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Investigating the impact of retrieval of carry-on luggage by passengers on aircraft evacuation using the airEXODUS aircraft evacuation simulation software

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12. Abstract

This report is the final deliverable of a contracted modelling effort requested in support of FAA efforts to address recommendations to investigate the effects of luggage retrieval on emergency evacuation of transport airplanes. The impact of passengers retrieving cabin luggage on evacuation performance was explored using state-of-the-art evacuation computer simulation. The analysis focused on a single-aisle, narrow-body aircraft configuration consisting of 185 passengers and crew in a cabin layout typical of the widely used B737/A320 aircraft. The airEXODUS agent-based aircraft evacuation modelling tool was enhanced to represent passenger luggage retrieval behaviour and was used to quantify evacuation performance, with and without passengers retrieving luggage. Furthermore, the exit scenario studied in this analysis consisted of the front pair of Type-C exits and the left pair of overwing Type-III exits, an exit combination often occurring in fatal accidents — and representing 50% of the normally available exits. Four luggage retrieval scenarios were investigated involving 0%, 25%, 50%, and 75% of passengers attempting to retrieve luggage, with each scenario repeated 1000 times and luggage retrievers randomly distributed throughout the aircraft for each repeat simulation. This report explores key takeaways and implications of the findings of the modelling effort.

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EXECUTIVE SUMMARY

(i) Context

This document represents the final report for a research project [1] exploring the impact of passenger retrieval of carry-on luggage during aircraft evacuation, conducted by the Fire Safety Engineering Group (FSEG) of the University of Greenwich (UoG) on behalf of FAA CAMI and Chickasaw Health Consulting (CHC) [2]. The objective of the analysis was to quantify, measure, and evaluate the effects of passengers attempting to retrieve carry-on luggage on passenger evacuation time and safety [3], and this was achieved using the state-of-the-art aircraft evacuation simulation software airEXODUS [4-16].

The study is based on a single-aircraft configuration consisting of a single-aisle narrow-body cabin layout typical of the popular B737/A320 models. The geometry consisted of:

- Two pairs of Type-C exits, one pair located in the front and the other in the aft of the aircraft,
- Two pairs of Type-III overwing exits, and
- Seating for 180 passengers with 2 flight deck and 3 cabin crew.

The evacuation scenario employed in the analysis was similar to that in the industry standard evacuation certification trial as described by FAR 25.803, consisting of half the normally available exits. However, to make the evacuation more challenging and representative of exit combinations typically found in real accidents [10,11,12], the available exit configuration utilised in this study consists of the following 50% of the normally available exits:

- the front pair of Type-C exits, and
- the left pair of Type-III exits.

To put this into context, it is similar to the exit availability in two noteworthy fatal fire incidents, the 1985 Manchester B737 [4, 20] and the 2019 Sheremetyevo Sukhoi Superjet-100 [21, 22, 23] fatal accidents that involved post-crash fires. In the Manchester fire, both forward exits and an overwing exit, representing 50% of the normally available exits, were viable in the accident, while in the 2019 Sheremetyevo Sukhoi Superjet-100 fire, only the two front exits were available for evacuation — which also represented 50% of the normally available exits. In both these cases, the external fire initially impacts the rear of the aircraft and eventually gains access to the rear of the aircraft cabin, allowing external fire hazards to initially impact those in the rear before spreading to cabin materials and to the front of the cabin. Initially, the passengers in the rear of the aircraft are at greatest risk, while passengers in the front of the aircraft are at least risk. Furthermore, the behaviour of the passengers represented in the model is also typical of behaviour observed in actual accidents in which passengers tend to utilise their nearest available exit [10,11,12].

Utilising this underlying scenario setup, four scenario variations are investigated, as specified in the statement of work (SOW):

- Scenario 1, Base Case. In this scenario, no passengers attempt to retrieve their luggage, and so this serves as the base case against which all other scenarios are compared.
- Scenario 2, 25% (42) of the passengers retrieve luggage.
- Scenario 3, 50% (84) of the passengers retrieve luggage.
- Scenario 4, 75% (126) of the passengers retrieve luggage.

Note: exit rows are excluded from seating luggage retrievers, reducing the potential number of luggage retrievers from 180 to 168.

Each scenario is run 1000 times, each with a different distribution of passengers and luggage retrievers. For each scenario, a range of results are presented, including the following:

- Minimum, median, and maximum TET for a scenario.
- Minimum, average, and maximum PET for a simulation and scenario.
- Minimum, average, and maximum Zonal Dwell time for a simulation and scenario.
- Minimum, average, and maximum Zonal PET for a simulation and scenario.

As part of this work, it was first necessary to establish an evidence base of typical luggage retrieval times that could be used in the modelling analysis [19]. Once this was established, it was necessary to modify the airEXODUS evacuation simulation software to enable the simulated agents to retrieve luggage as part of the evacuation process, as this was not represented in the current research version of the software. Only when this was completed and tested was it possible to undertake the identified four scenarios. This report sets out the work to establish the luggage retrieval time evidence base, modify the airEXODUS software to represent luggage retrieval, and provide detailed results and analysis for the four simulations.

As set out in the main report, there are a number of key findings at the end of each section describing the main conclusions of each phase of the work. These are summarised in section (ii) of the executive summary, with references to the main report should additional information be required. In the remainder of the executive summary, project limitations are summarised in section (iii), recommendations for additional analysis are summarised in section (iv), and the main project takeaways are presented in section (v).

(ii) Key Findings Summary

To interpret the simulation results correctly, it is important to note two key model assumptions: firstly, that passengers located in seat rows cannot by-pass a luggage retriever, and secondly, that aisle by-pass is only possible if there is sufficient space ahead of the luggage retriever (see Section 5.1).

1) Key findings related to the luggage retrieval time evidence base.

Presented in Section 4 is the work to establish the luggage retrieval time data set used in the modelling analysis. The key findings associated with this work can be found at the end of Section 4 and are summarised as follows:

Key Finding 4.1, Data sets available to characterise luggage retrieval time:
Two data sets are available that characterise luggage retrieval times, one being an experimental data set produced by the NRCC, the other being a data set based on real data collected from actual observations of passengers deplaning in non-emergency conditions. While the shape of the two distributions is quite different, both produce similar mean retrieval times, with the mean for the FSEG Flight Data being 5.3 s and the NRCC Trial Data being 7.1 s.

Key Finding 4.2, Selected luggage retrieval data set:
While neither luggage retrieval data set is ideal, the FSEG Flight Data has the advantage of being based on observations of real passengers, retrieving a variety of real luggage types on actual flights. Thus, the FSEG Flight Data are used in this analysis to represent passenger luggage retrieval times.

Key Finding 4.3, Luggage retrieval times:
The FSEG Flight Data set (51 data points) produces a log normal distribution of luggage retrieval times with a minimum of 2.0 s, a mean of 5.3 s, a maximum of 15.0 s, and a standard deviation

of 2.65 s. Using the FSEG Flight Data, there is a 6% chance of retrieval times between 12 s and 16 s.

2) Key findings related to the airEXODUS software enhancement.

Presented in Section 5 is the work to develop the enhancements to the airEXODUS software to represent passengers retrieving luggage during evacuation and the impact that they have on the evacuation of other passengers. The key findings associated with this work can be found at the end of Section 5 and are summarised as follows:

Key Finding 5.1, Enhancements to airEXODUS to represent luggage retrieval:

The modified software has the following new capabilities:

- Ability to represent a specified number of passengers (PAXs) designated as luggage retrievers.
- Delay the evacuation of the designated luggage retrievers once they enter the aisle from their seat for a duration of time derived from a luggage retrieval time distribution.
- Allow other PAXs in the aisle to attempt to by-pass the luggage retriever based on a by-pass probability. However, the PAX will attempt to by-pass only if there is sufficient space on the other side of the luggage retriever; otherwise, they will wait until space is available. As the PAX by-passing the luggage retriever is hindered by the obstacle created by the presence of the luggage retriever, their walk speed is reduced by an amount derived from the speed reduction distribution.
- Additional simulation output parameters have been defined to characterise the performance of the PAXs when interacting with luggage collectors.
- Ability to quantify PAX-based luggage retrieval parameters and evacuation performance over user-defined spatial zones.
- Other key model assumptions are specified in Section 5.1.

3) Key findings related to Scenario 1 (0% luggage retrievers) results.

Presented in Section 5.4 are the results and analysis for Scenario 1 (S1). The key findings associated with this work can be found at the end of Section 5 and are summarised as follows:

Key Finding 5.5, Scenario 1 (S1), Overall evaluation:

- In S1, the overall evacuation times (110.1 s to 138.5 s with an average of 121.1 s) are well in excess of 90 s. By 90 s, on average, only 146.2 (79%) occupants have evacuated, with 38.8 remaining onboard. As is to be expected, passengers located in the rear of the aircraft (Zone 05) have the greatest evacuation times, with an average of 99.0 s. They also have a large zonal dwell time of 65.0 s. While half the normally available exits are used in the evacuation scenario, as is required by FAR 28.803, the available exits are not optimally located as in the certification trial, i.e., one from each exit pair dispersed along the length of the aircraft. The two largest exits (Type-C), located at the front of the aircraft, are available, and the pair of left small overwing exits (Type-III) located in the centre of the aircraft are available. As passengers will tend to use their nearest exit, most of the passengers attempt to exit via the overwing exits. This and the greater travel distances contribute to the long evacuation times. In addition, given the nature of the scenario, both pairs of exits are utilised sub-optimally. For the front pair of Type-C exits, the single cabin aisle cannot supply passengers quickly enough to satisfy the capability of the two Type-C exits. Thus, the exits operate sub-optimally. For the overwing exits, the majority of the supply of passengers is from the rear, and so the supply of passengers to the dual Type-III exits is predominately from one side, which preferentially supplies the first of the exits (i.e., 3L) encountered by the passenger flow. This can result in sub-optimal usage of both exits, with gaps occurring in the exiting flow of both exits.

4) Key findings related to Scenario 2 (25% luggage retrievers) results.
Presented in Section 6.4 are the results and analysis for Scenario 2 (S2). Scenario 2 (S2) involved 25% of the passengers (42 passengers) attempting to retrieve their luggage during the evacuation. The key findings associated with this work can be found at the end of Section 6 and are summarised as follows:

Key Finding 6.1, Scenario 2, Overall Evacuation performance:

- With 25% (42) of the passengers designated as luggage collectors, the TET varied from approximately 111.7 s to 200.2 s (with an average of 136.8 s) and on average with 77% (143) of the 185 occupants evacuated by 90 s. The average PET varies from 54.2 s to 74.6 s. This is a wide variation in evacuation performance, with a significant increase in the maximum TET (45%) and a large increase in the maximum average PET (21%) compared to S1.

Key Finding 6.2, Scenario 2, Specific Evacuation performance:

- As the number of luggage retrievers within a spatial zone within the aircraft can vary significantly, as does their seating locations, it is inappropriate to simply base conclusions on any one simulation, e.g., a simulation producing median evacuation time, as this may provide an overly pessimistic or optimistic conclusion. It is more informative to consider the evacuation performance of several key simulations, such as the simulations producing the minimum, median, and maximum TET.
- Compared to S1, of the 1000 simulations for S2, the simulation producing the:
  - ***minimum TET*** experienced ***small increases*** in average PET (increasing from 52.1 s to 54.5 s (4.6%)) and TET (increasing from 110.1 s to 111.7 s (1.5%)),
  - ***median TET*** experienced ***large increases*** in average PET (increasing from 56.2 s to 61.1 s (8.7%)) and TET (increasing from 120.9 s to 135.0 s (11.7%)),
  - ***maximum TET*** experienced ***significant increases*** in average PET (increasing from 61.9 s to 74.6 s (20.5%)) and TET (increasing from 138.5 s to 200.2 s (44.5%)).
- In S2, for the simulation producing the median TET (135 s), there were 18 viable aisle by-pass events, of which 7 (39%) were successful. In addition, there were 35 occurrences where passengers in seat rows were prevented from by-passing the luggage collector blocking their exit from the seat row.

Key Finding 6.3, Scenario 2, Localised Evacuation performance:

- A deeper understanding of the impact of luggage retrievers on the overall evacuation can be derived from investigating localised evacuation parameters such as zonal dwell times and zonal evacuation times.
- In S2, with 25% of the passengers retrieving luggage, for those passengers starting in Zone 01 (the front eight seat rows),
  - the average Zone 01 dwell time is 31.5 s; thus, passengers in Zone 01 spend, on average, an additional 11.7 s (59%) exposed to the conditions of Zone 01 compared to S1.
  - the average Zone 01 evacuation time is 41.1 s, an increase of 11.0 s (37%) compared to S1.
  - in the event of post-crash fire gaining access to the rear of the cabin (consistent with the evacuation scenario), these dwell times and evacuation times may not pose a threat to some passengers in Zone 01, given they are far removed from the initial fire.
- In S2, with 25% of the passengers retrieving luggage, for those passengers starting in Zone 05 (rear six seat rows),
  - the average Zone 05 dwell time is 85.1 s; thus, passengers in Zone 05 spend, on average, an additional 20.1 s (31%) exposed to the conditions of Zone 05 compared to S1.

- o the average Zone 05 evacuation time is 111.9 s, an increase of 12.9 s (13%) compared to S1.
- o In the event of a serious post-crash fire that gains access to the rear of the cabin (consistent with the evacuation scenario), the large average dwell time (85.1 s) and average evacuation time (111.9 s) for passengers in Zone 05 can result in significant additional exposure to fire hazards compared to S1, which can have fatal consequences.

Key Finding 6.4, Scenario 2, Overall evaluation:

- In S2, with 25% of the passengers attempting to retrieve luggage, there is a **large increase** in both dwell times incurred by **some** passengers and the TET for the aircraft for **some** of the 1000 repeat simulations. **These increases are of concern, as they can compromise survivability in the event of a post-crash fire gaining access to the cabin, at least for some passengers.** However, with 25% of the passengers retrieving luggage, the outcome **is strongly dependent** on the random distribution of the luggage retrievers and the seating zone of the passengers, and so not all passengers are impacted equally by luggage collectors. Passengers in the rear of the aircraft are **more significantly** impacted by luggage collectors. Thus, in the event of a serious post-crash cabin fire that gains access to the rear of the cabin (consistent with the evacuation scenario), those most at risk are passengers seated in the rear of the aircraft (Zone 05) due to the **large increase** in average dwell times (85.1 s) and average evacuation times (111.9 s) resulting from passengers retrieving their luggage. The increased passenger exposure to hazardous fire products due to the incurred delays **is likely to** decrease passenger survivability. However, passengers seated in the front of the aircraft (Zone 01) and, hence, furthest removed from the initial fire are **marginally** impacted, incurring **moderate increases in** average dwell time (31.5 s) and average evacuation times (41.1 s).

General Observation related to Scenarios 2, 3 and 4.

Key Findings 6.3 (Scenario 2), 7.3 (Scenario 3) and 8.3 (Scenario 4), Localised Evacuation performance:

- A consequence of the imposed by-pass model behaviour is that gaps may occur in evacuation flow within the main cabin aisle as failed by-pass events prevent passengers behind the luggage retriever from progressing down the aisle to an exit. This, in turn, can result in periods of no flow at the exits.

5) Key findings related to the by-pass model sensitivity study.

Presented in Sections 6.2 and 6.4(e) are the results and analysis for a series of sensitivity studies conducted to explore model sensitivity to two key parameters in the by-pass model: the speed reduction factor employed during by-pass and the by-pass probability distribution. The key findings associated with this work can be found at the end of Section 6 and are summarised as follows:

Key Finding 6.5, Sensitivity of model predictions to speed reduction factor:

- Model predictions are not sensitive to the precise value of the minimum speed reduction factor (upper limit of range) employed in the by-pass model, with reduction factors of 0.4, 0.5, and 0.6 producing similar results. The minimum speed reduction factor implemented in the model assumes a value of 0.5, with the range in speed reduction factors being 0.1 to 0.5.

Key Finding 6.6, Sensitivity of model predictions to by-pass probability:

- Model predictions are sensitive to the nature of the by-pass probability (BPP) distribution (see Table ES1, which is reproduced from Table 42).

- Assuming a BPP of 0.0 (Sensitivity Case 1 or SC1) prevents all passengers from by-passing luggage retrievers, resulting in the longest evacuations as measured by global parameters such as TET, average TET, and average PET, as well as the longest local parameters, such as zonal dwell times. Using this simplified approach results in predictions that are overly pessimistic.
- Assuming a BPP of 1.0 (Sensitivity Case 3 or SC3) allows all passengers to by-pass luggage retrievers, resulting in the shortest evacuations as measured by global parameters such as TET, average TET, and average PET, as well as the shortest local parameters, such as zonal dwell times. This also results in a very large number of passengers that by-pass luggage collectors. Using this simplified approach results in predictions that are overly optimistic.
- Assuming a BPP described by a normal distribution with mean of 0.5 and standard deviation of 0.12 (Scenario 2 or S2) produces results that are positioned between the two extremes of no by-pass and all by-pass, albeit slightly biased to the no by-pass results. This is due to the nature of the model, which only allows the passenger attempting to by-pass one attempt and does not allow passengers from further back in the queue to push their way forward. As a result, significantly fewer passengers manage to successfully by-pass luggage retrievers than in the case with all passengers being able to by-pass.

Table ES1: Average PET and average TET values (from the 1000 simulations) for various by-pass probability scenarios (SC1, S2, SC3) and the scenario without luggage retrievers (S1).

	SC1 (BPP=0.0)	**S2 (BPP=distrib)**	**SC3 (BPP=1.0)**	**S1 (no luggage retrievers)**
Avg. PET (s) value	61.6	60.9	58.0	55.9
Avg. TET (s) value	139.3	136.8	128.9	121.1

- While some degree of by-pass behaviour is expected in real accident situations, it remains to be demonstrated that the degree of by-pass produced in the simulations is a reasonable reflection of reality. However, it would appear to be valid and reasonable to assume that by-passing does not and cannot occur in all situations and is strongly dependent on a number of factors, such as the size of the person retrieving the luggage, the size of the person attempting to overtake, dimensions of the cabin aisle, temperament of the person attempting to overtake, severity of the situation, etc.

6) Key findings related to Scenario 3 (50% luggage retrievers) results.

Presented in Section 7.3 are the results and analysis for Scenario 3 (S3). S3 involved 50% of the passengers (84 passengers) attempting to retrieve their luggage during the evacuation. The key findings associated with this work can be found at the end of Section 7 and are summarised as follows:

Key Finding 7.1, Scenario 3, Overall Evacuation performance:

With 50% (84) of the passengers designated as luggage collectors, the TET varied from approximately 124.7 s to 228.0 s (with an average of 168.7 s) and, on average, with 73% (134.8) of the 185 occupants evacuated by 90 s. The average PET varies from 58.2 s to 89.1 s. This is a wide variation in evacuation performance, with a significant increase in the maximum TET (65%) and maximum average PET (44%) compared to S1.

Key Finding 7.2, Scenario 3, Specific Evacuation performance:

- Compared to S1, of the 1000 simulations for S3, the simulation producing the:
  - ***minimum TET*** experienced ***large increases*** in average PET (increasing from 52.1 s to 59.3 s (13.8%)) and TET (increasing from 110.1 s to 124.7 s (13.3%)),

    - ***median TET*** experienced ***significant increases*** in average PET (increasing from 56.2 s to 69.0 s (22.8%)) and TET (increasing from 120.9 s to 167.6 s (38.6%)),
    - ***maximum TET*** experienced ***significant increases*** in average PET (increasing from 61.9 s to 89.1 s (43.9%) and TET (increasing from 138.5 s to 228.0 s (64.6%)).
- In S3, for the simulation producing the median TET (167.6 s), with twice as many luggage retrievers as in S2, there were 60 viable aisle by-pass events, of which 34 (57%) were successful. In addition, there were 82 occurrences where passengers in seat rows were prevented from by-passing the luggage collector blocking their exit from the seat row. Compared to S2, the number of possible aisle by-pass events has increased by 233% (42), the number of successful aisle by-pass events has increased by 386% (27), and the number of occurrences where passengers in seat rows are prevented from by-passing the luggage collector has increased by 134% (47).

