.
(2) exiting behaviour – different behaviour traits may be exhibited by different passengers, even on the same exit type. For example, some passengers jump through Type C exits, whereas others sit on the sill and push off.
(3) passenger physical attributes – the gender, age, and physical size of the passengers have also been found to have an impact on the hesitation time. However, there are currently insufficient data available to perform a meaningful analysis on all exit types.
(4) presence of cabin crew – the presence (or absence) of cabin crew at exits can enormously influence the behaviour exhibited by passengers at exits. Undirected passengers tend to take more time deciding how to use the exit and indeed, which exit to use.
(5) behaviour of cabin crew – when cabin crew are present at an exit, the degree of assertiveness they display also influences the hesitation times. As the level of assertiveness increases, the range of slower hesitation times decreases, thus increasing the overall flow throughput of the exit.
(6) Passengers carrying luggage – passengers carrying luggage may significantly influence passenger exiting behaviour, typically slowing them down.

The data used in this analysis correspond to PEDT distributions appropriate for crewed Type C exits and Type-III exits without crew assistance, derived from full-scale certification trials [17, 19]. Furthermore, in this analysis, it is assumed that passengers do not carry luggage to exits.

The airEXODUS software has a range of PEDT distributions derived from certification videos that are specific to exit type (e.g. Type C, Type A, Type-III) and level of crew assertiveness. For some crew-operated exits, PEDT distributions for assertive crew, unassertive crew, and crew who are neither assertive nor unassertive (defined as ‘in-between’) have been defined based on the available certification data. The in-between crew performance represents crew behaviour that can be defined as being assertive for much of the time during the evacuation, as well as periods of performance that can be described as unassertive. Thus, in-between crew are not working to their full potential throughout the evacuation, which may impact exit flow rate performance.

Typically, for simulations intended for certification applications, the assertive PEDT distribution is utilised. However, the reduced-assertiveness PEDT distributions can be used to represent crew at exits not working to their peak ability. This could be postulated to be a proxy for poorly trained crew or possibly fatigued crew; however, for the latter, it is not clear how significant the reduction in performance of fatigued crew is likely to be or if fatigue even impacts crew assertiveness at exits during emergencies (see discussion in Section 10.1(iv) and 10.4(i)b). Within the FSEG database, PEDT data for Type C exits are only available for assertive and in-between crew [17, 19].

The PEDT distribution used in the simulations for the Type C exits with assertive crew (see Annex 2) is based on video analysis of certification tests involving four aircraft, 6 Type C exits, and data from 355 passengers [17, 19]. The aircraft involved in the certification tests were B737-300 (1 exit), B737-400 (1 exit), B757 (2 exits), and B757-OW (2 exits).

The PEDT distribution used in the simulations for the Type C exits with in-between crew (see Annex 2) is based on video analysis of certification tests involving two aircraft, 2 Type C exits, and data from 123 passengers [17, 19]. The aircraft involved in the certification tests were B737-300 (1 exit) and B737-400 (1 exit).

The two PEDT distributions (see Annex 2) are similar, with both distributions having minimum values between 0.1 s and 0.2 s; however, the ‘assertive’ distribution has a smaller median PEDT of between 0.2 s and 0.3 s, while the ‘in-between’ distribution has a slightly larger median PEDT of between 0.3 s and 0.4 s. As a result, there is more of a chance of a passenger being given a smaller PEDT when using the ‘assertive’ distribution. Thus, the ‘in-between’ PEDT distribution is slightly biased towards larger PEDT.

The PEDT distribution used in the simulations for the Type-III exits is based on video analysis of certification tests involving seven aircraft, 12 Type-III exits, and data from 417 passengers [17, 19]. The aircraft involved in the certification tests were A320 (2 exits), B737-300 (1 exit), B737-400 (2 exits), B757-OW (2 exits), B767-200 (1 exit), B767-346 (2 exits), and DC9-80 (2 exits). The minimum hesitation time is 0.3 sec and the maximum is 5.4 sec (see Figure 2).

Figure 2

PAX exit hesitation time distribution for Type-III exits; values are in seconds (s).

Min	Max	Prob
0.300	0.400	0.002
0.400	0.500	0.007
0.500	0.600	0.017
0.600	0.700	0.026
0.700	0.800	0.057
0.800	0.900	0.072
0.900	1.000	0.081
1.000	1.100	0.074
1.100	1.200	0.072
1.200	1.300	0.053
1.300	1.400	0.069
1.400	1.500	0.074
1.500	1.600	0.084
1.600	1.800	0.104
1.800	2.000	0.074
2.000	2.100	0.026
2.100	2.200	0.024
2.200	2.300	0.021
2.300	2.400	0.007
2.400	2.500	0.005
2.500	2.600	0.004
2.600	3.700	0.033
3.700	4.200	0.010
4.200	5.400	0.004

(a) The Off-Time: Also referred to as slide-time, this is a non-predicted parameter specified by the user as part of the scenario specification for each exit used during the evacuation. The off-time is taken as the time between leaving the exit (typically touching the slide or clearing the exit) and the time at which the PAX is considered to be off the aircraft (typically touching the ground or passing some defined endpoint). For Type C exits, the process of passing through the exit and travelling to the ground can occur simultaneously, i.e., it is possible to have passengers passing through the exit and to have several passengers on the slide simultaneously. The off-time is assigned using a frequency distribution, the values of which are specified from analysis of actual evacuation certification demonstrations or full-scale experimentation [17, 19]. However, as stated in the proposal [1], the analysis presented in this report will not involve off-time, so only Out Of Aircraft (OOA) times are reported, i.e., on-ground times will not be predicted as part of this analysis.

(b) Passenger Response Times: The response time is a measure of the time from the call to evacuate to the time that the passenger has released their seat belt and is standing ready to commence their evacuation. The passengers defined in airEXODUS were 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 14 CFR 25.803 [23]. In airEXODUS, simply specifying the age and gender of each passenger is not sufficient. The population tools in airEXODUS allow a range for the response time attribute to be specified, so that when a person is created, the response time attribute is assigned a random value between the limits set (see Table 1).

The response time for crew is described in Section 3.2.

(c) Passenger Exit-Selection Behaviour: Passenger exit-selection behaviour involves passengers preferentially selecting either their nearest (based on travel distance) available functioning exit or their optimal exit (based on minimised TET). The specific behaviour implemented is scenario-dependent (see Section 3). However, if there is excessive congestion at an exit, passengers may abandon their preferred exit and seek another exit.

3.6. Exit availability

In all the scenarios, the available exits involve 50% of the normally available exits. The specific exits that are available are scenario-dependent (see Section 3).

3.7. Exit flows

The simulated airplane is equipped with four Type C exits (two at the front, two at the rear) and four overwing Type-III exits—a pair on the port side and another pair on the starboard side. The spatial representation of the aircraft model (i.e., the space that the agents can use and represented using the nodal structure is depicted in Figure 1) in particular, in the vicinity of the exits, has undergone several iterations of modifications to ensure that exit flows achieved using the defined PEDT distributions (see Section 2.5b) are within the expected range of flows for the Type C exits with assertive crew and Type-III exits.

From past certification data [17, 19], FSEG has determined that the following exit flows are acceptable:

Type C exits with assertive crew: 53 people per minute (ppm) to 65 ppm with a mean of 61 ppm.
NOTE: Data for flow range for Type C exits are derived from certification data for four aircraft involving seven exits and 403 passengers; aircraft are B737-300 (2 exits), B737-400 (2 exits), B757 (1 exit), and B757-OW (2 exits).

Type-III exits without crew: 29 ppm to 43 ppm with a mean of 35 ppm.
NOTE: Data for flow range for Type-III exits are derived from certification data for six aircraft involving 10 exits and 347 passengers; aircraft are A320 (2 exits), B737-300 (1 exit), B737-400 (2 exits), B757-OW (2 exits), B767-200 (1 exit), and B767-346 (2 exits).

To test the flow that can be achieved by these exits within the model, all passengers were forced to use a single exit in turn to ensure a continuous flow of passengers and for the exits to reach saturation. As a result, four test cases were examined, one for each of the exits examined, i.e., L1, R1, L2, and L3 exits. For example, to determine the flow produced by the model for L1, all passengers were forced to exit the aircraft using this exit. This was then repeated 1000 times and repeated for each exit. The flows achieved during the test cases are listed in Table 3 and shown graphically in Figure 3, along with the certification data.

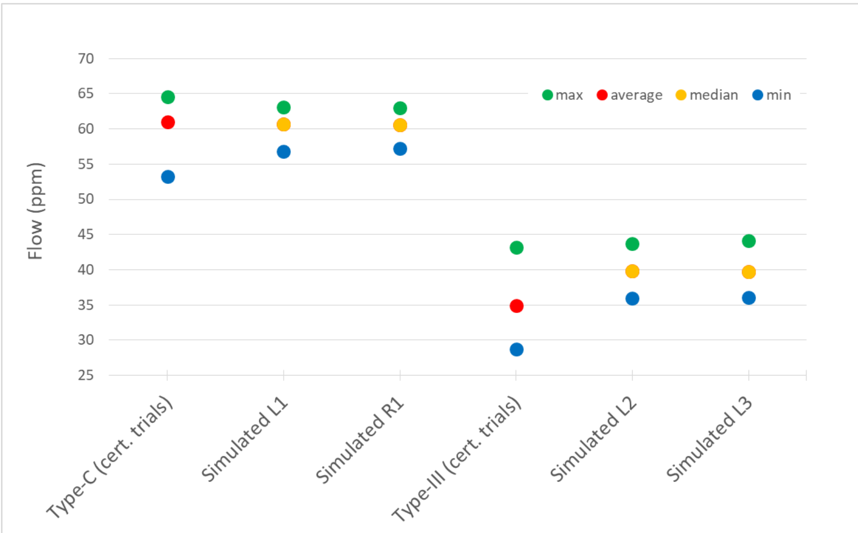
Table 3
Model-predicted exit flows (ppm) for Type C and Type-III exits compared with certification trial data

	Type C (cert. trials)	L1	R1	Type-III (cert. trials)	L2	L3
Min (ppm)	53.2	56.9	57.3	28.7	35.9	36.1
Average (ppm)	61	60.7	60.6	34.9	39.8	39.7
Median (ppm)	--	60.7	60.5	--	39.8	39.7
Max (ppm)	64.6	63.1	63.0	43.2	43.7	44.1

The results suggest that the model is producing acceptable flows for each exit, so the overall model is considered appropriate for use in the project, being capable of generating realistic evacuation results.

Figure 3

Model-predicted exit flows for Type C and Type-III exits compared with exit flows derived from certification trials



4. Phase 1: Evacuation Scenarios

The purpose of the selected evacuation scenarios is to undertake a sensitivity study examining the impact different parameters have on the rapid evacuation of a transport category aircraft. Clearly, there are a vast number of parameters that may influence evacuation performance that could be explored in this study and furthermore, influencing parameters may be dependent on aircraft type, i.e., narrow- or wide-body configurations. Exploring the entire problem space would require considerable time and resources, so in discussion with the CAMI and CHC [20], it was agreed that the sensitivity study should focus on one type of configuration— narrow body—and focus on three parameters [21, 22] as described in the research proposal [1], consisting of exit availability, passenger exit-selection behaviour (i.e., nearest exit or optimal exit), and assertiveness of crew at exits.

To demonstrate the sensitivity of the selected parameters, the evacuation performance for each scenario is compared with a Base Case consisting of a simulation configured to produce a standard certification evacuation analysis (as in the evacuation demonstration required by 14 CFR 25.803 [23]). However, unlike the standard evacuation demonstration trial, the Base Case scenario, by its very nature, demonstrates the impact of variability in passenger population specification on evacuation performance.

Each scenario is repeated 1000 times, producing a distribution of evacuation times and evacuation performance results. Each repeat simulation is performed with a different population satisfying the requirements specified in Section 2.3.

It is also important to note that the simulation scenarios represent ideal evacuation conditions i.e., assuming the aircraft is stationary, on its landing gear, there is no damage to the passenger cabin and all equipment functions as required.

4.1. The Scenario Specification

In all the scenarios, the available exits involve 50% of the normally available exits. In total, five evacuation scenarios were evaluated, with Scenario 3 having two variants. The five scenarios (Scenarios 1, 2, 3a, 3b, and 4) investigated are defined as follows:

(a) Scenario 1: Base Case – Standard certification analysis: This scenario is intended to be the computer simulation equivalent of the full-scale certification demonstration trial. This scenario involves one exit from each exit pair (all on one side), the exits are opened in certification-compliant times (see Section 2.5(a), Table 2), CC performing optimally at exits, i.e., assertively (see Section 2.5(b)), passengers selecting optimal exits (see Section 2.5(e)), and population demographics as specified in 14 CFR 25.803 [23] (see Section 2.3). This scenario provides a Base Case for comparison with the performance achieved in the other scenarios. It also demonstrates the impact of population variation on evacuation performance. The results for this scenario were reported in the interim report [24].

(b) Scenario 2: Sensitivity Case 1 – Exit availability: Essentially, this scenario involves the same setup as Scenario 1 (Base Case) but utilises a different combination of 50% of the available exits. For example, for the narrow-body aircraft configuration, possible exit combinations could involve (a) two forward exits and two of the overwing exits on one side or (b) two aft exits and two of the overwing exits on one side or (c) two overwing exit pairs or (d) two overwing exits on one side, one overwing exit on the other side and one forward exit, etc. Given budgetary constraints, only option (a) will be explored in this project. Furthermore, this combination of 50% of exits also maintains the mix of exit types as found in the certification demonstration trial, i.e., two Type C exits and two Type-III exits.

This combination of 50% of the normally available exits is of particular interest and importance as, unlike the exit combination used in the certification demonstration trial (i.e., one exit from each exit pair), it is consistent with a frequently occurring exit combination found in typical survivable accidents [10,11]. For this analysis, the configuration consists of the two forward (Type C) exits and the left two overwing (Type-III) exits.

Furthermore, this exit combination corresponds to the exit configuration explored in [16]; however, the case studied in this project will involve optimal-exit selection (see Section 2.5(e)) by passengers (note in [16], nearest-exit selection was incorporated). The importance of this scenario parameter on evacuation performance will be assessed through a comparison of simulation results with Scenario 1. The results for this scenario were reported in interim reports [25, 26].

(c) Scenario 3: Sensitivity Case 2 – Crew assertiveness at exits: Within the software, crew assertiveness at crew-operated exits (i.e., excluding Type-III exits) impacts the PEDT distribution, which in turn impacts exit flow. The software has a range of PEDT distributions derived from certification videos that are specific to exit type (e.g. Type C or Type A) and level of crew assertiveness (see Section 2.5(b)). Typically, for certification simulations, such as Scenario 1, the assertive data are utilised. Ideally, this scenario would have explored the impact of unassertive crew at the Type C exit; however, a reliable dataset based on certification data is not available for the Type C exit with unassertive CC. For this reason, in Scenario 3, the impact of in-between assertive crew behaviour will be explored.

As there are only two Type C exits in operation in the certification case, there are three possible combinations of assertiveness:
(a) 0% assertive crew, i.e., two in-between crew, one at each Type C exit,
(b) 50% assertive crew, i.e., one assertive crew, and one crew in-between, and
(c) 100% assertive crew, i.e., two assertive crew, one at each Type C exit (corresponding to Scenario 1).

The original design for this scenario involved two sub-cases, Scenario 3a (i.e., identified as case (a) above) and Scenario 3b (i.e., identified as case (b) above), with exit availability as in Scenario 1. However, the results for Scenario 3a demonstrated that there was little impact on evacuation times (see interim report [27]), so it was decided that there was no value in running Scenario 3b as originally specified. Thus, Scenario 3b was modified so that the exit availability corresponded to that of Scenario 2 (front two Type C exits and left pair of Type-III exits were available), and all the CC have in-between assertiveness. Thus, Scenario 3b incorporates changes to two parameters:

crew assertiveness and exit availability. The results for Scenario 3b were reported in the interim report [28].

The importance of this scenario parameter on evacuation performance is assessed through a comparison of simulation results for Scenario 3a with Scenario 1 and Scenario 3b with both Scenarios 1 and 2.

(d) Scenario 4: Sensitivity Case 3 – Passenger exit-selection behaviour: The two extremes of passenger exit-selection behaviour involve passengers selecting their near optimal exit (minimising the TET) and passengers selecting their nearest exit (resulting in longer, sub-optimal TET). In certification analysis, such as in Scenario 1, the evacuation simulation software is typically configured so that the passengers achieve near-optimal performance. This assumes that during a certification trial, crew are able to efficiently direct most passengers to their optimal exits. This is intended to represent the best possible performance that the aircraft, crew, and passengers can achieve. However, in actual accidents, this may not always be the case, and often, it is noted that a significant proportion of passengers utilise their nearest available exit [10, 11, 12]. Case 3 explores the impact of passengers attempting to exit using their nearest available functioning exit. This is a plausible and realistic scenario, as evidence from accident analysis suggests that passengers attempt to use their nearest exits [10,11]. In this scenario, passengers will be allowed to use their nearest exit, irrespective of whether the exit is in front or behind their seating location. All other model parameters defining this case will be identical to that of Scenario 1. The results for Scenario 4 were reported in the interim report [29].

The importance of this scenario parameter on evacuation performance is assessed through a comparison of simulation results for Scenario 4 with Scenario 1.

The five scenarios investigated are summarised in Table 4.

Table 4

Summary of the four basic scenarios and their respective settings

Scenario	Scenario Name	Exit Availability	CC Assertiveness	Passenger Exit Selection
1	Base Case*	1L,2L,3L,4L	Assertive	Optimal
2	Sensitivity Case 1	1L,1R,2L,3L	Assertive	Optimal
3a	Sensitivity Case 2a	1L,2L,3L,4L	In-between	Optimal
3b	Sensitivity Case 2b	1L,1R,2L,3L	In-between	Optimal
4	Sensitivity Case 3	1L,2L,3L,4L	Assertive	Nearest

It is important to note that the scenarios **DO NOT** include a CC-instigated cabin sweep prior to their evacuation. While airEXODUS has a capability to represent complex cabin sweep procedures (with CC being tasked to search allocated parts of the cabin prior to evacuating), for simplicity, this procedure has not been included in these simulations. This is primarily because there are many ways to implement the cabin sweep process, and these are often specified by the airline rather than the manufacturer. Thus, in all the scenarios analysed as part of this report, the CC evacuate as normal passengers at the appropriate time (i.e., once their area of responsibility is clear of passengers).

4.2. The Cabin Crew and Flight Deck Crew

The action of the CC is not explicitly modelled (i.e., they do not directly redirect passengers during the evacuation) and CC remain at their designated exit location until the area they are intended to control is clear of agents. CC remain in the cabin until the last agent in their cabin section has exited. Thus, CC at each active exit are typically the last to leave the aircraft. The response time for CC is incorporated within the exit ready time for Type C exits, so it is not explicitly stated (see Section 2.5a).

While the action of the CC in redirecting passengers is not explicitly modelled, it is assumed that CC are able to influence the exit choice of PAXs and direct them to utilise their optimal exit (i.e., Scenarios 1, 2, and 3). The nature of the PAX redirections implemented within these scenarios are limited to those that are considered plausible and achievable by well-trained CC. It is possible that even better evacuation performance could be achieved by implementing more ambitious PAX redirections, but these are unlikely to be achievable using the three available CC without either additional CC or additional technology to aid in directing PAXs to the desired exits.

The FDC are delayed by 20 s prior to starting their evacuation as passengers (see Section 2.5(d)), and the FDC will exit via a forward available exit (i.e., 1L or potentially 1R if it is available). This brief delay is intended to represent the time associated with shutting down the FDC. NOTE: The simulations are not sensitive to the length of the delay assigned to the FDC, assuming that they are not delayed beyond the time of the last passengers to exit via the relevant exit.

5. Interpreting Simulation Results

Several parameters are used to describe and quantify the predicted evacuation performance. The most important is evacuation time, which is a model-predicted time representing the time for each passenger to exit the aircraft. It is important to note that within these scenarios, passengers are only modelled up to the point at which they exit the aircraft. Hence, the modelling does not include the passenger's traversal of the slide or the time for them to reach the ground (see Section 2.5(c)).

An important parameter defining evacuation performance for the entire aircraft is the time for the final person evacuating the aircraft to reach the defined endpoint, referred to as the Total Evacuation Time or TET. The endpoint is usually defined as an On Ground (OG) TET, i.e., the time for the last participant to reach the ground (for exits with slides) or some other defined endpoint (for overwing exits). However, in the context of the analysis presented in this report, as the Off-Time (or slide time) is not considered (see Section 2.5c), the endpoint is not defined using the OG time but the Out Of Aircraft (OOA) time. This is defined as the time for the last agent to exit the aircraft. Thus, the TET for the evacuation simulations presented in this report is the OOA TET.

Other parameters of interest determined by the evacuation simulation software include the Cumulative Wait Time (CWT), Distance Travelled (DT), and the Personal Evacuation Time (PET). The CWT, measured in seconds (s), is a measure of how much time each agent (i.e., passenger represented within the model) in the simulation wastes due to congestion, i.e., the agent being stationary and waiting to move or moving at a speed less than their maximum walk speed. Within a simulation, the CWT is determined for each agent by summing all their individual waits from when they start to move (i.e., after their response time) to when they exit the aircraft. For a simulation, the CWT can then be averaged over all the agents within that simulation to produce the simulation average CWT.

The software also determines the distance travelled by each agent from their seat to their exit point. This, again, can be averaged over all the agents in a simulation to produce the simulation average DT. The PET measures the time for an agent to exit the aircraft, measured from the start of the simulation to the time they have passed through the exit. The PET can be determined for all agents in a simulation and then averaged over all agents in the simulation to produce the simulation average PET.

A parameter used to measure how optimal the predicted simulation is in terms of minimising TET is the OPS or Optimal Performance Statistic. The OPS provides a normalised measure of the difference between exit finish times relative to the OOA evacuation times. The OPS varies between 0 and 1; the closer to 0, the closer all the exits are to finishing at the same time and so the closer to optimality is the simulation. Simulations producing OPS values less than 0.1 are considered very close to optimal.

The OPS is defined as follows:

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

Where, n = number of exits used in the evacuation, EET_n = Exit Evacuation Time (time last person out) of exit n (seconds), and TET = Total Evacuation Time (seconds), i.e., max [EET].

The data generated for a scenario is presented in a series of tables. As a scenario is repeated 1000 times, the tables include key simulation data relating to the simulations producing the minimum, maximum, median, and 95th percentile OOA TET for a scenario. The median TET represents the time for the 501st longest TET (determined by ranking the simulations in order from the lowest to the highest TET). The 95th percentile TET represents the time for which 95% of the 1000 predicted TETs (i.e., 950 cases) are less than or equal to this time. For certification applications, it is recommended that the 95th percentile TET is used as the representative time for a scenario [6, 14]. In addition, tables are presented that report the minimum, maximum, mean and 95th percentile values for the key parameters across the 1000 simulations. Note that the parameter data presented in the values tables do not result from a specific single simulation but represent the maximum, mean, or minimum values for that parameter.

In interpreting the predicted OOA TET produced by the simulations for the various scenarios, it is useful to have a comparative value derived from actual certification demonstration trials. The TET usually reported in certification demonstration trials is the OG TET. However, the OOA TET for a certification demonstration trial can also be determined using the video footage from the certification trial. Unfortunately, for the configuration investigated in this study (180 PAXs and 5 crew), the video footage of the certification trial or the official report was not available.

However, video footage from a certification demonstration trial for a similar aircraft configuration is available and has been analysed by FSEG [17,19]. On 11 June 1988, an aircraft with a similar cabin and exit configuration with 188 passengers and 6 crew underwent a full-scale evacuation certification demonstration trial in compliance with 14 CFR 25.803 [23] and achieved an OG TET of 82.0 s and an FSEG-determined OOA TET of 80.4 s. While this aircraft had eight more passengers and one more CC than the aircraft used in this analysis, it is very similar and provides some indication of the likely OOA TET that the modelled aircraft may have achieved in a certification demonstration trial.

Assuming a linear relationship between OOA time and the number of people to exit (80.4/194 = 0.4144 s/person), this suggests that the OOA TET for 185 people would be approximately 76.9 s. Thus, 76.9 s approximates the OOA TET that the configuration modelled is likely to have achieved in a certification demonstration trial and so provides an experimental data point to compare with model predictions. Furthermore, the distribution of exit usage achieved in this trial was 57 people using the forward exit, 72 using the pair of overwing exits, and 65 using the aft exit. Finally, based on the OG TET for the forward exit, the pair of overwing exits, and the aft exit, the OPS (see

Equation 1) for this certification evacuation is 0.115, which suggests that the evacuation in the demonstration trial was not quite optimal.

5.1. Scenario 1 Key findings

Scenario 1 (Base Case) is intended to be representative of the evacuation certification demonstration trial and produce results indicative of the expected ***optimal*** performance of the configuration in the evacuation certification demonstration scenario. Of all the scenarios investigated, Scenario 1 is intended to be the closest modelling representation of the certification demonstration trial.

Scenario 1 produces **OOA TETs of between 62.9 s and 77.0 s** with a **median TET of 67.7 s** and a **95th percentile TET of 71.3 s**. By repeating the scenario 1000 times, with each simulation using a different representative population, the spread in OOA TETs is 14.1 s, with an interquartile range of 2.5 s (25th quartile TET = 66.6 s and 75th quartile TET = 69.1 s). This suggests that while 50% of the 1000 simulations are within +/- 1.25 s of the median TET (67.7 s), 50% of the simulations are outside this range—with 20% (200 cases) between the 75th quartile (TET = 69.1 s) and 95th percentile (71.3 s). This large variation in OOA TETs (14.1 s) and the relatively high (compared to the median) 95th percentile OOA TET (71.3 s) are produced simply by repeating the certification demonstration trial with a different population. The predicted variation in evacuation performance cannot be captured by the current certification demonstration trial protocol, i.e., 14 CFR 25.803 [23], as only a single demonstration trial is required.

The interpolated certification demonstration trial OOA TET for the 185-person variant of the aircraft (based on the actual certification performance for the 194-person variant) is estimated to be 76.9 s with an OPS of 0.115. Thus, the trial OOA TET falls within the range of simulated OOA TETs. This suggests that the predicted simulation results are a reasonable approximation of the likely certification performance for the aircraft. Furthermore, while the estimated certification trial TET (i.e., 76.9 s) is towards the high end of the predicted TET range, its OPS (i.e., 0.115) is equivalent to the sub-optimal OPS produced by the simulation in the high end of the predicted TET distribution (where OPS varies from 0.117 to 0.140 and corresponding predicted TETs vary from 75.6 s to 77.0 s). The simulation within the tail of the TET distribution producing an OPS (i.e., 0.117) equivalent to that of the certification trial (i.e., 0.115) corresponds to a predicted TET of 75.6 s, which is just 1.7% (1.3 s) smaller than the certification time.

6. Phase 1, Scenario 1: Base Case Results and Analysis

6.1. Summary of Scenario 1 (Base Case) Setup

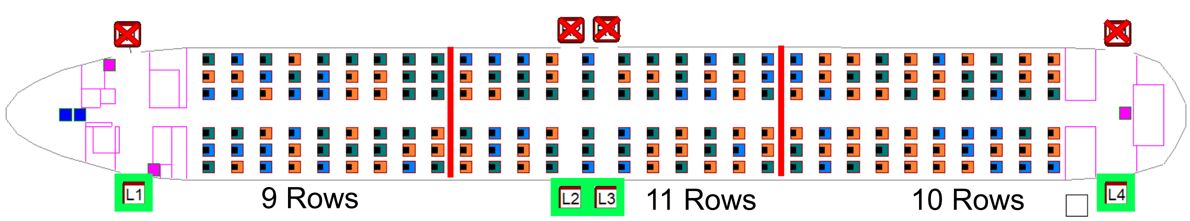
Within Scenario 1 (Base Case), one exit from each exit pair, all on the left side, i.e., 1L, 2L, 3L, and 4L, are available. Each available exit is assumed to open in certification-compliant times, i.e., 8.1 s for the Type C exits and 11.6 s for the Type-III exits (see Section 2.5a). The CC are also assumed to perform optimally in directing PAXs to their optimal exits, and the model assumes the assertive PEDT distribution for Type C exits (see Section 2.5b). The PEDT distribution for the Type-III is for an exit without crew assistance (see Section 2.5b). The population demographics are assumed to correspond to those specified in 14 CFR 25.803 [23] (see Section 2.3). The allocation of agents to specific exits is assumed to be implicitly the result of CC-instigated redirection, so limits are imposed on the nature of the agents that are redirected. Furthermore, agents are also able to instigate their own redirections if they are caught in sufficient congestion.

Presented in Figure 4 is an indication of the exits utilised by agents in Scenario 1 (Base Case). Available exits are marked with a green box, while unavailable exits are marked with a red cross. Also presented are the cabin splits (represented by the red lines) required to produce near-optimal results. These represent the cabin splits that the CC are attempting to achieve in order to produce near-optimal evacuation performance. The identified cabin split is considered fixed for all 1000 repeat simulations, i.e., in each of the 1000 simulations, the same cabin split is imposed. To achieve the identified near-optimal exit strategy will require the CC to achieve the following:

- The two CC located in the front of the cabin must attract the PAXs seated in the front 9 rows forward to use the L1 exit.
- The CC located in the rear of the cabin must attract the PAXs seated in the rear 10 rows back to use the L4 exit.
- The remaining 11 rows of seated PAXs must attempt to utilise the L2 and L3 exits.

Figure 4

The B737 cabin split resulting in optimised exit usage in Scenario 1 (Base Case)



The theoretical number of PAXs and crew that should use each exit, assuming a 100% compliance to the assigned optimal-exit behaviour, is 58, 66, and 61 for the 1L, 2L+3L, and 4L exits, respectively (see Table 5). However, interactions between PAXs during the evacuation process may result in PAXs not always using their intended exit; for example, within the model, agents may change their targeted exit due to experiencing excessive congestion.

Table 5
Theoretical exit usage for Scenario 1 (Base Case)

	1L	2L + 3L	4L	Total
Num. of PAXs	54	66	60	180
FC + CC	4	0	1	5
Total	**58**	**66**	**61**	**185**

6.2. Scenario 1 (Base Case) Results and Analysis

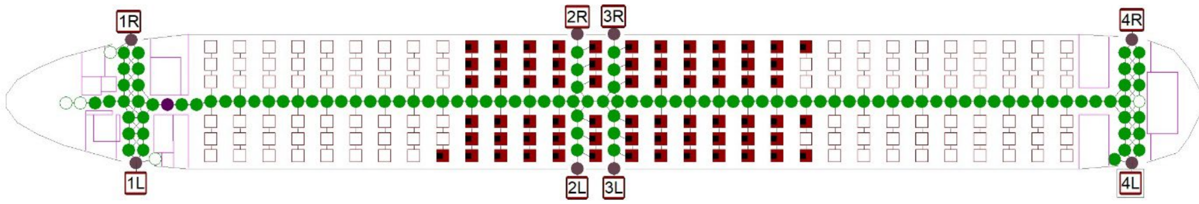
6.2.1 Scenario 1 Results and Discussion

(a) **Exit Usage**
Presented in Figure 5 is an indication of the exits utilised by passengers in the simulation producing the ***median*** TET for Scenario 1. In the ***median*** simulation, the TET was 67.7 s, with 57 agents using the forward exit 1L (those in the ***white*** seats forward of the overwing exits) and 58 agents using the aft exit 4L (those in the ***white*** seats aft of the overwing exits). In addition, 70 agents used the overwing exits 2L and 3L (those in the ***red*** seats). More agents used the overwing exits in the median case than expected from the theoretical distribution presented in Table 5. As suggested previously, this is due to behavioural interactions between the simulated agents. If congestion becomes excessive, some agents may change their targeted exit. Furthermore, in some cases, an agent may become hindered by a much slower-moving agent and decide to change their targeted exit. Departures from the targeted exit usage will result in inefficiencies in overall evacuation performance, resulting in longer evacuation times.

Furthermore, it is noted that even in the ideal case presented in Table 5, there was an imbalance in exit usage, with the overwing exits being used by more agents than the forward and aft Type C exits combined. The imbalance in exit usage is expected, as the centre Type-III exits are the closest exits to the majority of passengers, so naturally, they will potentially attract more passengers than the end exits. This is supported by research (survey of members of the public who had recently flown), which suggests that many people were unaware of the exit distribution on common aircraft (such as the one used in this study), including the number of exits, exit location, relative size of the exits, and the impact exit size would have on exit flows [9]. Also, as there are no crew located near the centre exits, and the available crew are located at the extreme ends of the cabin, it is difficult for crew to exert a strong influence on these passengers.

Figure 5

Exit usage in Scenario 1 for the median simulation; agents seated on white seats forward of the overwing exits utilise 1L, while agents seated on white seats aft of the overwing exits utilise 4L. Agents seated on red seats utilise 2L and 3L.



If each of the 1000 simulations were optimal, we could expect that each exit would finish last an approximately equal number of times (with the L2 and L3 exit being classed as one exit). This would result in each exit finishing last approximately 333 times. However, as shown in Table 6, this is not the case, with the centrally located overwing exits (i.e., L2 and L3) finishing last most often. However, this measure does not take into account how closely the exits were to finishing last and so is only a rough measure of optimality.

The OPS (see Equation 1) is a measure of the optimality of a particular simulation. As described in Section 4, it provides a normalised measure of the difference between exit finish times relative to the TET. The OPS varies between 0 and 1; the closer to 0, the closer the exits are to finishing at the same time, so the closer to optimality is the simulation. The OPS values shown in Table 9 are quite small, indicating near-optimal performance except for the maximum simulation. For the maximum simulation, the 3L exit finishes last at 77.0 s, while the 4L exit finishes first at 62.9 s, resulting in the larger OPS value for this simulation (see Table 7). In total, only 7.7% (i.e., 77) of the simulations produce an OPS value greater than 0.1 and so are considered sub-optimal.

Table 6

Number of times each exit finished last for Scenario 1 (Base Case) for all 1000 simulations

	L1	L2	L3	L4	Total
Number of times exit is last to finish	268	246	163	323	1000

Exit usage and exit finish times for the minimum, median, maximum, and 95th percentile cases are presented in Table 7, while the ranges in exit usage and exit finishing times are presented in Table 8. The exit finish times presented in Table 7 demonstrate that all the exits in a simulation are finishing at close to the same time, apart from the maximum simulation and, to a lesser extent, the 95th percentile case. As seen in Table 8, there is also a large variation in the number of agents utilising the overwing exits, with the number varying from 56 to 82, resulting in finish times for these exits varying from 51 s to 77 s. This indicates the large variation that can occur in this scenario and the need to run multiple repeat simulations to capture the variation in performance.

Table 7

Exit usage and exit finish times for the minimum, median, maximum, and 95th percentile simulations for Scenario 1 (Base Case) (from 1000 repeat simulations

Base Case: Optimal-Exit Usage	L1 No. Used	L1 Last Out (s)	L2 No. Used	L2 Last Out (s)	L3 No. Used	L3 Last Out (s)	L4 No. Used	L4 Last Out (s)
Min Sim	56	61.1	35	61.5	37	61.8	57	62.9
*Median Sim	57	62.8	38	67.7	32	64.5	58	59.1
Max Sim	57	63.2	37	73.3	37	77.0	54	62.9
95th% Sim	59	68.4	33	65.5	33	59.6	60	71.3

**Median sim is the 501st simulation from the 1000 repeat simulations ranked in ascending TET*

Table 8

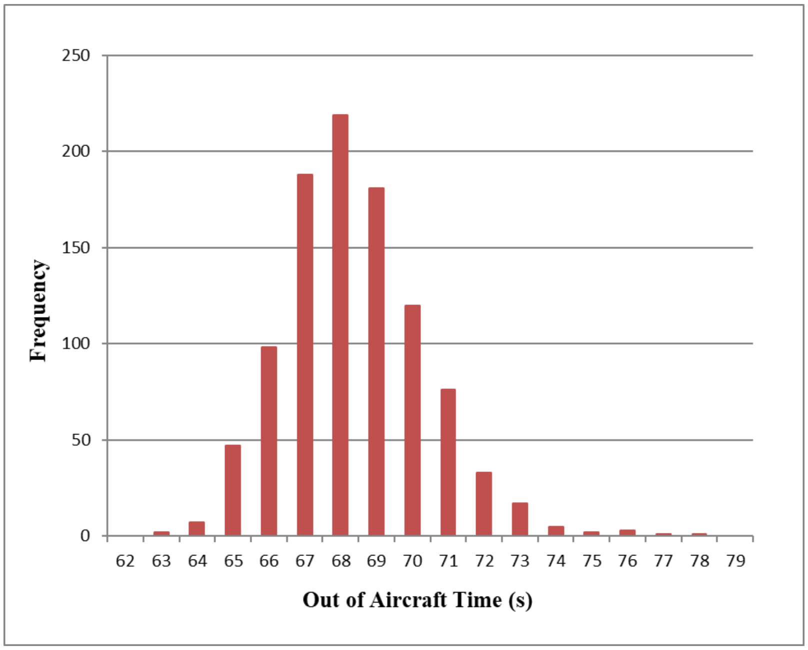
Exit usage and exit finish times for the Min, Median, Max, and 95th percentile values from the 1000 repeat simulations for Scenario 1 (Base Case)

Base Case: Optimal-Exit Usage	L1 No. Used	L1 Last Out (s)	L2 No. Used	L2 Last Out (s)	L3 No. Used	L3 Last Out (s)	L4 No. Used	L4 Last Out (s)
Min Value	54	57.7	28	51.7	28	51.0	53	57.2
Mean Value	57.6	65.1	35.0	64.8	34.7	64.1	57.6	65.2
Max Value	63	72.5	41	77.0	41	77.0	63	73.4

(b) **Predicted Evacuation Time Distribution**

The TET distribution for Scenario 1 is presented in Figure 6 . As can be seen, the distribution is near normal, with a mean of 67.9 s, a median of 67.7 s, and a standard deviation of 1.98 s. The distribution has a tail of long TETs from 75 s to 77 s, with five simulations producing a TET of greater than 75 s (75.6 s, 75.6 s, 76.0 s, 77.0 s, and 77.0 s), each of which produced an OPS greater than 0.1 (0.119, 0.117, 0.138, 0.140, and 0.137, respectively) and so were sub-optimal.

Figure 6
Distribution of TET for Scenario 1 produced from 1000 repeat simulations



(c) **Evacuation Exit Curves**
The evacuation exit curves for the Scenario 1 simulations producing the minimum, median, and maximum TETs are presented in Figure 7, while the exit curve for the 95th percentile simulation is presented in Figure 8. As can be seen, the minimum and median simulations produce similar exit curves, with the median curve significantly departing from the minimum curve at around 60 s. This corresponds to the time that the rear (L4) exit finishes, which is closely followed by the front (L1) exit finishing at 63 s (see Table 7). As these large exits are no longer supplied by passengers, the exit flow is based on the Type-III exits, resulting in a reduction in the exit flow and the downturn in the median exit curve towards the end of the simulation. The exit curve for the maximum simulation departs from the other curves early and is the result of a combination of factors, such as the higher level of congestion experienced by the agents, with an average CWT of 24.5 s (see Table 9), which is close to the maximum CWT observed in all the simulations (25.6 s, see Table 10) and the high number of agents using the Type-III exits (74, see Table 7). In addition, the significant downturn in exit flow towards the end of the maximum simulation (at around 63 s) results from the large difference in exit finishing times, producing a gap of 14 s between the first exit to finish, i.e., L4 at 62.9 s (see Table 7) and the last exit to finish, i.e., L3 at 77.0 s (see Table 7), resulting in the large OPS for this simulation.

Figure 7

Evacuation exit curves for the minimum, median, and maximum simulations for Scenario 1

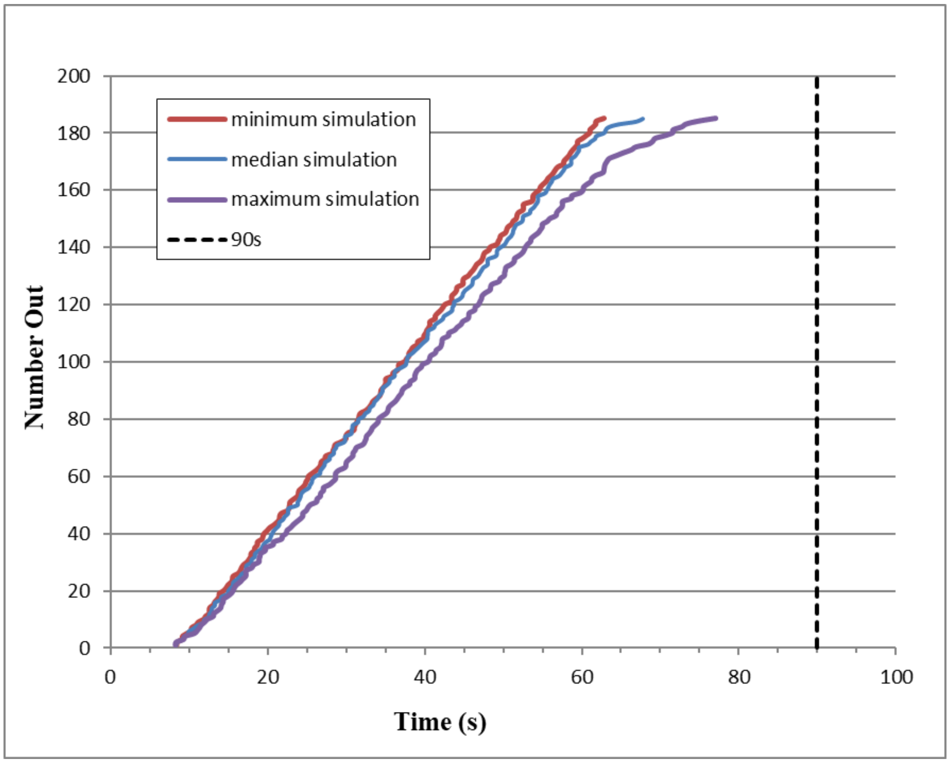
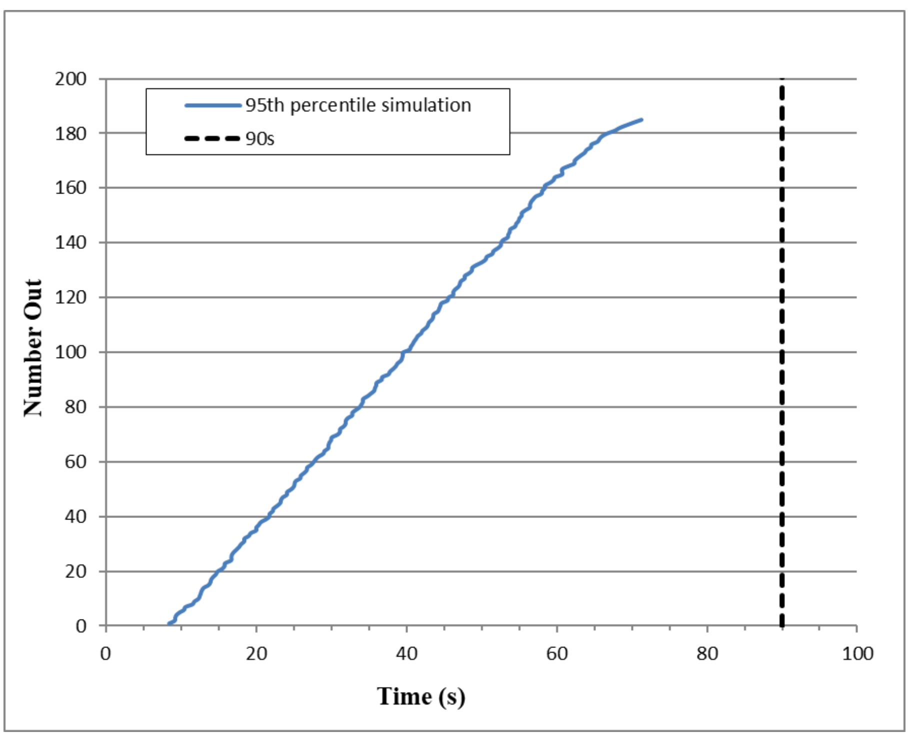


Figure 8

Evacuation exit curve for the 95th percentile simulation for Scenario 1



(d) Predicted Evacuation Times

By repeating Scenario 1 1000 times, with each simulation using a different population, **the OOA TET produced varies between 62.9 s and 77.0 s** with a **median time of 67.7 s** and a **95th percentile time of 71.3 s** (see Table 9). The spread in OOA TETs is 14.1 s, with an interquartile range of 2.5 s (25th quartile TET = 66.6 s and 75th quartile TET = 69.1 s). This suggests that while 50% of the 1000 simulations are within +/- 1.25 s of the median TET (67.7 s), 50% of the simulations are outside this range—with 20% (200 cases) between the 75th quartile (TET = 69.1 s) and 95th percentile (71.3 s). However, from a life safety viewpoint, clearly the simulations that produce TETs greater than the 75th quartile TET are of concern, which is why the 95th percentile TET (which excludes extreme outliers) is considered appropriate to define the representative certification performance for the configuration. The large variation in OOA TETs (14.1 s) and the relatively high (compared to the median) 95th percentile OOA TET (i.e., 71.3 s) are produced simply by repeating the certification demonstration simulation with a different population. The predicted variation in evacuation performance cannot be captured by the current certification demonstration trial protocol, i.e., 14 CFR 25.803 [23], as only a single demonstration trial is required.

Table 9

Scenario 1 main evacuation parameters for the min, median, max, and 95th percentile simulations (from 1000 repeat simulations)

Scenario 1 Base Case with Optimal-Exit Usage	Avg. CWT (s)	Avg. Distance (m)	Avg. PET (s)	TET (s)	OPS
Min Sim	21.4	6.48	35.2	62.9	0.022
***Median Sim**	21.9	6.61	35.9	67.7	0.082
Max Sim	24.5	6.61	38.8	77.0	0.137
95th% Sim	23.5	6.65	37.9	71.3	0.096

**Median sim is the 501st simulation from the 1000 repeat simulations ranked in ascending TET*

The minimum, mean, maximum, and 95th percentile values for the key simulation parameters derived from the 1000 repeat simulations are presented in Table 10. As can be seen, the average distance travelled by an agent varies from 6.4 m to 6.8 m, the time spent in congestion varies from 20.7 s to 25.6 s, while the average PET is 34.9 s to 39.9 s. This suggests that the majority of the time (over 60%, based on minimum and maximum simulations) that an individual spends evacuating is primarily due to congestion experienced during the evacuation, i.e., either being stationary in exit queues or moving at a rate less than their preferred walk speed in congested regions of the cabin.

Table 10
Scenario 1 min, mean, max, and 95th percentile values for the main evacuation parameters (from 1000 repeat simulations)

Scenario 1 Base Case with Optimal-Exit Usage	Avg. CWT (s)	Avg. Distance (m)	Avg. PET (s)	TET (s)
Min Value	20.71	6.39	34.88	62.87
Mean Value	22.88	6.61	37.04	67.89
Max Value	25.58	6.84	39.85	77.02
95th % Value	24.10	6.73	38.36	71.32

(e) **Improving Evacuation Performance**
The simulation results not only characterise the evacuation performance of the configuration but also provide insight into the causes of the predicted sub-optimal performance. For example, the high levels of congestion (as evidenced by the large values of average CWT relative to average PET (see Table 9) suggests that improvements in overall evacuation performance can be achieved by means implemented to reduce congestion, e.g., larger exits and wider aisles will improve exit flow, with larger exits able to sustain higher flow rates and wider aisles supplying a higher flow of passengers to sustain the flow capabilities of the wider exits. While Scenario 1 produced a large number of simulations with optimal OPS values, the larger TET values in the tail of the distribution (i.e., greater than 75 s; see Figure 6) are associated with sub-optimal OPS (values greater than 0.1). This suggests that the overall TET for this configuration could be improved with more efficient redirection of the agents to underutilised exits. This could be achieved either through additional CC, in particular CC located beside the overwing exits, or the use of technological aids to guide passengers to underutilised viable exits.

(f) **Verification**
The validity of the airEXODUS model predictions has been demonstrated previously through direct comparison with actual certification demonstration trials [14] and in forensic analysis of fatal incidents such as the Manchester B737 fire [4]. Unfortunately, a direct comparison of the configuration under investigation in this analysis with certification trial data has not been performed, as the complete certification data set for the aircraft configuration was not available. However, it is estimated, based on interpolation using data for the certification performance of a similar aircraft configuration (with 188 PAXs and six crew), that the certification OOA TET for 185 persons is approximately 76.9 s (see Section 4). Thus, the estimated certification performance for the configuration falls within the range of simulated OOA TETs produced by the optimal scenario (62.9 s to 77.0 s) and is some 7.8% (5.6 s) greater than the predicted 95th percentile OOA TET of 71.3 s. The maximum simulation OOA TET is only 0.1 s greater than the estimated certification trial performance.

In addition, the exit usage for the 194-person certification trial was 57 people using the forward exit, 72 using the pair of overwing exits, and 65 using the aft exit (see Section 4 and Table 11), and the OPS (see Equation 1) achieved in the certification trial was 0.115, suggesting that the certification trial evacuation was sub-optimal. This OPS is similar to the OPS values produced by the simulations in the tail of the TET distribution (see Figure 6), i.e., 0.119, 0.117, 0.138, 0.140, and 0.137, resulting in TETs of greater than 75 s, i.e., 75.6 s, 75.6 s, 76.0 s, 77.0 s, and 77.0 s, respectively. Thus, while the estimated certification trial TET (i.e., 76.9 s) is towards the high end of the predicted TET range, its OPS (i.e., 0.115) is equivalent to the sub-optimal OPS produced by the simulation in the high end of the predicted TET distribution. The simulation within the tail of the TET distribution producing an OPS (i.e., 0.117) equivalent to that of the certification trial (i.e., 0.115) corresponds to a predicted TET of 75.6 s, which is just 1.7% (1.3 s) smaller than the certification time. This suggests that the predicted simulation results are a reasonable approximation of the likely certification performance for the aircraft.

Comparing the trial results with the simulation results, we note that the exit usages for both the 95th percentile and maximum simulation cases are similar to that achieved in the certification trial for the 194-person variant (see Table 11). In particular, it is noted that the centre Type-III exits are overutilised in both the simulation and the certification demonstration trial (see Table 11). While the 95th percentile case is borderline optimal, the maximum simulation and the certification demonstration trial are clearly sub-optimal in terms of exit performance.

Table 11
Comparison of exit performance for the 95th percentile and maximum simulation and the 194-person certification demonstration trial

		Forward exit	Overwing exits	Aft exit	TET	OPS
95th percentile SIM (185 persons)	**Number**	59	66	60	71.3 (OOA)	0.096
	OOA time (s)	68.4	65.5	71.3^{+}		
Max SIM (185 persons)	**Number**	57	74	54	77.0 (OOA)	0.137
	OOA time (s)	63.2	77.0^{+}	62.9		
Certification trial (194 persons)	**Number**	57	72	65	82.0 (OG)	0.115
	OG time (s)	67.3	82.0^{+}	77.9	80.4 (OOA*)	

** Determined by FSEG from video footage (see Section 4); + Last exit*

Thus, the evacuation performance achieved in the certification demonstration trial for the 194-person variant is towards the upper end of the predicted range of likely evacuation performance. It is likely that if the certification trial was repeated, a shorter evacuation time could be achieved with better exit usage by passengers, i.e., with fewer passengers utilising the overwing exits.

7. Phase 1, Scenario 2: Sensitivity Case 1 – Exit Availability Results and Analysis

7.1. Summary of Scenario 2 (Sensitivity case 1 – exit availability) Setup

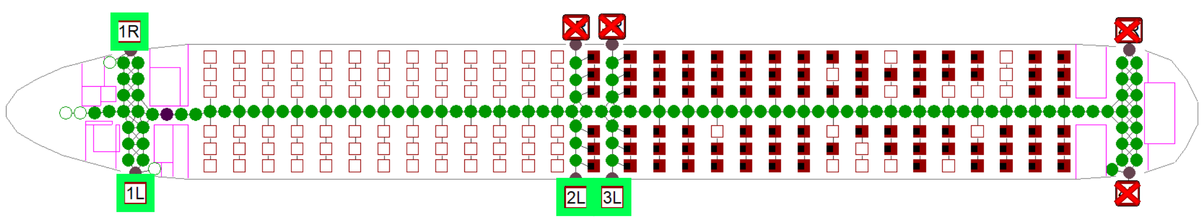
Scenario 2 (exit availability) investigates the impact of having a different combination of available exits on evacuation times. Essentially, this scenario involves a similar setup to Scenario 1 (see Section 5.1), except for the exit availability, employing a different combination of 50% of the available exits. In Scenario 2, the 1L, 1R, 2L, and 3L exits are available. As in Scenario 1, the scenario assumes the assertive PEDT distribution for Type C exits (see Section 2.5b), while the PEDT distribution for the Type-III exits is for an exit without crew assistance (see Section 2.5b). The population demographics are assumed to correspond to those specified in 14 CFR 25.803 [23] (see Section 2.3). Similarly, the exit ready times for the available Type C and Type-III exits are 8.1 s and 11.6 s, respectively.

The exit availability in this scenario corresponds to that previously explored in [16]; however, the scenario investigated in the current study involves optimal-exit selection by passengers, whereas in the previous study, passengers selected their nearest exit [16].

To achieve optimal evacuation performance within this scenario, it is necessary for passengers seated ahead of the overwing exits to move forward and use the 1L/1R Type C exits and for most of the passengers seated aft of the overwing exits to use the 2L and 3L overwing exits (see Figure 9), but with a number of these passengers deciding to by-pass the overwing exits to move forward and use the 1L and 1R exits.

Figure 9:

Exit usage in Scenario 2 (case d) for median simulation; agents seated on white seats utilise 1L and 1R, while agents seated on red seats utilise 2L and 3L



In reality, this would be difficult to achieve without direct crew intervention. Ideally, a crew member would be located in the aisle area by the pair of overwing exits and would attempt to control the flow of passengers, pulling passengers forward when congestion occurs at the entrance to the two seat rows supplying the pair of overwing exits and the aisle ahead was reasonably clear. However, while this type of intervention is likely to reduce the overall total evacuation time (TET), it will increase individual personal evacuation times (PETs) for those passengers who by-pass the overwing exits. Thus, in most cases, this would not be a desirable detour for those passengers, as it will prolong their PET, given that the forward exits are much further away than the overwing exits and the relatively short queue to the overwing exits. It is thus unlikely that passengers would adopt this behaviour unless directed to by CC. Furthermore, in the early stages of the evacuation, there is likely to be a long queue leading to the forward exits, so passengers by-passing the short queue to the overwing exits will simply join the longer (but faster-moving) queue for the forward exits (i.e., 1L and 1R). Thus, without CC located at the overwing exit, it is difficult to envisage that many passengers would elect to move forward. Within the airEXODUS model, it is also difficult to achieve the required by-pass behaviour given the nature of the configuration, i.e., narrow aisle, proximity of Type-III exits, and the relatively short queue to the overwing exits from the aisle.

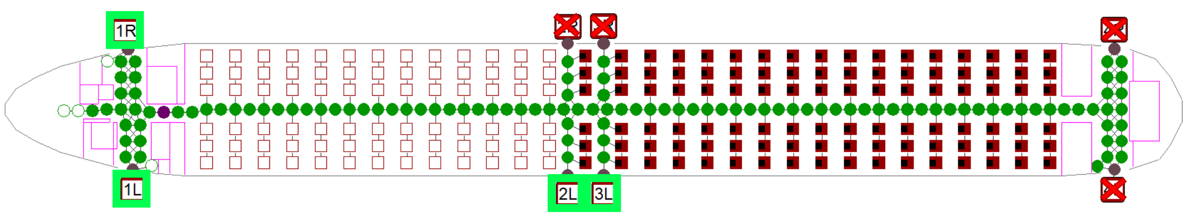
In order to fully investigate the effect of passenger by-pass of the overwing exits on the TET, four separate scenario variants were investigated. These scenario variants differed as regards the passenger's ability to by-pass the overwing exits. The full analysis for each of these scenarios can be found in the interim reports [25, 26]. Here, a summary of the different scenarios is presented, along with a detailed analysis of the results for the accepted representative scenario (i.e., Scenario 2d).

- **Variant 1, Scenario 2a (No exit by-pass)**

Within this scenario variant, no overwing exit by-pass was permitted; hence, all passengers move forward to their nearest exit. As a result, within this scenario, all the passengers on the white seats in Figure 10 simply evacuate via the forward 1L and 1R exits, while those initially on the red seats evacuate via either of the available overwing exits (i.e., 2L and 3L). Within this scenario, 82 passengers used the forward Type C exits (i.e., 1L or 1R), while 103 passengers utilised the overwing exits (i.e., 2L or 3L).

Figure 10

Exit usage in Scenario 2a for all simulations; agents seated on white seats utilise 1L and 1R, while agents seated on red seats utilise 2L and 3L

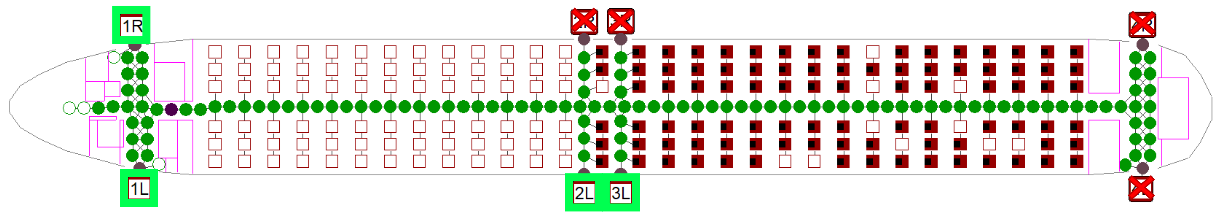


- **Variant 2, Scenario 2b (By-pass only during congestion)**

As in Scenario 2a, all passengers move forward to their nearest exit. However, in this scenario, passengers can decide to by-pass the overwing exit. A passenger by-pass is instigated only when there is congestion in the exit row for the overwing exits (i.e., 2L or 3L). Even though passengers will incur a greater PET by going forward, they avoid spending time in congestion at the overwing exit and potentially reduce the time for other passengers (behind them) to evacuate. Presented in Figure 11 is an indication of the exits utilised by passengers in the simulation producing the ***median*** TET for Scenario 2b. In the ***median*** simulation, 93 passengers used the forward Type C exits (those in the ***white*** seats), while 92 passengers utilised the overwing exits (those in the ***red*** seats). In total, 11 passengers seated aft of the overwing exits have by-passed the overwing exits to use the forward Type C exits (i.e., 1L or 1R).

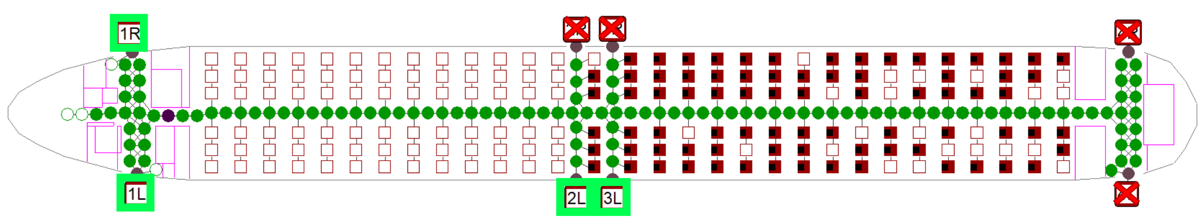
Figure 11

Exit usage in Scenario 2b for median simulation; agents seated on white seats utilise 1L and 1R, while agents seated on red seats utilise 2L and 3L



• **Variant 3, Scenario 2c (50:50 chance of by-pass)**
Within Scenario 2c, more passengers can by-pass the overwing exits than in Scenario 2b. A passenger by-pass can be instigated when a passenger reaches the aisle space between the 2L and 3L exits. A by-pass will be instigated by the passenger when the exit row leading to overwing exit 3L is full of queuing passengers, and the queuing passenger moves forward to the row leading to overwing exit 2L. Once at this location, passengers have a 50:50 chance to by-pass or use the 2L exit. Even though passengers will incur a greater PET by going forward, they avoid spending time in congestion at the overwing exit and potentially reduce the time for other passengers (behind them) to evacuate. Presented in Figure 12 is an indication of the exits utilised by passengers in the simulation producing the ***median*** TET for Scenario 2c. In the ***median*** simulation, 105 passengers used the forward Type C exits (those in the ***white*** seats), while 80 passengers utilised the overwing exits (those in the ***red*** seats). In total, 23 passengers seated aft of the overwing exits by-pass the overwing exits to use the forward Type C exits (i.e., 1L or 1R). This compares with only 11 passengers by-passing the overwing exits for Scenario 2b.

Figure 12
Exit usage in Scenario 2c for median simulation; agents seated on white seats utilise 1L and 1R, while agents seated on red seats utilise 2L and 3L



• **Variant 4, Scenario 2d (50:50 chance of by-pass with 70 s cut-off)**
In Scenario 2d, as in Scenario 2c, passengers who by-pass 3L due to congestion also have a 50:50 chance of by-passing the 2L exit; however, after a critical time, passengers are no longer permitted to by-pass the 2L exit and so will queue to utilise the exit. In Scenario 2b, with by-pass permitted only when there was sufficient congestion at the 2L exit, the TET was sub-optimal, as there were insufficient passengers by-passing the overwing exit, i.e., only 11 passengers elected to by-pass the overwing exit in the median case. However, in Scenario 2c, with a 50:50 chance of passengers by-passing the overwing exit, the TET was significantly sub-optimal, with too many passengers by-passing the overwing exit, i.e., 23 passengers by-pass the overwing in the median case. This resulted in passengers by-passing the overwing exit 2L towards the end of the evacuation and, hence, in some cases, extending the overall TET as a result of the increased distance they needed to evacuate. Clearly, achieving an optimal performance for this

exit configuration requires passengers to by-pass the overwing exits for a period but to stop the by-pass behaviour after a critical time, as it is no longer beneficial to redirect to the forward exits. Through trial-and-error simulation, the critical time was determined to be approximately 70 s [26].

If by-pass is prevented after 70 s, there are very few passengers left on board, and as the overwing exits are now clear of congestion, they offer the fastest route off the aircraft. Prior to 70 s, as in Scenario 2c, even though passengers will incur a greater PET by by-passing the overwing exits, they avoid spending time in congestion at the overwing exits and potentially reduce the time for other passengers (behind them) to evacuate. However, unlike in Scenario 2c, they will not by-pass near the end of the evacuation, and unlike Scenario 2b, more passengers will by-pass the overwing exits.

Thus, the optimal performance for Scenario 2 is achieved if passengers decide to by-pass the overwing exit in the earlier stages of the evacuation. Within the simulation, to achieve optimal performance for this scenario, it is assumed that passengers have a 50:50 chance of deciding to by-pass the overwing exit **ONLY IF** there is sufficient congestion at the overwing exit **AND** they will only contemplate by-passing for the first 70 s of the evacuation, as after this time, by-passing the overwing exit will increase their PET and the TET for the aircraft.

Presented in Figure 9 is an indication of the exits utilised by passengers in the simulation producing the ***median*** TET for Scenario 2d. In the ***median*** simulation, 98 passengers used the forward Type C exits (those in the ***white*** seats), while 87 passengers utilised the overwing exits (those in the ***red*** seats). In total, 16 passengers seated aft of the overwing exits have by-passed the overwing exits to use the forward Type C exits.

To achieve the identified near-optimal exit strategy for Scenario 2 requires:

- The two CC located in the front of the cabin must assertively attract the PAXs seated in the front cabin section to move forward to use the L1/R1 exits while assertively maintaining the flow through their exits.
- The CC located in the rear of the cabin must assertively direct the PAXs seated in the rear cabin section (aft of the overwing exits) forward to use the L2 and L3 exits.
- The passengers seated in the rear of the cabin (aft of the overwing exits) to instigate exit by-pass when there is sufficient congestion at the overwing exits and, when doing so, potentially reduce their PET and the aircraft’s TET.

7.2 Scenario 2 (Sensitivity case 1 – exit availability) Results and Analysis

7.2.1. Scenario 2 Key Findings

Scenario 2 (exit availability) investigates the effect of differing exit availability on overall evacuation performance and evacuation times. Essentially this scenario involves a similar scenario setup to Scenario 1 (see Section 5.1) but utilises a different combination of 50% of the available exits. In this scenario, the 1L, 1R, 2L, and 3L exits are available. As in Scenario 1, the passengers attempt to select their optimal exit for evacuation, producing a minimum TET for this exit configuration.

The simulation produces **OOA TETs of between 80.3 s and 102.7 s** with a **median TET of 88.6 s** and a **95th percentile TET of 94.7 s**. Over one-third (i.e., 34.8% or 348 simulations) of the 1000 simulations produce a TET of 90 s or greater. The spread in OOA TETs is 22.4 s, with an interquartile range of 4.6 s (25th quartile TET = 86.6 s and 75th quartile TET = 91.2 s). This suggests that while 50% of the 1000 simulations are within +/- 2.3 s of the median TET (88.6 s), 50% of the simulations are outside this range, with 20% (200 cases) between the 75th quartile (TET = 91.2 s) and 95th percentile (94.7 s). From a life safety viewpoint, this is clearly a concern, as even the 75th quartile TET exceeds 90 s.

Thus, simply changing the available exits while maintaining 50% exit availability AND the mix of exit types (i.e., two Type C and two Type-III exits), the 95th percentile TET for the configuration increases from 71.3 s to 94.7 s, an increase in evacuation time of 23.4 s or 32.8%. More significantly, this change in exit availability results in a different conclusion concerning the acceptability of evacuation performance, from a pass (in Scenario 1) to a failure (in Scenario 2d) in terms of satisfying the 90 s certification requirement.

The poor performance of Scenario 2d is primarily due to the inability of the narrow cabin aisle to supply sufficient flow to maintain both Type C exits in an exit pair working at their full capabilities. As a result, each Type C exit in the forward pair of exits produces a sustained average exit flow of 41.3 ppm. In contrast, in Scenario 1, a single Type C exit from the forward pair of Type C exits is supplied by the forward portion of the main aisle, while a single Type C exit from the aft pair of Type C exits is supplied by the aft portion of the main aisle, with each Type C exit producing an average sustained exit flow of 61.0 ppm. Thus, in Scenario 1, the combined two Type C exits produce a sustained average exit flow of 122 ppm, while in Scenario 2d, the two available Type C exits can only manage 82.5 ppm and so are some 30% less effective.

Furthermore, the evacuation performance in Scenario 2d is highly susceptible to slow-moving passengers who can create momentary gaps in the supply of passengers to both Type C exits, further reducing evacuation performance. While the same slow-moving passengers exist in Scenario 1, their impact is less noticeable, as their behaviour will only impact one of the two Type C exits at any one time. Thus, performance in Scenario 2d is subject to random variations in passenger seating allocation, which is unlikely to be identified if only a single evacuation trial is performed, as in the case of the certification demonstration.

The predicted evacuation performance cannot be captured by the current certification demonstration trial protocol i.e., 14 CFR 25.803 [23], as only a single exit combination is selected for certification demonstration, and the exit combination is the combination that will provide the shortest evacuation time possible. Furthermore, as only a single evacuation demonstration trial is performed, it is unlikely that the impact of slow-moving passengers on evacuation performance will be identified.

7.2.2 Scenario 2 Results and discussion

(a) **Exit Usage**
Presented in Figure 9 is an indication of the exits utilised by passengers in the simulation producing the ***median*** TET for Scenario 2. In the ***median*** simulation, the TET was 88.6 s, with 98 passengers using the forward Type C exits (those in the ***white*** seats), while 87 passengers utilised the overwing exits (those in the ***red*** seats). In total, 16 passengers seated aft of the overwing exits have by-passed the overwing exits to use the forward Type C exits.

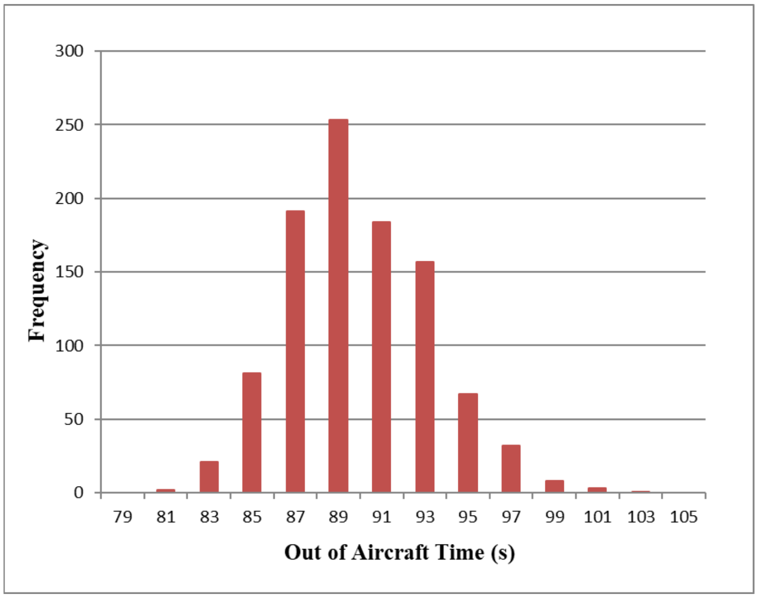
If each of the 1000 simulations were optimal, we could expect that each exit would finish last approximately an equal number of times (with the L2 and L3 exit being classed as one exit). This would result in each exit finishing last approximately 333 times. However, as shown in Table 12, this is not the case with the centrally located overwing exits (i.e., L2 and L3), finishing last for more than 80% of the simulations. As described previously, the OPS is a better measure of optimality. The OPS values shown in Table 13 are quite small, indicating near-optimal performance, except for the maximum simulation. In total, only 7.7% (i.e., 77) of the simulations produce an OPS value greater than 0.1 and so are considered sub-optimal, and all of these produced TETs of greater than 87 s.

Table 12
Number of times each exit finished last in Scenario 2d (from 1000 repeat cases)

No. of Times	1L	1R	2L	3L	Total
Last Out	138	50	246	566	1000

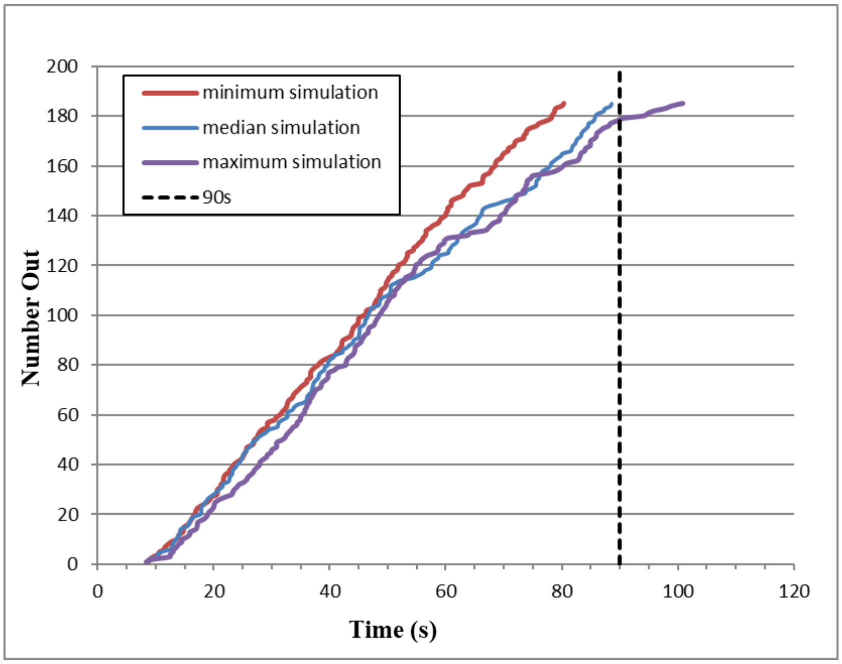
(b) **Predicted Evacuation Time Distribution**
Presented in Figure 13 is the TET distribution for Scenario 2d. As can be seen, the distribution is near normal, with a mean of 89.0 s and a median of 88.6 s, with a standard deviation of 3.3 s. The distribution has a tail of long TETs from 99 s to 103 s, with four simulations producing a TET of greater than or equal to 99.0 s (99.0 s, 99.2 s, 100.8 s, and 102.7 s), each of which produced an OPS greater than 0.1 (0.123, 0.101, 0.116, and 0.138, respectively) and so were sub-optimal.

Figure 13
Distribution of TET for Scenario 2d produced from 1000 repeat simulations



(c) **Evacuation Exit Curves**
The evacuation exit curves for the Scenario 2d simulations producing the minimum, median, and maximum TETs are presented in Figure 14 (while the exit curve for the 95th percentile simulation is presented in Figure 24). As can be seen, the minimum and median simulations produce similar exit curves up to around 49 s. At around this time, the median curve significantly departs from the minimum curve with a reduction in exit flow (indicated by the reduction in gradient), and again at 65 s. These reductions in exit flow correspond to a brief interruption in the flow to the forward Type C exits resulting from slow passengers holding up the queue in the aisle. Both incidents are caused by female agents aged 53 and 57 with particularly slow fast-walk speeds of 0.52 m/s and 0.54 m/s, respectively. This type of event is more significant in Scenario 2d than Scenario 1, as a single passenger can interrupt the flow to two Type C exits. Similar incidents occur in the maximum simulation, for example, at around 60 s, caused by a slow-moving 55-year-old female with a fast-walk speed of 0.53 m/s. Furthermore, the slope of the maximum simulation curve displays a significant reduction towards the end of the simulation resulting from the flow to the forward Type C exits finishing at around 86 s—resulting in the large OPS for this simulation.