Key Finding 7.3, Scenario 3, Localised Evacuation performance:

- In S3, with 50% of the passengers retrieving luggage, for those passengers starting in Zone 01 (the front eight seat rows),
    - the average Zone 01 dwell time is 41.4 s; thus, passengers in Zone 01 spend on average an additional 21.6 s (109%) exposed to the conditions of Zone 01 compared to S1.
    - the average Zone 01 evacuation time is 50.0 s, an increase of 19.9 s (66%) compared to S1.
    - in the event of post-crash fire gaining access to the rear of the cabin (consistent with the evacuation scenario), these dwell times and evacuation times may pose a threat to some passengers in Zone 01, even though they are far removed from the initial fire.
- In S3, with 50% of the passengers retrieving luggage, for those passengers starting in Zone 05 (rear six seat rows),
    - the average Zone 05 dwell time is 109.8 s; thus, passengers in Zone 05 spend on average an additional 44.8 s (69%) exposed to the conditions of Zone 05 compared to S1.
    - the average Zone 05 evacuation time is 134.7 s, an increase of 35.7 s (36%) compared to S1.
    - Both the Zone 05 average dwell time and average evacuation time significantly exceed 90 s.
    - In the event of a serious post-crash fire that gains access to the rear of the cabin (consistent with the evacuation scenario), the excessively long average dwell time (109.8 s) and average evacuation time (134.7 s) for passengers in Zone 05 can result in significant additional exposure to fire hazards compared to S1, which can have fatal consequences.

Key Finding 7.4, Scenario 3, Overall evaluation:

- In S3, with 50% of the passengers attempting to retrieve luggage, **there is a significant increase** in both dwell times incurred by **many** passengers and the TET for the aircraft for many of the 1000 repeat simulations. **These increases are of great concern as they seriously compromise survivability in the event of a post-crash fire gaining access to the cabin for many passengers.** However, even with as many as 50% of the passengers retrieving luggage, the outcome **is still dependent** on the random distribution of the luggage retrievers and the seating zone of the passengers, and so not all passengers are impacted equally by luggage collectors. Passengers in the rear of the aircraft are **significantly** impacted by luggage collectors. Thus, in the event of a serious post-crash cabin fire that gains access to the rear of the cabin (consistent with the evacuation scenario), those most at risk are passengers seated in the rear of the aircraft (Zone 05) due to the **significant increase** in average dwell times (109.8 s) and average evacuation times (134.7 s) resulting from passengers retrieving their luggage. The increased passenger exposure to hazardous fire products due to the incurred delays **is likely to seriously** decrease passenger survivability. Furthermore, even passengers seated in the front of the aircraft (Zone 01) and, hence, furthest removed from the initial fire are **significantly** impacted, incurring **long** average dwell times of 41.4 s and average evacuation times of 50.0 s.

7) Key findings related to Scenario 4 (75% luggage retrievers) results.

Presented in Section 8.3 are the results and analysis for Scenario 4 (S4). S4 involved 75% of the passengers (126 passengers) attempting to retrieve their luggage during the evacuation. The key findings associated with this work can be found at the end of Section 8 and are summarised as follows:

Key Finding 8.1, Scenario 4, Overall Evacuation performance:

- With 75% (126) of the passengers designated as luggage collectors, the TET varied from approximately 153.7 s to 271.5 s (with an average of 199.7 s) and on average with 66% (121.3) of the 185 occupants evacuated by 90 s. The average PET varies from 65.8 s to 100.7 s. This is a wide variation in evacuation performance, with a significant increase in the maximum TET (96%) and maximum average PET (63%) compared to S1. Furthermore, the average PET exceeded 90 s for some simulations.

Key Finding 8.2, Scenario 4, Specific Evacuation performance:

- Compared to S1, of the 1000 simulations for S4, the simulation producing the:
  - ***minimum TET*** experienced ***significant increases*** in average PET (increasing from 52.1 s to 65.8 s (26.3%)) and TET (increasing from 110.1 s to 153.7 s (39.6%)),
  - ***median TET*** experienced ***significant increases*** in average PET (increasing from 56.2 s to 79.1 s (40.7%)) and TET (increasing from 120.9 s to 198.6 s (64.3%)),
  - ***maximum TET*** experienced ***significant increases*** in average PET (increasing from 61.9 s to 88.8 s (43.5%)) and TET (increasing from 138.5 s to 271.8 s (96%)).
- In S4, for the simulation producing the median TET (198.6 s) with three times as many luggage retrievers as in S2, there were 66 viable aisle by-pass events, of which 31 (47%) were successful. In addition, there were 137 occurrences where passengers in seat rows were prevented from by-passing the luggage collector blocking their exit from the seat row. Compared to S2, the number of possible aisle by-pass events has increased by 267% (48), the number of successful aisle by-pass events has increased by 343% (24), and the number of occurrences where passengers in seat rows are prevented from by-passing the luggage collector seat events has increased by 291% (102).

Key Finding 8.3, Scenario 4, Localised Evacuation performance:

- In S4, with 75% of the passengers retrieving luggage, for those passengers starting in Zone 01 (the front eight seat rows),
  - the average Zone 01 dwell time is 50.8 s; thus, passengers in Zone 01 spend, on average, an additional 31 s (157%) exposed to the conditions of Zone 01 compared to S1.
  - the average Zone 01 evacuation time is 59.2 s, an increase of 29.1 s (97%) compared to S1. This is almost double that of S1.
  - in the event of post-crash fire gaining access to the rear of the cabin (consistent with the evacuation scenario), these dwell times and evacuation times may pose a threat to some passengers in Zone 01, even though they are far removed from the initial fire.
- In S4, with 75% of the passengers retrieving luggage, for those passengers starting in Zone 05 (rear six seat rows),

- the average Zone 05 dwell time is 133.6 s; thus, passengers in Zone 05 spend, on average, an additional 68.6 s (106%) exposed to the conditions of Zone 05 compared to S1. This is more than double that of S1.
- the average Zone 05 evacuation time is 159.4 s, an increase of 60.4 s (61%) compared to S1.
- Both the Zone 05 average dwell time and average evacuation time significantly exceed 90 s.
- In the event of a serious post-crash fire that gains access to the rear of the cabin (consistent with the evacuation scenario), the excessively long average dwell time (133.6 s) and average evacuation time (159.4 s) for passengers in Zone 05 can result in significant additional exposure to fire hazards compared to S1, which is highly likely to have fatal consequences.

Key Finding 8.4, Scenario 4, Overall evaluation:

- In S4, with 75% of the passengers attempting to retrieve luggage, **there is a significant increase** in both dwell times incurred by **most** passengers and the TET for the aircraft for most of the 1000 repeat simulations. **These increases are of great concern, as they seriously compromise survivability in the event of a post-crash fire gaining access to the cabin for most passengers.** However, even with as many as 75% of the passengers retrieving luggage, the outcome **is still somewhat dependent** on the random distribution of the luggage retrievers and the seating zone of the passengers, and so not all passengers are impacted equally by luggage collectors. Passengers in the rear of the aircraft are **significantly** impacted by luggage collectors. Thus, in the event of a serious post-crash cabin fire that gains access to the rear of the cabin (consistent with the evacuation scenario), those most at risk are passengers seated in the rear of the aircraft (Zone 05), due to the **significant increase** in average dwell times (133.6 s) and average evacuation times (159.4 s) resulting from passengers retrieving their luggage. The increased passenger exposure to hazardous fire products due to the incurred delays **will seriously** decrease passenger survivability. Furthermore, even passengers seated in the front of the aircraft (Zone 01) and, hence, furthest removed from the initial fire are **significantly** impacted, incurring **very long** average dwell times of 50.8 s and average evacuation times of 59.2 s.

8) Key findings related to the comparative study of results.

Presented in Section 9 is a comparative analysis of all the findings for the various scenarios. The impact of luggage retrievers on evacuation performance is assessed, and two approaches to evaluating the cost, in terms of risk to life, of passengers attempting to retrieve luggage are discussed.

The first approach explores the implications of a fire imposed on the evacuation scenarios with luggage retrievers (i.e., S2, S3, and S4) compared to the case without luggage retrievers (S1). Given the exit availability considered in this study, a plausible fire scenario associated with the evacuation scenario would be similar to that in the 1985 Manchester B737 [4, 20] and the 2019 Sheremetyevo Sukhoi Superjet-100 [21, 22, 23] fatal post-crash fire incidents described previously.

The second and simpler approach involves a comparative analysis where the number of passengers remaining on board after 90 s in the luggage retriever scenarios (i.e., S2, S3, S4) are compared to the case without luggage retrievers (i.e., S1), where it is assumed that the situation without luggage retrievers (i.e., S1) is considered acceptable (based on the observation that the aircraft configuration satisfies the FAR 25.803 requirement when tested according to the regulatory requirements).

The key findings associated with this analysis can be found at the end of Section 9 and are summarised as follows:

Key Finding 9.1, Overall Evacuation performance:

- It is clear that as the number of randomly distributed luggage retrievers increases, there is not only a corresponding significant increase in the average TET and PET but also the number of simulations producing prolonged evacuations. The significant increase in TET and PET increases the likely severity of passenger exposure to potentially hazardous conditions for some passengers. Furthermore, the higher number of simulations producing significantly large TET and average PET increases the likelihood that passengers will be involved in a prolonged evacuation and, hence, the likelihood that passengers will experience greater exposure to potentially hazardous conditions.

Key Finding 9.2, Impact of luggage collection on individual passengers:

- For an individual passenger, the outcome of an evacuation in which passengers attempt to retrieve luggage is strongly dependent not only on the number of passengers attempting to retrieve luggage but also on the nature of the evacuation scenario (i.e., exit availability), the seating location of the passenger, and the random distribution of luggage retrievers. The last point contributes to the variability of evacuation performance for a particular scenario.

Key Finding 9.3, Localised Evacuation performance:

- Passengers seated in the front of the aircraft (Zone 01) and, hence, furthest removed from the initial effects of the fire are less impacted by luggage collectors, at least if there are relatively small numbers of luggage collectors. However, as the number of luggage retrievers increases, even passengers in Zone 01 are adversely impacted. With 50% of the passengers collecting luggage (S3), the average dwell time in Zone 01 is increased to 41.4 s, and with 75% luggage collectors, the average dwell time is 50.8 s.

  With 75% luggage retrievers, the average dwell time in Zone 05 more than doubles when compared to S1 (i.e., no luggage retrievers). This, in turn, is likely to more than double passenger exposure to heat and toxic gases and so greatly increase their inhaled Fractional Effective Dose (FED) of hazardous fire products, raising the likelihood of fatalities and the expected number of fatalities (*Note: the FED is a measure of the ratio of the dose of fire hazards received to the dose required to cause an effect, e.g., incapacitation or death*). Even in S2 (25% luggage retrievers), while the overall average Zone 05 dwell time is 85.1 s, average dwell times amongst the 1000 repeat simulations vary from 51.9 s to 128.5 s, and so some of the 1000 repeat simulations produce dangerously long dwell times (almost doubling the average dwell time for S1).

  The introduction of randomly located passengers retrieving luggage into the evacuation increases dwell time and PET for all passengers in all zones but with more significant consequences for those in Zone 05. In the event of a serious cabin post-crash fire, increasing the expected number of luggage retrievers will increase average dwell times, which, in turn, is likely to decrease the survivability of passengers in all zones, particularly in Zone 05, by increasing their exposure to the hazardous fire products. Furthermore, the increased exposure to toxic fire products, heat, and the obscuration effects of smoke will adversely impact the ability of exposed passengers to evacuate, further increasing their dwell time in Zone 05 and, hence, their exposure to severe fire hazards. This downward spiral is likely to result in a significant increase in the expected number of fatalities.

Key Finding 9.4, Cost of Overall Evacuation performance:

- A comparative cost of luggage retrieval on emergency evacuation outcome can be estimated by determining, for a given scenario, the additional number of passengers remaining on board after 90 s compared with a base case scenario involving no luggage retrieval (i.e., S1). Using this approach, for the exit scenario and narrow-body aircraft considered in this study, the incremental cost associated with 25% (S2), 50% (S3), and 75% (S4) of the passengers attempting to retrieve cabin luggage during evacuation is 2.9 passengers, 11.4 passengers, and 24.9 passengers, respectively.

(iii) Project Limitations

It is accepted that any modelling exercise is an approximation to 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 relate to the nature of the by-pass model introduced to represent the direct impact of the luggage retrievers on the evacuation process; these are discussed in Section 10 and include:

(1) Passengers are not modelled carrying retrieved luggage.
(2) Nature of aisle by-pass model.
(3) Nature of the by-pass probability distribution.
(4) Passengers blocked in seat rows.
(5) Luggage retrieval time data set.
(6) Location of luggage retrieval events.
(7) Luggage retrieval in life-threatening emergencies
(8) Exit hesitation times impacted by luggage.

(iv) Recommendations for Additional Analysis to Assist the Regulatory Process

While this work has addressed the key project questions concerning the likely impact of luggage retrieval on passenger evacuation in a narrow-body aircraft configuration, to further support the regulatory process, it is recommended that additional analysis be undertaken to better represent the impact of luggage retrievers on the evacuation process and to explore other scenarios. The recommendations are discussed in full in Section 11.2 and are summarised as follows:

(1) Repeat the evacuation analysis for other exit availability scenarios.
(2) Repeat the evacuation analysis for wide-body aircraft.
(3) Repeat the evacuation analysis for narrow-body aircraft using coupled fire-evacuation analysis as in [4].
(4) Enhance the model describing luggage retrieval. This could take into account a number of currently employed simplifying assumptions.
(5) Experimental data collection campaign to collect a reliable evidence base that can be used for evacuation modelling.
(6) Establish an evidence base of passenger experience of real evacuations involving luggage retrieval.

(v) Main Takeaways

The impact of passengers retrieving cabin luggage on evacuation performance was explored using state-of-the-art evacuation computer simulation. The analysis focused on a single-aisle, narrow-body aircraft configuration consisting of 185 passengers and crew in a cabin layout typical of the widely used B737/A320 aircraft. The airEXODUS agent-based aircraft evacuation modelling tool was enhanced to represent passenger luggage retrieval behaviour and was used to quantify evacuation performance with and without passengers retrieving luggage. Furthermore, the exit scenario studied in this analysis consisted of the front pair of Type-C exits and the left pair of overwing Type-III exits, an exit combination often occurring in fatal accidents and representing 50% of the normally available exits. Four luggage retrieval scenarios were investigated involving 0%, 25%, 50%, and 75% of passengers attempting to retrieve luggage, with each scenario repeated 1000 times and luggage retrievers randomly distributed throughout the aircraft for each repeat simulation.

- As the location of luggage retrievers is randomly distributed for each repeat simulation, their number within a given cabin spatial zone can vary significantly, as does their specific seating locations. This can result in significant variation in evacuation outcome and performance between repeat simulations for a given scenario. Thus, when assessing the impact of a given number of luggage retrievers on evacuation performance, it may be misleading to consider any one simulation, as this may provide an overly pessimistic or optimistic conclusion. It is more informative to consider the evacuation performance of several key simulations, such as the simulations producing the minimum, median, and maximum total evacuation time (TET).

- As the number of randomly distributed luggage retrievers increases, there is not only a corresponding significant increase in the average TET and average personal evacuation time (PET) but also the number of simulations producing prolonged evacuations. For example, with 0%, 25%, 50%, and 75% luggage retrievers, the TET for the simulation producing the ***median*** TET is 120.9 s, 135.0 s (an increase of 11.7%), 167.6 s (an increase of 38.6 %), and 198.6 s (an increase of 64.3%), respectively. While none of the 1000 repeat simulations in the case with 0% luggage retrievers produce a TET in excess of 140 s, with 25%, 50%, and 75% luggage retrievers, there are 365, 961, and 1000 cases, respectively, producing TET in excess of 140 s.

- The significant increase in TET and average PET increases the likely severity of passenger exposure to potentially hazardous conditions for some passengers. Furthermore, the higher the number of simulations producing significantly large TET and average PET increases the likelihood that passengers will be involved in a prolonged evacuation with greater exposure to potentially hazardous conditions.

- For individual passengers, the outcome of an evacuation in which passengers attempt to retrieve luggage is strongly dependent not only on the number of passengers attempting to retrieve luggage but also on the random distribution of luggage retrievers, the seating location of the passenger, and the nature of the exit scenario (i.e., exit availability).

- The introduction of randomly located passengers retrieving luggage in the evacuation increases dwell time and PET for all passengers in all cabin zones but with more significant consequences for those in the rear cabin zone (i.e., the rear five seat rows).

- In the event of a serious cabin post-crash fire, increasing the expected number of luggage retrievers will increase average dwell times, which, in turn, is likely to decrease the survivability of passengers in all cabin zones, particularly those in the rear zone, by increasing their exposure to hazardous fire products. Furthermore, the increased exposure to toxic fire products and heat and the obscuration effects of smoke will adversely impact the ability of exposed passengers to evacuate, further increasing their dwell time in the rear cabin zone and, hence, their exposure to severe fire hazards. This downward spiral is likely to result in a significant increase in the expected number of fatalities.

- A comparative cost of luggage retrieval on emergency evacuation outcome is estimated by determining, for a given scenario, the additional number of passengers remaining on board after 90 s compared to the scenario involving no luggage retrieval. Using this approach, for the aircraft configuration and exit scenario investigated (with 185 occupants), the average incremental cost associated with 25%, 50%, and 75% of the passengers attempting to retrieve luggage during the evacuation is 2.9 passengers, 11.4 passengers, and 24.9 passengers, respectively.

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Glossary of Commonly Used Terms

Agent: Simulated person within the evacuation simulation.
Average Dwell Time (s): Average of the individual dwell times for all agents originating in a zone for a simulation or a scenario.
Average PET (s): Average time for each agent within a simulation to exit the aircraft; can also be determined for a scenario, i.e., all 1000 simulations defined a scenario.
Average TET (s): Average TET for a series of simulations, typically 1000 simulations for a specific scenario.
CC: Cabin crew.
CWT (s): Cumulative wait time (s). Time an agent wastes in congestion once they have started to evacuate.
Dwell Time (s): Time spent by an agent within a user-defined zone.
FED: Fractional Effective Dose. The FED is a measure of the ratio of the dose of fire hazards received to the dose required to cause an effect, e.g., incapacitation or death.
FC: Flight crew
LC: Agent designated as a luggage collector. Also referred to as luggage retriever.
Luggage retrieval time (s): Time required for a passenger to retrieve their cabin luggage from the overhead bin.
PAX: Passenger.
PET (s): Personal evacuation time (s). Time for a particular agent to exit the aircraft.
PPM: People per minute
TET (s): Total evacuation time (s). Time for last agent to exit the aircraft in a simulation.

1 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] regarding the impact of passenger retrieval of carry-on luggage during aircraft evacuation 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 September 2023. It concerns undertaking an analysis using the state-of-the-art airEXODUS evacuation simulation software [4-16] to investigate the potential impact of passengers retrieving carry-on luggage during the evacuation of a narrow-body (single-aisle) aircraft configuration.

As part of this project, FSEG, in consultation with CHC and CAMI, performed a detailed analysis of passenger evacuation from a narrow-body aircraft configuration, in which some passengers attempt to retrieve carry-on luggage. The objective of the analysis was to quantify, measure, and evaluate the effects of passengers attempting to retrieve carry-on luggage on passenger evacuation time and safety.