Figure 14
Evacuation exit curves for the minimum, median, and maximum simulations for Scenario 2d.



(d) **Predicted Evacuation Times**
By repeating Scenario 2d 1000 times, with each simulation using a different population, **the OOA TET produced varies between 80.3 s and 102.7 s** with a **median time of 88.6 s** and a **95th percentile time of 94.7 s** (see Table 13). In total, 34.8% (348 simulations) of the 1000 simulations produce a TET of 90 s or greater. The spread in OOA TETs is 22.4 s, with an interquartile range of 4.6 s (25th quartile TET = 86.6 s and 75th quartile TET = 91.2 s). This suggests that while 50% of the 1000 simulations are within +/- 2.3 s of the median TET (88.6 s), 50% of the simulations are outside this range, with 20% (200 cases) between the 75th quartile (TET = 91.2 s) and 95th percentile (94.7 s). From a life safety viewpoint, this is clearly a concern, as even the 75th quartile TET exceeds 90 s. Furthermore, the predicted evacuation performance cannot be captured by the current certification demonstration trial protocol, i.e., 14 CFR 25.803 [23], as only a single exit combination is selected for certification demonstration, and the exit combination is the combination that will provide the shortest evacuation time possible.

Scenario 2d has greater variability than Scenario 1 (larger variation in TETs (22.4 s vs. 14.1 s), larger interquartile range (4.6 s vs. 2.5 s), and larger standard deviation (3.3 s vs. 1.98 s)), suggesting that the outcome for this scenario is more strongly dependent on individual redirection decisions made by agents. This large variation in evacuation outcome is produced simply by repeating the evacuation simulation with a different population. The predicted variation in evacuation performance cannot be captured by the current certification demonstration trial protocol, i.e., 14 CFR 25.803 [23], as only a single demonstration trial is required.

The minimum, mean, maximum, and 95th percentile values for the key simulation parameters derived from the 1000 repeat simulations for Scenario 2d are presented in Table 14. As can be seen, the average distance travelled by an agent varies from 9.9 m to 11.2 m, the time spent in congestion varies from 23.5 s to 30.8 s, while the average PET is 42.0 s to 49.7 s. This suggests that the majority of the time (over 57% based on minimum and maximum simulations) that an individual spends evacuating is primarily due to congestion experienced during the evacuation, i.e., either being stationary in exit queues or moving at a rate less than their preferred walk speed in congested regions of the cabin.

Table 13

Scenario 2d main evacuation parameters for min, median, max, and 95th percentile simulations (from 1000 repeat simulations)

Scenario 2d: 1L, 1R, 2L, 3L Exit Availability	Avg. CWT (s)	Avg. Distance (m)	Avg. PET (s)	TET (s)	OPS
Min Sim	24.6	10.7	43.3	80.3	0.026
***Median Sim**	27.7	10.6	46.9	88.6	0.029
Max Sim	28.2	10.4	46.8	102.7	0.138
95th% Sim	26.8	10.5	45.5	94.7	0.110

**Median sim is the 501st simulation from the 1000 repeat simulations ranked in ascending TET*

Table 14

Scenario 2d min, mean, max, and 95th percentile values for the main evacuation parameters (from 1000 repeat cases)

Scenario 2d: 1L, 1R, 2L, 3L Exit Availability	Avg. CWT (s)	Avg. Distance (m)	Avg. PET (s)	TET (s)	OPS
Min Value	23.5	9.9	42.0	80.3	0.005
Mean Value	26.3	10.4	45.2	89.0	0.056
Max Value	30.8	11.2	49.7	102.7	0.166
95th % Value	28.3	10.8	47.2	94.7	0.109

(e) **Improving evacuation performance**

As discussed in Section 2.7, the average exit flow achieved by a Type C exit in certification trials is 61 ppm (see Table 3). In the exit flow tests presented in Section 2.7, the airEXODUS model was able to produce sustained exit flows for Type C exits of 60.7 ppm. This suggests that the Type C exits in the model are capable of producing a good representation of the expected exit flows. In Scenario 1, the 1L (forward) and 4L (aft) Type C exits each achieve a sustained average exit flow of 61 ppm over the 1000 repeat simulations, as expected. However, in Scenario 2d, the 1L (forward left) and 1R (forward right) Type C exits each produce a sustained average exit flow of 41.3 ppm. While the two functioning Type C exits (i.e., 1L and 4L) produce a combined average sustained exit flow of 122 ppm in Scenario 1, the two functioning Type C exits in Scenario 2d (i.e., 1L and 1R) produce a combined average sustained exit flow of 82.5 ppm. Thus, in Scenario 2d, the two Type C exits are some 30% less efficient than the two Type C exits in Scenario 1. This is because the single narrow aisle cannot supply passengers at a sufficient rate to keep two Type C exits functioning at full capacity. Improving evacuation performance for this exit availability requires a significantly wider cabin aisle to increase the flow through the aisle supplying the two Type C exits.

8. Phase 1, Scenario 3: Sensitivity Case 2 – Crew Assertiveness

8.1. Summary of Scenario 3 (Sensitivity case 2 – crew assertiveness) Setup

Scenario 3 (crew assertiveness) investigates the effect of crew assertiveness on overall evacuation times. There are two variants of this scenario: Scenario 3a and Scenario 3b, which involve different exit availability options reflecting Scenario 1 and Scenario 2, respectively

8.1.1 Scenario 3a

Essentially, Scenario 3a involves an almost identical setup as Scenario 1 (see Section 5.1) but utilises reduced assertiveness of the CC at the Type C exits. As a result, one exit from each exit pair, all on the left side, i.e., 1L, 2L, 3L, and 4L, are available. Each available exit is assumed to open in certification-compliant times, i.e., 8.1 s for the Type C exits and 11.6 s for the Type-III exits (see Section 2.5a). The population demographics are assumed to correspond to those specified in 14 CFR 25.803 [23] (see Section 2.3). However, unlike Scenario 1, which assumes that the CC at the Type C exits behave in an assertive manner (and, hence, the PEDT distribution for Type C exits with assertive crew is used), in Scenario 3a, they are assumed to exhibit the 'in-between' assertiveness behaviour, i.e., neither fully assertive nor fully unassertive (see Section 2.5b). Thus, in Scenario 3a, the CC at Type C exits use the PEDT distribution for 'in-between' CC (see Section 2.5b). The PEDT distribution used to represent the Type-III exit is for a Type-III exit without crew assistance (see Section 2.5b).

However, it is important to note that while the CC at the Type C exits are assumed to display 'in-between' behaviour while encouraging passengers through their assigned exit, they are still considered to be just as effective as assertive crew in achieving the required cabin splits for an optimal scenario, i.e., the passengers are directed towards their optimal exits rather than their nearest exits. Thus, the required cabin splits for Scenario 3a are the same as those for Scenario 1 and are presented in Figure 4. It is noted that a slightly less optimal cabin split was also investigated (see interim report [27]) as an option for Scenario 3a (identified as Scenario 3aii); however, this only increased the TET for the 95th percentile TET marginally (0.7 s or 0.9%) and was not adopted for this analysis. The full analysis for Scenario 3a (including Scenario 3aii) can be found in the interim report [27].

8.1.2 Scenario 3b

Essentially, Scenario 3b involves an almost identical setup as Scenario 2d (see Section 6.1) but utilises reduced assertiveness of the CC at the Type C exits. As a result, exits 1L, 1R, 2L, and 3L are available. Each available exit is assumed to open in certification-compliant times, i.e., 8.1 s for the Type C exits and 11.6 s for the Type-III exits (see Section 2.5a). The population demographics are assumed to correspond to those specified in 14 CFR 25.803 [23] (see Section 2.3). However, unlike Scenario 2d, which assumes that the CC at the Type C exits behave in an assertive manner (and, hence, the PEDT distribution for Type C exits with assertive crew is used), in Scenario 3b, they are assumed to exhibit the 'in-between' assertiveness behaviour, i.e., neither fully assertive nor fully unassertive (see Section 2.5b). Thus, in Scenario 3b, the CC at Type C exits use the PEDT distribution for ‘in-between’ CC (see Section 2.5b). The PEDT distribution used to represent the Type-III exit is for a Type-III exit without crew assistance (see Section 2.5b). The passenger exit by-pass behaviour is also as described in Scenario 2d.

Furthermore, as in Scenario 3a, while the CC at the Type C exits are assumed to display ‘in-between’ behaviour while encouraging passengers through their assigned exit, they are still considered to be just as effective as assertive crew in achieving the required cabin splits for an optimal scenario, i.e., the passengers are directed towards their optimal exits rather than their nearest exits. Thus, the CC behaviour in achieving the near-optimal exit strategy and cabin splits for Scenario 3b are the same as those for Scenario 2d described in Section 6.1. The full analysis for Scenario 3a (including Scenario 3aii) can be found in the interim report [28].

8.2. Scenario 3 (Sensitivity case 2 – crew assertiveness) Results and Analysis

8.2.1. Key findings Scenario 3a

Scenario 3a (crew assertiveness) investigates the effect of crew assertiveness on overall evacuation performance and evacuation times for the certification scenario in which exits 1L, 2L, 3L, and 4L are available. Essentially, this scenario involves a similar setup to Scenario 1 (see Section 5.1) and so is identical to the standard certification demonstration trial. However, unlike Scenario 1, the CC at the Type C exits are not assertive but have been assigned ‘in-between’ assertiveness, so they are slightly less assertive compared to the CC in Scenario 1. As in Scenario 1, the passengers attempt to select their optimal exit for evacuation, producing a minimum TET for this exit configuration.

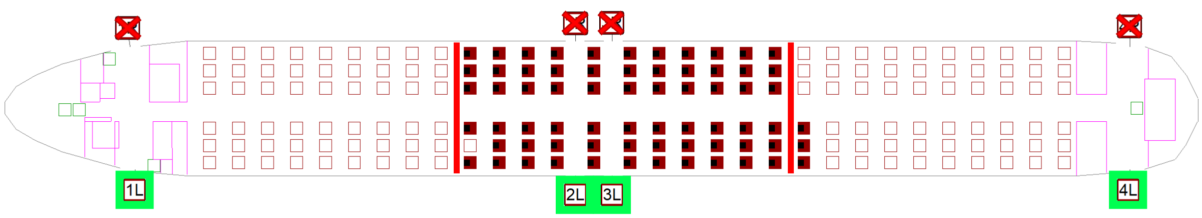
By repeating Scenario 3a 1000 times, with each simulation using a different population, **the OOA TET produced varies between 63.5 s and 76.6 s** with a **median TET of 68.4 s** and a **95th percentile TET of 72.3 s.** The spread in OOA TETs is 13.1 s, with an interquartile range of 2.7 s (25th quartile TET = 67.2 s and 75th quartile TET = 69.8 s). This suggests that while 50% of the 1000 simulations are within +/- 1.35 s of the median TET (68.4 s), 50% of the simulations are outside this range, with 20% (200 cases) between the 75th percentile (TET = 69.8 s) and 95th percentile (72.3 s). The large variation in OOA TETs (13.1 s) and the relatively high (compared to the median) 95th percentile OOA TET (i.e., 72.3 s) are produced simply by repeating the certification demonstration simulation with a different population. As noted for Scenario 1, the predicted variation in evacuation performance cannot be captured by the current certification demonstration trial protocol, i.e., 14 CFR 25.803 [23], as only a single demonstration trial is required.

Furthermore, with the assertiveness of crew at both the forward and aft Type C exits slightly reduced from ‘assertive’ to ‘in-between’, the 95th percentile TET for Scenario 3a is only marginally increased from **71.3 s** (in Scenario 1; see Section 5.2) **to 72.3 s**, an increase of only 1.4%. This slight increase in TET is the result of the small decrease in average exit flow resulting from the PEDT distribution associated with ‘in-between’ assertiveness (see Annex 3). While this is only a small increase in TET, it does not necessarily represent a full impact of CC assertiveness on evacuation performance. The use of unassertive CC operating the exits is likely to further reduce average flow rates achieved, thereby decreasing evacuation performance. Furthermore, the assertiveness of CC is also likely to impact the effectiveness of CC in achieving the cabin splits required for optimal evacuation performance, which was not considered in this scenario.

8.2.2 Scenario 3a Results and Discussion

(a) **Exit Usage**
Presented in Figure 15 is an indication of the exits utilised by passengers in the simulation producing the ***median*** TET for Scenario 3a. In the ***median*** simulation, the TET was 68.4 s, with 59 agents using the forward exit 1L (those in the ***white*** seats forward of the overwing exits) and 58 agents using the aft exit 4L (those in the ***white*** seats aft of the overwing exits). In addition, 68 agents used the overwing exits 2L and 3L (those in the ***red*** seats). As in Scenario 1 (see Section 5.2.2), more agents used the overwing exits in the median case than expected from the theoretical distribution presented in Table 5. As suggested previously, this is due to behavioural interactions between the simulated agents. If congestion becomes excessive, some agents may change their targeted exit.

Figure 15
Exit usage in Scenario 3a for median simulation; agents seated in white seats on the left utilise 1L, agents seated in white seats on the right utilise 4L, while agents seated in red seats utilise 2L and 3L



For the evacuation to be optimal, all exits should finish at approximately the same time. The closer the exits are to finishing at the same time, the closer the simulation is to optimal performance. If each of the 1000 simulations were optimal, we could expect that each exit would finish last approximately an equal number of times (with the 2L and 3L exits being classed as one exit). This would result in each exit finishing last approximately 333 times. As can be seen in Table 15, the number of times an exit finishes last is fairly evenly distributed, with 1L finishing last 329 times, 2L+3L finishing last 319 times, and 4L finishing last 352 times. This suggests that the exit usage is near optimal, with just the rear exit 4L finishing last more often than the others.

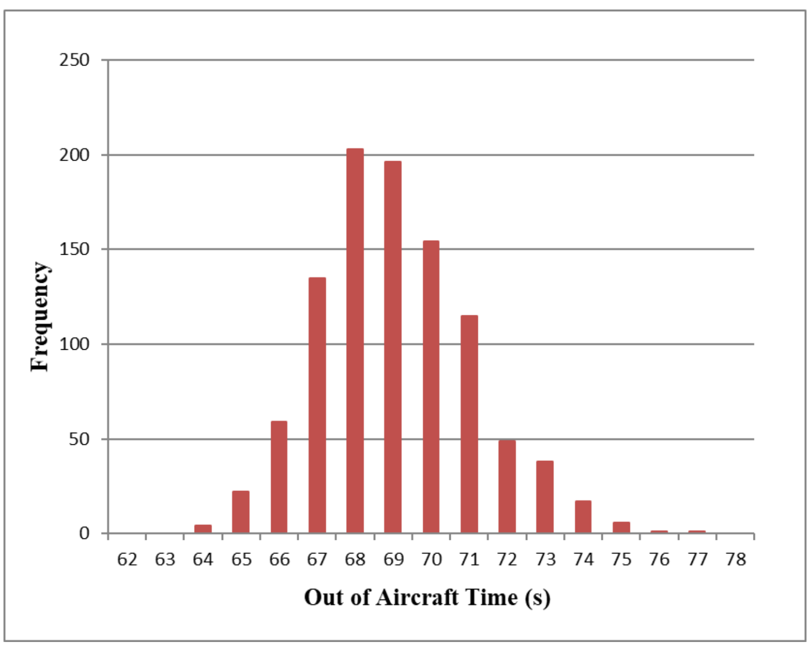
Table 15
Number of times each exit finished last in Scenario 3a (from 1000 repeat cases)

No. of Times	1L	2L	3L	4L	Total
Last Out	329	198	121	352	1000

However, this measure does not take into account how closely the exits were to finishing last and so is only a rough measure of optimality. As discussed previously, the OPS provides a better measure of scenario optimality as it is a normalised measure of the difference between exit finish times relative to the TET. The OPS varies between 0 and 1; the closer it is to 0, the closer the exits are to finishing at the same time, so the closer to optimality is the simulation. The OPS values shown in Table 16 and Table 17are quite small, indicating near-optimal performance, except for the maximum and 95th percentile simulation. For the maximum simulation, the 2L exit finishes last at 76.6 s, while the 4L exit finishes first at 60.4 s, resulting in the larger OPS value for this simulation. In total, 13% (i.e., 130) of the simulations produce an OPS value greater than 0.1 and so are considered sub-optimal.

(b) **Scenario 3a Predicted Evacuation Time Distribution**
Presented in Figure 16 is the TET distribution for Scenario 3a. As can be seen, the distribution is near normal, with a mean TET of 68.6 s, a median TET of 68.4 s, and a standard deviation of 2.02 s. The distribution has a tail of long TETs from 74 s to 77 s, with eight simulations producing a TET of greater than 74 s (74.2 s, 74.2 s, 74.4 s, 74.5 s, 74.5 s, 74.8 s, 75.5 s, and 76.6 s), each of which produced an OPS greater than 0.1 (0.131, 0.106, 0.169, 0.114, 0.160, 0.104, 0.159, and 0.136, respectively) and so were sub-optimal.

Figure 16
Distribution of TET for Scenario 3a produced from 1000 repeat simulations



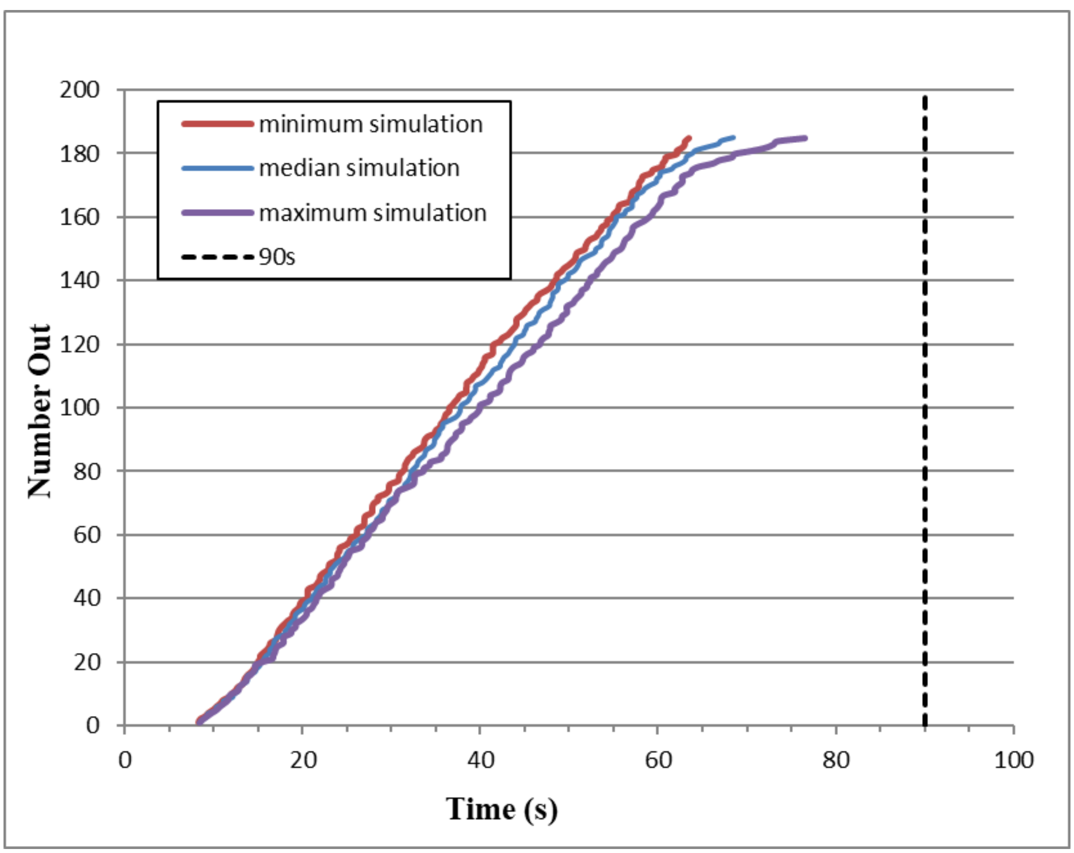
(c) **Scenario 3a Evacuation Exit Curves**

The evacuation exit curves for the Scenario 3a simulations producing the minimum, median, and maximum TETs are presented in Figure 17. As can be seen, the minimum and median simulations produce similar exit curves, with the median curve significantly departing from the minimum curve at around 60 s. This corresponds to the time that the rear overwing (3L) exit finishes (59.8 s), which is closely followed by the forward overwing (2L) exit finishing at 63.2 s. As these exits are no longer supplied by passengers, the exit flow is based solely on the Type C exits. After 63.8 s, the aft Type C exit (L4) finishes and only the front Type C exit (L1) is functioning, resulting in a reduction in the exit flow and the slight downturn in the median exit curve towards the end of the simulation.

The exit curve for the maximum simulation departs from the other curves early and is the result of a combination of factors, such as the higher level of congestion experienced by the agents, with an average CWT of 24.8 s (see Table 16), which is close to the maximum CWT observed in all the simulations (25.8 s, see Table 17), and the high number of agents using the Type-III exits (74). In addition, the significant downturn in exit flow towards the end of the maximum simulation (at around 63 s) results from the large difference in exit finishing times, producing a gap of 16.2 s between the first exit to finish, i.e., 4L at 60.4 s (closely followed by the 1L exit at 64.6 s), with the last exit to finish, i.e., 2L, at 76.6 s—resulting in the large OPS for this simulation. From 65 s, only the two Type-III exits are active.

Figure 17

Exit curves for the minimum, median, and maximum simulations for Scenario 3a



(d) **Scenario 3a Predicted Evacuation Times**
By repeating Scenario 3a 1000 times, with each simulation using a different population, **the OOA TET produced varies between 63.5 s and 76.6 s** with a **median TET of 68.4 s** and a **95th percentile TET of 72.3 s** (see Table 16). The spread in OOA TETs is 13.1 s, with an interquartile range of 2.7 s (25th quartile TET = 67.2 s and 75th quartile TET = 69.8 s). This suggests that while 50% of the 1000 simulations are within +/- 1.35 s of the median TET (68.4 s), 50% of the simulations are outside this range, with 20% (200 cases) between the 75th quartile (TET = 69.8 s) and 95th percentile (72.3 s). The large variation in OOA TETs (13.1 s) and the relatively high (compared to the median) 95th percentile OOA TET (i.e., 72.3 s) are produced simply by repeating the certification demonstration simulation with a different population. As noted for Scenario 1, the predicted variation in evacuation performance cannot be captured by the current certification demonstration trial protocol, i.e., 14 CFR 25.803 [23], as only a single demonstration trial is required.

Furthermore, with the assertiveness of crew at both the forward and aft exits reduced from ‘assertive’ to ‘in-between’, the 95th percentile TET for Scenario 3a is only marginally increased from **71.3 s** (in Scenario 1; see Section 5.2) **to 72.3 s**, an increase of 1.4%. This increase in TET is the result of the small decrease in average exit flow resulting from the PEDT distribution associated with ‘in-between’ assertiveness (see Annex 3).

Table 16
Scenario 3a main evacuation parameters for minimum, median, maximum, and 95th percentile simulations (from 1000 repeat simulations)

	Avg. CWT (s)	Avg. Distance (m)	Avg. PET (s)	TET (s)	OPS
Min Sim	21.1	6.6	35.2	63.5	0.027
***Median Sim**	21.8	6.7	36.3	68.4	0.09
Max Sim	24.1	6.5	38.1	76.6	0.136
95th% Sim	23.7	6.6	37.9	72.3	0.133

**Median sim is the 501st simulation from the 1000 repeat simulations ranked in ascending TET*

The minimum, mean, maximum, and 95th percentile values for the key simulation parameters derived from the 1000 repeat simulations are presented in Table 17. As can be seen, the average distance travelled by an agent varies from 6.4 m to 6.9 m, the time spent in congestion varies from 20.6 s to 25.8 s, while the average PET is 35.0 s to 40.1 s. These results are very similar to those in Scenario 1 (see Table 10). As in Scenario 1, this suggests that the majority of the time (approximately 60% or more based on minimum and maximum simulations) that an individual spends evacuating is primarily due to congestion experienced during the evacuation, i.e., either being stationary in exit queues or moving at a rate less than their preferred walk speed in congested regions of the cabin.

Table 17

Scenario 3a minimum, mean, maximum, and 95th percentile values for the main evacuation parameters (from 1000 repeat simulations)

	Avg. CWT (s)	Avg. Distance (m)	Avg. PET (s)	TET (s)	OPS
Min Value	20.6	6.4	35	63.5	0.003
Mean Value	23	6.6	37.3	68.6	0.066
Max Value	25.8	6.9	40.1	76.6	0.205
95th % Value	24.2	6.7	38.6	72.3	0.124

8.2.3 Key findings Scenario 3b

Scenario 3b (crew assertiveness) investigates the effect of crew assertiveness on overall evacuation performance and evacuation times for an identical exit availability as in Scenario 2 (see Section 6.1), in which exits 1L, 1R, 2L, and 3L are available. However, unlike Scenario 2d, the CC at the Type C exits are not assertive but have been assigned ‘in-between’ assertiveness and so are slightly less assertive compared to the CC in Scenario 2d. As in Scenario 2d, the passengers attempt to select their optimal exit for evacuation, producing a minimum TET for this exit configuration.

By repeating Scenario 3b 1000 times, with each simulation using a different population, **the OOA TET produced varies between 79.7 s and 103.2 s** with a **median TET of 88.9 s** and a **95th percentile TET of 95.3 s.** The spread in OOA TETs is 23.5 s, with an interquartile range of 5.0 s (25th quartile TET = 86.6 s and 75th quartile TET = 91.6 s). This suggests that while 50% of the 1000 simulations are within +/- 2.5 s of the median TET (88.9 s), 50% of the simulations are outside this range, with 20% (200 cases) between the 75th quartile (TET = 91.6 s) and 95th percentile (95.3 s). From a life safety viewpoint, this is clearly a concern, as even the 75th quartile TET exceeds 90 s.

However, with the assertiveness of CC at both forward Type C exits slightly reduced from ‘assertive’ to ‘in-between’, the 95th percentile TET for Scenario 3b is only marginally increased from **94.7 s** (in Scenario 2d, see Section 6.2) **to 95.3 s**, an increase of only **0.6%**. This negligible increase in TET is the result of the small decrease in average exit flow resulting from the PEDT distribution associated with ‘in-between’ assertiveness (see Annex 3). While this is only a small increase in TET, it does not necessarily represent the full impact of CC assertiveness on evacuation performance. The use of unassertive CC operating the exits is likely to further reduce average flow rates achieved, thereby decreasing evacuation performance. Furthermore, the assertiveness of CC is also likely to impact the effectiveness of CC in achieving the cabin splits required for optimal evacuation performance, which was not considered in this scenario.

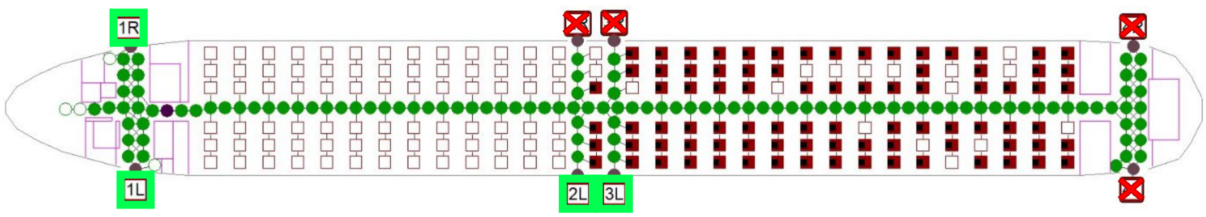
8.2.4 Scenario 3b Results and discussion

(a) **Scenario 3b Exit Usage**

Presented in Figure 18 is an indication of the exits utilised by passengers in the simulation producing the ***median*** TET for Scenario 3b. In the ***median*** simulation, the TET was 88.9 s, with 99 passengers using the forward exits 1L and 1R (those in the ***white*** seats) and 86 passengers using the overwing exits 2L and 3L (those in the ***red*** seats). In total, 17 passengers seated aft of the overwing exits have by-passed the overwing exits to use the forward Type C exits.

Figure 18

Exit usage in Scenario 3b for median simulation; agents seated on white seats utilise 1L and 1R, while agents seated on red seats utilise 2L and 3L



As can be seen in Table 18, the number of times the forward exits (i.e., 1R and 1L) finished last was 192 (i.e., 149 + 43), compared to the overwing exits (i.e., 2L and 3L), which finished last 808 times (i.e., 237 + 571). In comparison, in Scenario 2d, the times that the forward exits and overwing exits finished last were 188 and 812 times, respectively. Thus, the times each of the exits finished last in Scenario 3b are comparable with those in Scenario 2d, with the change in assertiveness of the crew at the Type C exit not significantly impacting the number of times each exit finished last.

Table 18

Number of times each exit finished last in Scenario 3b (from 1000 repeat simulations)

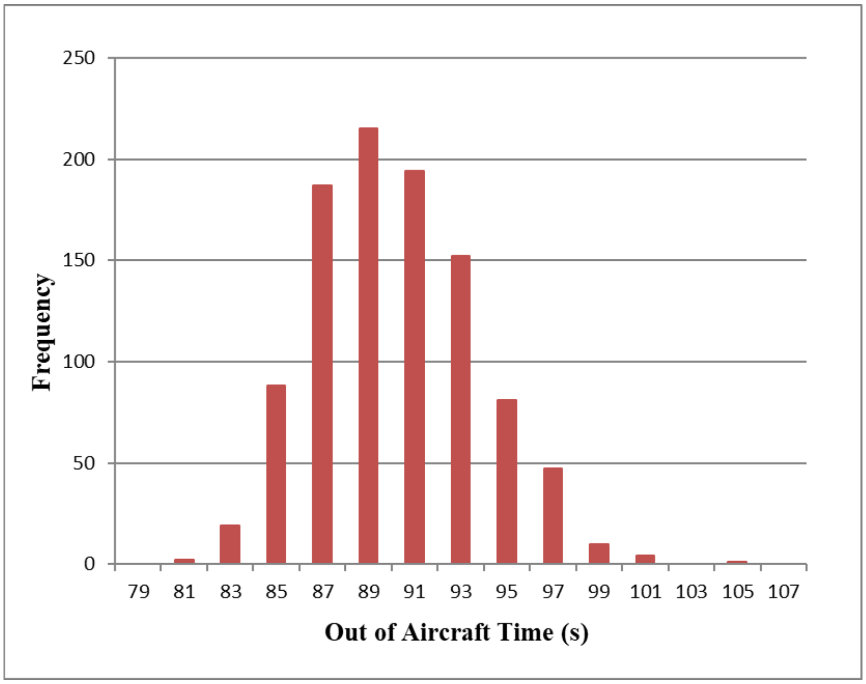
No. of Times	1L	1R	2L	3L	Total
Last Out	149	43	237	571	1000

As described previously, the OPS is a better measure of optimality. The OPS values shown in Table 19 are quite small, indicating near-optimal performance, except for the maximum simulation. In total, only 10.1% (i.e., 101) of the simulations produce an OPS value greater than 0.1 and so are considered sub-optimal.

(b) **Scenario 3b Predicted Evacuation Time Distribution**

Presented in Figure 19 is the TET distribution for Scenario 3b. As can be seen, the distribution is near normal, with a mean of 89.2 s, a median of 88.9 s, and a standard deviation of 3.48 s. The distribution has a tail of long TETs from 99 s to 103 s, with five simulations producing a TET of greater than or equal to 99.0 s (99.94 s, 99.97 s, 100.5 s, 100.5 s, and 103.2 s), each of which produced an OPS greater than 0.1 (0.141, 0.161, 0.142, 0.146, and 0.147, respectively) and so were sub-optimal.

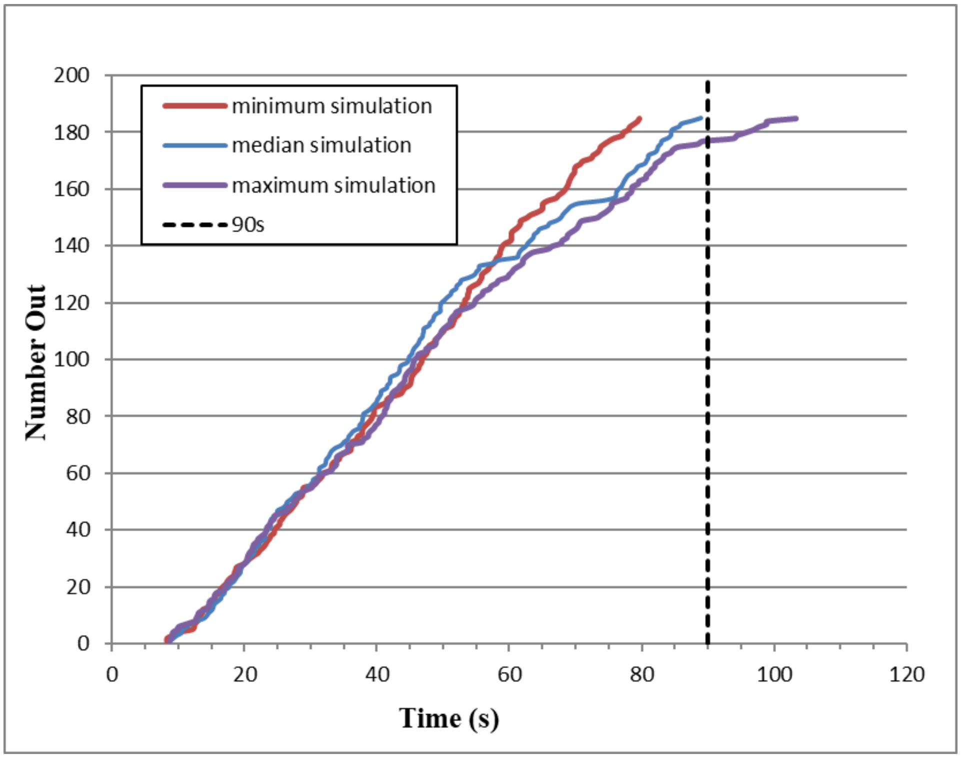
Figure 19
Distribution of TET for Scenario 3b produced from 1000 repeat simulations



(c) **Scenario 3b Evacuation Exit Curves**
The evacuation exit curves for the Scenario 3b simulations producing the minimum, median, and maximum TETs are presented in Figure 20. In comparing the exit curves, it is important to recall that the simulations are simply ranked on TET, and so the evacuation dynamics during the evacuation may be very different for each of these simulations; for example, the simulation producing the median TET may outperform the simulation producing the minimum TET at times during the evacuation (as it does between 40 s and 52 s). Also, as noted in Scenario 2d (see Section 6.2.2c), this scenario is particularly susceptible to slow passengers interpreting the flow to the forward pair of Type C exits. These temporary disruptions to the aisle flow effectively temporarily deprive the Type C exits of passengers, decreasing their average flow. This type of event is more significant in Scenario 3b and Scenario 2d than Scenario 1 or Scenario 3a, as a single passenger can interrupt the flow to two Type C exits. These temporary interruptions in flow appear as short periods where the slope of the exit curve decreases for a period of time (as the Type C exits are deprived of passengers) and then recovers as the flow is resumed. This occurs in the median curve at 50 s and again at 70 s. In contrast, the significant decrease in the slope of the maximum curve at approximately 83 s is caused by the forward two Type C exits finishing their flow at this time, as there are no more passengers using the exit; hence, slope does not recover.

In contrast to the medium and maximum simulations, the exit curve for the minimum evacuation has an essentially constant slope, as it does not suffer from slow passengers interrupting the flow to the Type C exits, and this is a fortuitous random effect of the 1000 repeat simulations—this is an important observation, as the impact of this type of behaviour may be completely missed within the certification demonstration due to the exit combination used in the certification trial (optimal-exit configuration with one exit from each pair) and because only a single trial is performed.

Figure 20
Exit curves for the minimum, median, and maximum simulations for Scenario 3b



Furthermore, the slope of the maximum simulation curve displays a significant reduction towards the end of the simulation resulting from the flow to the forward Type C exits finishing at around 86 s—resulting in the large OPS (0.147) for this simulation. In the maximum simulation, there is a 21.3 s gap between the first exit finishing (1R) and the last exit (3L). In contrast, all the exits in the minimum simulation finish at approximately the same time (approximately 79 s), resulting in a small OPS (0.024) and a small gap (3.9 s) between the first exit to finish (2L) and the last exit to finish (1R).

(d) **Scenario 3b Predicted Evacuation Times**
By repeating Scenario 3b 1000 times, with each simulation using a different population, and reducing the assertiveness of the CC at the Type C exits from ‘assertive’ to ‘in-between’, **the OOA TET produced varies between 79.7 s and 103.2 s** with a **median TET of 88.9 s** and a **95th percentile TET of 95.3 s** (see Table 19). In total, 37.9% (379 simulations) of the 1000 simulations produce a TET of 90 s or greater. The spread in OOA TETs is 23.5 s, with an interquartile range of 5.0 s (25th quartile TET = 86.6 s and 75th quartile TET = 91.6 s). This suggests that while 50% of the 1000 simulations are within +/- 2.5 s of the median TET (88.9 s), 50% of the simulations are outside this range, with 20% (200 cases) between the 75th quartile

(TET = 91.6 s) and 95th percentile (95.3 s). From a life safety viewpoint, this is clearly a concern, as even the 75th quartile TET exceeds 90 s.

Furthermore, with both forward Type C exits and the left pair of Type-III overwing exits available and the assertiveness of crew at the two forward exits reduced from ‘assertive’ to ‘in-between’, a **near-optimal 95th percentile TET of 95.3 s is produced**. While performance in this scenario, in terms of TET, is more than 5 s in excess of 90 s and considerably longer than the **71.3 s** achieved in Scenario 1 (1L, L2, 3L, and 4L exits and assertive crew) (see Section 5.2.2), it is only marginally increased compared to Scenario 2d (similar adverse exit availability and with assertive crew at the Type C exits), i.e., an increase of only 0.6%, from **94.7 s to 95.3 s** (see Section 6.2.2). This small increase in TET is the result of the small decrease in average exit flow resulting from the PEDT distribution associated with ‘in-between’ assertiveness (see Annex 3).

Thus, while the combined effect of these two parameters (i.e., exit availability and reduction in CC assertiveness) produces a worse outcome than either single parameter, the additional impact of the combination, in this case, is negligible. However, it must be noted that the conditions in Scenario 3b (as in Scenario 3a) do not reflect the worst possible case for these parameters, in particular, the assertiveness of the crew at the Type C exit. The worst case involves the crew at the Type C exits behaving in an ‘unassertive’ manner. However, data to specify the PEDT distribution for Type C exits with ‘unassertive’ crew are not currently available, so the PEDT distribution for the ‘in-between’ assertive behaviour was used, representing a less severe degradation in crew performance (see Annex 2 and Annex 3). It is expected that reducing the assertiveness level of the crew at Type C exits to ‘unassertive’ would have a more significant impact on evacuation performance.

As already noted in the discussion for Scenario 2d (see Section 6.2), the predicted evacuation performance produced by this scenario cannot be captured by the current certification demonstration trial protocol, i.e., 14 CFR 25.803 [23], as only a single exit combination is selected for certification demonstration, and the exit combination is the combination that will provide the shortest evacuation time possible.

Table 19

Scenario 3b main evacuation parameters for minimum, median, maximum, and 95th percentile simulations (from 1000 repeat simulations

	Avg. CWT (s)	Avg. Distance (m)	Avg. PET (s)	TET (s)	OPS
Min Sim	25.1	10.6	43.7	79.7	0.024
***Median Sim**	25.7	10.4	44.5	88.9	0.053
Max Sim	28.2	10.3	46.9	103.2	0.147
95th% Sim	28.8	10.6	48.3	95.3	0.063

**Median sim is the 501st simulation from the 1000 repeat simulations ranked in ascending TET*

Of the minimum, median, and maximum simulations, it is noted that the minimum simulation results in the maximum average distance travelled by the agents (10.6 m) and yet produces the minimum PET (43.7 s) and results in the minimum overall TET (79.7 s) (see Table 19). This is due to more exit by-pass occurring in this scenario compared to the other scenarios, resulting in the greatest use of the Type C exits (100 agents in the minimum scenario, 99 in the median, and 95 in the maximum scenario). The more efficient usage of exits reduces the average PET even though the average distance travelled increases.

The minimum, mean, maximum, and 95th percentile values for the key simulation parameters derived from the 1000 repeat simulations for Scenario 3b are presented in Table 20. As can be seen, the average distance travelled by an agent varies from 9.9 m to 11.0 m, the time spent in congestion varies from 23.3 s to 29.4 s, while the average PET varies from 42.1 s to 48.7 s. This suggests that the majority of the time (over 57% based on minimum and maximum simulations) that an individual spends evacuating is primarily due to congestion experienced during the evacuation, i.e., either being stationary in exit queues or moving at a rate less than their preferred walk speed in congested regions of the cabin. These results are very similar to those produced in Scenario 2d (without the reduction in CC assertiveness) (see Section 6.2).

Table 20

Scenario 3b minimum, mean, maximum, and 95th percentile values for the main evacuation parameters (from 1000 repeat simulations).

	Avg. CWT (s)	Avg. Distance (m)	Avg. PET (s)	TET (s)	OPS
Min Value	23.3	9.9	42.1	79.7	0.002
Mean Value	26.3	10.5	45.2	89.2	0.057
Max Value	29.4	11.0	48.7	103.2	0.161
95th % Value	28.1	10.8	47.1	95.3	0.116

9. Phase 1, Scenario 4: Sensitivity Case 3 – Passenger Exit Selection

9.1. Summary of Scenario 4 (Passenger Exit Selection) Setup

Essentially, Scenario 4 involves the same setup as Scenario 1 (see Section 5.1) but utilises nearest-exit selection by the passengers rather than optimal-exit selection as in Scenario 1. As a result, one exit from each exit pair, all on the left side, i.e., 1L, 2L, 3L, and 4L, are available. Each available exit is assumed to open in certification-compliant times, i.e., 8.1 s for the Type C exits and 11.6 s for the Type-III exits (see Section 2.5a). The population demographics are assumed to correspond to those specified in 14 CFR 25.803 [23] (see Section 2.3). However, unlike Scenario

1, which assumes that the passengers attempt to utilise their optimal exits in order to minimise TET (as is typical of certification demonstration trials), in Scenario 4, passengers are assumed to use their nearest exit (as is typical in accidents).

9.2. Scenario 4 (Passenger Exit Selection) Results and Analysis

9.2.1. Scenario 4 Key findings

Scenario 4 (passenger exit selection) investigates the effect of passengers selecting to use their nearest exit (as is likely to occur in accidents) rather than the optimal exits, as typically occurs in the evacuation certification demonstration trial. Essentially this scenario involves a similar setup to Scenario 1 (see Section 5.1); however, unlike Scenario 1, passengers use their nearest exits rather than the optimal exits.

By repeating Scenario 4 1000 times, with each simulation using a different population, **the OOA TET produced varies between 74.9 s and 96.5 s** with a **median TET of 84.3 s** and a **95th percentile TET of 90.1 s**. The spread in OOA TETs is 21.6 s, with an interquartile range of 4.6 s (25th quartile TET = 82.1 s and 75th quartile TET = 86.7 s). This suggests that while 50% of the 1000 simulations are within +/- 2.3 s of the median TET (84.3 s), 50% of the simulations are outside this range, with 20% (200 cases) between the 75th quartile (86.7 s) and 95th percentile (90.1 s). From a life safety viewpoint, this is clearly a concern, as the 95th percentile TET exceeds 90 s. Furthermore, 5.3% (53 simulations) of the 1000 simulations produce a TET of 90 s or greater.

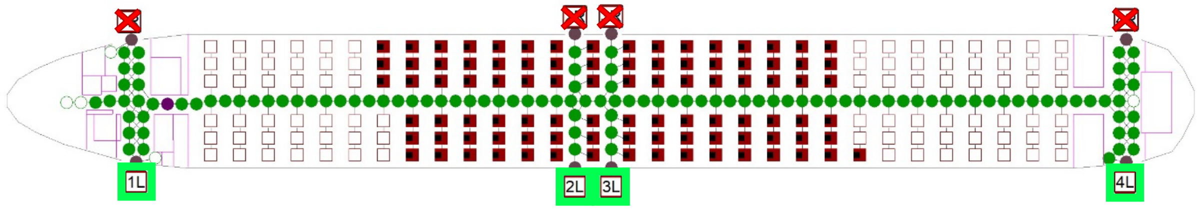
If passenger exit-selection behaviour is changed from optimal (as in most certification demonstration trials) to nearest exit (as is likely to occur in real accidents), evacuation efficiency is significantly reduced, with the 95th percentile TET increasing from **71.3 s** (in Scenario 1) **to 90.1 s** (in Scenario 4), an increase of **26%, and more significantly, results in a failure in terms of the certification demonstration trial performance.**

9.2.2. Scenario 4 Results and Discussion

(a) **Exit Usage**
Presented in Figure 21 is an indication of the exits utilised by passengers in the simulation producing the ***median*** TET for Scenario 4. In the ***median*** simulation, the TET was 84.3 s, with 43 agents using the forward exit 1L (those in the ***white*** seats forward of the overwing exits) and 48 agents using the aft exit 4L (those in the ***white*** seats aft of the overwing exits). In addition, 94 agents used the overwing exits 2L and 3L (those in the ***red*** seats). This demonstrates a significant imbalance in exit usage, with the overwing exits being used more than the forward and aft Type C exits combined (i.e., 1L and 4L). This is expected, as the centre exits are the closest exits to the majority of passengers, and in this scenario, it is assumed that passengers will elect to utilise their nearest exit. In comparison, in Scenario 1 (see Section 5.2.2a), where passengers are assumed to utilise near optimal exits, under effective guidance from the CC, only 70 passengers used the overwing exits in the median case.

Figure 21

Exit usage in Scenario 4 for the median simulation; agents seated on white seats forward of the overwing exits utilise 1L, while agents seated on white seats aft of the overwing exits utilise 4L. Agents seated on red seats utilise 2L and 3L



As can be seen in Table 21, in all 1000 simulations, the overwing exits (2L and 3L) always finish last. This is in stark contrast to Scenario 1, where the overwing exits finished last 409 times (see Section 5.2.2a, Table 6). Clearly, Scenario 4 is less optimal than Scenario 1 and so will result in longer TETs. As described previously, the OPS is a better measure of optimality. The OPS value for the median simulation is 0.218 (see Table 22), and the OPS values for all 1000 simulations are greater than 0.1 (see Table 23), indicating that all these simulations are not optimal.

Table 21

Number of times each exit finished last in Scenario 4 (from 1000 repeat cases)

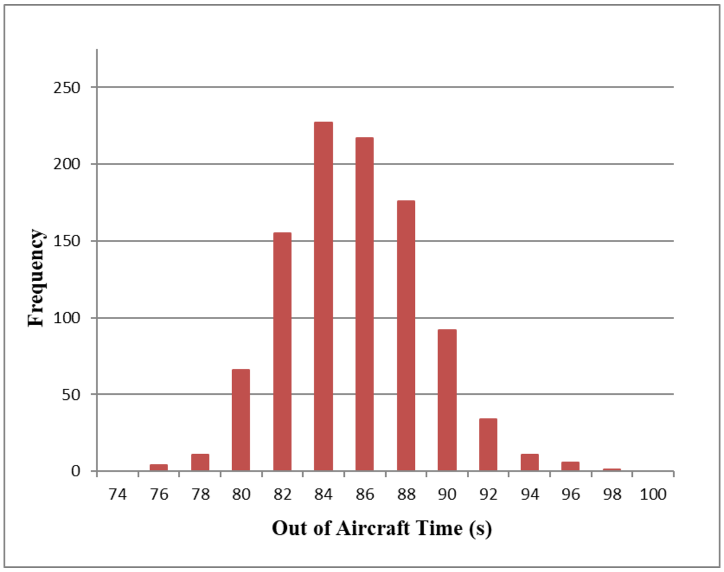
No. of Times	1L	2L	3L	4L	Total
Last Out	0	499	501	0	1000

(b) **Predicted Evacuation Time Distribution**

Presented in Figure 22 is the TET distribution for Scenario 4. As can be seen, the distribution is near normal, with a mean of 84.5 s, a median of 84.3 s, and a standard deviation of 3.34 s. The distribution has a tail of long TETs from 94 s to 96.5 s, with seven simulations producing a TET of greater than 94 s (94.0 s, 94.1 s, 94.3 s, 94.5 s, 95.4 s, 95.7 s, and 96.5 s), each of which produced an OPS greater than 0.1 (0.322, 0.292, 0.303, 0.336, 0.330, 0.315, and 0.354, respectively) and so were sub-optimal.

Figure 22

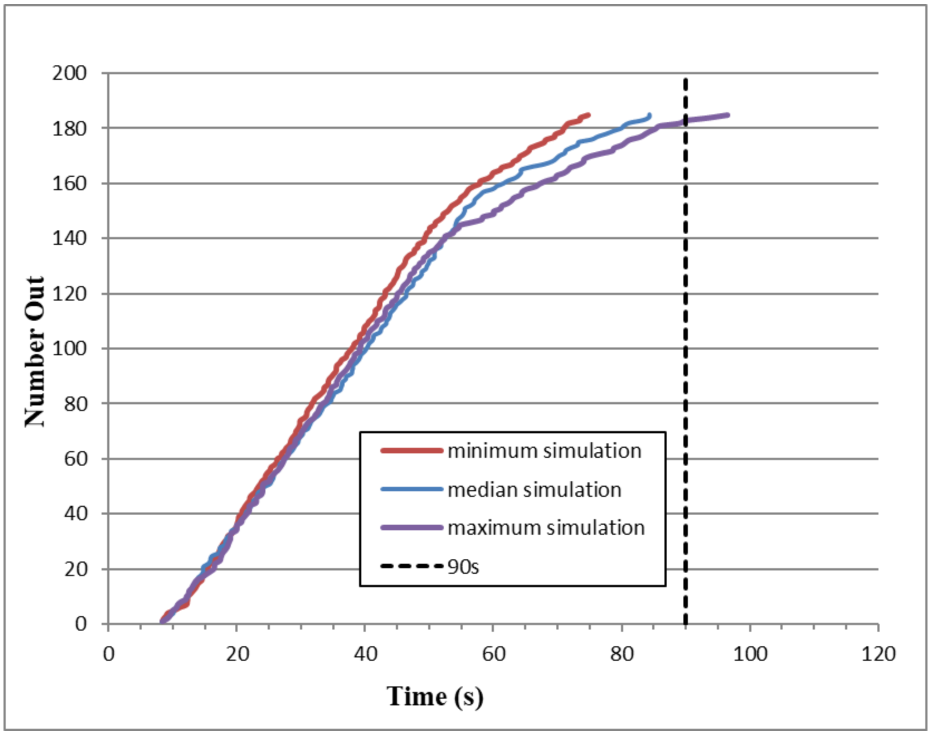
Distribution of TET for Scenario 4 produced from 1000 repeat simulations



(c) **Scenario 4 Evacuation Exit Curves**

The evacuation exit curves for the Scenario 4 simulations producing the minimum, median, and maximum TETs are presented in Figure 23. As can be seen, the minimum and median simulations produce similar exit curves, with the minimum curve generally producing the faster evacuation throughout the evacuation evolution. All three curves display a significant downturn in slope, indicating a slower evacuation due to the early finishing of the forward (1L) and aft (4L) Type C exits. For the minimum case, this is after 56 s (both Type C exits have finished at this time); for the median case, this is after 58 s; and for the maximum case, this is after 52 s.

Figure 23
Exit curves for the minimum, median, and maximum simulations for Scenario 4



Furthermore, as described in Section 7.2.4c, when comparing the exit curves, it is important to recall that the simulations are simply ranked on TET, and so the evacuation dynamics during the evacuation may be very different for each of these simulations. For example, the simulation producing the maximum TET slightly outperforms the simulation producing the median TET at times during the evacuation (e.g., from 35 s to 50 s) but is slower overall, producing a larger TET than in the median case. The maximum TET simulation is slower than the median TET simulation overall due to a combination of factors, such as the higher average level of congestion experienced by the agents in the maximum case, with an average CWT of 26.6 s, compared with 25.4 s in the median case (see Figure 23); the greater number of agents using the overwing Type-III exits in the maximum case, i.e., 98, compared with 94 in the median case; and that the Type C exits finish sooner in the maximum case. Nevertheless, during the evolution of the evacuation in the median TET simulation, there is a particularly slow elderly person seated in the 3L exit row that creates an obstruction to the flow through the 3L Type-III overwing exit, which reduces the flow through the exit. They eventually move out of the way at approximately 47 s and exit the aircraft at approximately 50 s. In contrast, in the maximum TET simulation, the equivalent location is clear of obstructing passengers at approximately 26 s.

(d) **Scenario 4 Predicted Evacuation Times**
By repeating Scenario 4 1000 times, with each simulation using a different population, **the OOA TET produced varies between 74.9 s and 96.5 s** with a **median TET of 84.3 s** and a **95th percentile TET of 90.1 s** (see Table 22). In total, 5.3% (53 simulations) of the 1000 simulations produce a TET of 90 s or greater. The spread in OOA TETs is 21.6 s, with an interquartile range

of 4.6 s (25th quartile TET = 82.1 s and 75th quartile TET = 86.7 s). This suggests that while 50% of the 1000 simulations are within +/- 2.3 s of the median TET (84.3 s), 50% of the simulations are outside this range, with 20% (200 cases) between the 75th quartile (86.7 s) and 95th percentile (90.1 s). From a life safety viewpoint, this is clearly a concern, as the 95th percentile TET exceeds 90 s.

While performance in this scenario, in terms of TET, is only 0.1 s in excess of 90 s, it is considerably longer than the 95th percentile achieved in Scenario 1 (**71.3 s**), where passengers elected to use their optimal exits, i.e., an increase of 26.4 % (18.8 s), from **71.3 s to 90.1 s** (see Section 5.2). Thus, passengers electing to use their nearest exit to evacuate (as opposed to their optimal exit) significantly increases TET. This is due to an overusage of the overwing Type-III exits (see Figure 21)—the slowest exits on the aircraft. This type of evacuation performance, which is typical of real accidents, is unlikely to occur in the certification demonstration trial (i.e., 14 CFR 25.803 [23]), as in the ideal conditions of the certification trial, CC are usually effective in directing passengers to their optimal exits.

Furthermore, the large variation in OOA TETs (21.6 s) and the relatively high (compared to the median) 95th percentile OOA TET (i.e., 90.1s) are produced simply by repeating the simulation 1000 times using a different population. As noted for Scenario 1 (see Section 5.2), the predicted variation in evacuation performance cannot be captured by the current certification demonstration trial protocol, i.e., 14 CFR 25.803 [23], as only a single demonstration trial is required.

Table 22

Scenario 4 main evacuation parameters for min, median, max, and 95th percentile simulations (from 1000 repeat cases

Scenario 4	Avg. CWT (s)	Avg. Distance (m)	Avg. PET (s)	TET (s)	OPS
Min Sim	23.5	6.2	37	74.9	0.2
***Median Sim**	25.4	6.2	39.3	84.3	0.218
Max Sim	26.6	6.3	40.3	96.5	0.354
95th% Sim	26.5	6.3	40.3	90.1	0.285

**Median sim is the 501st simulation from the 1000 repeat simulations ranked in ascending TET*

The minimum, mean, maximum, and 95th percentile values for the key simulation parameters derived from the 1000 repeat simulations are presented in Table 23. As can be seen, the average distance travelled by an agent varies from 6.1 m to 6.5 m, the time spent in congestion varies from 22.5 s to 28.5 s, while the average PET varies from 36.1 s to 42.5 s. In Scenario 4 (nearest-exit usage), the mean average distance travelled by agents is 6.3 m, compared to 6.6 m in Scenario 1 (optimal-exit usage; see Table 10). Clearly, in Scenario 4, as agents use their nearest exit, they will travel a shorter distance to exit compared to Scenario 1. However, while the average distance travelled is shorter in Scenario 4, the mean average CWT and PET experienced by agents are longer in Scenario 4, i.e., 25.3 s and 39.1 s, respectively, compared to 22.9 s and 37.0

s, respectively, in Scenario 1 (see Table 10). Thus, while the agents travel a shorter distance in Scenario 4, they experience greater congestion and, as a result, have longer personal evacuation times.

Furthermore, in Scenario 4, agents spend approximately 65% of their time evacuation time in congestion (i.e., either being stationary in exit queues or moving at a rate less than their preferred walk speed in congested regions of the cabin), compared with approximately 60% of their evacuation time in Scenario 1.

Table 23

Scenario 4 min, mean, max, and 95th percentile values for the main evacuation parameters (from 1000 repeat cases)

Scenario 4	Avg. CWT (s)	Avg. Distance (m)	Avg. PET (s)	TET (s)	OPS
Min Value	22.5	6.1	36.1	74.9	0.121
Mean Value	25.3	6.3	39.1	84.5	0.251
Max Value	28.5	6.5	42.5	96.5	0.354
95th % Value	26.8	6.4	40.6	90.1	0.3

10. Discussion of Phase 1 Results

Presented in Table 24 is a summary of the near-optimal evacuation performance achieved for the aircraft configuration in Scenario 1 (exits 1L, 2L, 3L, and 4L) (see Section 5.2), Scenario 2d (exits 1L, 1R, 2L, and 3L) (see Section 6.2), Scenario 3a (exits 1L, 2L, 3L, and 4L, and with CC with reduced assertiveness) (see Section 7.2.2), Scenario 3b (exits 1L, 1R, 2L, and 2L, and with CC with reduced assertiveness) (see Section 7.2.4), plus the evacuation results for the nearest-exit evacuation performance achieved for the aircraft configuration in Scenario 4 (exits 1L, 2L, 3L, and 4L) (see Section 8.2) and the nearest-exit variant of Scenario 2d (from [16]).

As can be seen, even though each scenario includes similar populations, and in each case, 50% of the available exits are utilised (with the same mix of exit types), the 95th percentile TET can vary significantly. Across all six scenarios, the 95th percentile TET varies from 71.3 s (Scenario 1) to 127.7 s (nearest-exit variant of Scenario 2d [16]).

Table 24

Main evacuation parameters for the simulations producing the 95th percentile TET for Scenario 1, 2d, 3a, and 3b with optimal passenger exit selection and Scenario 4 and the variant of Scenario 2d (from [16]) with nearest-exit passenger selection

Case	Avg. CWT (s)	Avg. Dist. (m)	Avg. PET (s)	95th percentile TET (s)	OPS
Scenario 1 Optimal, exits 1L, 2L, 3L, 4L	23.47	6.65	37.9	71.3	0.096
Scenario 2d Optimal, exits 1L, 1R, 2L, 3L	26.80	10.50	45.5	94.7	0.110
Nearest-exit variant of Scenario 2d (from [16]) Nearest, exits 1L, 1R, 2L, 3L	44.26	7.70	60.3	127.7	0.461
Scenario 3a Optimal, exits 1L, 2L, 3L, 4L 0% 'assertive' crew	23.70	6.60	37.9	72.3	0.133
Scenario 3b Optimal, exits 1L, 1R, 2L, 3L 0% 'assertive' crew	28.80	10.60	48.3	95.3	0.063
Scenario 4 Nearest, exits 1L, 1R, 2L, 3L	26.5	6.3	40.3	90.1	0.285

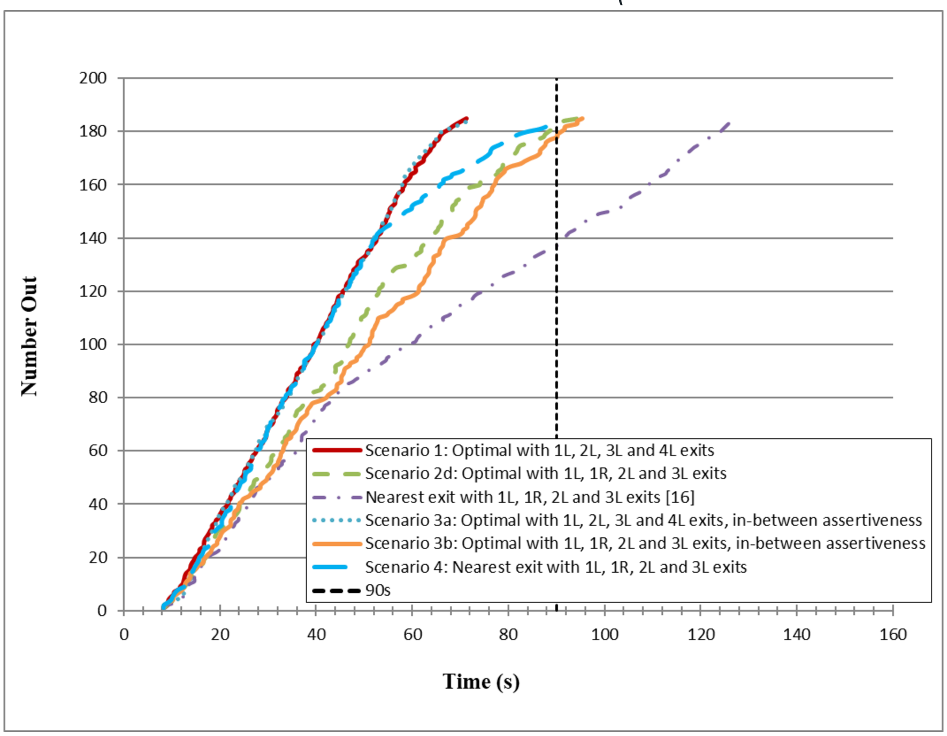
It is also worth noting that the evacuation performance achieved in Scenario 1 is intended to reflect the performance likely to be achieved in the actual certification trial. While the certification demonstration trial performance for the 185-seat variant of the airplane configuration investigated in this study was not available for comparison purposes, the actual certification performance for the 194-person variant of the airplane was available (see Section 4). This was used to estimate, using interpolation, the certification performance for of the 185-person variant of the aircraft studied in the current work. Using these data, it is estimated that the OOA TET for the 185-person variant in a certification trial would be 76.9 s with an OPS of 0.115 (see Section 4). The estimated certification trial performance falls within the range of predicted OOA TETs for

Scenario 1 (i.e., 62.9 s to 77.0 s; see Section 5.2.2d). This suggests that the predicted Scenario 1 simulation results are a reasonable approximation of the likely certification performance for the aircraft. Furthermore, while the estimated certification trial TET (i.e., 76.9 s) is towards the high end of the predicted TET range, its OPS (i.e., 0.115) is equivalent to the sub-optimal OPS produced by the simulation in the high end of the predicted TET distribution (where OPS varies from 0.117 to 0.140, and the corresponding predicted TETs vary from 75.6 s to 77.0 s (see Section 5.2.2b)). Thus, the estimated certification trial TET naturally fits within the tail of the predicted TET distribution. The simulation within the tail of the TET distribution producing an OPS (i.e., 0.117) equivalent to that of the certification trial (i.e., 0.115) corresponds to a predicted TET of 75.6 s, which is just 1.7% (1.3 s) smaller than the certification time.

Presented in Figure 24 are the evacuation curves for the simulations producing the 95th percentile TETs for the six scenarios presented in Table 24. As can be seen, five of the six scenarios produce very different exit curves and result in very different evacuation performance (i.e., all except Scenario 3a). Furthermore, four of the six scenarios (i.e., Scenario 2d, Scenario 3b, Scenario 4, and the equivalent nearest-exit variant of Scenario 2d (from [16])) produce TETs in excess of 90 s.

Figure 24

Evacuation performance of the 95th percentile cases for Scenarios 1,2d, 3a, and 3b optimal cases, and nearest-exit cases Scenario 4 and Scenario 2d (nearest-exit variant from [16])



Furthermore, the best evacuation performance is for Scenario 1 (exits 1L, 2L, 3L, and 4L), which is a scenario equivalent to the certification demonstration trial protocol (14 CFR 25.803 [23]), producing a 95th percentile TET of 71.3 s, while the worst performance is for the nearest-exit variant of Scenario 2d (exits 1L, 1R, 2L, and 3L), which produces a 95th percentile TET of 127.7 s. The significant differences between these two extremes of evacuation performance are the exit availability, i.e., which 50% of the available exits are used (while maintaining the mix of available exits, i.e., two Type C and two Type-III exits) and the passenger exit-selection behaviour. In Scenario 1, the passengers select their optimal exits, assuming that CC can direct passengers to their optimal exits (as usually occurs in the ideal conditions of a certification trial), while in the nearest-exit variant of Scenario 2d, passengers elect to use their nearest exit (as in accident scenarios). The small and relatively slow Type-III exits are the closest to the majority of passengers, so in the nearest-exit scenarios, these exits become overutilised.

In the remainder of this section, the impact of the key parameters on evacuation performance is discussed in turn.

(i) **Exit Availability**
With passengers exhibiting optimal exit-selection behaviour (Scenarios 1, 2d, 3a, and 3b) and assertive CC (Scenarios 1 and 2d), **simply selecting a different combination of 50% of the available exits (Scenarios 1 and 2d) can increase the 95th percentile TET from 71.3 s to 94.7 s, an increase in evacuation time of 23.4 s or 32.8%.** More significantly, this change in exit availability results in a different conclusion concerning the acceptability of the evacuation performance achieved by this airplane configuration, from a pass (Scenario 1) to a failure (Scenario 2d), in terms of satisfying the 90 s certification requirement. The reason for this significant difference in evacuation performance is that the two forward Type C exits in Scenario 2d are not able to achieve their maximum flow due to the inability of the narrow cabin aisle to supply a sufficient passenger flow to the two Type C exits.

In Scenario 2d (exits 1L, 1R, 2L, and 3L), the forward pair of Type C exits and the two left overwing Type-III exits are available. Thus, 50% of the available exits produce significantly slower TETs compared to Scenario 1 (exits 1L, 2L, 3L, and 4L), even though the same types of exits are available in both cases. This is due to the forward pair of Type C exits in Scenario 2d not being able to achieve and sustain their maximum flow rate due to the narrow cabin aisle not being able to provide sufficient flow to maintain two Type C exits operating at maximum flow. Thus, in Scenario 1, while each of the available Type C exits produces a sustained average exit flow of 61.0 ppm, in Scenario 2d, the Type C exits only manage a sustained average exit flow of 41.3 ppm each. Overall, the two Type C exits in Scenario 2d are 30% less effective than the two Type C exits in Scenario 1, increasing the TET for Scenario 2d by 33% compared to Scenario 1.

It is also worth noting that given the exit availability in Scenario 2d (exits 1L, 1R, 2L, and 3L), managing the cabin splits and exit by-pass required to provide sufficient passengers to maintain the forward Type C exits will be challenging without some form of intervention, such as additional CC positioned in the vicinity of the overwing exits or some technological aid to assist in directing passengers to utilise the forward exits. Finally, the evacuation performance in Scenario 2d is highly susceptible to slow-moving passengers (e.g., elderly or disabled (the latter not included in the simulation)) who can create momentary gaps in the supply of passengers to both Type C exits. While the same slow-moving passengers exist in Scenario 1, their impact is less noticeable, as their behaviour will impact only one Type C exit at any time.

(ii) **Crew Assertiveness**

If the assertiveness of the CC at the Type C exits is decreased only slightly, from 'assertive' to 'in-between', the TET is increased only marginally. Comparing Scenario 1 (exits 1L, 2L, 3L, and 4L, with 'assertive' crew) and Scenario 3a (exits 1L, 2L, 3L, and 4L, with 'in-between' crew), the 95th percentile TET increases from **71.3 s** (in Scenario 1; see Section 5.2) **to 72.3 s** (in Scenario 3a; see Section 7.2.2), an increase of only **1.4%.** Comparing Scenario 2d (exits 1L, 1R, 2L, and 3L, with 'assertive' crew) and Scenario 3b (exits 1L, 1R, 2L, and 3L, with 'in-between' crew), the 95th percentile TET increases from **94.7 s** (in Scenario 2d; see Section 6.2) **to 95.3 s** (in Scenario 3b; see Section 7.2.4), an increase of only **0.6%.**

This increase in TET is the result of the small decrease in average exit flow resulting from the PEDT distribution associated with 'in-between' assertiveness (see Annex 3). While this is only a small increase in TET, it does not necessarily represent a true impact of the importance of CC assertiveness on evacuation performance. As noted in Section 2.5b, the impact of unassertive CC on evacuation performance could not be assessed in this study, as PEDT data associated with unassertive CC for Type C exits are not currently available. The use of unassertive CC operating the exits is likely to further reduce average flow rates achieved, thereby decreasing evacuation performance (this has been observed in certification trials involving Type A exits [17, 19]). In addition, the assertiveness of CC is also likely to impact the effectiveness of CC in achieving the cabin splits required for optimal evacuation performance. In these simulations, it was assumed that a near-optimal cabin split would be achieved by CC that displayed 'in-between' assertive behaviour at their exit. While this may be a valid assumption, it is likely that if the CC were unassertive, this would not only greatly impact the flow rates achieved at the exit but also reduce the effectiveness of CC in achieving the required optimal cabin splits. In this case, the passenger exit selection may be more similar to the sub-optimal 'nearest exit' cabin split. The impact of changing the passenger exit selection from optimal to nearest exit is discussed in the next section.

(iii) **Passenger Exit Selection**

If passenger exit-selection behaviour is changed from near optimal (as in most certification demonstration trials) to nearest exit (as is likely to occur in real accidents), evacuation efficiency is significantly reduced, with a significant increase in TET. Comparing Scenario 1 (exits 1L, 2L, 3L, and 4L, with optimal-exit selection) and Scenario 4 (exits 1L, 2L, 3L, and 4L, with nearest-exit selection), the 95th percentile TET increases from **71.3 s** (in Scenario 1) **to 90.1 s** (in Scenario 4), an increase of **26% and more significantly, results in a failure in terms of the certification demonstration trial performance.** Comparing Scenario 2d (exits 1L, 1R, 2L, and 3L, with optimal-exit selection) and the nearest-exit selection variant of Scenario 2d (exits 1L, 1R, 2L, and 3L, with nearest-exit selection) from [16], the 95th percentile TET increases from **94.7 s** (in Scenario 2d) **to 127.7 s** (in nearest-exit variant of Scenario 2d), an increase of **35%.** Changing passenger exit selection bias from optimal to nearest-exit has a **significant** impact on evacuation performance.

The degradation in evacuation performance as measured by TET between Scenarios 1 and 4 is also reflected in the respective increase within their OPS values. The relatively low OPS value within Scenario 1 (i.e., 0.096) indicates a well-balanced use of the exits, with all exits finishing relatively closely to one another. In contrast, the much higher OPS value evident within Scenario

4 (i.e., 0.285) is indicative of poorly balanced exits that potentially finish a significant time apart from one another. This increase in OPS is a direct consequence of the significant overuse of the overwing exits, which are the closest exits for the majority of passengers.

The overall evacuation curves for Scenarios 1 and 4 generally demonstrate a large degree of similarity in the early stages of the evacuation (i.e., up to approximately **50 s**; see Figure 24). This is expected, as in the early stages of the evacuation, there is a steady flow of passengers to each of the four available exits (i.e., 1L, 2L, 3L, and 4L), and, hence, the overall flow from the aircraft is operating at its maximum. However, beyond approximately **50 s**, there is a marked reduction in the overall flow observed in Scenario 4 and, hence, a significant increase in TET. The point at which these curves deviate (approximately 50 s) corresponds to the time at which the flow to both the forward and aft Type C exits (i.e., 1L and 4L) has been exhausted. Consequently, beyond this point, the total flow from the aircraft corresponds to only those passengers exiting via the overwing exits (i.e., 2L and 3L). This is in direct contrast to Scenario 1 (i.e., optimal), where all four exits continued to be used until much later into the evacuation, resulting in greater overall exit flows and, hence, a reduced TET. Similar behaviour occurs in Scenario 2d (exits 1L, 1R, 2L, and 3L) and the nearest-exit variant of Scenario 2d [16]. However, in this case, the flow to the two forward Type C exits finishes at approximately **45 s** (see Figure 24).

(iv) **Crew Assertiveness and Exit Availability**

It is clear that both scenarios involving CC with marginally reduced assertiveness (set to ‘in-between’), i.e., Scenario 3a and Scenario 3b, are only marginally slower than their equivalent scenarios with fully assertive CC, i.e., Scenario 1 and Scenario 2d, respectively. However, while the evolution of the evacuation noted in Scenario 1 (exits 1L, 2L, 3L, and 4L with ‘assertive’ CC) and Scenario 3a (exits 1L, 2L, 3L, and 4L with ‘in-between’ CC) appear to be indistinguishable (both curves are virtually on top of each other), there are clear differences in the evacuation evolution noted in Scenario 2d (exits 1L, 1R, 2L, and 3L with ‘assertive’ CC) and Scenario 3b (exits 1L, 2L, 3L, and 4L with ‘in-between’ CC). In particular, Scenario 2d appears to allow more passengers to evacuate at each instant after approximately 50 s, up to the end of the evacuation.