Due to time and budgetary constraints, it was not possible to explore multiple aircraft configurations and multiple evacuation scenarios, so a representative aircraft configuration and evacuation scenario was selected for the first phase of this analysis. The aircraft configuration consisted of a single-aisle narrow-body aircraft configuration typical of the popular B737/A320 models. The evacuation scenario employed in the analysis was similar to that in the industry standard evacuation certification trial as described by FAR 25.803, consisting of half the normally available exits. However, in order to make the evacuation more challenging and representative of exit combinations typically found in accident scenarios, the front pair of Type-C exits and the left pair of Type-III exits (i.e., 50% of the normally available exits) were considered available for these simulations. This configuration of 50% of the normally available exits is more challenging than the combination typically used in FAR 25.803 certification trials, which consists of one exit from each exit pair. Furthermore, the behaviour of the passengers represented in the model is also typical of behaviour observed in actual accidents, in which passengers tend to utilise their nearest available exit [10,11,12].

The exit availability assumed in this study is based on studies of previous accidents [10,11,12], and to put this into context, it is also similar to the exit availability in two noteworthy fatal fire incidents, the 1985 Manchester B737 [4, 20] and the 2019 Sheremetyevo Sukhoi Superjet-100 [21, 22, 23] fatal accidents that involved post-crash fires. In the Manchester fire, both forward exits and an overwing exit, representing 50% of the normally available exits, were viable in the accident [4, 20]. In the 2019 Sheremetyevo Sukhoi Superjet-100 [21, 22, 23] fire, only the two front exits were available for evacuation — which also represented 50% of the normally available exits — as this aircraft does not have overwing exits. In both these incidents, an external post-crash fuel fire gained access to the cabin interior at the rear of the aircraft, and, hence, the rear exits were not viable for evacuation.

Utilising this underlying scenario setup, four scenario variations are investigated, as specified in the statement of work (SOW) [3] and described in the research proposal [1]:

- **Scenario 1, Base Case:** In this scenario, no passengers attempt to retrieve their luggage, and so this serves as the base case against which all other scenarios are compared.
- **Scenario 2, 25% of the passengers retrieve luggage:** In this scenario, imposed on the base case, 25% of the passengers will retrieve their luggage during the evacuation.

- **Scenario 3, 50% of the passengers retrieve luggage:** In this scenario, imposed on the base case, 50% of the passengers will retrieve their luggage during the evacuation.
- **Scenario 4, 75% of the passengers retrieve luggage:** In this scenario, imposed on the base case, 75% of the passengers will retrieve their luggage during the evacuation.

While Scenario 1 was initially simulated and analysed using the current release version of airEXODUS (see Section 3), the scenarios involving luggage retrieval were undertaken using an appropriately modified version of the airEXODUS software capable of representing the impact of passengers retrieving luggage (see Section 5). For completeness and consistency, the analysis of Scenario 1 was repeated using the modified software, and the definitive results for Scenario 1 are presented in Section 5.

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, Base Case Scenario, Scenario 1:** the aircraft configuration employed in the analysis, along with modelling parameters used to represent the geometry, including preliminary results for the base case scenario, i.e., in which no passengers attempt to retrieve luggage, are presented,
- **Section 4, Luggage Retrieval Times:** the identification of the data used in the analysis to represent the time required by passengers to retrieve cabin luggage is presented,
- **Section 5, Model Enhancements to represent Luggage Retrieval:** the enhancements to the airEXODUS model to represent luggage retrieval and the impact this has on other passengers are described, and final results for Scenario 1 (0% luggage retrievers) are presented and discussed,
- **Section 6, Scenario 2, 25% luggage retrievers:** The results and analysis for Scenario 2 are presented and discussed,
- **Section 7, Scenario 3, 50% luggage retrievers:** The results and analysis for Scenario 3 are presented and discussed,
- **Section 8, Scenario 4, 75% luggage retrievers:** The results and analysis for Scenario 4 are presented and discussed,
- **Section 9, Discussion:** The results from all four scenarios are reviewed and key findings discussed,
- **Section 10, Limitations:** Key limitations in the modelling are presented and discussed,
- **Section 11, Conclusions and Recommendations:** The conclusions and recommendations are presented,
- **Section 12, References:** References cited in the work are presented, and
- **Annexes:** Annexes referenced in the main report are presented.

2 PROJECT ASSUMPTIONS

The simulations were undertaken using the agent-based aircraft evacuation simulation software airEXODUS [4-16]. 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 [15] and verification demonstrations to explore real accident scenarios [4]. The software has been described many times in the literature, and so is not described here; however, a brief description of the airEXODUS software can be found in ANNEX A of this report.

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. These assumptions, together with key project assumptions related to the SOW [3], are described here.

(1) **Aircraft Configuration:** The analysis presented in this report is restricted to a single-aircraft configuration consisting of:
   a. Narrow-body aircraft configuration (see [3], 2.2).
   b. A single class configuration with six abreast seating (see [3], 2.2.1).
   c. Available exits on the aircraft consist of Type C (forward and aft) and two pairs of Type III (overwing) exits.
   d. The aircraft geometry is described in more detail in Section 3.

(2) **Crew:** The number of cabin crew (CC) is assumed to be three. 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. Two flight deck crew (FC) are also included in the analysis. The FC will evacuate the aircraft as passengers.

(3) **Cabin Sweep**: The evacuation analysis does **NOT** include a CC-instigated cabin sweep prior to their evacuation. Thus, the CC evacuate as normal passengers at the appropriate time. (i.e., once their area of responsibility is clear of passengers).

(4) **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 FAR 25.803 (referred to as Target population) (see [3], 2.2.1).
   a. A single target population is used for all simulations.
   b. The target population begins each simulation from within the configuration specified in (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.

(5) **Hazard Analysis:** The simulations do not involve the airEXODUS capabilities to represent smoke, toxic gases, and heat (see [3], 2.2.2). 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 (see [3], 2.2.2).

(6) **Slide Time:** The simulations do not include passenger slide time or time for passengers to traverse the wing. Thus, on-ground times are not reported in this analysis. The times that are reported include the out-of-aircraft time (see [3], 2.2.2).

(7) **Scenarios:** A total of four scenarios are considered; in each scenario, the aircraft is assumed to be fully occupied. The four scenarios involve:
  a. Scenario 1: no passengers retrieving luggage — the base case,
  b. Scenario 2: 25% of the passengers retrieving luggage,
  c. Scenario 3: 50% of the passengers retrieving luggage, and
  d. Scenario 4: 75% of the passengers retrieving luggage.

(8) **Number of Repeat Simulations:** 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 of (4) (see [3], 2.3).

(9) **airEXODUS simulation parameters:** To perform each simulation, a variety of data is required. This includes (a) exit ready times, (b) passenger exit delay times and (c) off-times.

  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 to the end point 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., 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.

  The data used in this analysis correspond to exit ready times obtained from the FSEG database [17] of exit ready times for Type C and Type III exits derived from full-scale certification trials (see Section 3).

  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 is one of 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:

- 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.
- 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.
- 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.

The data used in this analysis correspond to passenger exit delay times appropriate for Type-C exits with assertive crew as derived from full-scale certification trials and Type-III exits without crew assistance [17] (see Section 3). Furthermore, it is assumed that luggage will not impact the passenger exit delay times (this is necessary, as no passenger exit delay time data involving cabin luggage currently exist).

c. **The Off-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 end point). 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]. However, as stated in the SOW (see [3], 2.2.2), this analysis will not involve Off-Time, so only out-of-aircraft times are reported, i.e., on-ground times will not be predicted as part of this analysis.

(10) **Exit Configuration:** Only a single-seat configuration (i.e., that specified in (1)) and exit configuration are considered for the aircraft. The available exits involve 50% of the normally available exits and are consistent with those found in typical accidents [11]. For this analysis, the configuration consists of the two forward (Type-C) exits and the right overwing (Type-III) exit(s) (see [3], 2.2.1).

(11) **Passenger Exit Selection Behaviour:** Passenger exit selection behaviour involves passengers preferentially selecting their nearest (based on travel distance) available functioning exit. This is a plausible and realistic scenario, as evidence from accident analysis suggests that passengers head for their nearest exits [10] (see [3], 2.2.1). In these simulations, passengers will be allowed to use their nearest exit, irrespective of whether the exit is in front or behind their seating location. However, if there is excessive congestion at an exit, passengers may abandon their nearest exit and seek another exit. This type of behaviour (which does not typically occur in certification trials), representative of the most likely passenger behaviour in an actual accident, is expected to produce sub-optimal evacuation times, i.e., evacuation times in excess of 90 s.

(12) **Passenger Luggage Retrieval Behaviour:** To simplify the analysis and to remove potentially confounding behaviours from the analysis, agents assigned to retrieve luggage from overhead bins during the evacuation will adopt the following behaviours:

a. Luggage retriever agents exit their seat row and stand in the cabin aisle adjacent to their seat row to retrieve their luggage.
b. During luggage retrieval, agents retrieving luggage will be delayed for a period of time randomly selected from a luggage retrieval delay time distribution.
c. Agents representing other passengers directly impacted by the retrieval process and immediately adjacent to the agent retrieving their luggage within the cabin aisle will have the option to:
    i. Wait in the aisle until the luggage has been retrieved and the agent retrieving the luggage starts to move towards an exit.
    ii. Attempt to by-pass or squeeze past the agent retrieving the luggage. However, a by-pass event will only be considered possible if there is sufficient space on the other side of the luggage retriever for the by-passing passenger to move into.
d. Agents remaining in the seat row of the agent assigned to retrieve their luggage are not able to by-pass or squeeze past the luggage retriever while they are in the process of retrieving their luggage.
e. The agents selected to retrieve cabin luggage are randomly allocated for each repeat simulation.

As part of this project, the airEXODUS evacuation simulation model has been enhanced to incorporate these behaviours (see Section 5). However, it is noted that the following behaviours are not considered in the simulations:

a. Aisle walking speed is not impacted by carrying luggage.
b. Additional aisle space occupied by agents carrying luggage is not represented.
c. Passenger's exit hesitation time is not impacted by the carrying of luggage.
d. Discarded luggage at exits is not represented.

The omission of these considerations is for simplification purposes and is primarily due to the lack of data to support their inclusion within the modelling. Omitting these behaviours is expected to adversely impact the outcome of each simulation, so the results generated should be considered optimistic.

(13) **Passenger Luggage Retrieval Time:** A key parameter in the evacuation analysis concerns the time that passengers require to retrieve their luggage from the overhead bin once they have entered the cabin aisle (see [3], 2.2.1). This is a non-predicted parameter, so it must be prescribed in the simulation. As part of this project, FSEG has identified an appropriate

passenger luggage retrieval distribution based on the actual time incurred by passengers to retrieve luggage from overhead bins in non-emergency deplaning situations (see Section 4).

The implications of these assumptions are discussed throughout the report and summarised in Section 10, where project limitations are presented.

3 BASE CASE SCENARIO

In this section, the base model used in all the scenarios is developed and tested to ensure that it functions as intended. In particular, it is necessary to demonstrate that the exits perform as intended and that the model could be configured to provide the passenger behaviour for the 'nearest exit' scenario. Once the model was constructed, a series of exit flow test scenarios were run to establish that the cabin and model setup would achieve the expected flows for the Type-C and Type-III exits. In total, four separate test cases were examined, one for each viable exit, i.e., the two L1, R1 Type-C exits and the L2, L3 overwing Type-III exits.

As described in Section 2, the exit combination utilised in this analysis consists of the two forward Type-C exits and the two left overwing Type-III exits. In the 'nearest exit' scenario, agents will utilise their nearest viable exit. Given the aircraft geometry, the 'nearest exit' scenario will result in the forward pair of Type-C exits being underutilised while the two left overwing exits are overutilised. The 'nearest exit' scenario is essentially the base case scenario for the project. The base case will be configured to run under typical certification conditions, with the appropriately specified population, 50% exit availability, exits opened within prescribed times (based on certification data), crew at the staffed exits are assumed to be assertive, and all passengers attempt to exit the cabin using their nearest viable exit.

3.1 Development of the Aircraft Model

(a) The aircraft geometry:

The aircraft cabin layout consists of a single main cabin aisle running along the length of the cabin with cross aisles located at the front and rear of the cabin connecting both pairs of Type-C exits. The two pairs of Type-III overwing exits are separated by a seat row, and the seat pitch in the exit row is slightly greater than the normal seat pitch. There are several monuments located in the front (just before the first row of seats) and rear (just after the last row of seats) of the aircraft. There is a slight jog in the front cross aisle. The configuration is typical of the B737 or A320 type aircraft and is depicted in Figure 1. The seat pitch is set to 0.762 m with the exception of the overwing seats, where the seat pitch is set to 0.965 m. Exits L1, R1 and L4, R4 are Type-C, while exits L2, L3 and R2, R3 are Type-III.

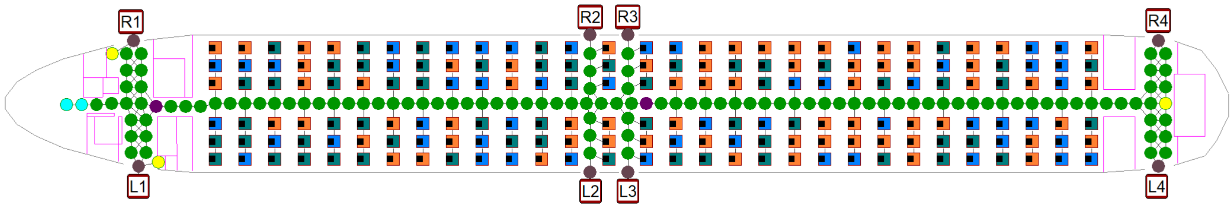


Figure 1: The cabin layout used in simulations.

The characteristics of the exits are summarised in Table 1.

The exit ready times for all the exits are the times derived from the UoG analysis of previous certification trials [17]. 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).

Table 1: Exit characteristics.

Location	Type	Width	Passenger Exit Hesitation Time	Exit Ready Times (s)
L1	Type C FWRD Entry	0.86m (34”)	Assume Assertive Crew: Distribution from certification data for Type-C assertive.	Time selected from certification data for Type-C exits. 8.1 s
R1, L4, R4	Type C Galley SVC	0.76m (30”)	Assume Assertive Crew: Distribution from certification data for Type-C assertive.	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) Population

The aircraft configuration consists of 180 passengers, 3 cabin crew, and 2 flight deck crew in total:

- 180 passengers: The passenger demographics and attributes are derived from the standard 90-second certification population.
- 3 cabin crew: The cabin crew (CC) have a 0 sec response time. Two CC are located at L1 and R1, respectively, and one crew is located at the rear L4/R4 exits. In the Nearest Exit scenario, the CC leave their area of responsibility once it is clear of PAXs.
- 2 flight deck crew: The flight deck crew (FC) are assumed to have a 20-second response time that represents them shutting down the flight deck. Once this time elapses, they then evacuate along with the other PAXs via L1 or R1.

The population implemented in the model corresponds to the 90-second population as specified in FAR/CS 25.803; see Table 2 for gender and age breakdown and response time range. The population consists of non-connected individuals (i.e., they do not form social or family groups). For each simulation, they begin from within the configuration specified in Figure 1, with each member of the population initially occupying a seat. The population consists of people with different movement capabilities, which reflects different age groupings and ability levels. A total of 1000 different population mixes are used in each scenario (i.e., 1000 different populations satisfying the 90-second criteria).

For each scenario, one simulation is performed for each population, resulting in 1000 repeat simulations for each scenario. During each repeat simulation, essentially, a different passenger seating allocation is simulated.

Table 2: 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	– 8.0

(c) Scenario specification

With the exception of the exit test cases, all the scenarios within the project will assume that the following exits are available: the two forward Type-C exits (L1, R2) and the two overwing Type-III exits (L2, L3), and that passengers will select their nearest viable exits. Furthermore, the Type-C exits are staffed by assertive cabin crew.

The passenger exit hesitation time distribution used in the simulations for the Type-C exits with assertive crew is based on video analysis of certification tests involving four aircraft, 6 Type-C exits, and data from 355 passengers [17]. 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 minimum hesitation time is 0.0 sec, and the maximum is 2.2 sec (see Figure 2).

The passenger exit hesitation time 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]. 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).

Min	Max	Prob
0.000	0.100	0.000
0.100	0.200	0.217
0.200	0.300	0.300
0.300	0.400	0.240
0.400	0.500	0.074
0.500	0.600	0.078
0.600	0.700	0.026
0.700	0.900	0.030
0.900	1.000	0.009
1.000	1.400	0.017
1.400	2.200	0.009

(a)

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

(b)

Figure 2: PAX exit hesitation time distributions (a) for Type-C exits and (b) for Type-III exits; values are in seconds (s).

3.2 Testing Model Performance

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 area that the simulated agents can use) in the vicinity of the exits has undergone several iterations of modifications to ensure that exit flows achieved are within the expected range of flows for the Type-C and Type-III exits.

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

- Type-C exits with assertive crew: 53 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; the 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; the 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 shown in Figure 3 and listed in Table 3, along with the certification data.

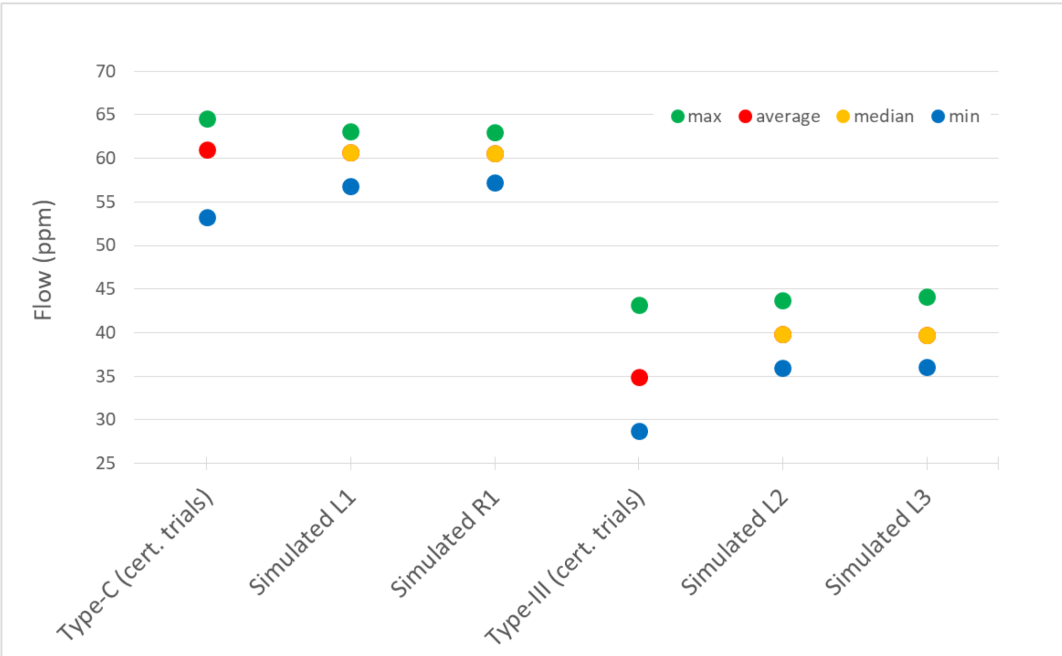


Figure 3: Model-predicted exit flows for Type-C and Type-III exits compared with exit flows derived from certification trials.

Table 3: Model-predicted exit flows 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	53.2	56.9	57.3	28.7	35.9	36.1
Average	61	60.7	60.6	34.9	39.8	39.7
Median	--	60.7	60.5	--	39.8	39.7
Max	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.

3.3 Results for Scenario 1, the Base Case Scenario, 0% Luggage Retrievers

(a) Base Case Scenario specification

In the Nearest Exit (NE) scenario, the passengers (PAXs) attempt to exit the cabin using their nearest exit. As described in Section 1, this is a plausible and realistic scenario, as evidence from accident analysis suggests that passengers utilise their nearest exits during emergency evacuation [11,12,13].

In these simulations, the flight crew (FC) are assigned an arbitrary 20 s response time — intended to represent shutdown of the flight deck and then evacuation (see Section 3.1(a)). Once this time elapses, the FC leave as normal PAXs via L1 or R2. The CC located by the active exits (L1, R1) leave once their area of responsibility clears of PAXs.

The theoretical cabin split for the NE scenario is depicted in Figure 4. All PAXs between the forward bulkhead and the blue line should utilise the L1/R1 exits, while all PAXs between the blue line and the aft bulkhead should utilise the L2/L3 exits. The theoretical number of passengers that should use each exit, assuming 100% compliance with the given cabin split, is described in Table 4. However, interactions between passengers during the evacuation process will result in PAXs not always using their intended exit.

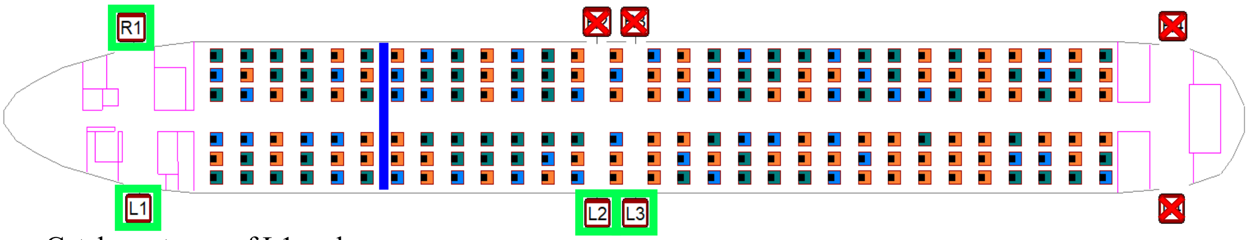


Figure 4: Cabin split for Scenario 1 (0% luggage retrievers); the image also shows the viable exits with green highlights and the unavailable exits with a red cross.

Table 4: Theoretical exit usage for Scenario 1 (0% luggage retrievers).

	L1	R2	L2 and L3
Num. of PAXs	18	18	144
FC + CC	2	2	1
Total	20	20	145

It is also assumed that PAXs reaching the L1/R1 exits have a 50% probability of choosing either L1 or R1. For PAXs reaching the L2/L3 exit pair, there is a 45%/55% probability of choosing L2 or L3, respectively. This is to represent the behaviour that PAXs arriving from the rear of the airplane will first encounter L3 and thus are more likely (i.e., greater probability) to use that exit to leave the cabin compared to the adjacent L2. However, as already stated, within the model, the exit that PAXs will attempt to utilise is dependent on the situation they encounter at the exit and the nature of the queues. Thus, PAXs do not always follow the prescribed imposed behaviour.

(b) Scenario 1 (0% luggage retrievers, Base Case) Results

Presented in Table 5 is a summary of key data from Scenario 1 (0% luggage retrievers). The results are from the 1000 repeat simulations and represent the results from the simulations producing the minimum, median, and maximum total evacuation time (TET). In this analysis, the TET is defined as the out-of-aircraft time (not the on-ground time).

Thus, from the 1000 repeat simulations, the minimum TET is 111.2 s, the median TET is 122.0 s, the maximum TET is 139.6 s, and the 95th percentile TET is 129.5 s. Also presented in the table are CWT (cumulative wait time), Average Distance Travelled and Average Personal Evacuation Time (PET). The CWT is a measure of how much time each agent in the simulation wastes in congestion. This is defined as being stationary or travelling at a slower speed than their maximum walk speed. Within a simulation, the CWT is determined for each agent and averaged over all the agents within that simulation to produce the 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 average distance travelled. The PET is the personal evacuation time for an agent. It measures the time from the start of the simulation to the point where the agent has exited the aircraft. The PET can be determined for all agents in a simulation and then averaged over all agents in the simulation. Thus, for the simulation producing the maximum TET (139.6 s), the average PET was 60.0 s and on average, passengers wasted 41.1 s in congestion and travelled 9.0 m to their exit. Clearly, the aircraft layout considered in this analysis, with two forward Type-C exits and two left Type-III exits available (representing 50% of the available exits) and with the passengers seeking to exit via their nearest exit, does not satisfy the 90 s requirement, with a minimum evacuation time of 111 s and a maximum evacuation time of 140 s.

Table 5: Summary performance data for Scenario 1 (0% luggage retrievers) for the simulations producing the minimum, median, maximum, and 95th percentile evacuation time.

Scenario 1 (0% luggage retrievers)	Avg. CWT (s)	Avg. Distance (m)	Avg. PET (s)	TET (s)
Min sim	34.2	8.9	52.3	111.2
Median* sim	37.0	9.1	55.5	122.0
Max sim	41.1	9.0	60.0	139.6
95th% sim	40.4	8.8	58.6	129.5

Note: Simulations are ordered by out-of-aircraft time, Min sim being the fastest evacuation simulation and Max sim being the slowest evacuation simulation.
**Median sim is the 501st simulation from the 1000 repeat simulations ranked in ascending TET.*

Presented in Table 6 is a summary of the minimum, mean, maximum, and 95th percentile values from all the simulations. This is intended to simply provide a measure for the spread in values for each parameter. The values in Table 6 are not necessarily derived from the same simulation but represent the range of values derived from all 1000 simulations. Thus, the minimum value is the smallest value of a particular parameter generated by all 1000 simulations. Thus, the smallest Average CWT observed was 33.4 s, while the largest was 43.5 s.

The distribution of the TET for all 1000 repeat simulations is presented in Figure 5. Each repeat simulation produces a different TET due to the different seating allocations, variation in population characteristics, and simply because an agent will not necessarily do the same thing if the simulation is repeated, as some of the behaviours are stochastic in nature. This includes the passenger exit selection. As can be seen in Figure 5, all 1000 repeat simulations for Scenario 1 produce TETs in excess of 90 s.

Table 6: Summary performance data for Scenario 1 (0% luggage retrievers) representing the minimum, mean, maximum, and 95th percentile values for key simulation parameters.

Scenario 1 (0% luggage retrievers)	Avg. CWT (s)	Avg. Distance (m)	Avg. PET (s)	TET (s)
Min value	33.4	8.4	51.0	111.2
Mean value	37.7	9.0	56.1	122.2
Max value	43.5	9.7	62.5	139.6
95th% value	40.4	9.3	59.0	129.5
Note: The data in the table are simulation-independent, i.e., the values are not necessarily from the same simulation.				

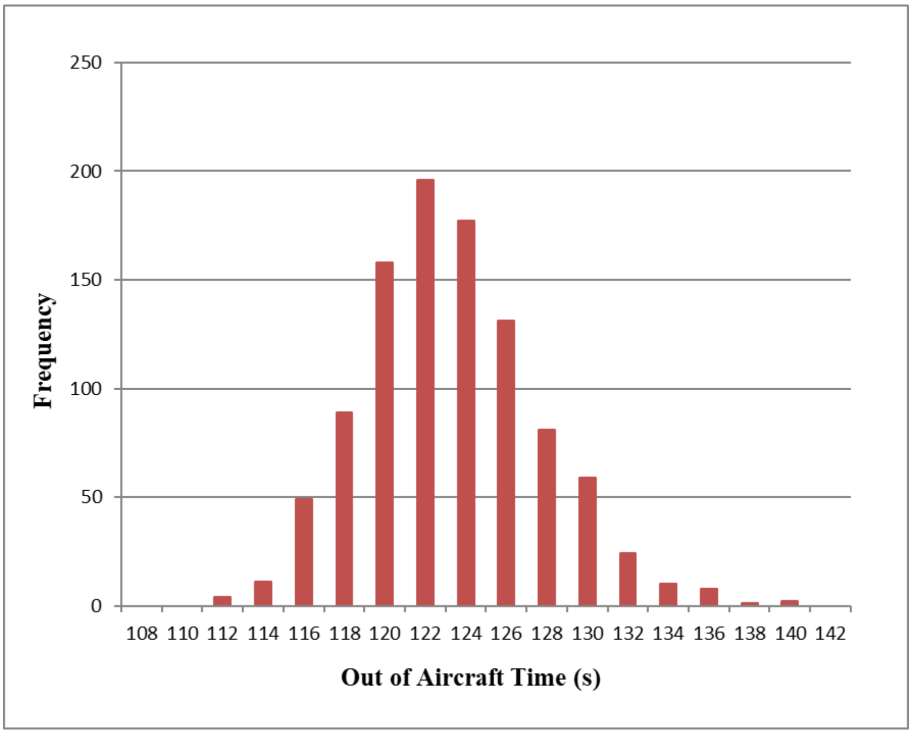


Figure 5: Distribution of TET for Scenario 1 (0% luggage retrievers).

The exit usage and flows produced for Scenario 1 are presented in Table 7 and Table 8. The minimum, mean, and maximum number of passengers attempting to use L1/R1 are approximately equal, as seen in Table 7. Slightly more passengers tend to use L3 compared to L2 due to L3 being reached first by passengers arriving from the rear of the cabin, but overall, these exits are also well balanced (see Table 7). The imbalance in the number of passengers using particular exit pairs (i.e., L1/R1 and L2/L3) will result in inefficiencies in exiting and, hence, lead to longer evacuation times. The imbalance in the numbers of passengers using the various exits will also impact the exit flows achieved, in particular the forward Type-C exits, given that the number of passengers using these exits is relatively low.

The number of passengers using each exit and the achieved flows for the minimum, median, maximum, and 95th percentile simulations are presented in Table 8. The simulation producing minimum TET generally achieves higher flows at each exit, while the maximum TET generally achieves lower flows at each exit.

Table 7: Minimum, mean, maximum, and 95th percentile values for exit flow and exit usage for Scenario 1 (0% luggage retrievers).

Scenario 1 (0% luggage retrievers)	L1 Avg. PPM	L1 No. Used	R1 Avg. PPM	R1 No. Used	L2 Avg. PPM	L2 No. Used	L3 Avg. PPM	L3 No. Used
Min value	18.2	14	21.6	12	29.6	58	33.7	63
Mean value	38.5	22	39.1	21	38.5	71	39.5	71
Max value	61.4	31	67.9	30	45.0	80	44.5	84
95th% value	51.1	18*	50.7	16*	41.9	66*	42.6	67*

Note: The data in the table are simulation-independent, i.e., the values are not necessarily from the same simulation.
** For these data, it shows that 95% of the time, it was this amount or higher.*

Table 8: Exit flow and exit usage for Scenario 1 (0% luggage retrievers) for the simulations producing the minimum, median, maximum, and 95th percentile evacuation time.

Scenario 1 (0% luggage retrievers)	L1 Avg. PPM	L1 No. Used	R1 Avg. PPM	R1 No. Used	L2 Avg. PPM	L2 No. Used	L3 Avg. PPM	L3 No. Used	All Exits Avg. PPM
Min sim	50.3	22	44.7	20	42.2	70	44.5	73	45.7
*Median sim	49.7	29	31.8	15	35.9	65	41.5	76	42.4
Max sim	40.6	20	45.2	23	33.7	72	34.3	70	36.2
95th% sim	29.7	18	41.9	23	35.2	69	39.8	75	34.9

Note: Simulations are ordered by out-of-aircraft time, with Min sim being the fastest evacuation simulation and Max sim being the slowest evacuation simulation.
**Median sim is the 501st simulation from the 1000 repeat simulations ranked in ascending TET.*

It is clear from Table 7 that there is a large spread in exit flow achieved by the various exits, with the Type-C and Type-III exits varying from approximately 18 to 68 ppm and 30 to 45 ppm, respectively (see also Figure 6 and Table 9).

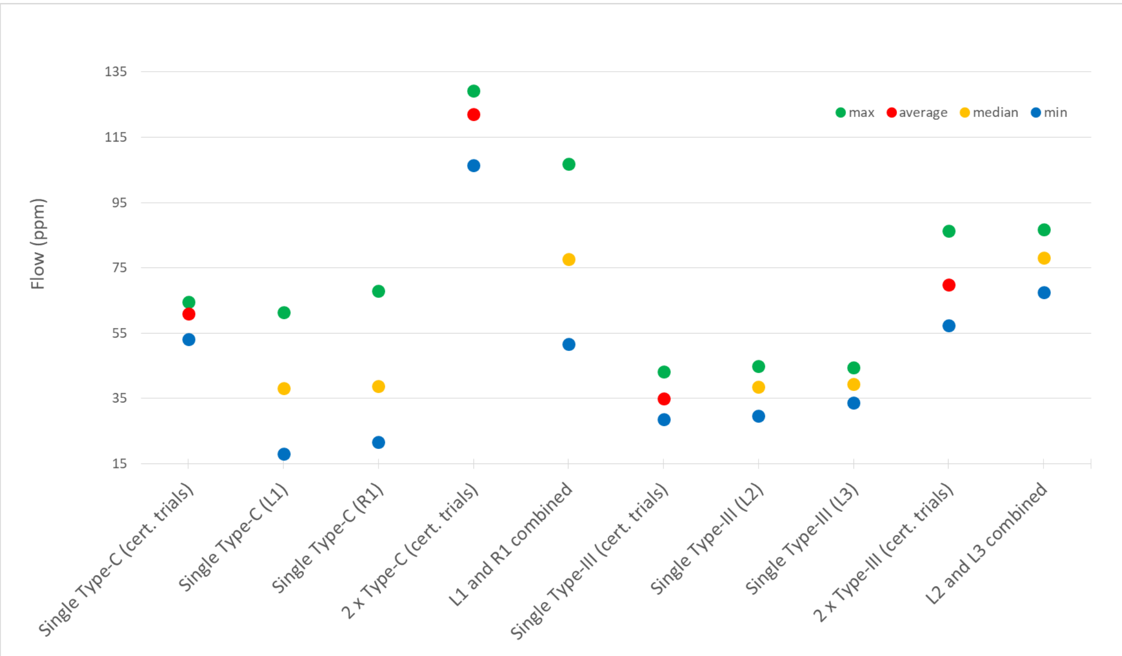


Figure 6: Exit flows for Type-C and Type-III exits obtained from certification trials and achieved for Scenario 1 (0% luggage retrievers) for each exit separately (L1, R1, L2, L3) and for all similar typed exits combined.

While the Type-III exits are performing as may be expected compared to their rated performance, the Type-C exits are significantly underperforming. The poor performance of the Type-C exits is due to the nature of the scenario and, in particular, the supply of passengers to the two exits. Essentially, the single cabin aisle cannot supply sufficient passengers to enable both Type-C exits to operate at their full capacity. This situation is compounded by the relatively small number of passengers that are able to use the two Type-C exits in this scenario (0% luggage retrievers). In contrast, the Type-III exits, which have a significantly lower flow capability than the Type-C exits (mean flow for Type-III is just 57% of the mean flow for Type-C), can be adequately supplied with passengers by the single cabin aisle. Indeed, the flow produced by the single cabin aisle is able to support both Type-III exits, so these exits operate in almost ideal conditions.

Table 9: Exit flows (ppm) for Type-C and Type-III exits obtained from certification trials and achieved for Scenario 1 (0% luggage retrievers).

Scenario 1 (0% luggage retrievers)	Type-C (cert. trials)	L1 Type-C (S1)	R1 Type-C (S1)	2x Type-C (cert. trials)	L1+R1 Type-C (S1)	Type-III (cert. trials)	L2 Type-III (S1)	L3 Type-III (S1)	2x Type-III (cert. trials)	L2+L3 Type-III (S1)
Min	53.2	18.2	21.6	106.4	51.7	28.7	29.6	33.7	57.4	67.5
Average	61	--	--	122	--	34.9	--	--	69.8	--
Median	--	38.2	38.8	--	77.6		38.6	39.5	--	78.0
Max	64.6	61.4	67.9	129.2	106.9	43.2	45.0	44.5	86.4	86.7

Essentially, while the single cabin aisle can maintain the flow to both Type-III exits to keep them functioning at peak performance, it is insufficient to support two Type-C exits at peak performance. Hence, the Type-C exits cannot perform to their rated capacities in these circumstances. This problem is also compounded by the nature of the nearest exit scenario, which limits the number of passengers that can use the Type-C exits. This can clearly be seen in Figure 6 and Table 9, where the two Type-C exits do not produce flows comparable to the rated performance of two Type-C exits, while the two Type-III exits are performing as expected.

The times for each exit to finish for the simulations producing the minimum, median, maximum, and 95th percentile simulations are presented in Table 10. Clearly, the forward L1/R1 exits finish well before the overwing L2/L3 exits due to the smaller number of passengers available in the nearest exit scenario. The forward L1/R1 exits dry up after 35 s to 44 s, depending on the particular simulation.

Table 10: Time for last person to exit from each door for Scenario 1 (0% luggage retrievers) (45:55) for the simulations producing the minimum, median, maximum, and 95th percentile evacuation time.

Scenario 1 (0% luggage retrievers)	L1 Last Out (s)	R1 Last Out (s)	L2 Last Out (s)	L3 Last Out (s)
Min sim	34.6	33.9	111.2	110.2
*Median sim	42.3	34.8	119.7	122.0
Max sim	36.4	37.5	139.6	134.3
95th% sim	44.0	39.7	129.5	123.8
*Note: Simulations are ordered by out-of-aircraft time, Min sim being the fastest evacuation simulation and Max sim being the slowest evacuation simulation. *Median sim is the 501st simulation from the 1000 repeat simulations ranked in ascending TET.*				

Finally, the exit curves for Scenario 1 (0% luggage retrievers) are presented in Figure 7 and Figure 8. For approximately the first 35 s to 44 s, the evacuation is proceeding with maximum exit flow produced by all four exits working together. However, after between approximately 35 s and 40 s, the Type-C exits are no longer working, as they have exhausted their supply of passengers, and only the Type-III exits are operating. At this time, the exit flow has significantly decreased, resulting in a reduction in the slope of the curves. As can clearly be seen in Figure 7 and Figure 8, all 1000 simulations produce TETs at least 23% (21 s) greater than the critical regulatory requirement of 90 s. Of the 185 occupants, only 139 (75%), 142 (77%), 147 (79%), and 155 (84%) occupants are evacuated at 90 s in the simulations producing the maximum, 95th percentile, median, and minimum TET simulations, respectively.

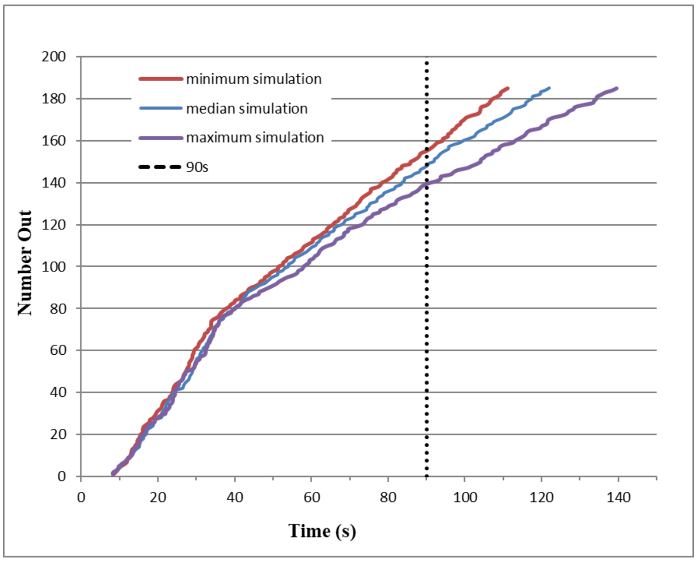


Figure 7: Scenario 1 (0% luggage retrievers) exiting curves for simulations producing the minimum, median, and maximum TETs, where the dotted line represents the 90 s mark.

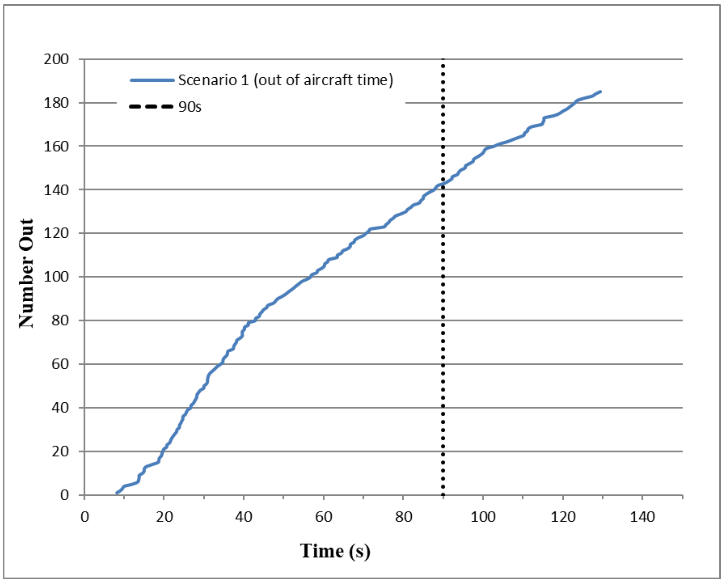


Figure 8: Scenario 1 (0% luggage retrievers) exiting curve for the simulation producing the 95th percentile TET, where the dotted line represents the 90 s mark.