However, these differences in evacuation evolution are not the result of the differences in assertiveness of the CC but more to do with the nature of the scenario and the exit availability, i.e., 1L, 1R, 2L, and 3L. In Scenarios 2d and 3b, the two forward pairs of Type C exits and the two left overwing Type-III exits are available, and as described in (i), this combination of exits produces significantly slower TETs, as the forward Type C exits cannot achieve their maximum flow rate due to the narrow cabin aisle not being able to provide sufficient flow to maintain two Type C exits operating at maximum flow.

In addition, given that the performance of the two forward Type C exits in Scenarios 2d and 3b are dependent on the same portion of narrow cabin aisle, evacuation performance with this exit availability is highly susceptible to slower-moving passengers who can create momentary gaps in the supply of passengers to both Type C exits. While the same slower-moving passengers exist in Scenario 1, their impact is less noticeable, as their behaviour will only impact one of the two Type C exits at any one time. Furthermore, as the simulations are repeated 1000 times with randomly generated populations and seating allocations, it is possible that some of these repeat simulations will randomly assign a number of slow-moving passengers to the portion of the cabin where they can have the greatest impact on evacuation performance in Scenarios 2d and 3b, i.e., in the forward part of the cabin. This is why it is possible for the evacuation curves for Scenarios 2d and 3b to appear very different, while Scenarios 1 and 3a are almost identical.

Furthermore, in Scenarios 3b and 2d, the evacuation performance is dependent on the by-pass behaviour exhibited by passengers around the 2L/3L exits. This is strongly dependent on congestion around the 2L/3L and 1L/1R exits, and the resolution of passenger behaviour has a stochastic component.

(v) **Combining Two Parameters: Exit Availability and Passenger Exit Selection**
Combining the impact of two parameters, **i.e., exit availability and passenger exit selection,** in the nearest-exit variant of Scenario 2d (exits 1L, 1R, 2L, and 3L available) **significantly increases 95th percentile TET** compared to Scenario 1 (exits 1L, 2L, 3L, and 4L available and optimal passenger exit selection) **from 71.3 s to 127.7 s, an increase of 56.4 s or 79%.**

11. Phase 2: The Use of Evacuation Modelling to Enhance Certification

In this chapter, we discuss the current evacuation certification requirements and explore how advanced agent-based evacuation modelling could be used to enhance the current evacuation certification process.

11.1. Potential Limitations in Current 14 CFR 25.803 Evacuation Demonstration Protocol

P rior to exploring how agent-based evacuation modelling could potentially be used to enhance the evacuation certification process, it is useful to summarise the current evacuation certification protocol and highlight several potential limitations in the process.

Before an airplane can be licensed to carry passengers on commercial flights, the manufacturer must demonstrate that their airplane design (seating more than 44 passengers) can meet the evacuation requirements of 14 CFR 25.803 (also known as FAR 25.803), along with Appendix J to Part 25, Title 14 (also known as Appendix J to Part 25, FAR) [23]. These requirements are also commonly referred to as ’90-second certification test’ or ’90-second demonstration’ or the ‘full-scale demonstration’. Presented in Annex 4 is the text of 14 CFR 25.803 and Appendix J.

Essentially, the 90-second certification test is a full-scale evacuation trial for commercial airplanes. It is a measure of the evacuation performance of the airplane design, evacuation equipment, crew performance, and the appropriateness of the crew procedures in a prescribed evacuation scenario. The trial is intended to demonstrate that the maximum seating capacity, including the number of crewmembers required by the operating rules for which certification is requested, can be evacuated from the airplane to the ground under the simulated emergency conditions (as stipulated in Appendix J) within 90 s.

Key aspects of the 90-second certification test include (but are not limited to) the following aspects:

- Only half (50%) of the normally available exits can be used in the trial, which must consist of one exit from each exit pair (requirement (p) in Appendix J, see Annex 4).
- Trial participants are selected according to a specified demographic to be representative of the travelling public (age and gender distribution) and must be in normal health (requirement (h) in Appendix J, see Annex 4).
- Crew and passengers do not know beforehand which exits will be made available (requirement (l) in Appendix J, see Annex 4).
- The trial is conducted in conditions of low visibility (darkness); only the airplane's emergency lighting system may provide illumination (requirement (d) in Appendix J, see Annex 4).
- Carry-on luggage and blankets, approximately half of the total average amount of carry-on luggage, are positioned in aisles and emergency exit accessways (cross-aisles) to create minor obstructions (requirement (k) in Appendix J, see Annex 4).
- Prior to entering the demonstration aircraft, participants may be advised to follow directions of CC, and once participants are seated on board, they are given the normally required pre-flight safety briefing (requirement (n) in Appendix J, see Annex 4).

For each new airplane design, **only a single** 90-second certification trial is required, so **only a single population demographic** and a **single passenger seating allocation** are considered.

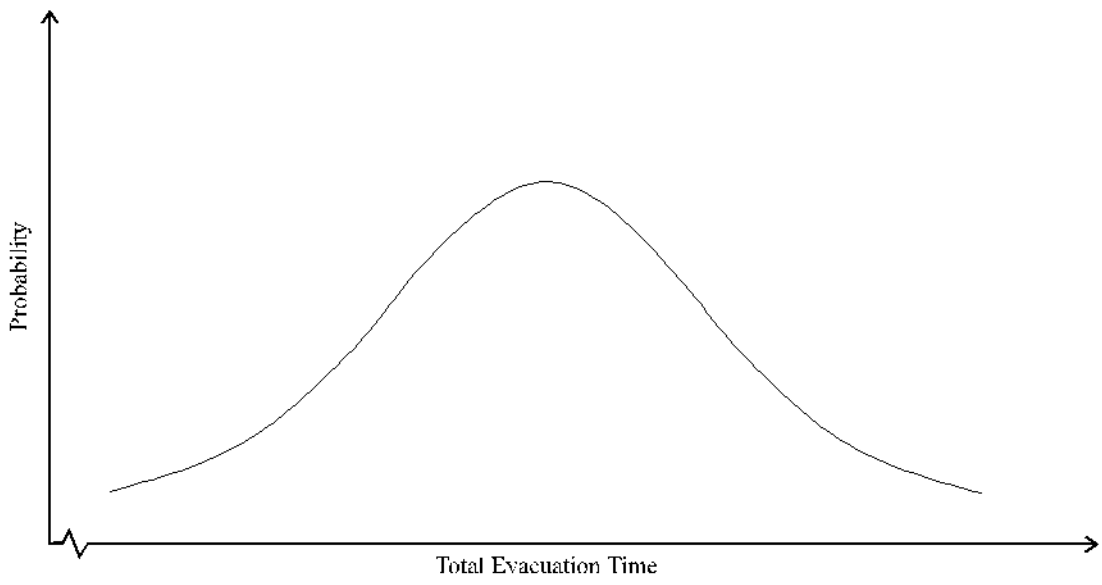
Given the nature of the evacuation certification protocol outlined above, several limitations in the process can be identified.

(i) Only a single evacuation trial is performed

By its very nature, the evacuation dynamics resulting from passenger interactions during aircraft evacuation are stochastic, so the outcome of an aircraft evacuation is a stochastic event. Thus, if the evacuation is repeated under the same conditions, with the same passengers in the same seats or the same passengers with different seat allocations or with different passengers meeting the prescribed demographic, the evacuation time will be different. If the trials were repeated a sufficient number of times, it is likely that the distribution of total evacuation times would be approximately normally distributed (see Figure 25) or would be a skewed normal distribution if different types of populations were included, as suggested in (ii). With only a single evacuation conducted for the certification trial, it is not possible to distinguish a lucky fast evacuation time produced by an inherently slow design from an unlucky slow evacuation time produced by an inherently fast design.

Figure 25

Hypothetical distribution of the Total Evacuation Time for repeated evacuations of a given aircraft configuration and a given evacuation scenario, assuming different populations satisfying the population demographics for the certification demonstration trial



To truly understand the likely performance of the aircraft under the prescribed certification trial conditions, it is therefore necessary to repeat the evacuation a number of times, thereby generating a distribution of expected evacuation performance. As only a single evacuation trial is stipulated by the current certification requirements, there can be, at best, limited confidence that the trial result—whether successful or not—truly represents the evacuation capability of the aircraft. Furthermore, as only a single trial is conducted, it is not possible to specify a confidence level for the achieved evacuation performance, as the single evacuation time data point could fall on any part of the evacuation time distribution (see Figure 25).

However, associated with the need to run multiple evacuation trials is the risk of injury to participants. Published statistics for the period between 1972 and 1991 reveal that a total of 378 volunteers (or 6% of participants) sustained injuries ranging from cuts and bruises to broken bones, with the most serious injury to date resulting in permanent paralysis [30]. Finally, to implement and run a single full-scale evacuation demonstration trial is relatively expensive. For instance, an evacuation trial for a wide-body aircraft costs in the vicinity of $US 2 million (estimated cost from the early 1990s, and it is not inflation-adjusted) [30]. Thus, repeating the certification trial multiple times would significantly increase the number of likely (potentially serious) injuries sustained and the associated cost of the certification process.

(ii) Only a single population mix is selected

Identifying a representative population to be used in the one-off certification trial is a complex task and is currently simplified by selecting an appropriate population mix based simply on the age and gender of the participants. However, only a single population mix satisfying the specified demographic is tested, as only a single trial is conducted. This practice assumes that each population satisfying the imposed demographic will behave and perform in an identical manner and furthermore, that evacuation performance is not dependent on seating allocation. In reality, these assumptions are unlikely to be valid. Only selecting a single population satisfying the certification demographic and only testing a single seating allocation can impact the outcome of the certification demonstration trial in a random way—with higher or lower total evacuation times being possible if a different population mix and seating allocation were investigated.

Furthermore, the evacuation certification trial population specification assumes that each passenger is socially unconnected to other passengers. In reality, passenger behaviour during evacuation may be influenced by the presence of travelling companions (e.g., other adults, including elderly adults requiring assistance, children of walking age and infants) and the nature of the social bond that exists between them. For example, family groups are more likely to evacuate together as a group rather than as the same number of unconnected individuals. The movement speed of the group is also likely to be dictated by the speed of the slowest member of the group. Furthermore, if the group is separated prior to evacuation, for example, due to seating allocations, it is likely that the group will attempt to reunite prior to evacuating. An analysis undertaken using data from past accidents [10-12, 31] suggests that a significant proportion of passengers travel with a ‘companion’ [10]. (Note references 10, 11, 12, and 31 refer to the AASK database, which contains detailed information from 105 airplane accidents, including information from 1917 passengers and 155 cabin crew, with information relating to some 338 fatalities. The accidents included in AASK V4.0 cover the period 04/04/77 – 23/09/99.) The frequency of passengers travelling within groups, the size and composition of the groups, and the nature of the group dynamic during emergency evacuation situations may have significant implications for not only evacuation certification but also airplane operation and cabin crew training. However, this important component of evacuation dynamics, which is likely to have a negative impact on evacuation performance, is excluded from the certification trial, as the population mix does not represent social groups.

Another factor related to the population that is ignored by the certification trial is the presence of passengers with disabilities. As people with disabilities are not represented in the certification trial, their impact on evacuation efficiency—whatever that may be—is not measured. As it is not measured, it cannot be factored into the certification analysis. As used here, the term disability is intended to cover a range of conditions that are likely to impede rapid evacuation, including visual, cognitive, physical, and other medical conditions. In addition, some conditions may make it impossible for the disabled person to evacuate without the aid of a helper and/or a movement assistance device, while other disabilities allow the person to move unaided but at a slower rate. Also, some medical conditions that may impact the speed at which a passenger can evacuate may be temporary, such as an injury incurred prior to the flight or during the flight resulting from the accident or may simply be related to a natural condition, e.g., pregnancy. Finally, some people with disabilities can be easily identified, e.g., wheelchair users, while other people with disabilities who may impede rapid evacuation may not, e.g., a person with a medical condition such as heart disease. Furthermore, experimental trials undertaken by the FAA suggest that passengers with some forms of severe movement disability can require more than twice as much time (dependent on the nature of the disability) as non-disabled passengers to evacuate, unaided, from an aircraft [38]. This may have a significant impact on the overall evacuation efficiency and, hence, the maximum passenger capacity of the aircraft but is ignored in the current certification process and in the subsequent operation of the aircraft.

(iii) Only a single exit availability is tested, and this assumes one exit from each exit pair
Systematic studies of previous accidents suggest that the exit availability assumed in the certification protocol, i.e., one exit from each exit pair, while sometimes occurring in accidents, is not the most frequently occurring exit combination found in real accidents [10-12, 31]. Anecdotally, this observation is supported by evidence of several more recent accidents, such as the Hanada A350 accident in January 2024, in which only the two forward exits (1L, 1R) and one rear exit (4R) were used in the evacuation, representing three out of the eight exits [32, 33, 82]; the fatal Moscow Sukhoi Superjet accident in April 2019, in which just the front two exits (1L, 1R) were used (note this aircraft does not have overwing exits), representing two of the four available exits [34-36]; and the British Airways B777-200 accident at Las Vegas on 8 September 2015, where the two centre pairs of exits (2L, 2R, 3L, 3R) and one of the rear exits (4R) were not used, while the forward pair of exits (1L, 1R) and one rear (4L) exit were successfully used in the evacuation, representing three of the eight exits [37].

Furthermore, the exit configuration selected for use in the certification trial is not the most challenging combination of 50% of the available exits. This is because the certification selection of available exits minimises the travel distance of passengers to an available exit, and each available exit is supplied by all the passengers using the approach aisle(s)—enabling the exit to achieve its full flow rate potential [39]. In situations where both exits in an exit pair are available, the flow of passengers from the approach aisle(s) is split between two exits, neither of which receives a sufficient supply of passengers to operate to its full potential. This was the case in the B737 Manchester Airport fire of 1985, in which 55 people were killed, where the two front exits were available (as well as the overwing exit), and this sub-optimal exit combination was one of the contributors to the large loss of life in the tragedy [4]. This adverse exit combination, i.e., both exits in the forward pair of exits, may also have contributed to the 41 (53% of those on board) fatalities in the 2019 Moscow Sukhoi Superjet accident [34-36].

(iv) Lack of realism
Participant and cabin crew behaviour is unlikely to reflect that in a real accident because the certification trial lacks the realism of a challenging emergency evacuation, in part to reduce the risk of injury to participants (see 10.1(i)). Participants are not subject to psychological trauma or the physical ramifications of a real emergency, such as reduced visibility due to smoke and representative cabin debris (while luggage is strewn around the cabin, it is not weighted like bags on an actual flight). Trial participants are not surprised by the need to evacuate, and they and the cabin crew are not fatigued, as they may be if the accident occurs at the end of a long flight.

In certification trials, while passengers may be keen to exit as quickly as possible, the behaviour exhibited is essentially co-operative (in terms of passenger–passenger and passenger–crew interactions), whereas in real accident conditions, in particular in severe situations (e.g., involving fire), the behaviour of passengers may become competitive (e.g., passengers climbing over seats to by-pass congestion in aisles). Furthermore, cabin crew who are selected for certification trials are usually highly experienced and will have recently been trained in the emergency procedures for the aircraft, whereas in reality, cabin crew involved in an accident may be relatively inexperienced and have not refreshed their training for as long as 12 months prior to the accident. In addition, in certification trials, the environment is conducive for cabin crew instructions to be readily conveyed to participants, i.e., there are no adverse environmental conditions that make communications difficult. In the Hanada A350 accident, four of the cabin crew initially used loudhailers in an attempt to communicate with passengers. However, they eventually abandoned the use of the loudhailers as they felt that their instructions could not be heard clearly over the noise in the cabin and the engine noise (see end of Section 2.1.3 of [82]). Some of the passengers in the Haneda accident reported that they could not hear the cabin crew commands and simply followed other passengers during the evacuation (towards the end of Section 2.1.3 of [82]).

Furthermore, participants in certification trials are compliant and follow the direction and guidance of cabin crew directing participants to utilize optimal exits (not necessarily their nearest exit), thereby reducing the total evacuation time for the aircraft to a minimum. However, in accident scenarios, it is often observed that passengers tend to use their nearest exits [10-12, 31] rather than the optimal exits, thereby increasing the overall total evacuation time for the aircraft. It is also noted that passengers are encouraged to identify (and presumably use in the event of an emergency) their nearest exit by cabin crew in the pre-flight safety briefing. It is also now well established that in real accidents, many passengers attempt to evacuate with their carry-on cabin luggage, and this may have a significant negative impact on the evacuation [16]. These types of behaviour are not represented in the current certification protocol.

Finally, as specified in 14 CFR 25.803(a) [23] (see Annex 4), there must be emergency means to allow rapid evacuation in crash landings with the (a) landing gear extended, as well as (b) with the landing gear retracted. While the certification trial clearly demonstrates compliance with conditions associated with (a), it does not demonstrate that rapid evacuation can be achieved with conditions associated with (b). As part of the evacuation certification process, while it is also necessary to demonstrate that the slides can be deployed if the airplane has some of its landing gear retracted, when the airplane is in this state, it not only makes it difficult (and potentially dangerous) to use the escape slides (they are either too steep or too shallow), but it also makes passenger movement within the cabin difficult, with passengers having to travel over potentially long distances against adverse inclines. The recent Hanada [32, 33, 82] accident, where the airplane had a nose-down attitude, and the Moscow Sukhoi Superjet accident [34-36], where the airplane had a nose-up attitude, demonstrate that adverse cabin orientation can occur during emergency landings, making evacuation more challenging. This condition is clearly not represented in the certification trial.

11.2. Implications of the Phase 1 Model Sensitivity Analysis for the Current 14 CFR 25.803 Evacuation Demonstration Protocol

The model sensitivity analysis presented in Phase 1 for scenarios 1 to 4 (see Sections 5 to 8) provides some support for the suggested limitations in the current 14 CFR 25.803 evacuation demonstration protocol identified in Section 10.1. Furthermore, the model sensitivity analysis discussed in Section 9 provides some quantification of the suggested limitations.

The identified limitations in the current 14 CFR 25.803 evacuation demonstration protocol that are supported by the model sensitivity analysis are each discussed in turn.

(i) The impact of only considering a single evacuation trial (i.e., 10.1 (i)) and only a single population (i.e., 10.1 (ii)), as demonstrated by Scenario 1

Scenario 1 (see Section 5.2.1) was intended to be representative of the evacuation certification demonstration trial and produce predicted TETs indicative of the expected ***optimal*** performance of the configuration in the evacuation certification demonstration scenario. Of all the scenarios investigated, Scenario 1 is intended to be the closest modelling representation of the certification demonstration trial. However, unlike the certification scenario, the simulation was repeated 1000 times, each time with a different population representative of the population stipulated in Appendix J to 14 CFR 25.803 (see requirement (h) as detailed in [23] and presented in Annex 4) to demonstrate and quantify the impact of repeated simulations.

While a different population was used for each repeat simulation, and 1000 simulations were performed, the different populations did not include agents representing disabled passengers or agents connected via a social bond (such as family groups). Thus, while the same demographic as required by the certification demonstration protocol was used each time, a different population was generated. This ensured that there was a thorough mix of passengers with a range of movement capabilities considered to be within the ‘normal health’ range as required by the certification protocol (see Appendix J requirement (h)).

Scenario 1 produced a range of **OOA TETs varying between 62.9 s and 77.0 s** with a **median TET of 67.7 s** and a **95th percentile TET of 71.3 s**, as depicted in the predicted TET probability distribution presented in Figure 6. By repeating the scenario 1000 times, with each simulation using a different representative population, the spread in OOA TETs is 14.1 s, with an interquartile range of 2.5 s (25th quartile TET = 66.6 s and 75th quartile TET = 69.1 s). This suggests that while 50% of the 1000 simulations are within +/- 1.25 s of the median TET (67.7 s), 50% of the simulations are outside this range, with 20% (200 cases) between the 75th quartile (TET = 69.1 s) and 95th percentile (71.3 s). This large variation in OOA TETs (14.1 s) and the relatively high (compared to the median) 95th percentile OOA TET (71.3 s) are produced simply by repeating the certification demonstration trial with a different population.

The predicted variation in evacuation performance cannot be captured by the current certification demonstration trial protocol, i.e., 14 CFR 25.803 [23], as only a single demonstration trial is required (as discussed in 10.1 (i)). Thus, if only a single trial is required for certification purposes, it is unclear if the performance achieved by the single trial represents a random fast time (to the left of the distribution median value in Figure 6 or Figure 25) or a random slow time (to the right of the distribution median value). Furthermore, if the certification trial result represented a ‘just pass’ situation and was one of the faster times on the TET probability distribution (i.e., to the left of the distribution median value in Figure 6 or see Figure 25), then this would suggest that the configuration under question would likely fail if the certification trial was repeated multiple times. As a result, it is difficult to determine whether the tested configuration truly satisfies the intent of the certification requirement and what margin of safety is achieved.

(ii) The impact of exit availability and only considering evacuation scenarios with one exit from each exit pair (i.e., 10.1 (iii)) as demonstrated by Scenario 2

Scenario 2 (see Section 6.2.1) was intended to investigate the impact of exit availability on evacuation performance with all other factors being similar to the requirements of the certification demonstration trial. Thus, rather than selecting one exit from each exit pair (resulting in two Type C exits and two Type-III exits being available) as stipulated in Appendix J to 14 CFR 25.803 (see requirement (p) as detailed in [23] and presented in Annex 4), a different exit combination was selected, i.e., both the forward Type C exits and left pair of Type-III exits were available (i.e., 1L, 1R, 2L, and 3L). This combination of available exits still utilised 50% of the available exits AND utilised the same mix of exit types as required in the certification trial. Thus, the ***theoretical*** total exit flow rate that was available in Scenario 2 was identical to what would be achieved using the certification requirements. Furthermore, the exit availability used in Scenario 2 was representative of exit availability in real accidents [10-12, 31]. As in Scenario 1, Scenario 2 was repeated 1000 times, each with a different population satisfying the certification requirements.

Scenario 2 produced a range of **OOA TETs varying between 80.3 s and 102.7 s** with a **median TET of 88.6 s** and a **95th percentile TET of 94.7 s**, as depicted in Figure 13. Over one-third (i.e., 34.8% or 348 simulations) of the 1000 simulations produce a TET of 90 s or greater. The spread in OOA TETs is 22.4 s, with an interquartile range of 4.6 s (25th quartile TET = 86.6 s and 75th quartile TET = 91.2 s). This suggests that while 50% of the 1000 simulations are within +/- 2.3 s of the median TET (88.6 s), 50% of the simulations are outside this range, with 20% (200 cases) between the 75th quartile (TET = 91.2 s) and 95th percentile (94.7 s). From a life safety viewpoint, this is clearly a concern, as even the 75th quartile TET exceeds 90 s.

Thus, by simply changing the available exits, while maintaining 50% exit availability AND the mix of exit types, over a third of the 1000 repeat simulations produce a TET of over 90 s, with the 95th percentile TET increasing from 71.3 s to 94.7 s, an increase in evacuation time of 23.4 s or 32.8%. More significantly, this change in exit availability results in a different conclusion concerning the acceptability of evacuation performance, from a pass (in Scenario 1) to a failure (in Scenario 2) in terms of satisfying the 90 s certification requirement. As described in Section 9(i), the poor performance achieved by this exit combination (i.e., 1L, 1R, 2L, 2R) is primarily due to the inability of the narrow cabin aisle to supply sufficient flow to maintain both Type C exits in an exit pair working at their full capabilities. Furthermore, under these conditions, the evacuation performance is highly susceptible to slow-moving passengers who can create momentary gaps in the supply of passengers to both Type C exits, further reducing evacuation performance. Thus, under these conditions, evacuation performance is subject to random variations in passenger seating allocation, which is unlikely to be identified if only a single evacuation trial is performed, as in the case of the certification demonstration.

The predicted evacuation performance cannot be captured by the current certification demonstration trial protocol, i.e., 14 CFR 25.803 [23], as only a single exit combination is selected for certification demonstration (as discussed in 10.1 (iii)), and the exit combination is the combination that will provide the shortest evacuation time possible. Furthermore, as only a single evacuation demonstration trial is performed (as discussed in 10.1 (i)), it is unlikely that the impact of slow-moving passengers on evacuation performance can be identified.

(iii) The impact of lack of realism (i.e., 10.1 (iv)) as demonstrated by Scenario 4
As identified in Section 10.1 (iv), there are many issues concerning the general lack of realism in the certification trial protocol that bring into question whether the passenger and CC behaviours exhibited in the certification trial are likely to reflect evacuation performance in a challenging real emergency.

Scenario 4 was intended to investigate just one such aspect related to passengers selecting their nearest exit rather than the optimal exit as directed by CC (see Section 8.2.1). All other factors in Scenario 4 were similar to the requirements for the certification demonstration trial (and so were identical to Scenario 1 (see Section 5.2.1)). Thus, rather than passengers following the guidance of CC and utilising the optimal exits to minimise overall TET (as typically occurs in certification trials), passengers in Scenario 4 elect to utilise their nearest exits (as often occurs in accident situations [10-12, 31]).

Scenario 4 produced a range of **OOA TETs varying between 74.9 s and 96.5 s** with a **median TET of 84.3 s** and a **95th percentile TET of 90.1 s**, as depicted in Figure 22. Furthermore, 5.3% (53 simulations) of the 1000 simulations produce a TET of 90 s or greater. The spread in OOA TETs is 21.6 s, with an interquartile range of 4.6 s (25th quartile TET = 82.1 s and 75th quartile TET = 86.7 s). This suggests that while 50% of the 1000 simulations are within +/- 2.3 s of the median TET (84.3 s), 50% of the simulations are outside this range, with 20% (200 cases) between the 75th quartile (86.7 s) and 95th percentile (90.1 s). From a life safety viewpoint, this is clearly a concern, as the 95th percentile TET exceeds 90 s.

Thus, if passenger exit-selection behaviour is changed from optimal (as in most certification demonstration trials) to nearest-exit (as is likely to occur in real accidents), evacuation efficiency is significantly reduced, with the 95th percentile TET increasing from **71.3 s** (in Scenario 1) **to 90.1 s** (in Scenario 4), an increase of **26%, and more significantly, results in a fail in terms of the certification demonstration trial performance.**

The negative impact of passengers selecting their nearest exits in preference to the CC-directed optimal exits is even more pronounced if in addition, exit availability is different to that in the certification trial. Comparing the nearest-exit variant of Scenario 2 (exits 1L, 1R, 2L, and 3L) from [16] to Scenario 1 (exits 1L, 2L, 3L, and 4L available and optimal passenger exit selection) **significantly increases 95th percentile TET from 71.3 s (Scenario 1) to 127.7 s, an increase of 56.4 s or 79%.**

(iv) The impact of lack of realism (i.e., 10.1 (iv)) not demonstrated by the sensitivity study

Section 10.1 (iv) identified a number of issues concerning the general lack of realism in the certification trial protocol that could have been explored in the model sensitivity analysis. However, as discussed in 10.2 (iii), only passenger exit selection has been investigated as part of the current study. It is noted that several of these issues were originally recommended by FSEG to be investigated as part of the current study but were eventually rejected, as the study had limited time and budget and so could not explore all the issues of interest. The eventual list of issues that were explored in this project was agreed upon by three parties: FAA CAMI, CHC, and FSEG. The other cases that were recommended as part of this modelling sensitivity analysis but not explored in this study are discussed below, together with other possible cases that could be investigated:

(1) The impact of passenger luggage collection during evacuation. This was not selected as a sensitivity case, as it was part of an earlier recent modelling study [16]. The aircraft configuration used in the luggage collection study was identical to that used in the current study, the exit availability consisted of that used in Scenario 2, i.e., 1L, 1R, 2L, and 3L, and the passenger exit selection was nearest exit, as in Scenario 4. Therefore, the case examined in [16] consisted of three factors that increase realism compared with the certification trial, i.e., passenger luggage collection during evacuation, realistic accident-based exit availability, and passengers selecting their nearest exit rather than optimal exits, as is typical in accidents. Four scenarios were considered, with 0%, 25%, 50%, and 75% of the passengers collecting their luggage prior to evacuation. In the Base Case (0% luggage collection but with exit availability as described in Scenario 2 with nearest-exit behaviour), the median TET (i.e., derived from 1000 repeat simulations) was 120.9 s, and with 25%, 50%, and 70% of passengers collecting luggage during evacuation, the median TET was increased by 11.7% (135.0 s), 38.6% (167.6 s), and 64.3% (198.6 s), respectively [16]. These results suggest that passengers retrieving luggage during evacuation can have a significant negative impact on evacuation performance.

Furthermore, these results can be compared to the median TET for Scenario 1 of the current study (see Section 5.2.1) in which the available exits comply with the certification demonstration trial, passengers select their optimal exits, and there is no luggage collection, i.e., 67.7 s. The combined impact of the three realistic adverse factors (i.e., luggage collection, adverse exit availability, and passengers selecting their nearest exits) compared to the standard certification scenario (i.e., Scenario 1 of the current study) results in a *doubling* of the median TET in the case of just 25% of the passengers attempting to retrieve luggage, i.e., increasing median TET from 67.7 s (Scenario 1) to 135.0 s [16].

(2) The impact of passengers with movement disabilities. It was suggested that the impact of including passengers with movement disabilities could be analysed assuming that the disabled passengers could move unaided but at a greatly reduced speed. While there are limited data concerning the movement rates for disabled passengers on airplanes, the suggested study would have utilised data from the FAA study of movement speeds for disabled passengers [38].

(3) The impact of a greater number of elderly passengers. It was suggested that the impact of a population demographic that was skewed to include a higher proportion of elderly passengers could have been considered. This would simply involve increasing the number of passengers with reduced movement rates.

(4) The impact of group dynamics. It was suggested that a sensitivity scenario could have been investigated that included passengers in social groups. The behaviour of the individuals within the social group could be modified so that the group of passengers would move at the speed of the slowest member of the group so that all members of a group would utilise the same exit, and if the members of the group were initially separated, they would reunite prior to evacuating.

(5) The impact of seat pitch. It was suggested that the impact of seat pitch on evacuation time could be investigated using the proxy variable of time required to exit a seat row. While it is not currently possible to explicitly model the time required for a passenger to exit a seat row as a function of body size and available space, by imposing an increasing delay to the time required for a passenger or group of passengers to exit a seat row, the impact this would have on TET could be explored. This approach could identify the critical delay in row exiting times and the required number of passengers experiencing the critical delay that would significantly negatively impact TETs. Delay times associated with passengers exiting seat rows could also be based on experimental data, such as that collected by FAA CAMI [40].

(6) The impact of fire, smoke, and toxic fire gases. It was suggested that the impact of fire, smoke, and toxic fire gases on evacuation performance could be explored by identifying a plausible fire scenario, e.g., similar to the Manchester airport B737 fire of 1985 [4], performing a Computational Fluid Dynamics (CFD) fire simulation [13], and coupling this to the aircraft evacuation simulation [4, 5]. Furthermore, it is not necessary for the external fire to gain access to the passenger cabin for the external fire to impact evacuation; even the presence of smoke in the cabin can negatively impact evacuation. The obscuration effects of smoke can make evacuation difficult, as passengers cannot see clearly, and the smoke also contains toxic and irritant gases that can incapacitate passengers. In the Haneda A350 aircraft, the external fire did not gain access to the cabin for approximately 10 minutes after the airplane came to rest. However, smoke entered the cabin from the (closed) door 3 position almost immediately after the airplane came to rest and rapidly spread to the front of the cabin. By the time the evacuation started, the cabin aft of door 3 was filled with a considerable amount of smoke, making evacuation more difficult (see Section 2.16.1(2) of [82]).

While there are many uncertainties associated with such an analysis, it could provide insight into how a developing fire impacts the evolving evacuation.

(7) The impact of adverse cabin orientation. If the airplane comes to rest nose down or nose up, this can make movement within the cabin challenging. In either case, movement is difficult, as passengers may need to travel up or down the slope depending on their position relative to their targeted exit. Travelling up the slope can slow passenger movement, while travelling down the slope can also make movement difficult for some passengers as they may not be able to descend the slope in a controlled manner. Experience from other physical environments suggests that the impact of adverse cabin orientation on movement rates is likely to be dependent on age, gender, and physical ability of the passengers [61-64]. Both of these cabin orientations can be represented in evacuation modelling, and similar conditions involving

adverse orientation have been included in evacuation modelling associated with passenger ships [61- 63] and rail cars [64]. Clearly, an experimental data set describing passenger movement rates and behaviour associated with likely airplane adverse orientation must be collected to improve the reliability of the proposed evacuation modelling; however, some preliminary analysis is possible using data derived from other application areas.

11.3. Assessing Evacuation Performance in Other Industries

The need for regulators to assess an environment for its evacuation capabilities is not restricted to the aviation industry. Around the world, the design of buildings of all types (e.g., commercial, retail, residential, transportation, stadia, etc.,) are assessed for both their fire safety and their ability to safely evacuate their occupants in a timely manner. This is usually achieved through the use of national (e.g., UK Approved Document B [41]) or regional (e.g., NYC fire code [42]) regulations and guidelines. In the maritime industry, the design of passenger ships that sail within national waters (e.g., ferries) must satisfy national fire and evacuation safety regulations (e.g., UK MCA regulations [43]). Passenger ships that sail in international waters, e.g., cruise ships, must satisfy international guidelines set down by the International Maritime Organization (IMO) [44], and even naval vessels have a similar set of guidelines [45].

A significant difference between these environments is the time considered appropriate for safe evacuation: in buildings, it is usually a couple of minutes; in maritime applications, it is usually 60 minutes to 80 minutes depending on the type of vessel; and in aviation, it is 90 seconds irrespective of the type of airplane. The physical spaces in the building, maritime, and aviation environments and the type of emergency requiring rapid evacuation are very different, and as a result, there are different expectations as to the maximum permitted time to safely evacuate; it is informative to review how compliance with evacuation safety requirements is achieved in the building and maritime industries.

(i) Building Industry

Around the world, the majority of building fire safety standards and codes are prescriptive in nature. Prescriptive building regulations or guidelines (e.g., in England and Wales, Approved Document B [42]) are essentially a set of design and construction rules that stipulate a particular set of essentially configurational regulations concerning travel distances, number of exits, and exit widths; stipulate the use of appropriate specified types of building materials; and require the installation of passive or active means for fire containment and/or suppression. If these rules are followed, it should be possible to limit the size and spread of fire and fire effluent so that occupants either do not need to evacuate, as the fire will be contained for sufficiently long enough for the fire department to extinguish the fire, or that occupants will be able to safely evacuate in a pre-defined acceptable amount of time (typically 2.5 minutes).

However, for more than 20 years, the building industry regulatory environment around the world has been adopting the performance-based approach to fire safety engineering [46, 47]. In contrast to the traditional perspective approach, the performance-based building regulation focuses on the outcomes that are required for a building design to be considered acceptable, given it may be subject to a range of plausible fires. To assess the suitability of the building design, a series of plausible design fires are specified (based on the nature of the building, how it will be used, and the materials present), which are then simulated using an appropriate fire model and the time determined for occupant tenability criteria to be reached. This time is known as the Available Safe Egress Time or ASET—the time for untenable conditions to develop that may compromise safe evacuation.

The accepted tenability criteria may vary depending on jurisdiction and recommendations from professional bodies [48-53], but essentially, they set maximum/minimum levels for critical components of fire effluent that may impede safe evacuation or result in injury to occupants. For example, a set of tenability criteria for a building (floor area less than 100 m^2) could include the following:

- Smoke temperature above 2.1m < 185°C
- Smoke temperature below 2.1m < 60°C
- Radiative flux less than 2.5kW/m²
- Visibility in smoke below 2.1m > 5m
- CO concentration < 2000 ppm

Once the ASET is determined, the time required to safely evacuate is determined using an appropriate evacuation model. The evacuation time determined by the evacuation model is known as the Required Safe Egress Time or RSET—the time required for the population to safely evacuate. The performance-based approach attempts to establish whether, for the design fire, the ASET (which is driven by the fire development and determined by a fire simulation model) is greater than the RSET (which is driven by human behaviour and determined by an evacuation simulation model) plus some specified safety factor (which is required to compensate for modelling inaccuracies, simplifications, and omissions).

Clearly, 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 design fire scenarios (including fire loads, fire evolution, fire size, fire location, etc.) are postulated along with credible evacuation scenarios (including number and type of occupants, including disabled occupants, occupant response characteristics, occupant walking speeds, etc.).