3.4 Key Findings (Preliminary) for Scenario 1 (Base Case, 0% Luggage Retrievers)

Key Finding 3.1, Development and testing of aircraft model:

An aircraft geometry representative of B737/A320 configurations was developed within the airEXODUS software. The geometry consisted of:

- Two pairs of Type-C exits located in the front and aft of the aircraft,

- Two pairs of Type-III overwing exits,
- Seating for 180 passengers with 2 flight deck and 3 cabin crew, and
- A seat pitch of 0.762 m with the exception of the overwing seats, where the seat pitch is set to 0.965 m.

In model testing, the exits produced exit flows of:

  - Type-C exits: 56.9 to 63.1 ppm, which is considered appropriate for this type of exit.
  - Type-III exits: 35.9 to 44.1 ppm, which is considered appropriate for this type of exit.

Key Finding 3.2, Preliminary results for Scenario 1, 0% luggage retrievers:
The base case scenario (0% luggage retrievers) for the narrow-body aircraft configured with two forward Type-C exits and two left Type-III exits available (representing 50% of the available exits) and with the passengers seeking to exit via their nearest exit:

- Does not satisfy the 90 s requirement,
- Produces a distribution of evacuation times ranging from a minimum of 111 s to a maximum of 140 s,
- Results with between 75% (139) and 84% (155) of the 185 occupants being evacuated by 90 s., and
- In Section 5.4, Scenario 1 is rerun using the modified airEXODUS software (with additional capabilities to represent luggage retrievers) to produce the definitive data set for the base case.

4 LUGGAGE RETRIEVAL TIMES

To represent the impact of luggage retrieval on aircraft evacuation using agent-based evacuation modelling, it is essential to define a realistic representation of the time required by passengers to retrieve carry-on luggage from overhead stowage bins. Very little data are currently available in the open literature to quantify these times, and the data that are available are based on contrived laboratory trials conducted by the National Research Council of Canada (NRCC) [18], here identified as 'NRCC Trial Data'. The Fire Safety Engineering Group (FSEG) of the University of Greenwich (UoG) collected data of actual passengers stowing and retrieving luggage on actual flights through video footage analysis [19], here identified as 'FSEG Flight Data'.

Here, the two data sets are presented, identifying the strengths and weaknesses in both. While either can be used in the evacuation modelling analysis, the retrieval time distributions from each source are significantly different in appearance, so the use of either data set may have a profound impact on the conclusions of the analysis. It is thus essential that the appropriate data set is selected for use in the modelling to meet the requirements of the project. Furthermore, it is noted that neither data set was collected under evacuation conditions, so the collected data do not include instances where other passengers may be interfering with the luggage retrieval process by, for example, attempting to push past the luggage retriever. This type of behaviour is expected to result in longer luggage retrieval times than identified in the data sets reported here.

4.1 The Luggage Retrieval Time Data Sets — FSEG Flight Data

FSEG staff collected a series of video footage of passengers stowing and collecting carry-on luggage from the overhead bins during the boarding process. These are videos from actual flights covering the period 2014 – 2016 [19]. There is a total of 173 videos (5h:30m:33s) from 53 flights for a variety of narrow- and wide-bodied aircraft [19]. The data were collected for an internal FSEG project to characterise luggage stowage and retrieval times for agent-based modelling of the passenger boarding/disembarkation process. During the boarding process, passengers were observed retrieving stowed luggage after the passengers had taken their seats. Here, luggage retrieval data collected during the boarding process are considered.

Data associated specifically with luggage retrieval from overhead bins cover the period 8 September 2014 to 21 June 2016 and include data from 25 flights involving the following aircraft types: A319, A320, A321, B737, and B777. The flights also covered all seasons and times of day, as shown in Table 11.

Table 11: FSEG Flight Data individual luggage collection datapoints (51) flight details.

Detail	Breakdown
Season	1 x Spring, 31 x Summer, 15 x Autumn, 4 x Winter
Time of Day	4 x Morning, 35 x Day, 12 x Night

The 51 luggage-retrieval datapoints were generated by 46 passengers (three passengers collected two separate items, and one passenger collected three separate items). The approximate age and gender distribution of the passengers is presented in Table 12.

The various retrieval actions consisted of the following:

- remove a bag from the overhead bin,
- remove a coat from the overhead bin,
- remove an item from the overhead bin, e.g., laptop bag, small case, plastic carrier bag containing items,
- search for item in a large bag and remove the smaller item.

Table 12: FSEG Flight Data passenger age/gender.

Gender	Adult (age 18-50)	Older (age>50)	Totals (%)
Male	34	10	44 (86.3%)
Female	6	1	7 (13.7%)
Totals (%)	40 (78.4%)	11 (21.6%)	51 (100%)

Note: Age and gender have been best estimated visually from video footage, so they are subjective.

A breakdown of these actions is presented in Table 13.

Table 13: FSEG Flight Data luggage retrieval action types.

Collection Action	Count
Collect Bag	36
Collect Coat	6
Collect Item	7
Search and Retrieve Item	2

The types of bags collected are described in Table 14.

Table 14: FSEG Flight Data types of bags retrieved.

Luggage Type	Count
Roller	13
Bag/Rucksack	13
Small Bag/Small Rucksack	10
Total	36

FSEG engineers analysed the video footage frame by frame to collect the timing of the retrieval sequences. A data dictionary was developed that defined key measurement points and other relevant parameters to be recorded. In each case where a measurement is made, the passenger is located in the aisle beside the appropriate overhead bin. In the case of luggage retrieval, the overhead bins could have been open or closed. However, in all but two cases, the overhead bin was open. From video analysis (of retrieval and stowage events), it takes approximately 1 s to open or close an overhead bin; however, this is dependent on the nature of the bin.

For the retrieval data presented here, the following start and end points were defined:

- Start of luggage retrieval: action of commencing to raise hands towards the overhead bin.
- End of luggage retrieval: retrieved item is removed from overhead bin, and hands are lowered to waist height or item is placed on seat.

In no cases did the passenger attempt to close the overhead bin when they retrieved their luggage, so the retrieval times do not include the time to close the overhead bin. This is considered to be appropriate for this project, as during an evacuation, it is unlikely that a passenger would take the time to close the overhead bin while trying to evacuate. However, if it is considered necessary to include this time, 1 s could be added to each data point.

Similarly, in all but two of the cases, the overhead bin was already open. Hence, the retrieval times (for all but two data points) do not include the time to open the overhead bin. In representing luggage retrieval during an evacuation, it is possible that the overhead bin has been opened by other passengers, so the current data may be appropriate as is. However, if opening the overhead bin is considered necessary, 1 s could be added to each data point to represent the time required to open the bin.

A statistical summary of the FSEG Flight Data for luggage retrieval times, with minimum (min), maximum (max), mean, and median times and standard deviation (stdv) presented in Table 15, with the distribution shown in Figure 9.

Table 15: FSEG Flight Data luggage retrieval time data.

	Time (s)
min	2.0
mean	5.3
median	4.0
max	15.0
stdv	2.65
Total number of data points	51

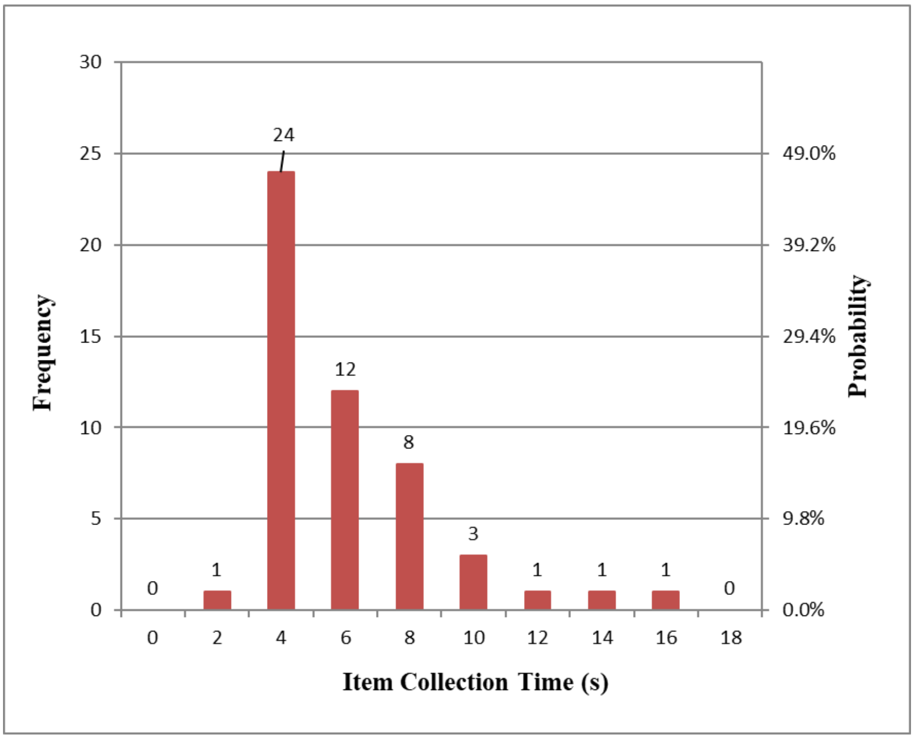


Figure 9: FSEG Flight Data luggage retrieval times.
Note: The numbers above each column indicate the frequency.

The advantages and disadvantages of using the FSEG Flight Data set can be summarised as follows:

Advantages of using the FSEG Flight Data set include:

- Represents real passengers travelling on real flights.
- Represents a range of real luggage and personal items of value, not just roller bags (roller bags, large rucksacks, small rucksacks, laptops, small cases, coats).
- Items from within stowed bags are retrieved, not just luggage.
- A variety of aircraft types is considered.
- All four seasons are included, representing the different types of valuables that passengers may carry, e.g., coats and luggage.
- Different times of the day are considered, which may impact retrieval performance.
- The overhead bins are not empty.
- Sometimes, the overhead bin is open, and sometimes it is closed (this could be the case in a real situation).
- The retrieval times do not include the time to close the overhead bin, which is likely to be consistent with behaviour during an evacuation.
- 21.6% of the participants are estimated to be over the age of 50.

Disadvantages of using the FSEG Flight Data set include:

- Data are generated by relatively few participants, i.e., 46 individuals generating 51 data points.
- The retrieval times primarily exclude the time required to open the overhead bin. However, if this is considered necessary, 1 s could be added to all the retrieval times.
- Only 13.7% of the data points are generated by females.
- The data do not represent an actual emergency situation.

4.2 The Luggage Retrieval Time Data Sets — NRCC Trial Data

The NRCC trials [18] were designed to collect a range of data from an experimental facility representing three rows of an A320 aircraft cabin. The data collected from the trials included luggage retrieval times, luggage stowage times, time required to enter/exit a seat row (with different seat pitches), time to traverse a seat row, time to fasten/release a seat belt, time to walk down an aisle with luggage, etc. [18]. Thus, trial participants were required to undertake a range of actions multiple times, with the participation requiring approximately 2 hours. In total, the 35 participants were involved in 490 trials and engaged in 14 different trial treatments [18]. The NRCC trial data associated with luggage retrieval can be summarised as follows:

- The 35 subjects were of working age (ranging from 20 to 70 years of age, with an average of approximately 31 years of age); approximately 70% of the 35 participants were adult males. Heights ranged from 1.47 m to 1.91 m, and weights ranged between 43.1 kg and 136.0 kg
- Did not include mobility-impaired participants.
- One size of roller luggage was used for all participants; the rolling luggage was 13.5 in x 20.5 in x 6.5 in (34 cm × 52 cm x 17 cm).
- The roller was only filled with paper (1.5 kg), so much lighter than typical.
- The participants were required to open and close the luggage bin, so these times are included in the reported luggage retrieval times.
- The experiment followed a procedure where the participants first performed the measured action in a modular manner and then repeated the experiment in a flow manner (modular form — actions being measured were separated by staff instruction that halted the trial after each micro-behaviour) or in a continuous flow (flow form — where staff simply reminded them of upcoming actions, but did not halt the trial after each activity).
- A total of 90 luggage retrieval data points were collected.

- This means that the 35 participants have each contributed multiple data points for the luggage retrieval action.
- There was an observed reduction (8%) in how long it took participants to stow/retrieve the luggage between the modular and flow data. This may be due to them having gained experience during the modular experiment and having optimised their actions for the repeated flow experiment.
- All the overhead bins were empty during the trials.
- The participant was alone in the mock-up during the trials.

As with the FSEG Flight Data analysis, the NRCC developed a data dictionary to define the start and end points for the various actions to be measured. For the NRCC retrieval data presented here, the following start and end points were defined:

- Start of luggage retrieval: initial hand movement towards overhead bin.
- End of luggage retrieval: hand breaks contact with the closed overhead bin door, and luggage is on the floor.

A statistical summary of the NRCC Trial Data for luggage retrieval times, with minimum (min), maximum (max), mean, and median times and standard deviation (stdv) is presented in Table 16, with the distribution shown in Figure 10.

Table 16: NRCC Trial data for luggage retrieval time.

	Time (s)
min	1
mean	7.1
median	7.3
max	10
stdv	1.74
Total number of data points	**90**

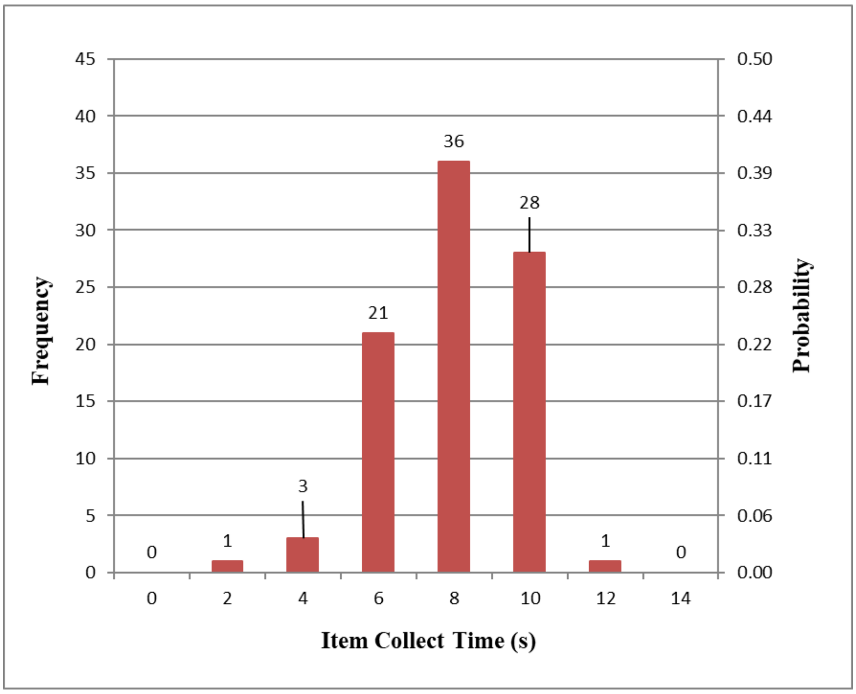


Figure 10: NRCC Trial Data luggage retrieval times.
Note: The numbers above each column indicate the frequency.

The advantages and disadvantages of using the NRCC trial data set can be summarised as follows:

Advantages of using the NRCC trial data set include:
- There are 90 data points.
- There is consistency in the measured values, as data are collected in a controlled laboratory environment.
- There is a high proportion of females.
- All overhead bins were initially closed, so were required to be opened.

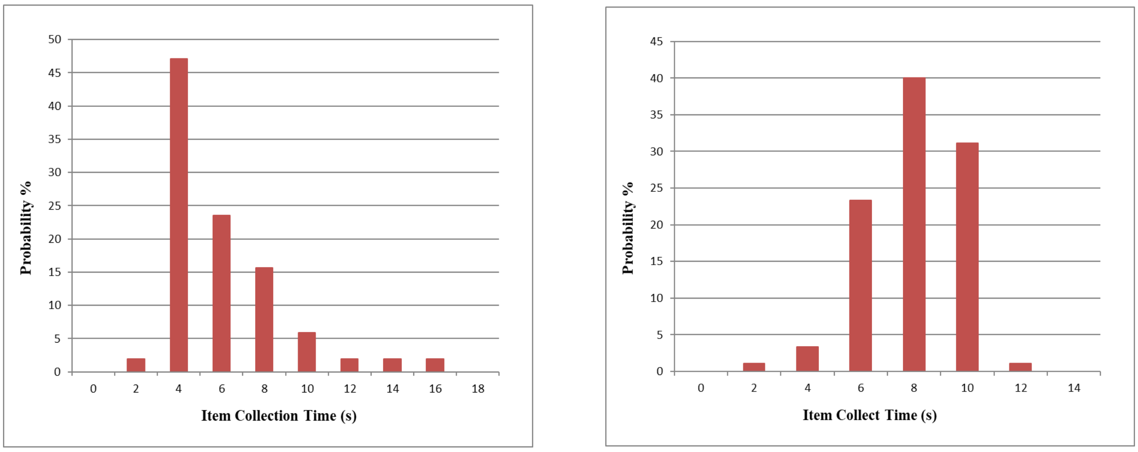
Disadvantages of using the NRCC trial data set include:
- Data are generated by relatively few participants, i.e., 35 individuals.
- Each person contributed multiple data points, so learning could impact the process (second repeat data set was, on average, 8% faster).
- All luggage used in the trial was empty, so are not representative of actual passenger luggage.
- All luggage is identical, so do not represent range of appropriate carry-on luggage.
- Only a single aircraft configuration is used.
- The participants are not actual passengers on a flight, and participants know the task that they are there to perform, so they are prepared.
- Cabin is empty, i.e., no other passengers, so all actions are performed in isolation.
- The overhead bins are empty, i.e., they do not contain other luggage, so the situation is ideal.
- All measurements required overhead bins to be opened; it is likely in an emergency that some of the bins will already be open.
- The end point of the measurement includes closing the overhead bin; this is an unlikely action in the event of an emergency.
- The data do not represent an actual emergency situation.

A direct comparison of the two data sets is presented in Table 17 and Figure 11 & Figure 12. From Figure 11 & Figure 12, it is clear that the nature of the two distributions is quite different, with the NRCC trial data resembling a normal distribution, while the FSEG Flight Data more closely resembles a log normal distribution. From Table 17, the mean and median for the NRCC trial data are also similar, again suggesting similarity to a normal distribution, while the FSEG Flight Data have a larger mean than the median, suggesting a distribution skewed to the left.

Table 17: Summary of luggage retrieval data.

	FSEG Flight Data (s)	**NRCC Trial Data (s)**
minimum	2.0	1.0
mean	5.3	7.1
median	4.0	7.3
maximum	15.0	10.0
studv	2.65	1.74
Number of data points	51	90
Number of participants	46	35
skew	To left	To right

Furthermore, the FSEG Flight Data have a long tail stretching towards the longer luggage retrieval times, with a maximum of 15.0 s (15.0 s, so it appears in the 16 s bin) observed, compared to only 10.0 s (10.2 s, so it appears in the 12 s bin) for the NRCC Trial Data. The NRCC data set appears to be representative of a population undertaking the same task under the same conditions, producing a quasi-normal distribution, as is to be expected.



(a) FSEG Flight Data (b) NRCC Trial Data

Figure 11: The two data sets for luggage retrieval times.