A more sophisticated approach involves the coupling of the CFD output describing the spread of fire effluent with the evacuation modelling. This enables the agents in the evacuation simulation to be exposed to fire effluents during the evacuation as the fire is developing. The evacuating agents inhale the toxic fire products (e.g., CO and HCN), are exposed to irritant fire gases (e.g., HCL) and the convective and radiative heat produced by the fire and must wayfind in situations with reduced visibility due to the obscuration caused by fire smoke. The impact of each component of the fire effluent on the evacuating agents is determined using a Fractional Effective Dose (FED) model [54,55]. This model compares the accumulating toxic/irritant/heat dose that each agent in the evacuation is acquiring to the doses required for some endpoint, such as incapacitation or death. When the FED is equal to 1.0, the endpoint is deemed to have been reached, and the agent is considered no longer able to evacuate. Furthermore, as the FED approaches 1.0, the movement capabilities of the agent may also be reduced. This approach has successfully been applied to many applications [4, 5, 56-59].

Using this approach, fire and evacuation models provide a means by which the complex interacting system of the building layout, the fire environment, and the population can be assessed under a variety of challenging scenarios.

(ii) Maritime Industry

For passenger ships that sail in international waters, the organisation that sets fire and evacuation regulations and guidelines is the IMO. The IMO has a set of prescriptive regulations for the construction of vessels that cover the fire safety aspects of the vessel. If a shipbuilder wishes to explore alternative designs that cannot be accommodated with the prescriptive approach, there is also a set of performance-based fire and evacuation regulations [53]. As in the building industry, these make use of appropriate fire models to determine the ASET and appropriate agent-based ship evacuation models to determine the RSET [60, 61].

Nevertheless, the majority of passenger ship designs adopt the prescriptive approach, as it is considerably simpler to implement. However, the prescriptive approach adopted by the maritime industry consists of a mix of prescriptive and performance components. While the fire aspects of the regulation are set in a prescriptive manner (as in the building industry), the evacuation capabilities of the proposed design are assessed using a performance approach involving agent-based ship evacuation modelling [60,61]. Furthermore, the available safe egress time is not determined by fire modelling analysis (as in the performance approach adopted in the building industry) but is set prescriptively and is either 60 minutes or 80 minutes depending on the nature of the ship design [44, 45].

In addition, the nature of the evacuation modelling that is required to demonstrate compliance with the evacuation requirements is specified in a prescriptive manner—unlike in the building industry, where it is up to the design engineer to define all the evacuation parameters. In maritime applications, the evacuation scenarios to be investigated are prescribed, unlike in the building industry, where the nature of the scenarios are agreed by the engineer in consultation with the regulator for each proposed design application. The scenarios for passenger ships consist of four core cases [44], while the equivalent naval guidelines consist of six core cases [45]. These scenarios include situations considered to be appropriate for normal operations and also damaged states of the vessel where not all the means of egress within the vessel are available.

Furthermore, other parameters required to configure the scenario, such as passenger response times, nature of the population demographics, including the proportion of disabled passengers (who can evacuate unaided, but at reduced walking speed), walking speeds, etc., are all prescribed as part of the IMO guidelines. The guidelines also stipulate that each scenario must be repeated 500 times (with a different population satisfying the stipulated demographics), that the evacuation time for the 95th percentile simulation is adopted as the representative evacuation (i.e., assembly) time and that a safety factor of 25% is added to the predicted evacuation time to accommodate modelling approximations and simplifications to the scenario specification. For a proposed vessel design to be considered acceptable, each of the required scenarios must satisfy the evacuation time requirement, based on the 95th percentile time from the 500 repeat simulations plus the 25% safety factor.

It is worth noting that the modelling approach adopted by the IMO for passenger ship evacuation analysis addresses the shortcomings of the certification demonstration trial used in the aviation industry (i.e., 14 CFR 25.803 [23]) identified in Section 10.1. These include:

- Only a single demonstration trial is required (see 10.1(i)) – the IMO requirement stipulates that 500 simulations are to be performed.
- Only a single population is considered (see 10.1(ii)) – the IMO requirements involve using a different population meeting the prescribed demographic for each of the 500 repeat simulations. Furthermore, the population demographic includes disabled passengers who can move unaided, albeit at reduced walking speeds.
- Only a single exit availability is considered (see 10.1(iii)) – the IMO imposed scenarios include a damage state where not all the evacuation routes are available.
- Lack of realism (see 10.1(iv)) – the IMO requirements include a safety factor of 25% to compensate for realistic aspects of the imposed scenarios that are excluded, for example, the impact of vessel heel, the presence of smoke and fire, the action of the ship's crew, etc. However, it is also acknowledged that a safety factor of 25% is arbitrary and may not be adequate to cover all simplifications and model omissions.

11.4. The Proposed Use of Evacuation Modelling to Enhance Airplane Evacuation Certification

The limitations of the current 14 CFR 25.803 [23] evacuation certification trial protocol were discussed in Section 10.1. However, when considering the limitations of the demonstration trial, it is important to consider that its original intent was to provide an indicative measure of the performance of the airplane under an artificial benchmark evacuation scenario. It was not intended to be a predictor of the airplane performance under plausible or realistic accident scenarios. Furthermore, in its current form, the certification trial provides a means of comparing the evacuation performance of different airplane configurations under a set of identical—if somewhat artificial—evacuation scenario conditions.

In this section, four options are proposed to enhance airplane evacuation certification that are either informed by evacuation modelling (**Option 1**) or make use of evacuation modelling (**Options 2 and 3**). While Option 3 is the preferred option, Options 2 and 3 should be considered together, as Option 3 is an extension of Option 2. While not strictly within the scope of the current project, a fourth option is proposed to update the ASET currently imposed in the 14 CFR 25.803 evacuation protocol, i.e., the 90 s requirement (**Option 4**).

(i) Option 1: Improve the realism of the certification trial.
While it is desirable to increase the realism of the current certification trial, this cannot be achieved by compromising participant safety and preferably not greatly increasing the cost of

the certification analysis. If these principles are adopted, then many of the limitations identified in Section 10.1, such as repeated trials, adverse airplane orientation, passengers retrieving (heavy) carry-on luggage, introduction of (theatrical, i.e., non-toxic) smoke in the cabin, introduction of elderly or disabled passengers, etc., could not be considered for implementation in a modified certification trial. However, several of the identified certification trial limitations could be addressed within a modified trial protocol without compromising safety or increasing the costs of the trials. These include:

(a) **Exits used during the trial evacuation (see Section 10.1(iii)).**
Rather than selecting one exit from each exit pair, as in the current certification demonstration trial, the exits selected for testing in the certification trial should be representative of frequently occurring accident exit combinations. Furthermore, the selected exits would be specific to aircraft type, e.g., wide-body or narrow-body, etc. So that the proposed modified trial maintains some consistency with previous trials, the exits used should still represent 50% of the available exits and utilise the same mix of exit types as would be used in the current protocol. For example, for the narrow-body aircraft used in the sensitivity analysis, the exit combination would be (1L, 1R, 2L, 3L), as in Scenario 2. An alternative exit combination could be the next most common accident combination, e.g., (2L, 3L, 4L, 4R). While this would be a relatively minor procedural change to the certification trial protocol, it would improve the realism of the scenario by ensuring that the available exits were representative of accident scenarios, as well as making the certification scenario more challenging (as suggested by modelling Scenario 2 (see Section 6.2.2)). Furthermore, the suggested change does not increase the risk of injury to the participants and would not increase the cost of the certification trial.

(b) **Cabin Crew fatigue (see Section 10.1(iv))**
Accidents requiring rapid emergency evacuation can occur during take-off or landing. For short-haul flights, the accident, whether at take-off or landing, could occur at the end of a long duty day for CC who may have already worked many hours on previous flights on the day of the accident and thus may be fatigued. On long-haul flights, the accident may occur at the end of a long sector where the CC have worked many hours prior to landing, and on ultra-long flights, even though there may be a second CC team, their sleep and rest on board the aircraft may be disturbed, so they may also be fatigued.

A detailed review of 27 papers concerning fatigue in CC suggests that CC have an alarmingly high prevalence of fatigue (ranging from 63.5% to 77.4% reported), and nearly half of the CC experienced excessive sleepiness [65]. Furthermore, research studies have found that fatigue (and sleepiness) can reduce cognitive and physical abilities in a similar manner to alcohol intoxication. Moderate levels of fatigue and/or sleep deprivation decrease performance in a manner equivalent to a blood alcohol concentration of 0.05–0.1%, which exceeds the legal alcohol limit in many jurisdictions [65]. Another study found that a loss of 2 hours of sleep can negatively impact performance and alertness and increase the risk of errors and accidents [65].

An FAA retrospective study of fatigue in CC involving 9,180 participants found that 84% reported being fatigued during their previous work period. Furthermore, of the CC experiencing fatigue while on duty, 71% reported their safety-related performance was affected. Of those, 60%

believed their ability to respond to passenger needs (including service and safety-related items) was compromised, 36% reported cabin safety performance (e.g., arming/disarming doors, verifying seatbelts fastened) was affected, 34% felt their vigilance regarding cabin security (e.g., passenger risk assessment) was impeded, and 14% indicated preflight safety briefings were affected [65, 66].

An important issue not currently covered by quantitative research is whether CC fatigue (and sleepiness) may severely impact CC abilities to efficiently manage an emergency evacuation, and if so, how severe this impact may be. The impact of CC fatigue (and sleepiness) could include CC time to react to the emergency and make critical decisions concerning whether a cabin door should be opened, delay the opening of cabin doors and slide deployment, and adversely impact their ability to behave in an assertive manner in ushering passengers out of the cabin (see results from Scenario 3, Section 7.2) and their ability to manage the required cabin splits (see results from Scenario 4, Section 8.2). Each of these potential degradations in CC performance will have a negative impact on evacuation times, increasing the time required for evacuation. While the current certification evacuation protocol makes use of front-line CC, it is unlikely that the CC used are fatigued, as they may be in practice.

It is recommended that research is conducted into the impact of fatigue and sleepiness on CC ability to manage a cabin evacuation. Furthermore, if research suggests that CC fatigue can have a significant negative impact on their ability to efficiently manage an evacuation, consideration should be given to modifying the certification trial protocol so that it utilises CC that have induced fatigue levels appropriate for an evacuation that may occur at the end of a typical duty cycle.

(c) **Cabin Crew experience (see section 10.1(iv))**
During an emergency evacuation, CC play a vital role in ensuring the success and safety of passengers. To ensure a rapid and safe evacuation, CC must react quickly and decisively to the emergency, making critical decisions concerning whether a cabin door should be opened, and if it should be opened, quickly opening the door and deploying the slide, behave in an assertive manner in ushering passengers out of the cabin (see results from Scenario 3, Section 7.2), and manage the movement of passengers to achieve the required cabin splits (see results from Scenario 4, Section 8.2).

The experience of CC (measured in terms of length of service) could potentially impact performance in these evacuation management tasks and so should be controlled by the certification protocol. Furthermore, when the CC last completed the 12-month recurrent training, it could also potentially impact evacuation performance and so should also be managed by the certification protocol. For example, while five of the nine CC on the Haneda A350 aircraft had more than two years’ experience (cabin manager (located near L1), 35 years’ experience; L1, 10 years’ experience; R1, 4 years’ experience; L2, 22 years’ experience; and L4, 25 years’ experience), four CC (i.e., 44%) had less than two years' experience, with three having only three or four months’ experience. Furthermore, three of the CC had completed recurrent training more than 6 months prior to the accident (R1, 6 months 10 days; L2, 6 months 20 days; and L4, 6 months 11 days) (see Section 2.5.2 of [82]).

It is suggested that consideration should be given to modifying the certification trial protocol so that 50% of the CC are considered relatively inexperienced (e.g., less than 2 years of service) and that all CC should have completed their last recurrent training at least 6 months prior to taking part in the certification trial. This approach would prevent using the most experienced and highly trained CC in the certification demonstration trial, making the certification trial more representative of conditions that may occur in a real accident. It is also recommended that research should be conducted to explore if CC experience is a significant influential factor in evacuation performance.

(ii) Option 2: Expand the scope of the evacuation certification protocol beyond the experimental trial with additional scenarios simulated using agent-based evacuation models.

Regardless of whether the certification trial is updated as suggested in Option 1, the result from the certification demonstration trial represents valuable insight and quantification of how the airplane will perform in a benchmark evacuation scenario, albeit a somewhat artificial evacuation scenario. Evacuation modelling using advanced and validated agent-based models should be considered as a means to address the limitations of the certification trial, as highlighted in Section 10.2. Furthermore, agent-based evacuation models are routinely used in both the building and maritime industries as part of the regulatory certification process (see Section 10.3), so there is precedent for adopting their use in airplane certification.

The approach suggested for using agent-based evacuation models as part of the airplane evacuation certification process follows that adopted by the maritime industry, as outlined in Section 10.3(ii). This involves specifying additional scenarios to be investigated using evacuation modelling, specifying the relevant parameters to be used in the modelling, specifying the number of repeat simulations and how the evacuation time is selected from the distribution produced by the repeat simulations, and finally, specifying the pass/fail acceptance criteria. Each of these components of the suggested enhanced certification protocol is briefly outlined below. In addition, they can be expanded through further discussion with stakeholders, including the regulatory authorities, the manufacturers, the airlines, unions, professional bodies, etc.

(a) **Identification of appropriate additional candidate certification model scenarios.**
As noted in Section 10.3(ii), the maritime industry evacuation certification guidelines include four basic evacuation scenarios that must be analysed for passenger ship applications [44] and six basic evacuation scenarios for naval applications [45]. These are a combination of typical normal operations scenarios and damage scenarios in which not all the normally available evacuation routes are considered available. In a similar manner, the aviation regulatory authorities could identify a range of certification model scenarios that could be included in the enhanced certification protocol. A Certification Model Scenario (CMS) selected for inclusion in the enhanced certification protocol should provide important additional information not captured by the current certification demonstration trial. In addition, the CMS should provide additional insight into how the airplane is likely to perform in scenarios that are more representative of accident situations than the current certification demonstration trial scenario. Finally, note that

while cabin sweep procedures were not included in any of the Phase 1 model sensitivity scenarios (see Section 3.1), appropriate cabin sweep procedures should be included as part of each of the proposed CMSs.

Based on the model sensitivity study presented in Sections 5 to 9 and the discussion in Sections 10.1 and 10.2, several suitable candidate CMSs are suggested for consideration.

CMS1 (one exit from each exit pair, optimal passenger exit selection): This scenario is intended to be the equivalent of the evacuation certification demonstration trial and produce results indicative of the expected ***optimal*** performance of the configuration in the evacuation certification demonstration scenario with assertive CC. In this scenario, one exit from each exit pair is available (see Scenario 1, Section 5.2 for an example appropriate to narrow-body airplanes). The results from this scenario expand on the result derived from the certification demonstration trial due to the number of times the scenario is repeated, addressing the limitations identified in Section 10.2(i).

CMS2 (accident exit availability, optimal passenger exit selection): This scenario is intended to represent the impact of exit availability representative of that commonly occurring in accidents for the airplane type being certified. For a narrow-body aircraft, this consists of the front pair of exits and the left overwing exits (see Scenario 2, Section 6.2 for an example appropriate to narrow-body airplanes). This scenario is expected to produce ***optimal*** performance for the exit combination, and it makes use of assertive CC. This scenario addresses the limitation identified in Section 10.2(ii) and makes use of a combination of 50% of the available exits that are not optimal and that are representative of exit availability in accidents.

CMS3 (one exit from each exit pair, nearest-exit passenger exit selection): This scenario is the equivalent of CMS1 but where the passengers make use of their nearest exit, rather than the optimal exits. This scenario addresses the limitation identified in Section 10.2(iii) and utilises passenger exit selection typical of behaviour observed in accidents.

CMS4 (accident exit availability, nearest-exit passenger exit selection): This scenario is the equivalent of CMS2 but where the passengers make use of their nearest exit rather than the optimal exits. This scenario addresses the limitation identified in Section 10.2(iii) and utilises passenger exit selection typical of behaviour observed in accidents.

These four CMSs are the proposed core scenarios that could be considered for inclusion in the enhanced certification protocol. Additional CMSs that could be considered, but may be challenging to implement in practice, given that further model development and validation may be required or additional data may be required to specify some of the required parameters (e.g., CMS6 and CMS7), include:

CMS5 (as CMS1/CMS2/CMS3/CMS4, with passenger luggage retrieval): This scenario is the equivalent of CMS1 or CMS2 or CMS3 or CMS4 in which passengers also attempt to retrieve carry-on cabin luggage prior to evacuation (see [16] for details). This scenario addresses the limitation identified in Section 10.3(iv)(1) and could utilise luggage retrieval data presented in [16]. If this scenario is to be included, the regulator should identify which of the core scenarios to enhance with the inclusion of luggage retrieval and the proportion of passengers that attempt to retrieve their luggage.

CMS6 (**as CMS1/CMS2/CMS3/CMS4, with modified passenger population):** This scenario is the equivalent of CMS1 or CMS2 or CMS3 or CMS4 but using a modified population demographic that could include additional elderly passengers, disabled passengers (able to self-evacuate), family groups, etc. This scenario addresses the limitation identified in Section 10.3(iv)(3, 4, 5). The nature of the population demographics would need to be specified, along with the required data to specify and characterise modified passenger behaviours. Furthermore, some additional model development is likely to be required by most aviation evacuation models to represent these population characteristics and associated passenger behaviours. It is noted that the ability to represent social groups and a range of associated group behaviours has been implemented in building-specific evacuation models such as buildingEXODUS [57, 59]. If this scenario is to be included, the regulator should identify which of the core scenarios to modify.

CMS7 (**as CMS1/CMS2/CMS3/CMS4, with adverse cabin orientation):** This scenario is the equivalent of CMS1 or CMS2 or CMS3 or CMS4 but with the airplane in a nose-down or nose-up attitude, reflecting damage to the landing gear. This scenario addresses the limitation identified in Section 10.3(iv)(7). The data required to specify and characterise modified passenger movement behaviour under these adverse cabin orientations would need to be provided. Furthermore, some additional model development is likely to be required by most aviation evacuation models to represent this condition and associated passenger behaviours. It is noted that the ability to represent adverse orientations and the associated occupant behaviours has been implemented in maritime and railcar-specific evacuation models such as maritimeEXODUS [61, 62] and railEXODUS [64]. If this scenario is to be included, the regulator should identify which of the core scenarios to modify.

The number and type of CMSs eventually included in the proposed enhanced certification protocol should ideally be decided by the regulator in consultation with stakeholders. Furthermore, the number of CMSs introduced into the enhanced certification process may be small initially, with the number and scope of CMSs included expanded as confidence in the proposed enhanced protocol is established. For example, the proposed enhanced certification process may initially only include one CMS, for which there is the greatest confidence in the veracity of the modelling predictions and similarity to the current demonstration certification scenario, i.e., CMS1. As confidence in the enhanced certification protocol grows, additional CMSs could be introduced into the analysis, as in the maritime evacuation certification protocols [44, 45].

(b) **Specification of the relevant parameters to be used in certification modelling.** Within the maritime industry regulatory guidelines for the use of evacuation modelling to demonstrate compliance with evacuation requirements [44,45], all the data required to define the scenario are provided within the regulatory guidance documents. Engineers wishing to demonstrate that their vessel design meets the regulatory guidance must utilise the data provided in the documentation. A similar approach is suggested for aviation applications. Some of the data that would be required include the following:

Airplane Configuration Specification: Specified by the Layout of Passenger Accomodation (LOPA) for the configuration to be certified, including exit types, supplied by the manufacturer.

- Airplane Environment Specification: Consists of the nature of the airplane orientation, e.g., for proposed modelling scenarios CMS1 to CMS6, this consists of the airplane having all landing gear correctly deployed, while for CMS7, the nature of gear failure must be specified.
- Exit Characteristics: For each type of exit commonly used (e.g., Type C, Type-III, Type A), the protocol will specify acceptable (i) exit ready times (see Section 2.5a), (ii) slide times (see Section 2.5c), and (iii) range of acceptable average exit flows (see Section 2.7).
- CC Behaviour at Exits: For each of the proposed scenarios, it is assumed that CC at each exit will be assertive to achieve the best exit flow conditions (related to Exit Characteristics). However, if suitable exit data are available to represent unassertive crew, then this could be considered (see Section 2.5b).
- CC Cabin Sweep: Specify whether a cabin sweep should be performed by CC prior to evacuating as part of each scenario. If a cabin sweep is required, the nature of the cabin sweep will need to be specified by the manufacturer or launch customer. (Note that in each of the sensitivity scenarios, a cabin sweep was not implemented, for simplicity; however, the airEXODUS software is capable of representing complex cabin sweep procedures (see Section 3.1)).
- Passenger Population Distribution and Characteristics: The protocol will specify the nature of the population demographics (for proposed modelling scenarios CMS1 to CMS5 and CMS7, this consists of the standard certification trial demographic (see Section 2.3)) and the range of passenger response times and walking rates (see Section 2.3)). If a modified population demographic is proposed, as in the proposed modelling scenario CMS6, then the modified population must be specified along with the required data to characterise the population performance.
- Passenger Exit-Selection Behaviour: The protocol will specify the passenger exit-selection behaviour to be implemented in each of the CMSs. For the proposed scenarios CMS1 and CMS2, passengers will select their near optimal exits. For proposed modelling scenarios CMS3 and CMS4, passengers will select their nearest exits.

(c) **Specification of the number of repeat simulations and selection of the representative TET.**

Within the maritime industry regulatory guidelines for the use of evacuation modelling to demonstrate compliance with evacuation requirements [44, 45], the number of repeat simulations that must be performed for each scenario is specified and set to 500 repeat simulations. Furthermore, a statistical method has been developed using the concept of confidence intervals to test if 500 repeat simulations are sufficient or necessary to meet the intended requirement [67]. This approach can be used if fewer than 500 repeat simulations is considered appropriate and sufficient.

A similar approach is suggested for aviation applications. However, the critical number of repeat simulations that is required is likely to be dependent on the nature of the software used to perform the evacuation simulations. For the airEXODUS software, given the stochastic nature of the agent decision-making process, the manner in which the exit flows are determined by the PEDT statistical distribution, and the requirement to explore different populations and seating allocations, a total of 1000 repeat simulations is considered appropriate. Nevertheless, whatever the number of repeat simulations specified, it should be described as a minimum value with the actual number of repeat simulations required being determined by the nature of the software tool used for the analysis.

In addition, given that a distribution of predicted TETs is generated for each scenario, a method for identifying the representative TET for the scenario must be specified. Considering Scenario 1 (see Figure 6 for the TET distribution), this produced a near-normal distribution of TETs varying from 62.9 s to 77.0 s, with a median TET of 67.7 s and a 95th percentile TET of 71.3 s. It was also noted that the TET distribution had a tail of long times varying from 75 s to 77 s, with five simulations producing a TET of greater than 75 s, each of which was sub-optimal (with an OPS greater than 0.1). While these sub-optimal performances are legitimate, they are outliers from the other 995 simulations, so it would be inappropriate to consider these times as representative of the evacuation performance of the airplane configuration in this scenario. Similarly, it is inappropriate to consider the median time (67.7 s) as representative of the evacuation performance, as 50% of the simulations (499 cases) produce a TET exceeding this value. As the evacuation analysis forms part of a safety case, it is reasonable to adopt the plausible worst-case result from the TET distribution. This approach has been adopted within the maritime guidelines, where the 95th percentile time from the distribution of predicted evacuation times is considered the representative time for the scenario [44, 45]. It is therefore recommended that a similar approach is adopted in the aviation application, and the 95th percentile TET is adopted as the representative evacuation time for the scenario.

(d) **Pass/Fail criteria.**
Within the proposed enhanced certification protocol as described in Option 2, there are at least two and possibly up to eight certification TETs for the airplane configuration being certified. This includes one TET resulting from the experimental certification demonstration trial and between one and seven model-predicted TETs, one for each of the Certification Model Scenarios included, i.e., CMS1 to CMS7. (Note: The actual number of CMSs to be included in the enhanced certification protocol will be determined by the regulatory authority).

As there is now more than one certification TET for consideration, the challenge is how to determine if the airplane configuration has satisfied the evacuation certification requirement. Consider the airplane configuration examined in the sensitivity study presented in this report. Based on the sensitivity analysis presented in this report, there are five possible CMSs that could be included in the enhanced certification protocol and one certification demonstration trial result. The five CMSs are CMS1, CMS2, and CMS3, which are based on Scenario 1 (see Section 5.2.1), Scenario 2 (see Section 6.2.1), and Scenario 4 (see Section 8.2.1), respectively; CMS4, which is based on the nearest-exit variant of Scenario 2 derived from [16]; and CMS5, which is based on CMS4 with 25% of the passengers retrieving luggage, derived from [16]. Presented in Table 25 are the TET results for five CMSs and the interpolated certification demonstration trial TET.

If the process employed by the maritime industry in their evacuation certification protocol [44, 45] is adopted, then all scenarios must produce a TET of less than 90 s for the airplane configuration to be considered acceptable. If the proposed enhanced evacuation protocol only consisted of the certification trial result and one CMS, i.e., CMS1, then using the suggested approach, the airplane configuration would be considered acceptable, as both TETs (i.e., certification trial result and CMS1 result) are less than 90 s (i.e., 76.9 s and 71.3 s, respectively; see Table 25). However, if more than one CMS is considered as part of the enhanced protocol, the airplane is deemed to fail, as all the other predicted TETs are greater than 90 s (see Table 25).

Table 25

The 95th percentile Total Evacuation Time (TET) for the proposed Certification Modelling Scenarios (CMSs) and the interpolated certification demonstration trial TET for the 185-person narrow-body airplane configuration

Trial or Scenario	Scenario description	Trial or 95th percentile TET (s)
Certification Trial	Interpolated certification trial result derived from 194-person configuration; see Section 4 (1L, 2L, 3L, and 4L exits)	76.9[1] s
CMS1	Scenario 1 – similar exit availability to certification trial, optimal passenger exit selection; see Section 5.2.1 (1L, 2L, 3L, and 4L exits)	71.3[2] s
CMS2	Scenario 2 – accident exit availability, optimal passenger exit selection; see Section 6.2.1 (1L, 1R, 2L, and 3L exits)	94.7[2] s
CMS3	Scenario 4 – similar exit availability to certification trial, nearest-exit passenger exit selection; see Section 8.2.1 (1L, 2L, 3L, and 4L exits)	90.1[2] s
CMS4	Nearest-exit variant of Scenario 2 from [16] (1L, 1R, 2L, and 3L exits)	127.7[3] s
CMS5	Nearest-exit variant of Scenario 2 with 25% of passengers collecting cabin luggage from [16] (1L, 1R, 2L, and 3L exits)	165.9[3] s

[1] – See Section 4; [2] – See Table 24; [3] – see [16].

It is important to note that in the maritime case, all the evacuation times are produced by model simulations, whereas in the aviation case, one of the evacuation times is generated from the real-world evacuation certification demonstration trial. This is an important distinction between the maritime and aviation applications, even though the aviation evacuation demonstration trial is for a somewhat unrepresentative scenario and results from only a single trial (as discussed in Section 10.1). It could be argued that the real-world result based on the certification trial should be assigned greater importance than the results from the CMSs in determining the pass/fail status for the airplane configuration. Furthermore, given the uncertainty associated with model predictions for some of the CMSs, it is also questionable as to whether each CMS should be considered of equal importance in determining the pass/fail status. These issues are addressed in Option 3, Section 10.4(iii).

(iii) Option 3: Weighted sum of certification trial time and simulated certification evacuation model scenario times.

Option 2 presented in Section 10.4(ii) introduced a methodology for identifying additional certification modelling scenarios (i.e., the CMSs) to be considered as part of the enhanced certification protocol (see Section 10.4(ii)a), specified the data required for the CMSs (see Section 10.4(ii)b), identified the number of required repeat simulations to be performed for each CMS, and provided a means of selecting the representative TET from the distribution (see Section 10.4(ii)c). Furthermore, a means of determining pass/fail criteria for the airplane configuration was suggested (see Section 10.4(ii)d).

As noted in Section 10.4(ii)d, the suggested pass/fail criteria based on the maritime evacuation certification protocol were not considered appropriate, primarily because they treated the certification demonstration trial result and the modelling results to be of equal importance. Furthermore, the maritime approach assumes that the results for each CMS are considered to be of equal importance, relevance, and reliability. Given that some of the CMSs may be considered less likely events and that the modelling of these events may be less reliable due to less reliable datasets to characterise passenger behaviour, different importance could be assigned to the model predictions for the various CMSs.

Using these concepts, a weighted sum methodology can be adopted to characterise the definitive certification evacuation performance of the airplane configuration, i.e., TET_{cert}. It is worth noting that a similar concept was used to combine evacuation simulation results for various scenarios to assess the human factors performance of competing designs for naval vessels [68].

In the weighted sum approach, two sets of weights are defined. One set of weights is used to distinguish between the relative importance of the experimental trial result (i.e. W1) and the TET determined from the CMSs (i.e., W2). The second set of weights is used to rank the relative importance of each of the proposed CMSs, i.e., the weight associated with CMS1 is MW1, CMS2 is MW2, etc.

For both sets of weights, the larger the weight, the greater the relative importance of the TET associated with the weight. Furthermore, so that the definitive TET used to characterise the certification performance of the airplane design, i.e., TET_{cert}, is representative of the individual component TETs, i.e., the TET associated with the trial, TET_{trial}; the TET associated with CMS1, TET_{CMS1}; the TET associated with CMS2, TET_{CMS2}, etc., the sum of each set of weights should be 1.0 (see Equation 2).

$$W1 + W2 = 1.0 \text{ and } MW1 + MW2 + MW3 + \ldots\ldots = 1.0 \qquad \textbf{(2)}$$

Using this two-layered weighted sum approach, the combined TET representing the definitive TET for the airplane, i.e., TET_{cert}, is given by Equation (3).

$$TET_{cert} = W1 * TET_{trial} + W2 * TET_{CMS} \qquad \textbf{(3)}$$

where TET_{CMS} is given by Equation (4).

$$TET_{CMS} = MW1 * TET_{CMS1} + MW2 * TET_{CMS2} + MW3 * TET_{CMS3} + \ldots\ldots\ldots \qquad \textbf{(4)}$$

For the airplane configuration to be considered to satisfy the certification requirement, not every CMS would need to satisfy the requirement, but it is necessary to demonstrate that

$$TET_{trial} < 90 \text{ s, and } TET_{cert} < 90 \text{ s} \qquad \textbf{(5)}$$

Furthermore, using this approach, the enhanced certification protocol still produces a definitive TET, i.e., TET_{cert}, that can be used to compare one design with another, as is possible with the current certification protocol. But rather than the comparative TET generated for the airplane configuration being based solely on a single demonstration trial result, i.e., TET_{trial}, it is now based on a weighted sum of the certification trial and several certification modelling scenarios, i.e., TET_{cert}.

It is proposed that the regulatory authority would define a set of definitive weights reflecting the importance and confidence the industry has in the model predictions for the various CMSs, and these weights would be specified as part of the certification protocol. Furthermore, the weights could be modified by the regulatory authority as confidence in the approach is established, additional data are made available to more reliably set model parameters, and additional CMSs are introduced.

Several examples of how the weights could be set are presented and discussed. As in Section 10.4(ii)d, consider the example of the airplane configuration examined in the sensitivity study presented in this report. Presented in are the TET results for TET_{trial}, TET_{CMS1}, TET_{CMS2}, TET_{CMS3}, etc. For demonstration purposes, presented in Table 26 are example weight allocations for the two sets of weights and the associated TET_{cert} generated using the specified weights (using Equation (3)).

(a) Equal importance allocated to TET from certification trial and combined CMSs, and equal importance allocated to TET from each CMS

If the TET derived from the demonstration certification trial (i.e., TET_{trial}) is considered to be of equal importance to the TET derived from the CMSs (i.e., TET_{CMS}) and if the TET derived from each CMS (i.e., TET_{CMS1}, TET_{CMS2}, ...) are considered to be of equal importance to each other, then the weighted method is essentially equivalent to the method described in method 2 (see Section 10.4(ii)d), in that equal importance is attributed to each individual component.

In this case, all the TETs are considered of equal importance, so the weights are defined as shown in Equation (6).

W1 = W2 = 0.5, and MW1 = MW2 = MW3 = MW4 = MW5 = 0.2 **(6)**

Using these weights, TET_{cert} = 93.4 s (see row 1 in Table 26). Thus, the airplane configuration is determined to have a significantly higher definitive certification TET (i.e., TET_{cert} = 93.4 s) than it achieved in the certification demonstration trial (TET_{trial} = 76.9 s). Furthermore, as TET_{cert} > 90 s, the configuration is deemed to fail the certification requirement since both TET_{trial} and TET_{cert} must be less than 90 s to satisfy the certification requirement. Thus, with equal weights, the same conclusion is derived as that in Section 10.4(ii)d, where all the individual TETs were considered of equal importance (as in the maritime evacuation certification protocol). It is also worth noting that TET_{CMS} = 109.9 s.

(b) Equal importance allocated to TET from certification trial and combined CMSs, but different importance allocated to TET from each CMS

If the TET derived from the demonstration certification trial (i.e., TET_{trial}) is considered to be of equal importance to the TET derived from the combined CMSs (i.e., TET_{CMS}), while the TET derived from each CMS (i.e., TET_{CMS1}, TET_{CMS2}, ...) are considered to be of different importance, a significantly different TET_{cert} compared to that generated in (a) is expected, with a potentially different pass/failure outcome.

Table 26

Hypothetical weights for the Option 3 Enhanced Certification Protocol and resulting combined TET for the 185-person narrow-body airplane configuration

Description	W1	W2	MW1	MW2	MW3	MW4	MW5	TET_{cert}
Cert trial weighted 50%, CMSs have equal weights	0.5	0.5	0.2	0.2	0.2	0.2	0.2	93.4 s
Cert trial weighted 50%, CMSs have different weights	0.5	0.5	0.30	0.25	0.20	0.15	0.10	87.9 s
Cert trial weighted 70%, CMSs have equal weights	0.7	0.3	0.2	0.2	0.2	0.2	0.2	86.8 s
Cert trial weighted 70%, CMSs have different weights	0.7	0.3	0.30	0.25	0.20	0.15	0.10	83.5 s
Cert trial weighted 80%, CMSs have equal weights	0.8	0.2	0.2	0.2	0.2	0.2	0.2	83.5 s
Cert trial weighted 80%, CMSs have different weights	0.8	0.2	0.30	0.25	0.20	0.15	0.10	81.3 s
Cert trial weighted 90%, CMSs have equal weights	0.9	0.1	0.2	0.2	0.2	0.2	0.2	80.2 s
Cert trial weighted 90%, CMSs have different weights	0.9	0.1	0.30	0.25	0.20	0.15	0.10	79.1 s

Cert trial weighted 45%, CMSs have different weights	0.45	0.55	0.30	0.25	0.20	0.15	0.10	89.0 s
Cert trial weighted 100%	1.0	0.0	0.0	0.0	0.0	0.0	0.0	76.9 s

For example, consider the weight distribution presented in the second row of Table 26. The rationale for the weight distribution for the various CMSs is as follows:

MW1: CMS1 is the modelling equivalent of the current certification trial and has the greatest confidence associated with the model predictions. Thus, CMS1 has the highest weight, i.e., 0.3.

MW3: CMS3 is virtually identical to CMS1; however, the agents in the model attempt to use their nearest exit, as is common in real accidents. As this behaviour is not commonly observed in certification trials, where participants tend to follow CC commands, the weight for CMS3 is reduced slightly compared to CMS1 and is assigned a weight of 0.2.

MW2: CMS2 has a different exit combination to that used in the certification trial and in CMS1 and CMS2. The exit combination is commonly found in accidents and leads to generally poor exit flow through the front pair of Type C exits, but within the model, passengers attempt to use optimal exits as directed by the CC. As this is never tested in certification trials, there is little evidence to support the accuracy of the model predictions. While it is a core scenario, it is given a weight slightly less than that of CMS1 but greater than CMS2 and is assigned a weight of 0.25.

MW4: CMS4 is virtually identical to CMS2; however, the agents in the model attempt to use their nearest exit, as is common in real accidents. As with CMS3, the weight assigned to CMS4 is reduced compared to CMS2 and is assigned a weight of 0.15.

MW5: CMS5 is virtually identical to CMS4; however, 25% of the agents in the model attempt to retrieve their luggage during evacuation. This case is the furthest removed from the certification demonstration trial, as it utilises a different available exit combination, passengers attempt to use their nearest exits, and 25% of passengers attempt to retrieve their luggage. As such, while this scenario is perhaps closest to reality, it is the least reliable. This scenario is assigned the smallest weight of 0.1. In comparison, the weight for CMS1 is 200% larger.

Using the suggested differential weight allocation allows greater importance to be given to the CMSs that are considered most important, most relevant, and most reliable.

Using the suggested non-equal CMS weights, TET_{cert} = 87.9 s (see row 2 in Table 26). As both TET_{cert} and TET_{trial} (TET_{trial} = 76.9 s) are less than 90 s, the aeroplane configuration is deemed to have passed the certification requirement. However, the airplane configuration is determined to have a higher definitive certification TET (i.e., TET_{cert}) than it achieved in the certification demonstration trial (TET_{trial} = 76.9 s).

(c) Greater importance allocated to TET from certification trial compared to the combined CMSs

As can be seen in Table 26, the greater the importance (and, hence, weight) associated with the TET derived from the certification trial (i.e., TET_{trial}), the closer TET_{cert} is to TET_{trial} (i.e., 76.9 s; see row 10 in Table 26) and, hence, the less influential the modelling components of the enhanced certification process become.

For example, if the weight for TET_{trial} is increased from 0.5 to 0.7, while the weights for the CMSs are defined as in (b), TET_{cert} DECREASES from 87.9 s (see row 2 in Table 26) to TET_{cert} = 86.8 s (see row 3 in Table 26). If the weight for TET_{trial} is increased so that it is 0.9, while the weights for the CMSs are defined as in (b), then TET_{cert} = 79.1 s (see row 8 in Table 26). This value for TET_{cert} is only 2.2 s (2.9%) greater than the value derived just from the certification demonstration trial (i.e., TET_{trial} = 76.9 s) but takes into consideration contributions from five realistic certification modelling scenarios.

Furthermore, as both TET_{cert} (TET_{cert} = 79.1 s) and TET_{trial} (TET_{trial} = 76.9 s) are less than 90 s, the aeroplane configuration is deemed to have passed the certification requirement.

(d) Greater importance allocated to TET derived from the combined CMSs compared to the certification trial

If greater importance (and, hence, weight) is associated with the TET derived from the combined CMSs (i.e., TET_{CMS}), the closer TET_{cert} becomes to TET_{CMS} and, hence, the less influential the certification demonstration trial component of the enhanced certification process becomes.

For example, if the weight for TET_{trial} is decreased from 0.5 to 0.45, while the weights for the individual CMSs are defined as in (b), TET_{cert} INCREASES from 87.9 s (see row 2 in Table 26 to TET_{cert} = 89.0 s (see row 9 in Table 26. If the weight for TET_{trial} is decreased further, even greater importance is placed on the CMS.

Furthermore, as both TET_{cert} (TET_{cert} = 89.0 s) and TET_{trial} (TET_{trial} = 79.1 s) are less than 90 s, the aeroplane configuration is deemed to have passed the certification requirement. However, the airplane configuration is determined to have a significantly higher definitive certification TET (i.e., TET_{cert}) than it achieved in the certification demonstration trial (TET_{trial} = 76.9 s).

Clearly, if the importance of the TET associated with the combined CMSs (i.e., TET_{CMS}) is increased further (i.e. W2 > 0.55), the airplane configuration is unlikely to satisfy the certification requirement, as TET_{cert} > 90 s. This is because greater emphasis will be placed on the certification model scenarios, and four of these result in TETs > 90 s (see Table 25).

The challenge in the weighted sum approach is to select a meaningful distribution of weights that reflects the importance of the CMS to the certification process and regulator and stakeholder confidence in the ability of the airplane evacuation models to accurately simulate airplane evacuation in the identified scenarios. To a certain extent, the selected weight distribution will be a measure of the regulator's confidence in the quality of the model validation presented and the relevance of the verification test cases (see Section 10.5).

Enhancing the certification process through evacuation modelling using the weighted sum approach addresses a number of challenging issues:

1) It maintains the importance and influence of the standard demonstration certification trial to the certification process. This provides the regulatory community and the aviation industry with consistency to the previous protocol while enabling the potential of introducing new and relevant scenarios enabling safer airplane designs.

2) It provides a means of introducing into the certification process additional challenging and relevant accident scenarios without increasing the risk to participants through the use of evacuation modelling.

3) It provides the regulatory authorities with a means of gradually phasing in the use of evacuation modelling into the certification process by controlling (a) the number and type of certification modelling scenarios included in the certification process and (b) the relative importance of the certification trial and the model predictions through a series of weights.

4) The specific modelling scenarios and associated weights used in the enhanced evacuation protocol can be reviewed by the regulatory authority, when deemed appropriate, to determine if they can be updated as the evacuation modelling tools mature and more data to define important modelling parameters become available.

5) It continues to provide a consistent means to compare the performance of one airplane configuration with another.

6) As the certification modelling scenarios and associated weights will be part of the defined regulatory process, they will be known by the airplane manufacturers well in advance of certification testing of the proposed new airplane configuration. As a result, they can be incorporated into the initial design process to derisk proposed airplane designs by ensuring that they are able to satisfy the modelling component of the enhanced evacuation certification protocol at the early design stage.

(iv) Option 4: Adopt fire modelling to identify a relevant ASET for airplane evacuation scenarios rather than continue to use the prescriptive 90 s.

While not strictly within the scope of the current project, it is useful to briefly explore a key component of 14 CFR 25.803 [23] associated with the prescriptive evacuation performance requirement, which is currently set to 90 s.

As part of the current evacuation certification process, the aviation industry has adopted a prescriptive ASET of 90 s. This is intended to represent the time that an airplane must be evacuated before the passenger cabin flashes over due to a post-crash fire, thereby making evacuation impossible. However, this time was set some 50 years ago for a completely different generation of aircraft, so it is questionable as to whether it still has relevance today.

In post-crash fires, the fire is assumed to originate outside the airplane as a result of the accident and is usually due to a fuel spill. Assuming no ruptures to the fuselage and that the fire is not adjacent to an open cabin door, the external fire will eventually burn through the fuselage and gain access to the interior cabin materials and any passengers remaining on board. As the fire gains access to the passenger cabin, the cabin materials will eventually start to burn in the vicinity of the burn-through, producing toxic gases, smoke, and heat. During this process, cabin doors will be opened to allow passengers to evacuate, creating a ventilation flow through the cabin, which in turn impacts the internal fire development. As the internal fire progresses, a point is reached when conditions in the cabin reach the flash point, and the localised fire explosively spreads throughout the cabin, creating the flashover event. The prescriptive 90 s set in 14 CFR 25.803 [23] is intended to indicate the time to flashover from the start of the evacuation, so all passengers must be successfully evacuated by this time.

The flashover event is highly dependent on many factors, including the nature of the external fire, the external wind conditions, the combustibility of the fuselage and window materials and the materials within the cabin (seats, carpets, wall linings, overhead bins, ceiling panels, carry-on luggage, etc.), the volume of the cabin space (e.g., A380 or B737), and the ventilation of the cabin space (resulting from burn-through and the open exits). Over the past 50 years, both fuselage (e.g., use of carbon fibre-reinforced polymer (CFRP) materials) and cabin interior materials (use of fire retardants) have changed substantially, with significant improvements in fire performance. Thus, while the 90 s requirement may have been a valid assumption at one time, it is questionable as to whether after 50 years of improvements in the fire performance of aircraft materials, it is still relevant.

For example, the A350 airplane involved in the recent Haneda airport accident [32, 33] is constructed mainly from composite fibre materials (53% of the airplane), with the fuselage consisting predominately of CFRP. While the accident involved a significant post-crash fire, as the fuselage remained intact (i.e., no hull ruptures), the external fire did not gain access to the cabin for approximately 10 minutes after the airplane came to rest. However, smoke entered the cabin from the door 3 position almost immediately after the airplane came to rest and spread to the front of the cabin. By the time the evacuation started, the cabin aft of door 3 was filled with a considerable amount of smoke (see Section 2.16.1(2) of [82]).

As a result, there is a need for an extensive range of laboratory-scale and full-scale fire tests to quantify the fire performance of individual materials (i.e., not simply determine the pass/fail status of the materials based on standards compliance testing as is the current common practice) and the airplane system as whole to establish an ASET suitable for the new generation of aircraft. In addition, the data generated from the proposed fire testing could be used to enhance CFD fire modelling for airplane fire applications. The aviation industry could then adopt CFD fire modelling, as in the building [46,47] and maritime [53] industries, to define an appropriate ASET for the airplane configuration being certified. It is noted that advanced CFD fire modelling has successfully been applied to aircraft fire applications [4,5,13] and coupled with aircraft evacuation models to produce coupled fire-evacuation analysis [4, 5].

If the CFD modelling approach was adopted to specify the ASET as part of an enhanced evacuation certification protocol, the protocol should be expanded to define the nature of the fire scenarios to be considered and the accepted values for key parameters to be used in the fire modelling, as described in Section 10.4(ii) for the evacuation analysis.

11.5. Quality control

As part of the proposed enhanced evacuation certification protocol, it is essential that measures are put in place to ensure the quality of the evacuation modelling analysis and the presentation of the results of the analysis. Regarding the evacuation modelling, it is important that appropriate evacuation models are used that can address the specific issues associated with aircraft evacuation. Each of these quality control issues is briefly described below. Furthermore, guidance on quality control measures associated with evacuation analysis for passenger ship certification can be found in [44] and for naval vessels in [45], and these are used to inform the discussion of suitable requirements for aeroplane certification applications.

(i) Evacuation Models

There are many evacuation models that are routinely used for building evacuation modelling applications that have varying levels of capabilities, varying from the simplistic flow models that use a coarse representation of space, e.g., evacuations [69], to very sophisticated agent-based models that accurately represent the space and simulate people–people (e.g., group dynamics), people–environment (e.g., impact on walking speed due to reduced visibility in smoke) and people–structure (e.g., agent use of stairs or elevators) interactions, e.g., pathfinder [70] and buildingEXODUS [71]. Several detailed reviews of these models and their capabilities are available in the literature [72-74]. However, there are fewer evacuation models that have been developed specifically for ship evacuation, and even fewer evacuation models developed specifically for airplane evacuation [6, 75].

Given the small number of aircraft specific evacuation models available, building-specific evacuation models are sometimes used for aircraft evacuation applications (e.g., see [76]). Airplane evacuation differs from building (and passenger ship) evacuation in a number of significant ways. First, the timescales for safe airplane evacuation are generally much shorter than for buildings and ships, so behavioural issues that may only slightly impede building evacuation, e.g., the proportion of slower-moving occupants, may have a more influential impact in airplane evacuation. Furthermore, occupant behaviour that may be considered positive in building evacuation may be considered negative in airplane evacuation, e.g., the majority of occupants using their nearest exits.

Exits are a key component to any evacuation. Ultimately, exits control the flow of occupants out of the enclosure and to a place of safety. Furthermore, the nature of most aircraft evacuations is significantly influenced by the instantaneous flows achieved through individual aircraft exits throughout the evolving evacuation. The exits on an airplane are fundamentally different to those in buildings, so airplane exits cannot be represented in the same simplistic manner as building exits—as a result, their representation in airplane models is expected to be different to that typically used in building models.

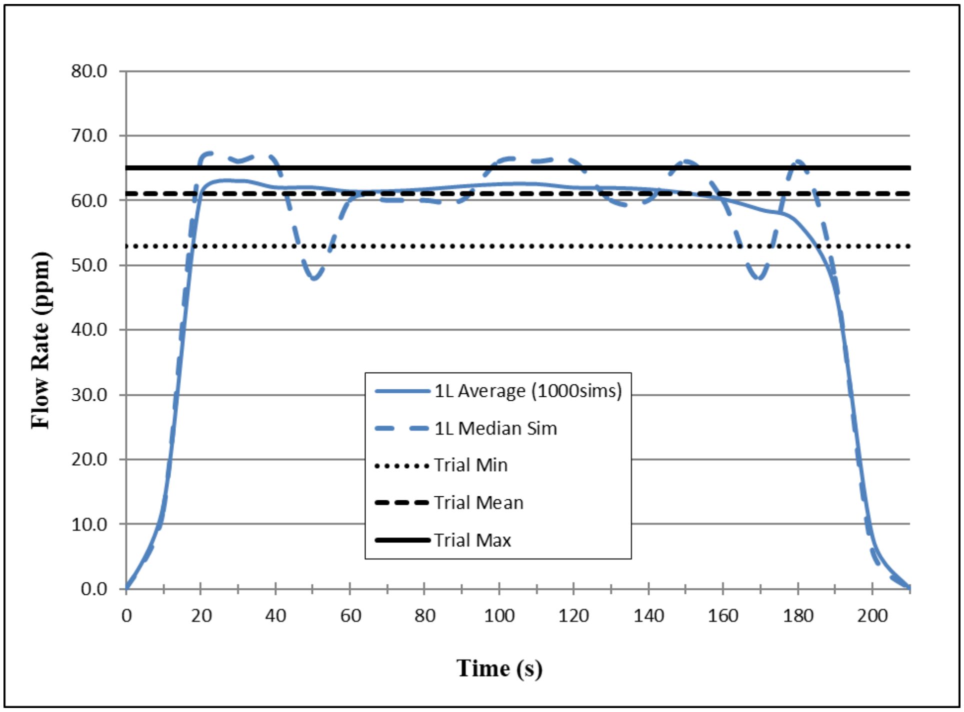
For floor-level exits, such as the Type C and Type A exits, passengers do not simply walk through the exit as they would through a building exit but need to transition from a standing position to a seated position as they transfer to the slide. In doing so, passengers incur a hesitation time (as they decide how to tackle the exit) and another delay time as they execute the manoeuvre. The total delay is called the Passenger Exit Delay Time or PEDT, as described in Section 2.5b. Furthermore, the PEDT is dependent on many factors, including passenger physical characteristics, so it is not uniform across all passengers. Thus, in addition to the need for airplane evacuation models to represent the slide, they must also take into consideration how the PEDT distribution impacts the exit flow. The PEDT has a profound impact on the flow rates achieved through these exits. Thus, even if there is a constant supply of passengers to a Type C or Type A exit, the flow through the exit can vary considerably depending on the individual PEDT experienced by the passengers as they negotiate the exit. Thus, simply representing an aircraft exit as an opening with a prescribed flow rate or that every occupant is delayed equally are crude approximations that are unlikely to provide a good representation of how the exit performs within a single evacuation simulation.

To demonstrate this point, consider a simulation where all the agents within the narrow-body airplane configuration used in this study can only use the 1L Type C exit. In this case, a quasi-steady supply of agents to the Type C exit will be established soon after the start of the simulation. Presented in Figure 26 are exit flow curves achieved for this case. In Figure 26, the exit flow rate is determined over 10 s intervals with the dashed curve representing the exit flow achieved for the simulation producing the medium TET from 1000 repeat simulations. As can be seen from the dashed curve, the flow rate through the exit varies considerably during a simulation. This is to be expected due to the individual PEDTs assigned randomly to each agent, competition between agents at the exit, and the nature of the approach to the exit, all of which impact the exit flow.

In contrast, the solid curve represents the average exit flow over the 1000 repeat simulations. This average curve flattens out the peaks and troughs in exit flow produced in each of the 1000 individual simulations. If this exit was represented as a building exit, the flow rate achieved through the exit for a single simulation would be far more uniform, similar to the average curve for the 1000 repeat simulations. As a result, if the airplane exit is treated simply as a building exit, it is unlikely that the simulation would represent exiting behaviour and flow rates achieved in airplane evacuations, and this would have an impact on queuing and congestion and, hence, influence other agent behaviours.

The three horizontal lines in Figure 26 represent the minimum (53 ppm), mean (61 ppm), and maximum (65 ppm) average Type C flow rates achieved in certification trials [17,19]. The plateaux in the average curve (see Figure 26) represents the maximum sustained flow rate that the Type C exit is predicted to produce over the 1000 simulations, which is very close to the mean average flow observed in certification trials.

Figure 26
airEXODUS-generated average flow rates through a single Type C for all 185 occupants, determined over 10 s intervals



**Solid lines represent the average from the 1000 simulations, and dashed lines represent the results from the median simulation. Horizontal lines represent average minimum, mean, and maximum flows achieved in certification trials*

A similar situation occurs for the overwing Type-III exit, which is also a complex exit, as it requires occupants to climb through the exit, with the height of the floor on the inside of the exit being different to that on the outside of the exit. Again, individual people tackle this exit very differently, and again, a PEDT distribution is used to define the flow that can be achieved by this exit.

Building evacuation models that have been used to simulate aircraft evacuation (e.g., [76]) ignore this complexity and treat the exit as a conventional building exit, while some specific aircraft evacuation models fail to make it clear how they treat exits apart from specifying an average exit flow appropriate for the type of exit [75].

Given the range of evacuation models available, it is essential that as part of the enhanced evacuation certification process, the models used are thoroughly described with appropriate evidence provided to demonstrate that they are capable of reliably simulating the proposed CMSs and supporting evidence provided of relevant validation (see Section 10.5(ii)) and verification (see Section 10.5(iii)).

(ii) Validation
Before airplane evacuation models can reliably be used for certification applications it is essential that they 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 [77]. Reliable and thorough datasets to validate evacuation models are extremely challenging to collect, as they require the collection of a vast amount of data. This includes the starting location of all occupants, the response time for each occupant, the path to exit taken by each occupant, and the time that each occupant has exited [77]. As a result, there are few datasets that possess sufficient information for thorough validation. Examples of datasets that come close to collecting this type of information include high-rise construction site evacuation [78], passenger ship evacuation [79], and rail car evacuation [64].

Furthermore, the nature of the evacuation trial producing the validation dataset can impact the quality and reliability of the dataset collected. The most reliable data are generated from unannounced evacuation trials, where the participants are completely unaware, they are participating in an evacuation trial [78]. In this case, as far as the participants are aware, they could be responding to a real emergency. The next most reliable are the so-called quasi-unaware evacuation trials, where participants know that they are going to be involved in an evacuation trial but not the time or day of the trial [79]. As with the participants involved in unaware trials, participants in quasi-unaware trials cannot be sure that the incident they are involved in is not a real emergency. Finally, the least desirable, but due to practical constraints, the most common, are specially contrived evacuation trials where participants know they are participating in an evacuation trial [64].

For airplane evacuation, data from experimental trials generally fall into the last category, i.e., specially contrived experimental trials where the participants are fully aware that they are participating in an experiment. Generally, these fall into one of two categories: they are either laboratory-based trials designed to address a particular research issue such as the impact of seat pitch or Type-III exits on overall evacuation time [80, 81], or they are full-scale evacuation trials designed to measure evacuation performance of an aircraft under specific conditions, e.g., the 14 CFR 25.803 [23] certification evacuation demonstration. The former may use a cabin mock-up that is like a real airplane but not an actual airplane, while the latter makes use of the actual airplane.

Furthermore, the nature of the experimental dataset used to validate the evacuation model must be relevant for the intended application. For example, an evacuation model that claims it has a demonstrated validation case history in building or maritime applications does not mean it is validated for airplane applications.

Data from the 14 CFR 25.803 [23] demonstration certification trials, if available, are a good source of validation data for aircraft evacuation models (see [14] for examples of aircraft evacuation model validation using certification trial data). Another potential source of data for aircraft model validation is real accidents, if sufficient detailed information has been collected from the incident (e.g., see [4]). This includes information such as interviews with all CC and passengers, seating allocation for all passengers, detailed demographics of passengers, detailed information concerning exit opening times and exiting times for all passengers and crew, etc. Such detailed information is seldom available for most accidents, but if the accident takes place at an airport, much of this information may be available from airport security CCTV.

As part of the proposed enhanced certification process, it is suggested that modelling submissions present validation evidence to support the use of their chosen evacuation model. Furthermore, it is recommended that aviation regulators develop a database of appropriate airplane validation test cases, preferably based on previous actual 14 CFR 25.803 demonstration trials.

It was noted in Section 2.1 that the state-of-the-art evacuation simulation software airEXODUS has undergone a number of validation exercises to demonstrate its ability to reproduce 14 CFR 25.803 [23] certification evacuation trials [14] and forensically explore real accident scenarios such as the analysis of Manchester Airport B737 fatal fire [4]. The validation evidence presented in [14] is extensive and includes detailed comparisons with six previous 14 CFR 25.803 certification trials, four for wide-body aircraft and two for narrow-body aircraft. Furthermore, the validation evidence provided, not only included comparisons of the TET but also the evacuation time of each passenger using the evacuation curve for the certification trial. It is also worth noting that some additional validation evidence for airEXODUS was provided in Section 5.2.2f based on certification data for the 194-person variant of the aircraft configuration investigated in the current study. While this evidence is not as strong as that provided previously [4,14], it does support the view that the evacuation simulation results presented in this document for the 185-person variant aircraft configuration used in this analysis are reasonable.

(iii) Verification

Given that validation data for airplane evacuation models is not currently readily available, it is recommended that in addition to providing evidence of validation, a series of verification cases be defined as part of the enhanced evacuation certification protocol. This is similar to the requirements set out by the IMO in their maritime evacuation protocol guidance [44]. In the maritime guidance some 12 ‘simple’ verification test cases are specified to demonstrate that the evacuation simulation software used in the certification analysis is capable of representing the basic functionality required for a ship evacuation model. It is noted that the verification cases are intended to demonstrate both qualitative and quantitative agreement with informed expectations.

As part of the proposed enhanced certification protocol, it is recommended that a series of verification test cases are specified that the evacuation software must satisfactorily complete and submit for consideration, as part of the enhanced certification test protocol.

While it is not the intent of this document to define a definitive set of verification test cases, the following eight example verification test cases are examples of what could be considered appropriate for inclusion in the proposed enhanced certification protocol.

As part of the aviation evacuation verification test cases, two hypothetical airplane LOPAs should be specified, one for a narrow-body airplane configuration (with a pair of forward and a pair of aft Type C exits and two pairs of overwing Type-III exits) and one wide-body airplane configuration (with four pairs of Type A exits). The verification cases could make use of these configurations.

(a) Proposed Verification Case 1: Passenger walking speed correctly implemented

Place a single passenger at the aft end of the central aisle of the narrow-body aircraft. Allocate them a walking speed of 1.2 m/s. Measure the central aisle distance from the distance from the aft to the extreme forward position of the cabin. Demonstrate that the time required to travel this distance is correct. Repeat the process with an allocated walk speed of 0.8 m/s.

(b) Proposed Verification Case 2: Correct allocation of specified population response times

Populate the narrow-body airplane with a certification population as specified in the protocol—identified as population 1. Demonstrate that population 1 is allocated response times as specified in the protocol. Repeat this process 10 times with 10 different randomly generated populations satisfying the population specification. Demonstrate that each population has a different distribution of response times satisfying the requirement.

(c) Proposed Verification Case 3: Exit ready times

For the narrow-body aircraft, allocate appropriate exit ready times as specified in the protocol for the Type C and Type-III exits. Populate the aircraft with a certification population as specified in the protocol. Demonstrate that the queues form by the exits until the allocated exit ready time has elapsed, that the exits open at the required times, and that passengers do not exit until after the exits are opened.

(d) Proposed Verification Case 4: Type C flow rate

For the narrow-body airplane, configure the airplane as required by the protocol for CMS1, and populate the aircraft as required. However, only allow the forward 1L Type C exit to open, forcing all the agents to utilise this exit. Repeat the simulation 1000 times. Generate an exit flow curve for the simulation producing the median TET, where the exit flow is determined in 10 s intervals similar to Figure 26. Also, produce an average exit flow curve based on the data produced for the 1000 simulations similar to Figure 26. How do they compare with the minimum, average, and maximum average exit flows produced for Type C exits (with assertive crew) from previous certification trials? Note, from Section 2.7, the minimum, mean, and maximum average flow achieved by a Type C exit with assertive crew (measured throughout the evacuation) in a certification trial is 53 ppm, 61 ppm, and 65 ppm, respectively [17,19].

(e) Proposed Verification Case 5: Type-III flow rate

For the narrow-body airplane, configure the airplane as required by the protocol for CMS1, and populate the aircraft as required. However, only allow the overwing 2L Type-III exit to open, forcing all the agents to utilise this exit. Repeat the simulation 1000 times. Generate an exit flow curve for the simulation producing the median TET, where the exit flow is determined in 10 s intervals similar to Figure 26. Also produce an average exit flow curve based on the data produced for the 1000 simulations similar to Figure 26. How do they compare with the minimum, average, and maximum average exit flows produced for Type-III exits (without crew assistance) from previous certification trials? Note, from Section 2.7, the minimum, mean, and maximum average flow achieved by a Type-III exit (measured throughout the evacuation) in a certification trial is 29 ppm, 35 ppm, and 43 ppm, respectively [17, 19].

(f) Proposed Verification Case 6: Type A flow rate

For the wide-body airplane, configure the airplane as required by the protocol for CMS1, and populate the aircraft as required. However, only allow the forward 1L Type A exit to open, forcing all the agents to utilise this exit. Repeat the simulation 1000 times. Generate an exit flow curve for the simulation producing the median TET, where the exit flow is determined in 10 s intervals similar to Figure 26. Also, produce an average exit flow curve based on the data produced for the 1000 simulations similar to Figure 26. How do they compare with the minimum, average, and maximum average exit flows produced for Type A exits (with assertive crew) from previous certification trials?

(g) Proposed Verification Case 7: Distribution of TETs for narrow-body simulation

For the narrow-body airplane, configure the airplane as required by the protocol for CMS1, and populate the aircraft as required. Run the simulation 1000 times and generate the TET distribution. Demonstrate that a near-normal distribution of TETs is produced. What is the range of TET, and what is the 95^{th} percentile TET? If available, how does this compare with regulator expectations?

(h) Proposed Verification Case 8: Distribution of TETs for wide-body simulation

For the wide-body airplane, configure the airplane as required by the protocol for CMS1, and populate the aircraft as required. Run the simulation 1000 times and generate the TET distribution. Demonstrate that a near-normal distribution of TETs is produced. What is the range of TET, and what is the 95^{th} percentile TET? If available, how does this compare with regulator expectations?

(iv) Documentation

It is recommended that the documentation supporting a modelling evacuation analysis of an airplane configuration following the proposed enhanced evacuation certification protocol should include several documents, as outlined below. Ideally, the proposed documentation describing the evacuation modelling for the airplane being certified would be submitted to the regulatory authority prior to running the live certification demonstration trial; however, this is not practical, as this would require the regulator to reveal to the manufacturer which specific exits will be available during the trial. Given this restriction, the certification modelling analysis and documentation can only be completed after the live trial has been run.

(1) Certification Analysis Report: A report describing the analysis for the airplane configuration undergoing the certification process should be submitted to the regulatory authority following the live full-scale certification trial. The numerical results for the CMSs (see Section 10.4(ii)a) should be provided in a detailed report that describes the model, any assumptions imposed on the simulations, and the data used to specify the scenarios. In addition, the exit curves for each CMS should be provided along with the exit curve for the certification demonstration trial. The trial exit curve should be compared with the exit curves produced by the CMS most closely resembling the certification demonstration trial (see, for example, the analysis presented in [14]) as a form of validation. The

report should include the analysis to determine TET_{CERT} (see Equation 3) and TET_{CMS} (see Equation 4). The input and output files for each of the CMSs should be provided and available for independent verification.

(2) Results of the Verification Cases: The results for the verification test cases (see Section 10.5(iii)) could be provided as an appendix to the Certification Analysis Report or as an appendix in the user guide of the airplane evacuation simulation software (see 10.5(iv)(4)). In addition to the written report describing the results of the verification cases, the input files required to generate the verification cases and the associated output files should be provided and available for independent verification.

(3) Evidence of Validation: Until a suitable airplane validation database is developed, evidence of relevant rigorous validation of the airplane evacuation simulation software should be provided, such as peer-reviewed academic publications or project reports. The documentation should describe the validation cases (including how the data were collected), the nature of the validation test cases, including the airplane configuration, the nature of the validation comparison (what experimental data is used for comparison purposes), and an assessment of how well the model predictions match the experimental data.

(4) Software User Guide: 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.

12. Project Limitations

It is accepted that any modelling exercise approximates reality, and so modelling incorporates a range of assumptions and, hence, limitations that need to be considered when reviewing and interpreting modelling results. This work is no exception. The modelling work presented here incorporates a range of limitations in terms of the data used in the modelling, the nature of the scenarios implemented, and the capabilities of the modelling tool. The primary limitations of the current study are identified as follows:

Off-Time not included. All the modelling analysis presented in this report excluded the off-time (also known as slide time) (see Section 2.5c) and so only the OOA times are presented. While the airEXODUS software has the capability to include the off-time, this was not included for simplicity. Appropriate off-times for Type C and Type-III exits, derived from certification trials, are available [17,19]. For the simulations to produce similar times to the live certification demonstration, the OG times are required, so the off-times should be included in the analysis.

(1) **Cabin sweep not included.** Prior to CC evacuating the aircraft, they typically undertake a sweep of the cabin to ensure that no passengers remain. This process was not represented in the modelling analysis presented in this report (see Section 3.1). The cabin sweep was not included in the analysis, as there are many possible cabin sweep procedures that could be implemented, and these are usually specific to the carrier. Cabin sweep procedures should be implemented as part of the proposed CMSs (see Section 10.4(ii)a). It is noted that the airEXODUS software has the capability to implement complex cabin sweep procedures.

(2) **Impact of unassertive CC not included.** The impact of unassertive CC on evacuation performance was not included in the analysis due to a lack of sufficient reliable data in the certification dataset [17, 19] to characterise exit flows at exits with unassertive crew (see Section 2.5b). However, the impact of reduced assertiveness was examined through the use of the 'in-between' assertiveness data, which represents CC that are not assertive or unassertive but perform in a manner that is in-between both extremes of assertiveness. As expected, this led to a very slight reduction in evacuation performance (see Section 7).

(3) **Simplifications to ensure parity with the certification trial.** A number of simplifications to the modelling analysis presented in this report were introduced to ensure parity with the current demonstration certification trial. These simplifications and omissions were discussed in Section 10.2(iv), so they are only briefly mentioned here.

(4) **Passenger luggage retrieval not included.** In addition to maintaining broad parity with the conditions of the certification trial, this aspect was not included, as it was investigated as part of another modelling study [16].

(5) **The impact of passengers with movement disabilities not included.** While it is possible to represent passengers with movement disabilities within the airEXODUS software (see CMS6), suitable data are required to quantify the reduction in movement capabilities. While some data exist [38], the date were collected in the 1970s and so may no longer be representative. Ideally, additional data should be provided that are appropriate for current airplane interior layouts and representative of disabilities prevalent in today's travelling public.

(6) **The impact of a greater number of elderly passengers not included.**

(7) **The impact of group dynamics not included.** It is possible to represent a range of passenger group dynamics within the current version of airEXODUS. However, it is necessary to identify the group behaviours that are required for inclusion into the CMSs (see CMS6) and determine if sufficient data to characterise these behaviours are available.

(8) **The impact of fire, smoke, and toxic fire gases not included.** airEXODUS has the capability to include the impact of fire effluents on the evacuation [4, 5, 13, 56-60], so CMSs involving the impact of fire could be included, as discussed in Section 10.4 (iv).

(9) **The impact of adverse cabin orientation not included.** Data specific to the movement behaviour and movement rates for passengers in airplane cabins with adverse orientation are currently not available. While data from maritime [61-63] and rail [64] could be used, ideally, experimental trials should be conducted to collect the required data in a suitable aviation environment (see 10.2(iv)(7) and the proposed CMS7).

13. Recommendations for Additional Analysis and Data to Assist the Regulatory Process

While this work has addressed key project aims to explore parameters that impact rapid airplane evacuation using modelling and to make recommendations to enhance the current regulatory process using evacuation modelling, it is recommended that additional analysis is undertaken to better understand model sensitivities and to further refine the suggested enhanced modelling certification protocol. To support the reliable use of evacuation models in certification applications, additional experimental data is required, so a range of experimental campaigns is recommended to collect the required data. Finally, while not strictly within the remit of this project, a recommendation concerning fire data is suggested to assist in updating the ASET currently imposed in the 14 CFR 25.803 evacuation protocol, i.e., the 90 s requirement.

(1) **Characterisation of the demographics of the travelling public.** A study should be undertaken to characterise the demographics of the travelling public that utilise air transportation. This should include not only age and gender, but body size, nature of any disability, and data relating to the type and frequency of social groups amongst passengers.

(2) **Experimental campaign to collect data on movement capabilities of disabled passengers.** While some data are available to characterise the movement speeds of people with disabilities in airplane configurations, these data were collected by the FAA in the late 1970s [38]. The scope of this study should be expanded to include airplane configurations and seating appropriate to current standards and also the range of disabilities that are common today in the travelling public. The study could initially focus on disabilities that allow unaided movement at reduced speed.

(3) **Experimental campaign to collect data on the impact of cabin orientation on movement speeds and behaviour.** Experimental data describing passenger movement rates and behaviour associated with likely airplane adverse orientation are required to support the understanding of how cabin orientation can impact evacuation times and passenger survivability.

(4) **Experimental campaign to collect data on the impact of CC fatigue on evacuation performance.** While it is well established that CC fatigue impacts decision-making, there is no research to explore the impact fatigue and sleepiness may have on the ability of CC to manage a cabin evacuation. It is recommended that research is conducted into this aspect that utilises CC who have induced fatigue levels appropriate for an evacuation that may occur at the end of a typical duty cycle.

(5) **Experimental campaign to collect data on the impact of CC experience on evacuation performance.** There is currently no comprehensive research that explores if CC experience influences the ability of CC to efficiently manage cabin evacuation. This includes factors such as the length of service and the length of time since the last recurrent training. It is recommended that research should be conducted to explore if CC experience is a significant influential factor in evacuation performance.

(6) **Extend the model sensitivity analysis to include wide-body aircraft.** A similar model sensitivity analysis to that conducted as part of the current study could be undertaken exploring issues associated with evacuation behaviour in wide-body airplanes.

(7) **The impact of passengers with movement disabilities.** The sensitivity analysis undertaken as part of the current study could be extended to explore the impact of passengers with movement disabilities on evacuation. This analysis would be restricted to passengers who can move unaided but at a greatly reduced speed. Until additional data are provided (see recommendation (2)), the analysis could make use of existing data [38].

(8) **The impact of a greater number of elderly passengers.** The sensitivity analysis undertaken as part of the current study could be extended to explore the impact of a population demographic

that was skewed to include a higher proportion of elderly passengers on the evacuation could be analysed.

(9) **The impact of group dynamics.** The sensitivity analysis undertaken as part of the current study could be extended to explore the impact of group behaviour associated with passengers in social groups on evacuation. The behaviour of the individuals within the social group could be modified so that the group of passengers would move at the speed of the slowest member of the group, all members of a group would utilise the same exit, and if the members of the group were initially separated, they would reunite prior to evacuating.

(10) **The impact of adverse cabin orientation.** The sensitivity analysis undertaken as part of the current study could be extended to explore the impact of adverse cabin orientation (e.g., nose up or nose down) on evacuation. Until additional data are provided (see recommendation (3)), the analysis could make use of existing data from other industries, such as the maritime [61- 63] and rail [64] industries.

(11) **Extend the scope of suggested CMSs.** The suggested certification modelling scenarios (see Section 10.4(ii)) should be extended to include issues such as passenger demographics, passengers with disabilities, social groups and group dynamics, adverse cabin orientation, fire, CC fatigue, and CC experience. Examples of their implementation in narrow-body and wide-body applications should be provided.

(12) **Apply the suggested 'weighted sum' approach for the enhanced evacuation certification process to existing aircraft**. In consultation with the regulator and an airplane manufacturer, apply the recommended 'weighted sum' approach (see Section 10.4(iii)) to an existing airplane that has successfully passed the 14 CFR 25.803 certification process and for which detailed video and documentary evidence of the certification demonstration trial is available. This analysis should include a range of CMSs (see Section 10.4(ii)) and be applied to both narrow-body and wide-body airplane configurations. The proposed analysis should also comply with the identified quality control processes (see Section 10.5).

(13) **Develop an appropriate set of airplane evacuation model verification cases. T**he suggested verification test cases (see Section 10.5(iii)) should be reviewed and expanded. In addition, to demonstrate the nature of expected acceptable responses to the verification cases, a comprehensive set of ideal model solutions to each of the verification cases should be prepared.

(14) **Develop an appropriate set of airplane evacuation model validation cases.** It is recommended that aviation regulators develop a database of appropriate airplane validation test cases, preferably based on previous actual 14 CFR 25.803 demonstration trials (for example, see [14]).

(15) **Experimental campaign to collect fire data to characterise the performance of new fuselage and cabin materials and establish an appropriate ASET.** The current ASET used in airplane evacuation certification (i.e., 90 s) was established over 50 years ago. Given the significant change in fuselage (i.e., use of CFRP materials) and cabin (i.e., use of fire-retarded materials) materials, it is unlikely that this value is still relevant. As a result, there is a need for an extensive range of laboratory-scale and full-scale fire tests to quantify the fire performance of individual materials (i.e., not simply determine the pass/fail status of the materials based on standards compliance testing, as is the current common practice) and the airplane system as whole to establish an ASET suitable for the new generation of aircraft. In addition, the data generated from the proposed fire testing could be used to enhance CFD fire modelling for airplane fire applications.