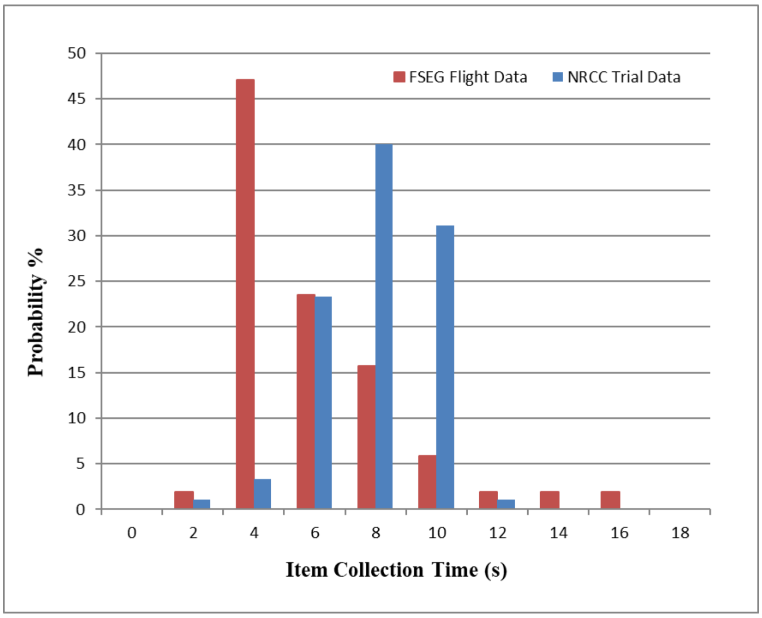


Figure 12: FSEG Flight Data & NRCC Trial Data luggage retrieval times.

However, in reality, luggage retrieval is not the same task repeated by different people, as the luggage being retrieved is likely to be different for each retrieval instance (physical dimensions and weight) with different stowage conditions, so we may expect to have a more skewed distribution, as represented by the FSEG Flight Data. While the NRCC trial data have a larger mean and median than the FSEG Flight Data, suggesting that, on average, longer luggage retrieval times will be achieved using the NRCC trial data, the long tail of the FSEG Flight Data suggests that some luggage retrieval times generated using these data are expected to be quiet long. Note that using the FSEG Flight Data, there is a 6% chance of retrieval times between 12 s and 16 s (inclusive), whereas, with the NRCC trial data, there is a 1% chance of retrieval times of 12 s. As each luggage retrieval evacuation modelling scenario will be repeated 1000 times, and there will be a number of passengers attempting to retrieve luggage within a simulation (each randomly allocated a retrieval time from the distribution), there are likely to be more simulations for a given scenario impacted by longer retrieval times when using the FSEG Flight Data.

While neither available luggage retrieval data sets are ideal, the FSEG Flight Data have the advantage of being based on observations of real passengers retrieving a variety of real luggage types on actual flights. Thus, the FSEG Flight Data are used in this analysis to represent passenger luggage retrieval times. Presented in Table 18 is the frequency distribution and probability delay time data for luggage retrieval that are implemented in the modified airEXODUS software described in Section 5.

Table 18: FSEG Flight Data luggage retrieval time data.

Time Range (s)	Frequency	Probability
[0 – 2]	1	2.0
[2 – 4]	24	47.1
[4 – 6]	12	23.5
[6 – 8]	8	15.7
[8 – 10]	3	5.9
[10 – 12]	1	2.0
[12 – 14]	1	2.0
[14 – 16]	1	2.0
[16 – 18]	0	0.0

4.3 Key Findings: Luggage Retrieval Data Set

Key Finding 4.1 Data sets available to characterise luggage retrieval time:
There is a lack of reliable data to characterise the time required for passengers to retrieve their luggage from overhead bins. However, two data sets are available that characterise luggage retrieval times, one being an experimental data set produced by the NRCC and the other being a data set based on real data collected from actual observations of passengers deplaning in non-emergency conditions. While the shape of the two distributions is quite different, both produce similar mean retrieval times, with the mean for the FSEG Flight Data being 5.3 s and that for the NRCC Trial Data being 7.1 s.

Key Finding 4.2 Selected luggage retrieval data set:
Neither available luggage retrieval data set is ideal, and both have their strengths and weaknesses. A significant weakness of the NRCC experimental data set is the highly contrived nature of the experiment, e.g., use of essentially empty bags, the same type of bag being used for all the trials, empty overhead bins, repeat use of participants, etc. The weaknesses of the FSEG Flight Data include the small number of data points — approximately half that of the NRCC Trial Data Set — and it involved fewer women than in the NRCC data set. Furthermore, neither data set represents luggage retrieval during an emergency evacuation situation. However, the FSEG Flight Data have the advantage of being based on observations of real passengers, retrieving a variety of real luggage types on actual flights. Thus, the FSEG Flight Data are used in this analysis to represent passenger luggage retrieval times.

Key Finding 4.3 Luggage retrieval times:
The FSEG Flight Data Set (51 data points) produces a log normal distribution of luggage retrieval times with a minimum of 2.0 s, a mean of 5.3 s, a maximum of 15.0 s, and a standard deviation of 2.65 s. Using the FSEG Flight Data, there is a 6% chance of retrieval times between 12 s and 16 s.

5 ENHANCEMENTS TO airEXODUS TO REPRESENT PASSENGER CABIN LUGGAGE RETRIEVAL

A novel *Cabin Luggage Collection Model* has been implemented in airEXODUS to represent the delay incurred by passengers retrieving their luggage during an evacuation. A key parameter required by the model is the time required by passengers to retrieve carry-on luggage from overhead stowage bins. The data set used to define the passenger luggage retrieval time was defined in Section 4 of this report and is the 'FSEG Flight Data' that were collected by the Fire Safety Engineering Group (FSEG) of the University of Greenwich (UoG) from actual passengers stowing and retrieving luggage on actual flights through video footage analysis.

The passenger retrieving their luggage also impacts other passengers by potentially delaying their evacuation by partially blocking the main cabin aisle. While some passengers may be able to push past the obstruction caused by the luggage retriever, others may not. This complex overtaking behaviour also needs to be represented within the modified model. Here, the modified model is presented and demonstrated. Furthermore, Scenario 1 has been repeated using the modified software to produce additional results as part of the baseline data set for comparison with the luggage retrieval scenarios.

5.1 Cabin Luggage Collection Model

Here, the developments made to the current research version of airEXODUS v6.0 to represent the impact of passengers retrieving cabin luggage during an evacuation are described and presented.

The luggage collection model that has been implemented within airEXODUS is based on several key assumptions, which are highlighted below. These modelling assumptions should be taken into consideration when reviewing model predictions. These modelling assumptions are further discussed in Section 10, where project limitations are summarised.

(1) Location of luggage stowage: It is assumed that the passenger's luggage is stowed above the seat of the luggage collector. Thus, the luggage collector only needs to move into the aisle location immediately adjacent to their seat to retrieve their luggage. This is a simplifying assumption, as the luggage could be stowed in any overhead bin, which could be behind or ahead of the passenger's allocated seat. If the luggage is stowed behind the passenger's seated position, this is expected to cause additional disruption to evacuation flows, as the passenger retrieving the luggage would need to walk in contraflow to the evacuating passengers. Furthermore, additional time may be required by the passenger, as they may not know the precise location of their stowed luggage. These aspects are not included in the current model, but they could be included in a later study.

(2) Luggage retrieval delay time: During the luggage retrieval process, the passenger attempting to retrieve luggage will remain stationary in the aisle, creating an obstruction, for a period of time determined by the 'FSEG Flight Data' as described in Section 4. It is noted that the luggage retrieval data set does not include instances where other passengers are interfering with the luggage retrieval process by, for example, attempting to push past the luggage retriever. This type of behaviour is expected to increase luggage retrieval times, so the data set used in this analysis is expected to result in optimistically short delays to other passengers and, hence, result in shorter predicted evacuation times than would be expected.

(3) Passengers in seat rows affected by luggage collectors: When a passenger is attempting to retrieve their luggage, they are assumed to effectively block other passengers in their seat row from entering the aisle. This is considered a reasonable assumption due to the difficulty for a person who is in the process of getting out of their seat in a confined space (and so is not in a fully upright position) to push past a luggage retriever that is effectively blocking the space into the aisle. Thus, other passengers still in the seat row will not be able to exit until the person has retrieved their luggage. Furthermore, if seated passengers were to push past the luggage retriever, this is expected to interfere with and, hence, delay the luggage retrieval process, increasing luggage retrieval times. While excluding seated passengers from pushing past luggage retrievers is considered a reasonable assumption for a narrow-body aircraft, in future work, the model could be modified to allow passengers located in seat rows to push past the luggage retriever, as do passengers in the main cabin aisle.

(4) Passengers in the main aisle affected by luggage collectors: It is assumed to be possible for some passengers in the main aisle to push past or by-pass the passenger attempting to retrieve luggage during the luggage retrieval process. There are many factors that determine whether a passenger can push past another in the process of retrieving their luggage from the overhead bin, including the physical size of the luggage retriever, the orientation of the luggage retriever during the retrieval process, the physical size of the passenger attempting to pass, the size of the aisle, the motivation of the passer, etc. Another key factor is whether there is sufficient space just past the passenger retrieving their luggage for the passing passenger to occupy. In the crowded situation encountered in aircraft evacuations, there are likely to be many situations where even though a passenger is capable of by-passing a luggage retriever, the lack of space makes it unlikely or impossible.

Within the model, it is assumed that an aisle passenger will only attempt to push past the luggage retriever if there is sufficient space on the other side for them to occupy once past the luggage retriever. Furthermore, given the lack of data currently available to describe and quantify the push-past process, it is not considered viable to develop a model that explicitly and reliably simulates this process. To represent the push-past process within the modified model, a probability function is used to approximate the process. Using this approach, a push-past probability of 0.0 represents the situation where no one can push past luggage collectors, an overly pessimistic assumption. In contrast, a push-past probability of 1.0 represents the situation where everyone can push past luggage collectors, an overly optimistic assumption. The reality is somewhere between these two extreme simplifications and represented by a push-past probability described by a normal distribution with a mean of 0.5 and a standard deviation of 0.12, producing probabilities between 0.0 and 1.0. Furthermore, each encounter should be represented by a unique push-past probability to take into account the inherent variability of each situation.

Using a probability function to represent the push-past probability allows every passenger to be allocated a different push-past probability that changes with each encounter the passenger may have with different luggage retrievers. This approach provides the necessary variability expected in each unique encounter. Furthermore, within the model, a passenger only has one attempt to push past a given luggage retriever; if the probability allocated to the encounter is such that the passenger cannot pass, they do not try again. However, they may go on to encounter another luggage retriever and repeat the process of attempting to by-pass by being allocated another by-pass probability. The use of the probability function to describe whether a passenger can by-pass a luggage retriever clearly falls between the two extremes of no one passing and everyone passing, so it is a reasonable approximation. However, whether the probability distribution employed is too optimistic or too pessimistic, an approximation is difficult to determine without testing (see Sections 6.2 and 6.3).

(5) By-Pass speed: As a passenger by-passes a luggage retriever, given their need to squeeze past, their walk speed during the by-passing manoeuvre is reduced. As with the by-pass probability, there are many factors that may influence this; however, given the lack of data currently available to describe speed reduction, an arbitrary speed reduction is imposed in the model. Whether the speed reduction factor employed is too optimistic or too pessimistic, an approximation is difficult to determine without testing (see Section 6.2).

(6) Luggage retriever: Once a passenger has retrieved luggage, they can go on to be impacted by another luggage retriever. In such circumstances, the previous luggage retriever is treated as a normal passenger.

(7) Carrying luggage once retrieved: Once the luggage has been retrieved, passengers will carry or roll the luggage to the exit. This is likely to have several effects on evacuation flow and efficiency. The passenger with luggage will occupy additional space, reducing the space available for other passengers. Depending on the size and shape of the retrieved luggage, in a crowded evacuation situation, this is likely to adversely impact evacuation efficiency. In addition, the movement rate of the passenger with luggage is also likely to be less than the movement rate for a passenger without luggage. However, this is only expected to potentially be an issue in low-density (uncrowded) situations where the passenger is able to move at their maximum walk speed. In crowded situations associated with aircraft evacuation, the expected reduction in walk speed is unlikely to significantly impact evacuation efficiency. At the exit point, passengers with luggage may be prevented by cabin crew from taking their luggage down the slide. In such circumstances, delays may be caused while retrieving the luggage from the passenger, and obstacles adversely impacting passenger flow at the exit may occur. Finally, if the passenger takes the luggage through the exit, this may impact the efficiency of the exit flow. For simplicity, none of these factors are included in the model. While these factors could be included in the model, additional data from experimental trials or real-world accidents is required to characterise parameters describing these behaviours. As all of these factors are expected to adversely impact evacuation efficiency, omission of these factors means that model predictions should be viewed as optimistic.

Given the above assumptions, the new model features that were designed and implemented within airEXODUS to represent the luggage retrieval process include:

- ***Luggage Collection Model*** — a flag that specifies whether the luggage collection model is enabled or not.
- ***Luggage Collectors %*** — defining the percentage of the overall passenger (PAX) population that will collect luggage during the evacuation simulation.
- ***Luggage Collectors Zone*** — defining the region within the cabin from which the agents (simulated PAXs) are assigned to be luggage collectors. This typically comprises all seat block regions. Note that this zone does not have to be defined as a continuous zone, as it may encompass several seat blocks.
- ***Luggage Nodes Zone*** — defining the region(s) from which the luggage collectors will collect their luggage. This typically comprises the aisle regions. Note that this zone does not have to be defined as a continuous zone, as it may encompass several aisle regions.
- ***Collection Delay*** — a time delay distribution derived from the 'FSEG Flight Data' and associated with the task of retrieving cabin luggage.
- ***Luggage Push-Past*** — a flag that specifies whether a PAX can by-pass (or overtake) another PAX while they are collecting their luggage.

- ***Push-Past Probability*** — a distribution defining the probability that a PAX may by-pass (or overtake) a PAX that is currently retrieving their luggage.
- ***Speed Reduction*** — defining a speed reduction factor imposed on PAXs that by-pass (or overtake) luggage collectors.
- ***Single Fixed Value*** — defining whether the same push-past probability and speed reduction factor is applied to all luggage collectors or not.
- ***Randomise All Sims*** — defining whether the luggage collectors will be associated with the same push-past probability and speed reduction factor or not for each repeat simulation.

The *Luggage Collectors Zone* and the *Luggage Nodes Zone* are defined by the user as *Compartment* zones from within *Scenario Mode*. The options to enable the *Luggage Collection Model* and all its associated parameters and flags can be found in the *Behaviour Control* dialogue box, which is accessed in *Simulation Mode*, *Rulebase* menu, *Behaviour Options*. The last tab in the *Behaviour Control* dialogue box is *airEXODUS*, under which is the *Luggage Models* group, which contains all the required parameters (see Figure 13).

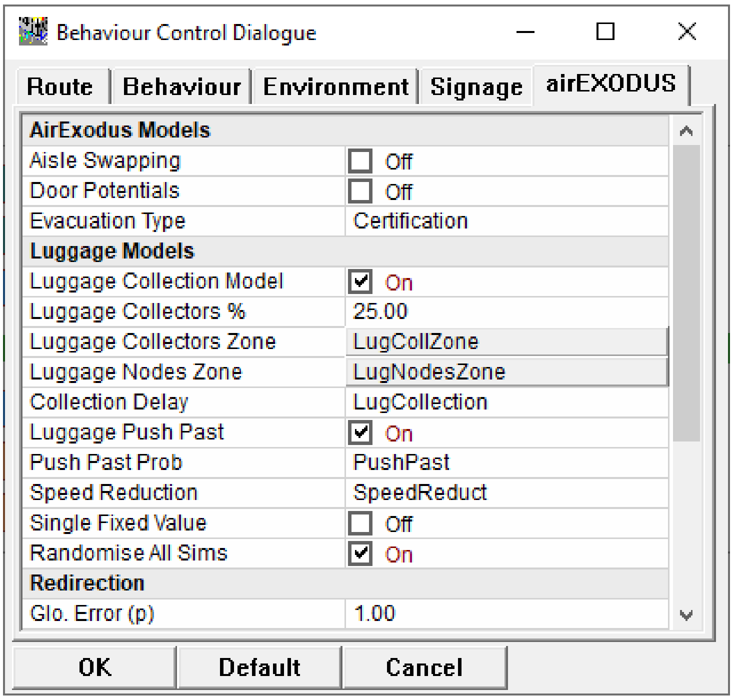


Figure 13: The airEXODUS tab of the Behaviour Options dialogue box.

A detailed description of the attributes and flags that have been implemented, defining the *Luggage model*, is presented in Table 19.

Table 19: Detailed description of the Luggage Model attributes and flags.

Attribute	Description
Luggage Collection Model	[On/Off] Defines whether or not the luggage collection model is enabled or disabled within the current simulation. If the *Luggage Collection Model* is disabled, then no agents will seek to collect luggage during their evacuation. Similarly, all the other luggage collection attributes will be disabled/greyed out within the *Behaviour Options* dialogue box. By default, the *Luggage Collection Model* is disabled.

Attribute	Description
Luggage Collectors %	[0 – 100] Defines the percentage of PAXs in the *Luggage Collectors Zone* (see below) who will be assigned as luggage collectors. By default, 25% of all PAXs in the defined zone are assigned as luggage collectors. Agents assigned as crew are not considered to be possible luggage collectors. It is important to note that this defines the total percentage of PAXs in the *Luggage Collectors Zone* — it does not represent the percentage chance each PAX will have of becoming a luggage collector. For example, if a zone containing 100 PAXs is selected and the *Luggage Collectors %* of 50% has been defined, then 50 PAXs will be randomly assigned as luggage collectors.
Luggage Collectors Zone	[Zone] Defines the specific zone/area from within which luggage collectors will be assigned. Typically, this area would correspond to all the passenger seats within the aircraft, thereby ensuring that any passenger could, in theory, be a luggage collector. If this zone is undefined, then ALL seats are assumed to be part of the *Luggage Collection Zone*, and hence, all PAXs initially located on seats can potentially be assigned as luggage collectors. By default, the zone is undefined. **NOTE: If the Luggage Collectors Zone is defined by the user, they should not include any seats adjacent to space (nodes) that leads to an exit (e.g., a cross aisle or seats adjacent to an overwing exit). This is to prevent agents in those seats being allocated as luggage collectors and creating contraflows when they attempt to reach their luggage collection node.** **NOTE: Within airEXODUS, the Luggage Collectors Zone must be created as a single *Compartment* zone, even if it encompasses discontinuous regions.**
Luggage Nodes Zone	[Zone] Defines the specific zone/area from which luggage will be collected. Typically, this would correspond to the aisles of the aircraft, i.e., the areas from within which PAXs would stand and retrieve their possessions from the overhead lockers. If defined, each luggage collecting agent, upon entering the *Luggage Nodes Zone,* will stop on the first node within the zone, with that node then being assumed to represent their corresponding luggage collection location. In most cases, this means that the luggage is assumed to be stowed in the overhead bin above their seat. **NOTE: If during their egress, an agent assigned to be a luggage collector does not enter a *Luggage Nodes Zone*, they will NOT stop and, hence, will leave without collecting luggage.** Upon first reaching a *Luggage Nodes Zone,* the agent will experience a delay, randomly selected from *Collection Delay* distribution (see below), simulating the time taken to extract their luggage from the overhead locker. By default, the *Luggage Nodes Zone* is undefined. **NOTE: The user should not include in the *Luggage Nodes Zone* any aisle nodes that may exist in front of the seat nodes that directly lead to an exit. This is to prevent luggage collector agents from collecting luggage from a location directly in front of their seats, blocking those who attempt to use that aisle to evacuate (see Figure 19).** **NOTE: Within airEXODUS, the Luggage Nodes Zone must be created as a single *Compartment* zone, even if it encompasses several non-continuous regions.**

Attribute	Description
Collection Delay	[Time Distribution] Specifies the time distribution defining the delay (in seconds) that luggage collectors will be subjected to in order to collect their luggage. It is important to note that this only refers to the time to directly collect luggage from the overhead locker and, hence, does not include the time taken to get to the location from which the overhead locker can be reached. If the *Collection Delay* distribution is ***undefined***, agents will be assumed to require 20 s to collect their luggage. By default, the *Collection Delay* distribution is set to the 'FSEG Flight Data' data set (see Section 4).
Luggage Push-Past	[On/Off] Defines whether agents are capable of by-passing stationary agents who are in the process of collecting their luggage. If this option is disabled, then agents will **NOT** be able to by-pass luggage collectors and will be forced to wait until the luggage collector has finished collecting their luggage and moved off before continuing their evacuation. Conversely, if the *Luggage Push-Past* option is enabled, then each luggage collector will be assigned a probability that other agents can push past them upon commencing their luggage collection. This probability will be randomly determined from the corresponding *Push-Past Prob* (see below). If the *Luggage Push-Past* option is disabled, then both the *Push-Past Prob* and the *Speed Reduction* attributes will be disabled/greyed out since they are both only applicable to push-past behaviour. By default, *Luggage Push-Past* is disabled. **NOTE: only agents who are already in the aisle are capable of pushing past a luggage collector. Hence, agents who are currently in seats and are obstructed by luggage collectors in the aisle are not permitted to squeeze past them.**

Attribute	Description
Push-Past Prob (also referred to as by-pass probability)	[Probability Distribution] Specifies the probability distribution, defining how likely it is that a PAX will be able to squeeze past luggage collectors. It is intended to take into consideration all the factors that influence whether a PAX will attempt to push past (or by-pass) a luggage retriever. These include such considerations as physical size of the luggage retriever, physical size of the passing PAX, size of the aisle, motivation of passer, etc. If a luggage collector is assigned a push-past (by-pass) probability of 0.0, this implies that no PAX will attempt to push past (by-pass) the luggage collector; conversely, a value of 1.0 implies that all PAX will attempt to push past (by-pass). If the *Push-Past Prob* (or by-pass probability, i.e., BPP) distribution is not defined by the user, luggage collectors are assigned the default push-past (by-pass) probability of 0.5. This implies that each PAX has a 50% chance of pushing past (by-passing) the luggage retriever. It is important to note that the luggage collector is assigned a push-past probability (or BPP) from this distribution upon commencing their luggage collection task. The ability of a PAX to push past (by-pass) a luggage collecting agent is randomly determined once during the simulation based upon this probability. This is determined when the PAX attempting to push past (by-pass) first encounters the luggage retriever, but only if there is sufficient space beyond the luggage retriever for them to move into (i.e., there is an empty available node). Thus, if there is not sufficient space due to congestion, PAXs will not consider passing the luggage retriever. Conversely, agents determined unable to squeeze past a luggage collector will simply be required to wait until the luggage collector has finished collecting their luggage and has moved off before then recommencing their own evacuation. It follows that all other passengers behind the agent who are waiting for the luggage collector will also have to wait before continuing with their evacuation. **NOTE: This attribute is defined via a probability distribution within airEXODUS. This distribution may be a random uniform distribution, normal distribution, log normal distribution, or user-specified frequency distribution. If a random uniform distribution is used, it enables the user to enter both a minimum and maximum limit, thereby defining a range of possible push-past (by-pass) probabilities. Alternatively, if the minimum and maximum values are the same, a fixed value is always used during the simulation.** **NOTE: The push-past probability (i.e., BPP) could be determined from many repeated observations of experimental evacuation trials. However, this would not necessarily reproduce a reliable approximation of the probability that a passenger would attempt to push past (by-pass) a passenger attempting to retrieve luggage in an actual emergency. Without data to base an estimation of the push-past probability (i.e., BPP), engineering judgement is used to define an appropriate push-past probability (i.e., BPP) to use in this analysis — see Section 6.** **NOTE: The ability of each agent to squeeze past a given luggage collector is randomly determined every time the agent encounters a luggage collector. Hence, if an agent encountered a luggage collector previously and was deemed unable to squeeze past, they may still be able to squeeze past other luggage collectors they encounter during egress.** **NOTE: Currently, within airEXODUS, there is no distinction between agents carrying luggage and those who are not when it comes to squeezing past a luggage collector. Hence, agents who have themselves already collected their luggage are still potentially capable of squeezing past another luggage collector.**

Attribute	Description
Speed Reduction	[Speed Reduction Distribution] Specifies the speed reduction distribution, defining how much the walking speed of agents squeezing past luggage collectors is reduced. **NOTE: Luggage collectors are assigned a speed reduction factor upon commencing their luggage collection process.** The speed reduction factor is a multiplicative parameter reducing the travel speed of each agent that squeezes past a luggage collector. **NOTE: The speed reduction is only applied to the agent's speed while they are in the process of squeezing past the luggage collector. Once they have passed the luggage collector, they are no longer deemed to be squeezing past, and so they continue the evacuation using their initially assigned walking speed.** As an example, if a given luggage collector was randomly assigned a speed reduction factor of 0.3, all agents squeezing past them while they collected their luggage would have a 0.3 speed reduction applied to their speed (i.e., their speed would be assumed to be 30% of their normal speed while squeezing past). If a *Speed Reduction* distribution is not defined, then each luggage collector will be assumed to have a speed reduction of 0.5. By default, the *Speed Reduction* distribution is not defined. **NOTE: This attribute (like the Push-Past Prob above) is defined via probability distribution within airEXODUS. See Section 6.** **NOTE: The speed reduction distribution could be determined from many repeated observations of experimental evacuation trials. While not ideal, this would be a reasonable approach to determining this parameter and is likely to be more reliable than estimating the push-past probability from similar data. However, without data to base an estimation of the speed reduction distribution, engineering judgement is used to define an appropriate distribution for use in this analysis — see Section 6.**
Single Fixed Value	[On/Off] Defines how both *Push-Past Probs* and *Speed Reductions* are applied to luggage collectors during a simulation. If enabled, then the same *Push-Past Prob* and *Speed Reduction* is applied to all luggage collectors. However, if this option is disabled, then each luggage collector is assumed to randomly get their own values from the corresponding distributions (i.e., the probability that agents will be able to squeeze past luggage collectors and the speed at which they will be able to do so will vary between luggage collectors). By **default**, the *Single Fixed Value* option is **disabled** (i.e., set to Off), and, hence, all luggage collectors will be assigned a different *Push-Past Prob* and *Speed Reduction* factor that will affect those PAXs who will overtake the luggage collector.
Randomise All Sims	[On/Off] Defines when agents deemed to be luggage collectors and their associated *Push-Past Probs* and *Speed Reductions* are redefined. If enabled, the designated luggage collectors and their associated *Push-Past Probs* and *Speed Reductions* are recalculated/re-determined every time the simulation is reset. Conversely, if this option is disabled, then these factors will not be re-determined at the start of each simulation, and, hence, the agents previously assigned as luggage collectors will remain the same, along with their corresponding previously assigned *Push-Past Prob* and *Speed Reduction.* By **default**, the *Randomise All Sims* option is **disabled** (i.e., set to Off). **NOTE: If enabled, the same percentage of PAXs will be allocated as luggage collectors from the *Luggage Collectors* zone.**

The settings associated with each of the new luggage collection behaviour attributes can be stored in an EXODUS option libraries file (*.ESO), thereby enabling the settings to be reloaded and applied to other scenarios.

5.2 Cabin Luggage Collection Model — Data Output

In addition to updating the model to enable the luggage collection process to be simulated, updates were also made to output data. Within airEXODUS, the results of any given simulation are typically output to a single text-based ASCII file (*.SIM). This file includes summaries of the population, lists of all the behavioural options enabled/disabled, in addition to details related to the evacuation of each individual agent. This typically includes the time taken for the agent to evacuate, the distance travelled during egress, the amount of time remaining stationary due to congestion, etc., as well as data related to their exposure to toxic products (assuming fire hazard data has been imported and has been used etc.). The data corresponding to multiple simulations can then be analysed in order to give an indication as to the distribution of results likely to occur for the given scenario.

Within the simulation output file (*.SIM), the egress results table has also been updated to include information related to the delays incurred by passengers when traversing *Compartment zones*. For each *Compartment zone,* three extra columns have been added to the end of each agent's data in the egress table (i.e., *Duration*, *TimeIn,* and *TimeOut*), as shown in Figure *14*. This includes information as to the total duration (in seconds) that the agent remained within the zone, the time they first entered the zone, and the time they last left the zone. Using this approach, if the time an individual agent entered the zone was recorded as 0 seconds, then it indicates that they initially started in the zone. Similarly, if an agent never entered a given zone, then its corresponding duration will be stated as 0 seconds, and both the times for entering and leaving the zone will be stated as -1 seconds (i.e., not applicable). It is important to note that the name of each column is prefixed by the name of the corresponding zone to which it refers (i.e., *Zone1.Duration*, *Zone1.TimeIn*, *Zone1.TimeOut,* etc.). Since these data are added as columns directly to the end of the passenger egress table, it should be automatically recognised by askEXODUS, thereby enabling users to perform queries on the data. In addition, the total number of times each agent pushed past luggage collectors during their egress has been added to the simulation output file.

|Compartment_Zone_2.Duration (s)|Compartment_Zone_2.TimeIn (s)|Compartment_Zone_2.TimeOut (s)|Zone_35.Duration (s)|Zone_35.TimeIn (s)|Zone_

8.65	0.00	0.00	0.44	2.50	2.50	2.50	0.00	0.00	2.94	0.00	0.00	-1.00	-1.00	-1.00
8.80	0.00	0.00	0.44	0.83	0.83	0.83	0.00	0.00	1.27	0.00	0.00	-1.00	-1.00	-1.00
8.91	0.00	0.00	0.44	1.67	1.67	1.67	0.00	0.00	2.11	0.00	0.00	-1.00	-1.00	-1.00
9.11	0.00	0.00	1.07	3.39	3.39	3.39	0.00	0.00	4.47	0.00	0.00	-1.00	-1.00	-1.00
9.35	0.00	0.00	1.20	2.16	2.16	2.16	0.00	0.00	3.36	0.00	0.00	-1.00	-1.00	-1.00
9.76	0.00	0.00	5.00	0.83	0.83	0.83	0.00	0.00	5.83	0.00	0.00	-1.00	-1.00	-1.00
9.83	0.00	0.00	3.13	2.05	2.05	2.05	0.00	0.00	5.17	0.00	0.00	-1.00	-1.00	-1.00
10.27	0.00	0.00	5.69	0.83	0.83	0.83	0.00	0.00	6.53	0.00	0.00	-1.00	-1.00	-1.00
10.47	0.00	0.00	1.07	6.64	6.64	6.64	0.00	0.00	7.71	0.00	0.00	-1.00	-1.00	-1.00
11.16	0.00	0.00	7.09	2.10	2.10	2.10	0.00	0.00	9.19	0.00	0.00	-1.00	-1.00	-1.00
11.48	0.00	0.00	5.78	2.92	2.92	2.92	0.00	0.00	8.69	0.00	0.00	-1.00	-1.00	-1.00
12.05	0.00	0.00	1.81	7.88	7.88	7.88	0.00	0.00	9.69	0.00	0.00	-1.00	-1.00	-1.00
12.40	0.00	0.00	8.52	1.67	1.67	1.67	0.00	0.00	10.19	0.00	0.00	-1.00	-1.00	-1.00
13.06	0.00	0.00	6.01	4.68	4.68	4.68	0.00	0.00	10.69	0.00	0.00	-1.00	-1.00	-1.00
13.15	0.00	0.00	5.16	6.03	6.03	6.03	0.00	0.00	11.19	0.00	0.00	-1.00	-1.00	-1.00
13.97	0.00	0.00	9.19	2.50	2.50	2.50	0.00	0.00	-1.00	0.00	0.00	-1.00	-1.00	-1.00
14.26	0.00	0.00	10.52	1.67	1.67	1.67	0.00	0.00	9.46	2.73	2.73	2.73	0.00	0.00
15.13	0.00	0.00	11.52	1.67	1.67	1.67	0.00	0.00	4.96	8.23	8.23	8.23	0.00	0.00
15.18	0.00	0.00	9.73	2.96	2.96	2.96	0.00	0.00	6.29	6.40	6.40	6.40	0.00	0.00
14.43	1.57	1.57	12.43	1.26	1.26	1.26	0.00	0.00	5.14	8.55	8.55	8.55	0.00	0.00
13.80	2.40	2.40	12.11	2.08	2.08	2.08	0.00	0.00	4.94	9.25	9.25	9.25	0.00	0.00
17.12	0.00	0.00	7.33	7.36	7.36	7.36	0.00	0.00	4.77	9.93	9.93	9.93	0.00	0.00
17.15	0.00	0.00	4.63	10.56	10.56	10.56	0.00	0.00	4.00	11.20	11.20	11.20	0.00	0.00
9.77	8.23	8.23	12.11	4.08	4.08	4.08	0.00	0.00	4.34	11.85	11.85	11.85	0.00	0.00
14.54	3.54	3.54	12.47	3.22	3.22	3.22	0.00	0.00	4.16	11.53	11.53	11.53	0.00	0.00

Figure 14: Extended passenger zone data columns.

Furthermore, for each zone, additional information is also outputted in their respective zone summary located below the egress results table (as indicated by the red square in Figure 15). This includes summary information for the use of the zone by both luggage collectors and non-luggage collectors. The data include the number of people initially in the zone (*Number Initially in Zone*, see Figure 15), followed by the time that the first PAX left the zone (*Min Duration*, see Figure

15), the time that the last PAX left the zone (*Max Duration*, see Figure 15), and the average time that PAXs initially in the zone left it (*Avg Duration*, see Figure 15). This is followed by the evacuation times of those originating in the zone, including the time of the first PAX to evacuate (see *Exit Times Starting in Zone — First*, Figure 15), the last PAX to evacuate (see *Last*, Figure 15), and the average time that PAXs initially located in the zone needed to evacuate the cabin (see *Avg*, Figure 15).

These data are followed by information regarding those PAXs who did not originate from the current zone (i.e., they are merely passing through the zone during their attempt to leave the cabin). These data include the minimum duration that a PAX not initially in the zone spent in it (see *Not in Zone — Min Duration*, Figure 15), the maximum duration that a PAX not initially in the zone spent in it (see *Max Duration*, Figure 15), and the average duration that all PAXs not initially starting in the zone spent in the zone (see *Avg Duration*, Figure 15).

The next data similarly summarise the durations spent in the zone for all PAXs to use the current zone, whether they originated from this zone or not. These data include the minimum duration spent in the zone (see *All — Min Duration*, Figure 15), the maximum duration spent in the zone (see *Max Duration*, Figure 15), and the average duration spent in the zone by all agents to traverse it (see *Avg Duration*, Figure 15).

The last piece of information relates to the number of luggage collectors that originated in this zone (see *Number of Luggage Collectors in Zone*, Figure 15) and the number of luggage collectors that are passing through this zone (see *Passing Through*, Figure 15).

```
LugCentralArea  Max Density:   68
Number Entering:  147  First In:   0.00 (s) Last : 134.26 (s) Avg PPM :  65.69
Flow Time: 134.26 (s) No Flow Time:  95.75 (s) MNS :  71.32 (%)
Number Leaving:  147  First Out:   2.19 (s) Last : 140.76 (s) Avg PPM :  63.65
Flow Time: 138.58 (s) No Flow Time:  76.24 (s) MNS :  55.02 (%)
Number Initially in Zone:   66  Min Duration:   2.19 (s) Max  Duration:  92.71 (s) Avg  Duration:  40.78 (s)
Exit Times Starting in Zone - First :  13.15 (s) Last :  95.38 (s) Avg : 43.82 (s)
Not in Zone - Min Duration:   4.75 (s) Max Duration:  43.42 (s) Avg Duration:  15.91 (s)
All - Min Duration:   2.19 (s) Max Duration:  92.71 (s) Avg Duration:  27.08 (s)
Number of Luggage Collectors In Zone:   14 Passing Through   22
```

Figure 15: Updated zone summary data; the new additional data are highlighted.

The existing simulation output was further extended to output the data related to luggage collection. Three new tables were added to the simulation output file, namely *Luggage Collector Data*, *Luggage Passing Data,* and *Luggage Failed Passing Data* (see Figure 16).

As the name suggests, the *Luggage Collection Data* table outlines the experiences of agents collecting luggage within the simulation. Each entry (i.e., row) in this table corresponds to a separate luggage collector. In each case, the name of the luggage collecting agent and their corresponding unique ID is stated, along with their corresponding start node and luggage collection location (in both cases, the name and unique ID of the corresponding node are provided). In addition, the corresponding *Pass Probability* and *Speed Reduction* factor applied to the luggage collector is also stated. The time (in seconds) that the luggage collector actually spent collecting their luggage is also stated via the *Delay* attribute, in addition to a count of the number of agents to successfully squeeze past them (if any) during the simulation.

The *Luggage Passing Data* conversely relates to a summary of the experiences of agents who, at some point during the simulation, successfully managed to squeeze past a luggage collector. Each entry (i.e., row) corresponds to a separate passing action. As a result, one agent may appear multiple times in this table if they passed multiple luggage collectors during their egress. For each passing action, the name/ID of the agent passing is stated, along with their corresponding start node. The name/ID of the luggage collecting agent they squeezed past is also provided, along with the corresponding node on which they were collecting their luggage when the agent squeezed past. The push-past probability and speed reduction rate assigned to the luggage collector are also stated. Finally, the *Passed* column corresponds to a counter of the number of luggage collectors squeezed past by the given agent. For example, the first passing action of a given agent will be numbered 1, with the second then being numbered 2, the third 3, etc.

The final table, entitled *Luggage Failed Passing Data,* outlines a summary of the experiences of agents who, at some point during the simulation, failed to squeeze past a luggage collector. Each entry (i.e., row) in the table corresponds to a failure of an agent to squeeze past a luggage collector. In each case, the name/ID of the agent failing to squeeze past is provided, along with the corresponding luggage collecting agent they failed to get past, their assigned *Pass Probability*, the node they were on when collecting their luggage, in addition to the node/ID the agent was on when they failed to squeeze past (i.e., *Failed Node*). Finally, the total *Wait* time (in seconds) that the agent spent waiting on the node for the luggage collector to finish collecting their luggage is also provided. It is important to note that this corresponds to the time the agent spent on the stated node during the luggage retrieval process. As such, it represents the additional delay incurred by the agent. It does not include additional time spent on the node after the luggage collector has finished collecting their luggage, i.e., as a result of the agent not being able to move from their current node as a result of congestion within the aircraft.

The tables outlined above will only be output to the simulation output file (*.SIM) if the *Luggage Collection Model* is enabled by the user (see Figure 13). Similarly, each table will only be output if data relating to the activity outlined were observed within the simulation. For example, if within a given simulation, no agents failed to pass a luggage collector, then the *Luggage Failed Passing Data* table will not be output within the simulation output file. The large amount of data output in these tables relating to both luggage collectors and those directly exposed to them enables a comprehensive analysis of the events within the simulation and, hence, provides an estimate of the effect that luggage collection will have on the overall evacuation process.