Conclusions

This project addressed two main aims—the first to explore several parameters that impacted the rapid evacuation of transport category aircraft using a state-of-the-art airplane evacuation model, and second, to make recommendations on how evacuation simulation could be used to enhance the current airplane certification protocol as defined in 14 CFR 25.803(c). The analysis made use of the airEXODUS airplane evacuation model produced by the Fire Safety Engineering Group of the University of Greenwich. Furthermore, the study is based on a single aircraft configuration consisting of a single-aisle narrow-body cabin layout, typical of the popular B737/A320 model airplane.

To address the first aim, the model sensitivity analysis investigated five evacuation scenarios:

a. **Scenario 1:** This scenario is the equivalent of the certification demonstration trial scenario specified in 14 CFR 25.803. In the modelling analysis, the scenario was repeated multiple times with different populations satisfying the certification demographic.
b. **Scenario 2:** As in Scenario 1, but with an exit availability typical of that frequently occurring in accidents while satisfying the certification requirement of involving 50% of the available exits and including a mix of exit types equivalent to that resulting from the certification requirements.
c. **Scenario 3a:** As in Scenario 1, but with the assertiveness of the cabin crew at the Type C exits slightly reduced (set to 'in-between'), so that the cabin crew behave assertively but on occasion they behave unassertively during the evacuation.
d. **Scenario 3b:** As in Scenario 2, but with the assertiveness of the cabin crew at the Type C exits slightly reduced (set to 'in-between'), so that the cabin crew behave assertively but on occasion they behave unassertively during the evacuation.
e. **Scenario 4:** As in Scenario 1, but passengers attempt to utilise their nearest exit, effectively not responding to cabin crew commands to redirect to optimal exits. The passenger exit-selection behaviour is representative of observed passenger behaviour in accidents.

Two additional scenarios that were undertaken as part of an earlier modelling study to investigate the impact of passenger retrieval of cabin luggage on evacuation performance are also included in part of the model sensitivity analysis:

f. **Scenario 5:** Equivalent to Scenario 2, but passengers attempt to utilise their nearest exit, effectively not responding to cabin crew commands to redirect to optimally utilise available exits. The passenger exit-selection behaviour is representative of observed passenger behaviour in accidents.
g. **Scenario 6:** Equivalent to Scenario 5, but with 25% of the passengers attempting to retrieve cabin luggage during evacuation.

From this analysis, it was identified that the airEXODUS software was able to produce a reasonable approximation of the expected certification result for the airplane in Scenario 1, the scenario most closely resembling the certification trial scenario. The predicted TETs from 1000 repeat simulations, each using a different population satisfying the certification trial demographic requirements, varied from 62.9 s to 77.0 s, with the certification trial performance (estimated from certification data for a similar aircraft) of 76.9 s falling within the predicted range.

The sensitivity analysis highlighted a number of issues impacting the rapid evacuation of transport category aircraft that are currently not represented within the 14 CFR 25.803 evacuation demonstration protocol. These include:

a. The use of a single evacuation demonstration trial, as required in the current evacuation certification protocol, is unlikely to characterise the evacuation performance of an airplane.
b. The use of a single population satisfying the current demographic is unlikely to be sufficient to characterise the evacuation performance of an airplane.
c. The exit availability currently used in the evacuation certification protocol (one exit from each exit pair, e.g., 1L, 2L, 3L, and 4L, as in Scenario 1), is conducive to producing short evacuation times. Other combinations of 50% of the available exits that result in the same mix of exit types and are likely to occur in accidents (e.g., 1L, 1R, 2L, and 3L, as in Scenario 2) will result in longer evacuation times. In the sensitivity analysis, the 95th percentile TET increased from 71.3 s (Scenario 1) to 94.7 s (Scenario 2), an increase of almost 33%. Furthermore, this change in exit availability results in a 95th percentile TET in excess of 90 s, so it would be considered a certification failure.
d. If passengers select their nearest exit, as is typical in accident scenarios (as in Scenarios 4 and 5), this will result in longer evacuation times than will be achieved if passengers utilise optimal exits under the guidance of cabin crew direction. Comparing Scenario 1 (exits 1L, 2L, 3L, and 4L, with optimal-exit selection) and Scenario 4 (exits 1L, 2L, 3L, and 4L, with nearest-exit selection), the 95th percentile TET increases from 71.3 s to 90.1 s, an increase of 26%, and more significantly, results in a failure in terms of the certification demonstration trial performance.
e. If the evacuation scenario includes three adverse but realistic factors, such as 25% of passengers retrieve carry-on luggage during the evacuation, adverse exit availability, and passengers select their nearest available exit (i.e., Scenario 6), evacuation efficiency is significantly reduced, with a large increase in TET. Comparing Scenario 1 with Scenario 6, the median TET increases from 67.7 s (in Scenario 1) to 135.5 s (in Scenario 6), a doubling of the TET compared to the expected certification trial performance, and results in a significant failure.

Based on the outcome of the model sensitivity analysis, four options were suggested to enhance the current airplane evacuation certification protocol as described in 14 CFR 25.803.

- **Option 1:** The first option proposed updating the nature of the certification demonstration trial so that it more closely reflected relevant accident scenarios, without increasing the risk to trial participants or the cost of the trial. For example, the exit availability could be modified so that it reflected challenging exit combinations that occur in accidents, such as that used in Scenario 2.
- **Option 2:** The second option proposed that in addition to the certification demonstration trial, several additional evacuation scenarios to be analysed using appropriate aircraft evacuation models could be included in the certification protocol. The proposed certification model scenarios included Scenarios 1, 2, 4, and 5 from the sensitivity analysis. The proposed approach is similar in concept to that adopted by the IMO for the evacuation certification of passenger ships sailing in international waters. Using this approach, each of the proposed certification scenarios (i.e., experimental trial and simulation scenarios) would need to satisfy the 90 s requirement.
- **Option 3:** The third option provided a means of assessing the evacuation performance of the airplane using a weighted sum of certification demonstration trial results and results from the model-based certification scenarios. Enhancing the certification process through evacuation modelling using the weighted sum approach addresses a number of challenging issues:

1) It maintains the importance and influence of the standard demonstration certification trial to the certification process.

2) It provides a means of introducing into the certification process additional challenging and relevant accident scenarios without increasing the risk to participants through the use of evacuation modelling.

3) It provides the regulatory authorities with a means of gradually phasing in the use of evacuation modelling into the certification.

4) The specific modelling scenarios and associated weights used in the enhanced evacuation protocol can be reviewed by the regulatory authority and updated as appropriate.

5) It continues to provide a consistent means to compare the performance of one airplane configuration with another.

6) The certification modelling scenarios can be used by airplane manufacturers as part of the design process to ensure that future airplane designs are able to satisfy evacuation safety requirements.

The challenge in the weighted sum approach is to select a meaningful distribution of weights that reflects the importance of the CMS to the certification process and regulator and stakeholder confidence in the ability of the airplane evacuation models to accurately simulate airplane evacuation in the identified scenarios. To a certain extent, the selected weight distribution will be a measure of the regulator's confidence in the quality of the model validation presented and the relevance of the verification test cases.

- **Option 4:** While not strictly within the scope of the current project, a fourth option was proposed to update the ASET currently imposed in the 14 CFR 25.803 evacuation protocol, i.e., the 90 s requirement. This would require an extensive range of laboratory-scale and full-scale fire tests to quantify the fire performance of individual materials (i.e., not simply determine the pass/fail status of the materials based on standards compliance testing, as is the current common practice) and the airplane system to establish an ASET suitable for the new generation of aircraft. The aviation industry could then adopt CFD fire modelling, as in the building and maritime industries, to define an appropriate ASET for the airplane configuration being certified.

As part of the proposed enhanced evacuation certification protocol (i.e., Options 2 and 3), it is essential that measures are put in place to ensure the quality of the evacuation modelling analysis and the presentation of the results of the analysis. A suggested process is presented and discussed for model selection, verification, and validation, as well as a process for reporting the results of the evacuation analysis.

While this work has addressed the key project questions concerning evacuation model sensitivity and suggested how evacuation simulation could be used to enhance the regulatory process, it is recommended that additional analysis be undertaken to better understand model sensitivities and to further refine the suggested enhanced modelling certification protocol. Furthermore, additional experimental data are required to support the reliable use of evacuation models in certification applications. This includes:

(1) Characterisation of the demographics of the travelling public.
(2) Experimental campaign to collect data on movement capabilities of disabled passengers.
(3) Experimental campaign to collect data on the impact of cabin orientation on movement speeds and behaviour.
(4) Experimental campaign to collect data on the impact of CC fatigue on evacuation performance.

(5) Experimental campaign to collect data on the impact of CC experience on evacuation performance.
(6) Extend the model sensitivity analysis to include wide-body aircraft.
(7) Extend the model sensitivity analysis to consider the impact of passengers with movement disabilities, a greater number of elderly passengers, group dynamics, and adverse cabin orientation.
(8) Extend the scope of the suggested CMSs, as in (7).
(9) Demonstrate the suggested ‘weighted sum’ approach for the enhanced evacuation certification process to both narrow- and wide-body airplanes that have available 14 CFR 25.803 certification data.
(10) Develop and demonstrate an appropriate set of evacuation model validation and verification cases.
(11) Experimental campaign to collect fire data to characterise the performance of new fuselage and cabin materials and establish an appropriate ASET.

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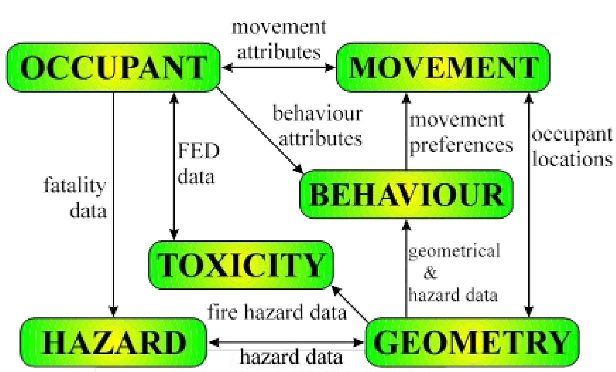
14. Annex 1: The airEXODUS Model

The airEXODUS aircraft evacuation model is part of a suite of software tools designed to simulate the evacuation of large numbers of people from a variety of complex enclosures. Development of the EXODUS concept began in 1989, and today, the family of models consists of buildingEXODUS, maritimeEXODUS, railEXODUS, urbanEXODUS, and airEXODUS for the built, maritime, rail, urban, and aviation environments, respectively. airEXODUS is designed for use in aircraft design, compliance with 90-second certification requirements, crew training, development of crew procedures, resolution of operational issues, and accident investigation. The software has been used extensively in the aviation industry for a variety of projects [4-9].

Application projects include design applications for aircraft manufacturers of large passenger aircraft, such as the A380 and A340-600; concept projects for manufacturers, e.g., Airbus BWB [5,7]; projects for operators assessing modifications to cabin layouts, such as B777 variants; design of regional aircraft for Bombardier and Mitsubishi, e.g., Dash 8-400, RJ, and MRJ; specialist evacuation analysis projects for aviation companies such as Jet Aviation, Zodiac, PEMCO, and Pt21 on aircraft ranging from B737 to VIP B747; and forensic accident reconstruction, such as the analysis of Manchester Airport B737 fatal fire [4]. There has also been extensive validation of the airEXODUS software. A report produced for the UK CAA presents results from an extensive validation exercise [14].

The EXODUS software takes into consideration people–people, people–fire, and people–structure interactions. It comprises five core interacting sub-models: the **Passenger, Movement, Behaviour, Toxicity, and Hazard** sub-models (see Figure 27). The software describing these sub-models is rule-based, with the progressive motion and behaviour of each individual being determined by a set of heuristics or rules. These sub-models operate on a region of space defined by the **GEOMETRY** of the enclosure. The model tracks the trajectory of each individual as they make their way out through the geometry or are overcome by fire hazards such as heat, smoke, and toxic gases. Each of these components will be briefly described in turn.

Figure 27
EXODUS Sub-model interaction



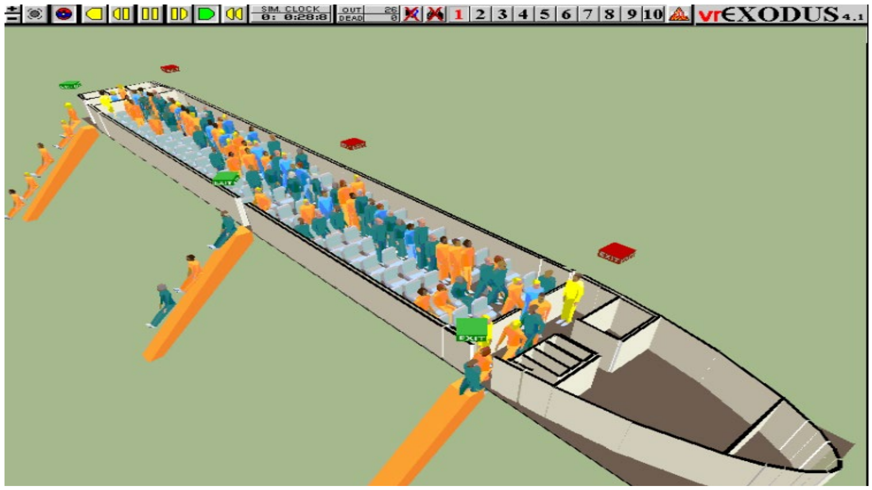
The **GEOMETRY** of the aircraft can be defined manually or read from a Computer Aided Design using the DXF format. Internally, the entire space of the geometry is covered in a mesh of nodes that are typically spaced at 0.5 m intervals. The nodes are then linked by a system of arcs. Each node represents a region of space typically occupied by a single passenger. The **MOVEMENT SUB-MODEL** controls the physical movement of individual passengers from their current position to the most suitable neighboring location or supervises the waiting period if one does not exist. The movement may involve such behaviour as overtaking, side-stepping, seat-jumping, or other evasive actions. The **HAZARD SUB-MODEL** 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 SUB-MODEL** determines the effects on an individual exposed to toxic products distributed by the hazard sub-model. These effects are communicated to the behaviour sub-model, which, in turn, feeds through to the movement of the individual.

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

The **BEHAVIOUR SUB-MODEL** 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 sub-model. The behaviour sub-model 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 most familiar exit, or exit via their allocated exit. The local behaviour of the passenger may also be affected through the intervention of cabin crew. While airEXODUS has the ability to represent "extreme" passenger behaviour of the type reported in actual aviation accidents [10,11], such as seat jumping, this type of behaviour is not included in certification application simulations. As certain behaviour rules, e.g., conflict resolution and model parameters, e.g., passenger exit hesitation times, are probabilistic in nature, the model will not produce identical results if a simulation is repeated. In studying a particular evacuation scenario, it is necessary to repeat the simulation a number of times in order to produce a distribution of results.

Figure 28

airEXODUS evacuation simulation depicted in the vrEXODUS software



While airEXODUS is capable of generating interactive two-dimensional graphics of the simulation, output files from airEXODUS can be replayed in vrEXODUS. For added realism, vrEXODUS creates a three-dimensional representation of the simulation (see Figure 28).

Certification Data used in airEXODUS

airEXODUS makes use of 90-second certification data to specify certain key parameters. In particular, data concerning the *EXIT READY TIME, PASSENGER EXIT DELAY TIMES and OFF-TIME,* and parameters for all the exits must be specified. Extensive data have been extracted by FSEG from past certification data [14, 17, 19], and these data are used within the software to specify these parameters. Each of these parameters is described briefly as follows:

(a) Exit Ready Time

Exits are opened by cabin crew or passengers. Within airEXODUS, it is possible to specify the time required to open the exit. In addition, the exit ready time can include the time required for the slide to deploy. In effect, the exit ready time specifies the time from the start of the simulation to when the exit is ready to allow passengers to pass through the exit. Exit ready times for aircraft involved in past certification trials have been analysed as part of the data extraction exercise reported in [17].

(b) Passenger Exit Delay Time

One of the most important parameters in airEXODUS 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. The precise point at which hesitation begins, and ends is based on a somewhat subjective decision and sometimes impossible to judge due to crowding, camera angle, light intensity, etc.

In general, the 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 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 separate events (controlled by exit delay time and Off-Time, respectively, within airEXODUS) that can occur in parallel.

Within airEXODUS, each passenger is randomly assigned a delay time as they pass through the exit. The delay time is assigned using a probability distribution derived from past certification trials [14, 17, 19] (as an example, see Figure 29**)**. The delay time is dependent upon a number of factors. The following list represents the most prevalent of these factors:

- **Exit type** – the exit type (thus size) causes different kinds of exiting techniques for each exit type; for example, passengers tend to crouch and climb out of Type-III exits and jump out of Type A exits.

- **Exiting behaviour** – different behaviour traits may be exhibited by different passengers, even on the same exit type. For example, some passengers jump through Type A exits, whereas others sit on the sill and push off.

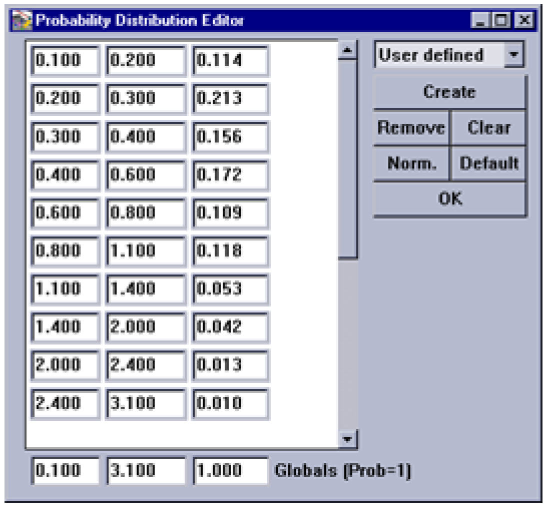
- **Passenger physical attributes** – The gender, age, and physical size of the passengers have also been found to have an impact on the hesitation time. However, there are currently insufficient data available to perform a meaningful analysis on all exit types. Thus, it is not possible to assign a likely passenger exit hesitation delay time to a passenger based on their physical attributes. Rather, it is assigned from a probability distribution derived from data relating to all passengers.

- **Presence of cabin attendants** – the presence (or absence) of cabin attendants at exits can enormously influence the behaviour exhibited by passengers at exits. Undirected passengers tend to take more time deciding how to use the exit, and indeed, which exit to use.

- **Behaviour of cabin attendants** – when cabin attendants are present at an exit, the degree of assertiveness they display also influences the hesitation times. As the level of assertiveness increases, the range of slower hesitation times decreases, thus increasing the overall flow throughput of the exit.

Figure 29

Example of passenger exit delay time distribution specification in airEXODUS



Within airEXODUS, the exit delay time distribution is segmented into subintervals described by uniform distributions. The manner in which this is defined in airEXODUS is depicted in Figure 29. The first column in the figure represents the lower limit (seconds) for the subinterval, while the second column represents the upper limit (seconds) for the subinterval. The third column represents the probability of a delay time falling in this range. The three numbers at the bottom of the dialogue box (label “Globals”) are a summary of the distribution: they specify the absolute minimum delay time, the absolute maximum delay time, and the total probability that a delay time will be allocated between this range. The technique is dependent on the user having a good representation of the actual delay time distribution. In the current version of the software, these data are extracted from past certification trials.

(f) Slide-Time

In airEXODUS, when a passenger has reached an exit, a further time penalty is added to reflect the time spent either travelling down a slide or across a wing. This is a non-predicted parameter specified by the user as part of the scenario specification for each exit used during the evacuation. The Slide-Time (also called Off-Time) is taken as the time between leaving the exit (typically touching the slide or clearing the exit) and the time at which the passenger is considered to be off the aircraft (typically touching the ground or passing some defined endpoint). In reality, this time will depend upon a number of factors, such as slide sill height, length of slide, nature of slide surface, nature of passenger clothing, whether the slide surface is wet or dry, and slide travel technique.

When added to the exit time of a passenger, this produces the on-ground time. Slide-Times for aircraft involved in past certification trials have been analysed as part of the data extraction exercise reported in [17]. Within airEXODUS, the Slide-Time is assigned using a random distribution, the values of which are specified from analysis of actual evacuation certification demonstrations or full-scale experimentation or simply a fixed value (average value derived from the certification data).

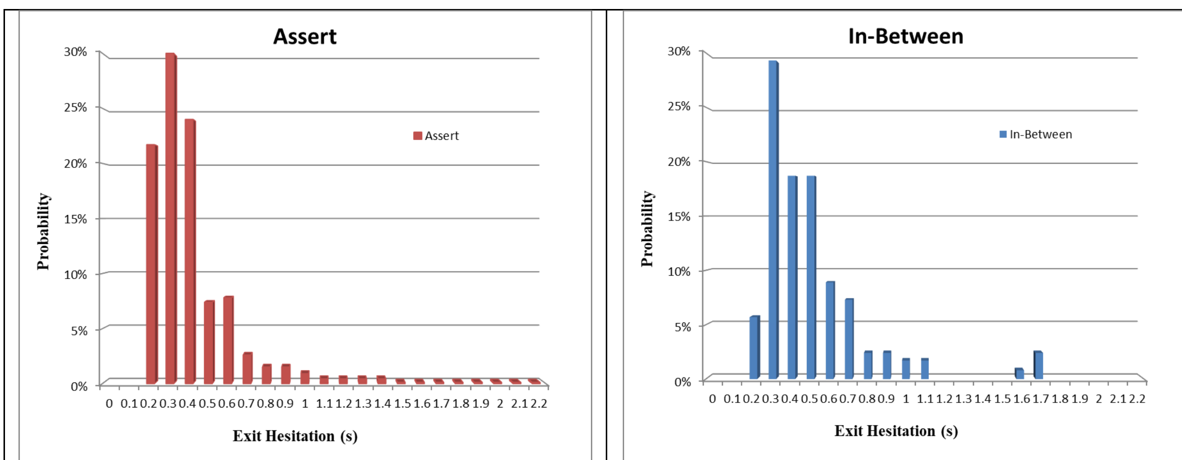
15. Annex 2: Comparison of Assertive and In-Between PEDT Distribution for Type C Exits

Presented in Figure 30 are the PEDT distributions for Type C exits with ‘assertive’ crew (see Figure 30a), ‘in-between’ crew (Figure 30b), and both ‘assertive’ and ‘in-between’ crew (Figure 30c) (data are derived from certification trials described in [19]). The two distributions are similar, with both distributions having minimum values between 0.1 s and 0.2 s; however, the ‘assertive’ distribution has a smaller median PEDT of between 0.2 s and 0.3 s, while the ‘in-between’ distribution has a slightly larger median PEDT of between 0.3 s and 0.4 s. There is more of a chance of a passenger being given a smaller PEDT when using the ‘assertive’ distribution. Thus, the ‘in-between’ PEDT distribution is slightly biased towards larger PEDT. However, the tail of the ‘assertive’ distribution extends further to higher maximum PEDT values of between 2.1 s and 2.2 s, whereas the maximum value from the ‘in-between’ distribution is between 1.6 s and 1.7 s. However, the frequency of achieving a higher PEDT is greater for the ‘in-between’ PEDT distribution. Thus, on average, a passenger is likely to be randomly allocated a slightly lower PEDT when exiting a Type C exit with ‘assertive’ crew compared to ‘in-between’ crew; there is a small probability that occasionally they may be allocated a larger PEDT than the maximum PEDT derived from the ‘in-between’ distribution.

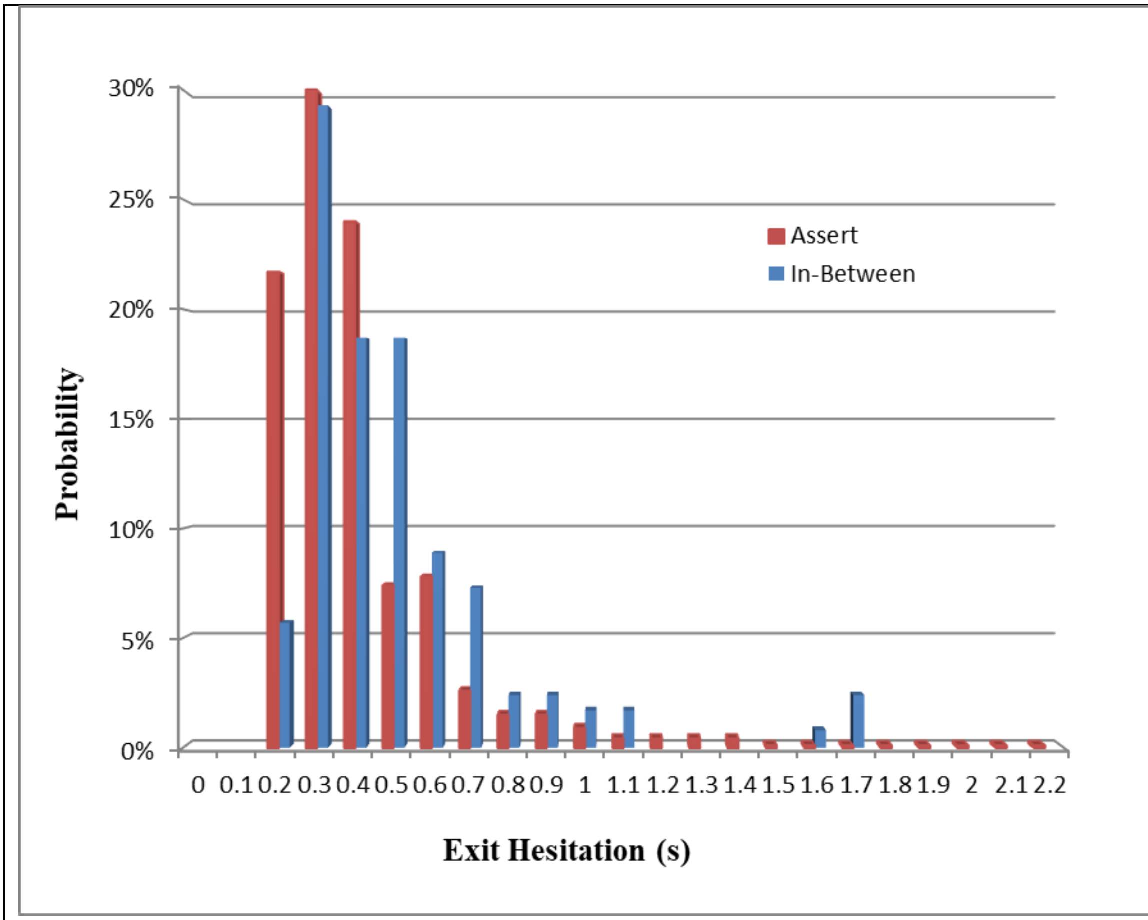
The impact the different PEDT distributions have on exit flow rates is demonstrated in Annex 3.

Figure 30

PEDT distributions for (a) ‘assertive’, (b) ‘in-between’, and (c) both ‘assertive’ and ‘in-between’ crew



(a) (b)


30%
25%
20%
15%
10%
5%
0%
Probability
Assert
In-Between
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2 2.1 2.2
Exit Hesitation (s)

(c)

16. Annex 3: Type C Exit Flow Rate Tests Assuming ‘Assertive’ and ‘In-Between’ Assertive Behaviors

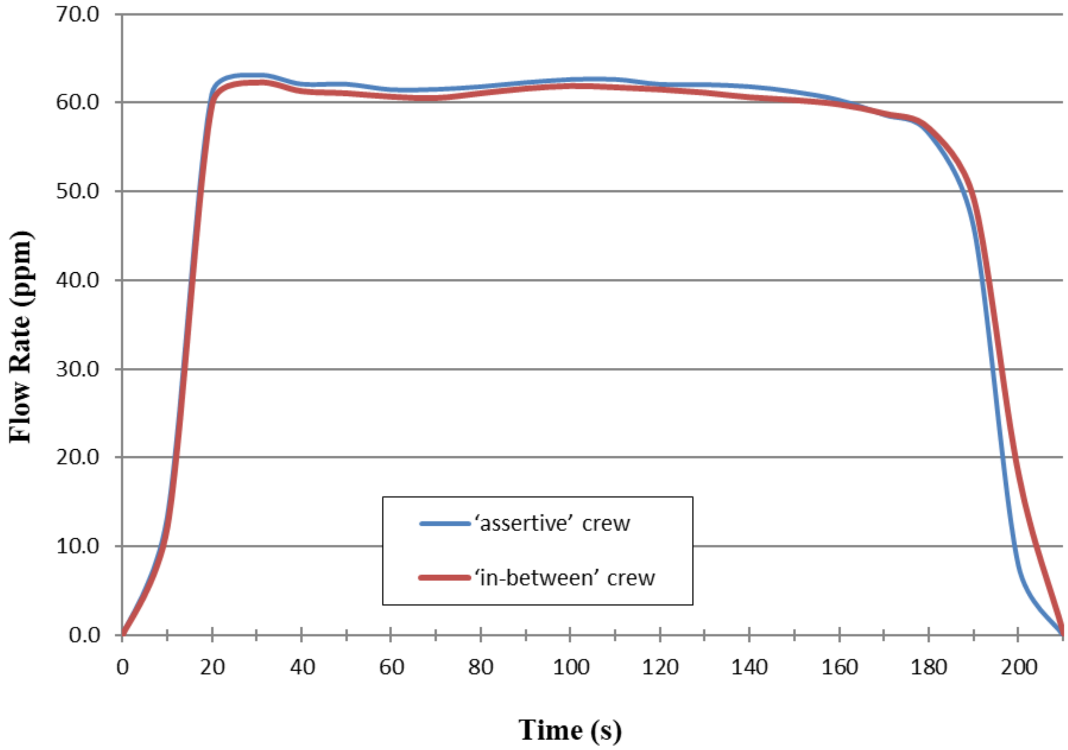
To demonstrate the impact on Type C exit flow rates of ‘assertive’ crew behaviour and ‘in-between’ crew behaviour, a series of flow rate tests was conducted in the B737 geometry presented in Figure 1. In the test cases, all 185 passengers utilise a single Type C exit, 1L. With such a large number of passengers using the exit, a more reliable estimate of exit flow rate is generated. Two cases are considered: in case 1, the crew at 1L are considered to be ‘assertive’, so the exit is assigned the PEDT distribution associated with assertive behaviour (see Figure 30a), while in case 2, the crew at 1L are considered to display ‘in-between’ assertiveness, so they are assigned the PEDT distribution associated with ‘in-between’ behaviour (see Figure 30b). Furthermore, each case is repeated 1000 times, and the average flow rate through the Type C exit is determined at each instant of the evacuation in 10 s intervals and averaged over all 1000 simulations (see Figure 31).

As can be seen from Figure 31, using the ‘assertive’ PEDT distribution results in a slightly higher exit flow rate at virtually every instant of the evacuation than the ‘in-between’ PEDT distribution. Furthermore, the overall average flow rate in the ‘assertive’ case is 60.8 ppm (people per minute), while in the ‘in-between' case, it is 60.0 ppm.

This small difference in exit flow rates explains the small differences observed in Scenario 3b versus Scenario 2d and Scenario 3a versus Scenario 1. It is, however, suggested that had PEDT data been available for ‘unassertive’ crew at a Type C exit, the differences in average flow rate, and, hence, overall evacuation performance, are expected to be greater.

Figure 31

Average flow rate per second for 'assertive' and 'in-between' crew determined in 10 s intervals (averaged over 1000 repeat simulations)



17. Annex 4: 14 CFR 25.803 and Appendix J

Presented in this annex is the text of 14 CFR 25.803 (also known as FAR 25.803) and Appendix J to Part 25, Title 14 (also known as Appendix J to Part 25, FAR), reproduced from [23].

A4.1 25.803 Emergency evacuation.

(a) Each crew and passenger area must have emergency means to allow rapid evacuation in crash landings, with the landing gear extended as well as with the landing gear retracted, considering the possibility of the airplane being on fire.

(b) [Reserved]

(c) For airplanes having a seating capacity of more than 44 passengers, it must be shown that the maximum seating capacity, including the number of crewmembers required by the operating rules for which certification is requested, can be evacuated from the airplane to the ground under simulated emergency conditions within 90 seconds. Compliance with this requirement must be shown by actual demonstration using the test criteria outlined in appendix J of this part unless the Administrator finds that a combination of analysis and testing will provide data equivalent to that which would be obtained by actual demonstration.

(d)-(e) [Reserved]

A4.2 Appendix J to Part 25—Emergency Evacuation

The following test criteria and procedures must be used for showing compliance with § 25.803:

(a) The emergency evacuation must be conducted with exterior ambient light levels of no greater than 0.3 foot-candles prior to the activation of the airplane emergency lighting system. The source(s) of the initial exterior ambient light level may remain active or illuminated during the actual demonstration. There must, however, be no increase in the exterior ambient light level except for that due to activation of the airplane emergency lighting system.

(b) The airplane must be in a normal attitude with landing gear extended.

(c) Unless the airplane is equipped with an off-wing descent means, stands or ramps may be used for descent from the wing to the ground. Safety equipment such as mats or inverted life rafts may be placed on the floor or ground to protect participants. No other equipment that is not part of the emergency evacuation equipment of the airplane may be used to aid the participants in reaching the ground.

(d) Except as provided in paragraph (a) of this appendix, only the airplane's emergency lighting system may provide illumination.

(e) All emergency equipment required for the planned operation of the airplane must be installed.

(f) Each internal door or curtain must be in the takeoff configuration.

(g) Each crewmember must be seated in the normally assigned seat for takeoff and must remain in the seat until receiving the signal for commencement of the demonstration. Each crewmember must be a person having knowledge of the operation of exits and emergency equipment and, if compliance with § 121.291 is also being demonstrated, each flight attendant must be a member of a regularly scheduled line crew.

(h) A representative passenger load of persons in normal health must be used as follows:

(1) At least 40 percent of the passenger load must be female.

(2) At least 35 percent of the passenger load must be over 50 years of age.

(3) At least 15 percent of the passenger load must be female and over 50 years of age.

(4) Three life-size dolls, not included as part of the total passenger load, must be carried by passengers to simulate live infants 2 years old or younger.

(5) Crewmembers, mechanics, and training personnel, who maintain or operate the airplane in the normal course of their duties, may not be used as passengers.

(i) No passenger may be assigned a specific seat except as the Administrator may require. Except as required by subparagraph (g) of this paragraph, no employee of the applicant may be seated next to an emergency exit.

(j) Seat belts and shoulder harnesses (as required) must be fastened.

(k) Before the start of the demonstration, approximately one-half of the total average amount of carry-on baggage, blankets, pillows, and other similar articles must be distributed at several locations in aisles and emergency exit access ways to create minor obstructions.

(l) No prior indication may be given to any crewmember or passenger of the particular exits to be used in the demonstration.

(m) The applicant may not practice, rehearse, or describe the demonstration for the participants, nor may any participant have taken part in this type of demonstration within the preceding 6 months.

(n) Prior to entering the demonstration aircraft, the passengers may also be advised to follow directions of crewmembers but may not be instructed on the procedures to be followed in the demonstration, except with respect to safety procedures in place for the demonstration or which have to do with the demonstration site. Prior to the start of the demonstration, the pre-takeoff passenger briefing required by § 121.571 may be given. Flight attendants may assign demonstration subjects to assist persons from the bottom of a slide, consistent with their approved training program.

(o) The airplane must be configured to prevent disclosure of the active emergency exits to demonstration participants in the airplane until the start of the demonstration.

(p) Exits used in the demonstration must consist of one exit from each exit pair. The demonstration may be conducted with the escape slides, if provided, inflated and the exits open at the beginning of the demonstration. In this case, all exits must be configured such that the active exits are not disclosed to the occupants. If this method is used, the exit preparation time for each exit utilized must be accounted for and exits that are not to be used in the demonstration must not be indicated before the demonstration has started. The exits to be used must be representative of all of the emergency exits on the airplane and must be designated by the applicant, subject to approval by the Administrator. At least one floor level exit must be used.

(q) Except as provided in paragraph (c) of this section, all evacuees must leave the airplane by a means provided as part of the airplane's equipment.

(r) The applicant's approved procedures must be fully utilized, except the flight crew must take no active role in assisting others inside the cabin during the demonstration.

(s) The evacuation time period is completed when the last occupant has evacuated the airplane and is on the ground. Provided that the acceptance rate of the stand or ramp is no greater than the acceptance rate of the means available on the airplane for descent from the wing during an actual crash situation, evacuees using stands or ramps allowed by paragraph (c) of this appendix are considered to be on the ground when they are on the stand or ramp.