Luggage Collector Data

Pos	Person	Label	Start Node	Label	Lug Node	Label	Pass Prb	Spd Rdt	Delay	Passed
1	Person_1	1	Chair_103	103	Aisle_24	24	0.67	0.51	2.37	0
2	Person_4	4	Chair_68	68	Aisle_12	12	0.67	0.51	5.98	1
3	Person_16	16	Chair_95	95	Aisle_20	20	0.67	0.51	7.85	1
4	Person_18	18	Chair_98	98	Aisle_22	22	0.67	0.51	6.07	3
5	Person_19	19	Chair_97	97	Aisle_22	22	0.67	0.51	6.80	0

Luggage Passing Data

Pos	Person	Label	Start Node	Label	Lug Person	Label	Lug Node	Label	Pass Prb	Spd Rdt	Passed
1	Person_1	1	Chair_103	103	Person_16	16	Aisle_20	20	0.67	0.51	1
2	Person_1	1	Chair_103	103	Person_18	18	Aisle_22	22	0.67	0.51	2
3	Person_9	9	Chair_77	77	Person_4	4	Aisle_12	12	0.67	0.51	1
4	Person_20	20	Chair_107	107	Person_18	18	Aisle_22	22	0.67	0.51	1
5	Person_24	24	Chair_111	111	Person_18	18	Aisle_22	22	0.67	0.51	1

Luggage Failed Passing Data

Pos	Person	Label	Lug Person	Label	Pass Prb	Failed Node	Label	Lug Node	Label	Wait (s)
1	Person_17	17	Person_16	16	0.67	Chair_94	94	Aisle_20	20	4.42
2	Person_19	19	Person_18	18	0.67	Chair_99	99	Aisle_22	22	0.58
3	Person_21	21	Person_18	18	0.67	Chair_100	100	Aisle_22	22	0.58
4	Person_24	24	Person_1	1	0.67	Aisle_25	25	Aisle_24	24	3.50
5	Person_8	8	Person_4	4	0.67	Chair_70	70	Aisle_12	12	1.58
6	Person_20	20	Person_16	16	0.67	Aisle_21	21	Aisle_20	20	0.36
7	Person_10	10	Person_4	4	0.67	Aisle_13	13	Aisle_12	12	6.55

Figure 16: The new data output related to luggage collection.

To aid in the visualisation of the luggage collection process, the existing analysis options present within the model were also extended. Within airEXODUS, users can typically colour agents during the simulation according to their current parameters. The *Analysis Options* dialogue box typically includes the ability to colour agents who are exposed to excessively high smoke concentrations or whose exposure to narcotic gases is dangerously high (i.e., FIN > 0.9). In addition to this existing functionality, the model was extended to enable agents to be coloured according to their current phase of luggage collection (i.e., en route to collecting luggage, currently collecting luggage, or alternatively having collected their luggage; see Figure 17).

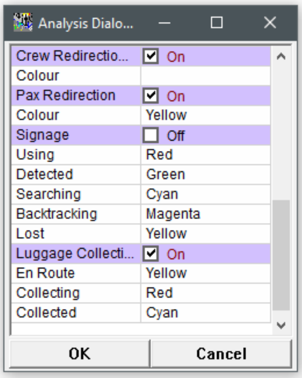


Figure 17: The Luggage Collection options within the Analysis dialogue box.

Using this approach, users can assign unique colours to each luggage collection phase and, therefore, at a glance understand what each agent is doing at any given point in the simulation. By default, agents who are en route to their given luggage collection location are coloured *Yellow*, while those who are currently in the process of collecting their luggage are coloured *Red*. Agents who have collected their luggage and moved off to commence their evacuation are, by default, coloured *Cyan*. However, users have the capability to change the corresponding colours as they see fit. It is important to note that any agents not assigned as luggage collectors will not be coloured using this approach and, hence, will retain their corresponding default colour. Figure 18 below shows agents coloured according to the default luggage collection colours outlined previously. All agents who are not assigned as luggage collectors are coloured *Magenta*.

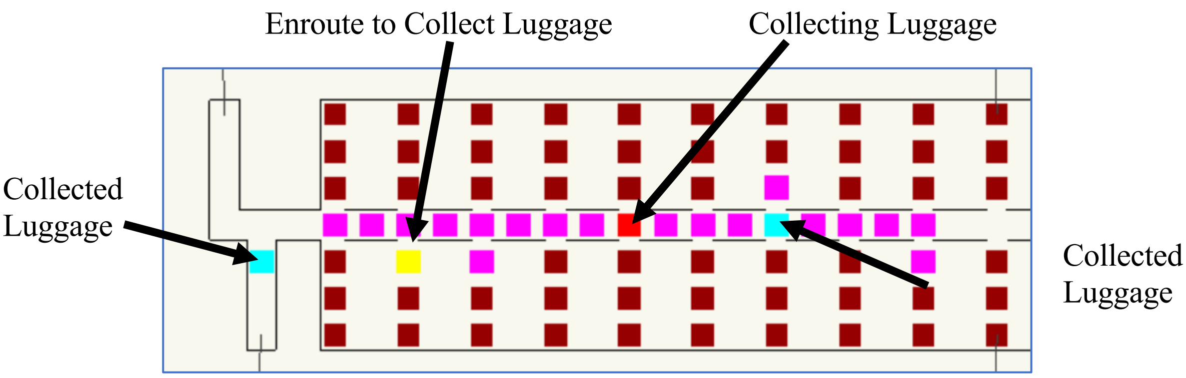


Figure 18: Agents coloured according to their given luggage collection phase.

5.3 Cabin Luggage Collection Model — Test Demonstration

The newly implemented luggage retrieval model is used on the aircraft cabin configuration described in Section 3.1 to demonstrate that the required functionality has been developed and that it functions according to the requirements.

(a) Luggage Collector's Zone Setup

The Luggage Collectors' Zone will cover the entire seating area. To achieve this, a *Compartment* zone is created that encompasses the seat blocks, as shown in Figure 19. Note that seat rows that lead to an exit and are directly in front of seat rows should not be included in the luggage collectors' zone. If included, potentially significant contraflows could develop on these cross aisles. PAXs who would attempt to evacuate via these cross aisles (e.g., through R2/R3 or through L2/L3) would encounter PAXs from the seats in those locations, moving in the opposite direction, trying to retrieve their luggage, and thus creating contraflows and significant blockages. While these types of events are possible, they are considered low-probability events (PAX seated so close to an exit would be either under significant pressure from cabin crew or other PAXs to evacuate), so these situations have been prevented by adopting the proposed methodology.

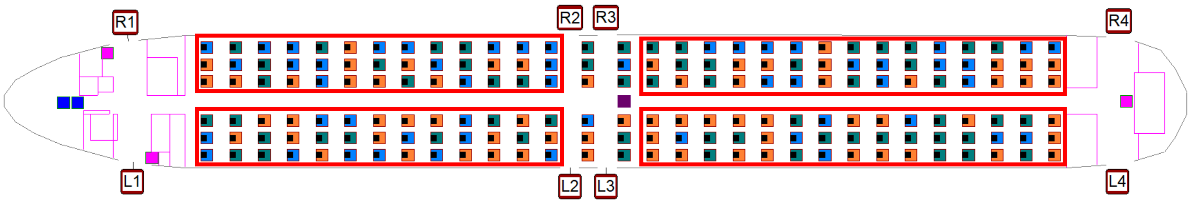


Figure 19: Luggage collector's zone consisting of four seat block regions covering the entire complement of seats, except for those seats that have aisles in front of them and lead to exits (i.e., between the L2/L3 and R2/R3 exits).

(b) Luggage Nodes Zones

The locations from which each PAX can collect their luggage is the first aisle node that they will encounter. These nodes are located in the main central aisle. Thus, the Luggage Nodes Zone should cover the main central aisle (except for the part that is between the overwing exits), as shown in Figure 20. To achieve this, a single compartment zone is created that covers the nodes within the central aisle. Multiple regions can be part of this compartment zone.

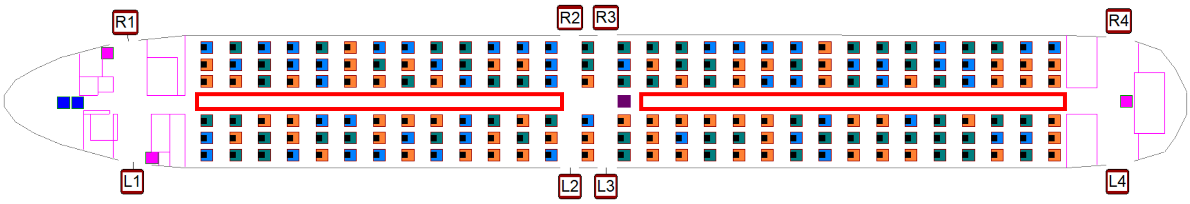


Figure 20: Luggage collection area corresponding to the luggage node locations on the central aisle.

(c) Data Collection Zones

To better understand how the luggage collection behaviour impacts the overall evacuation performance, five compartment zones were defined (see Figure 21). For each compartment zone, the additional information that is recorded and exported into the simulation data output file includes the time that a PAX entered the zone, the time a PAX left the zone, and the duration they spent inside that zone (dwell time). These values are coded to also indicate whether a PAX originated within that zone or originated from an adjacent zone, or whether they did not cross the said zone at all.

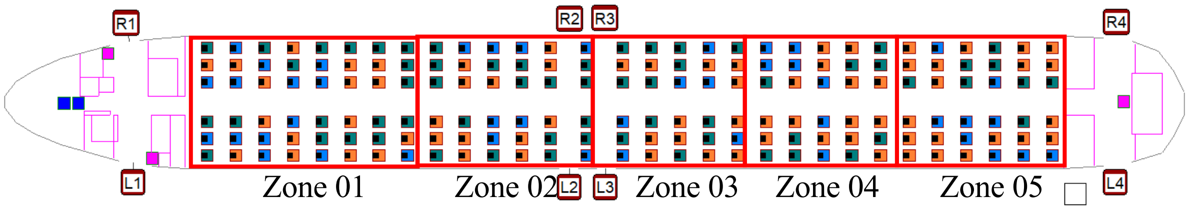


Figure 21: Partitioning the aircraft into five compartment zones.

Note: Each zone corresponds to a different area of interest for which EXODUS will be recording data related to the individual PAXs' experiences and the overall zone data (see Section 3 for further details).

(d) Example Simulation

A snapshot of a simulation running where PAXs are collecting luggage before evacuating is shown in Figure 22. The PAXs are coloured to show their current status in relation to luggage collection. A PAX who has been designated as a luggage collector and is moving towards their luggage collection point is coloured yellow. A PAX who is retrieving their luggage is coloured magenta. A PAX who has collected their luggage and is moving towards an exit is coloured cyan (see Figure 22). The data used that governs luggage collection has been described in Section 4.

(e) Test Case — A single PAX retrieving luggage

A simple test case is presented, utilising the cabin layout described in Section 3.1 (see Figure 23). The aircraft population consists of the default PAX distribution, with a single passenger, P_{LC} (located in seat 2C, see Figure 23a), who will retrieve luggage during the evacuation simulation. At the start of the simulation, this PAX is assigned to be a luggage collector. The data used to define the luggage collection times have been described in Section 4.2.

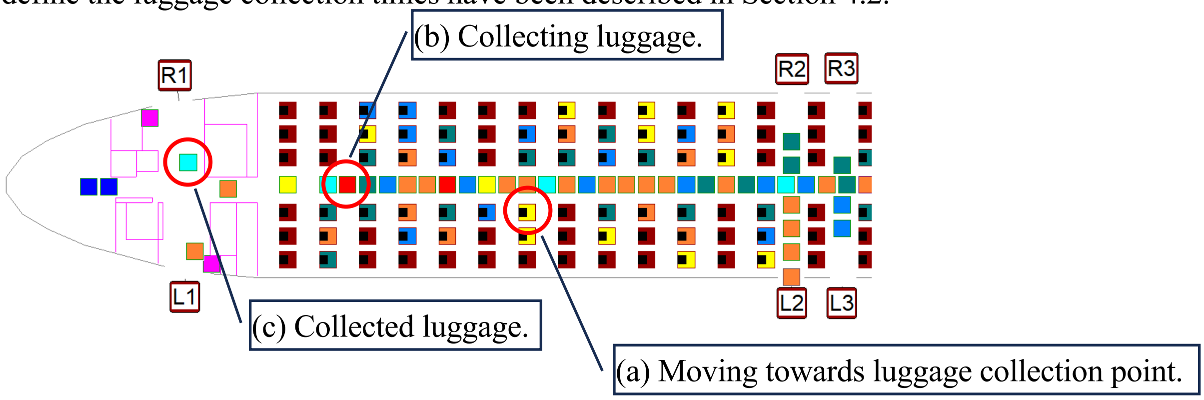
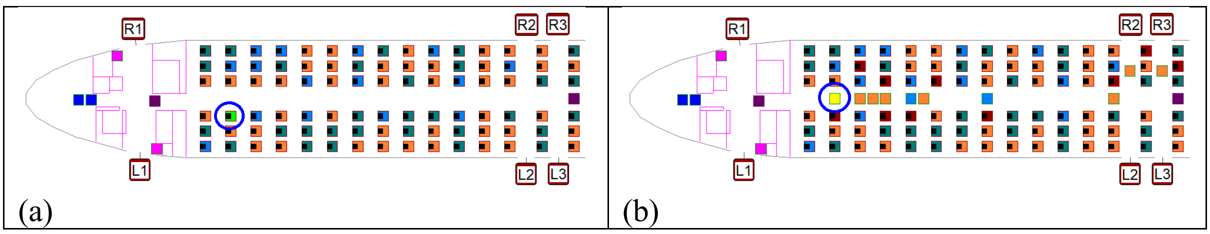


Figure 22: PAXs collecting luggage during a simulation.

Note: Three different PAXs are highlighted: (a) PAX moving out of the seat row and towards their luggage collection point on the aisle, (b) PAX is collecting their luggage from the overhead bins, and (c) PAX has collected their luggage and is heading towards the R1 exit.

Upon entering the main aisle, the PAX pauses to collect their luggage from the first aisle node they encounter. As P_{LC} retrieves their luggage, another PAX will attempt to overtake them (see Figure 23c). Once P_{LC} has collected their luggage, they proceed towards their nearest exit pair and choose to evacuate via R1 (see Figure 23g). The entire process, with screengrabs of key moments during the evacuation of P_{LC}, is shown on Figure 23.



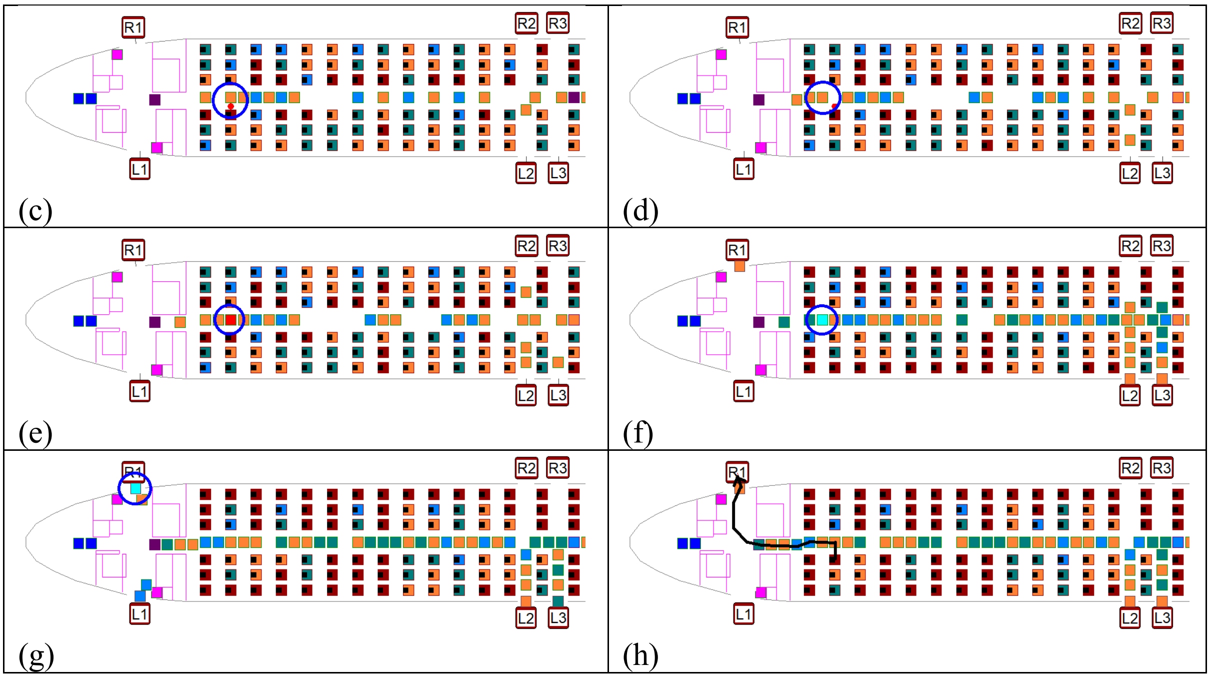


Figure 23: Luggage collection process for PAX P_{LC}.

Note: The different colours of the P_{LC} indicate the different stages they are currently in. (a) Initial location of P_{LC}, (b) the simulation has started, and P_{LC} is assigned to be luggage collector, and P_{LC} has reached luggage collection node, (c) P_{LC} appears as a red dot, as they are collecting their luggage while another PAX (orange square) is pushing past them, (d) P_{LC} is still retrieving their luggage, while the other PAX has overtaken them, (e) P_{LC} is still retrieving their luggage, (f) P_{LC} has now collected luggage, (g) P_{LC} has reached R1 exit with luggage, (h) P_{LC} path from initial location to exit R1.

With regard to the individual data recorded for the luggage collecting PAX P_{LC}, these are recorded in the Egress Results table (see Table 20) and in the Luggage Collector Data section (see Figure 24) of the simulation output file located after the overall evacuation results.

```
Luggage Collector Data

+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

  Pos|Person      |Label|Start Node   |Label|Lug Node     |Label|Pass Prb| Spd Rdt|Delay(s)|Start(s)| End (s)|  Passed|
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
    1|Person_127  |  127|Seat_D_23    |  112|Row_23       |  210|    0.60|    0.41|    3.60|    1.17|    4.83|       0|
```

Figure 24: Luggage Collector Data information.

Note: Identifying the agents retrieving luggage, their starting node, the node from which they collected the luggage, the push-past probability, the speed reduction factor, the delay incurred during luggage collection, and the number of people that overtook them. This information is found in the simulation output file in the Luggage Collector Data section located after the overall evacuation results.

Based on the aforementioned data, the P_{LC} luggage collector had a response time of 1.0 seconds, travelled 4.7 metres, and reached exit R1 in 12.6 seconds (see Table 20). Upon entering the aisle, the PAX took 5.5 seconds to retrieve their luggage (see Delay in Figure 24) from the overhead bin located there (see Figure 24).

PAX P_{LC} left the luggage collectors zone (i.e., the seating area) at 2.1 seconds (see *LugCollZone.TimeOut* (s) in Table 20), entering at the same time the luggage nodes zone, i.e., the aisle (see *LugNodesZone.TimeOut* (s) in Table 20), and left the luggage nodes zone, having collected their luggage, after 7.1 seconds (see *LugNodesZone.Duration* (s) in Table 20), at 9.1

seconds (see *LugNodesZone.TimeOut* (s) in Table 20). Note the '-1' values in Table 20 indicate that the luggage retriever, P_{LC}, did not enter these zones.

Information relating to the agents pushing past or attempting to push past the luggage retriever is presented in the simulation output file in the Luggage Passing Data and Luggage Failed Passing Data sections, respectively, located after the overall evacuation results (see Figure 25). In this hypothetical example, during the luggage retrieval process for P_{LC}, three agents (i.e., 41, 48, and 55; see Figure 25) push past the luggage collector, while two others failed to overtake P_{LC} (i.e., 7 and 26, see Figure 25). Those who pushed past the luggage retriever had a pass probability (see *Pass Prb* in Figure 25) of 0.8 and a speed reduction factor (see *Spd Rdt* in Figure 25) of 0.5. Those who failed to pass the luggage collector waited for 4.6 s and 3.5 s (see *Wait (s)* in Figure 25), while the luggage collector P_{LC} was retrieving their luggage (i.e., completing their collection task).

It should be noted that the PAXs who fail to push past a luggage collector may have to wait for a longer duration than the Collection Delay associated with the luggage collector, as there may be congestion in front of the luggage collector blocking their movement and thus delaying those behind the luggage collector too. However, the *Wait* time shown in the Luggage Failed Passing Data table only represents the wait incurred as a result of the delay caused by the luggage collector.

Table 20: Egress results for the luggage collector agent P_{LC}.

Pos	Gender	Start Node	Label	Name	**Response (s)**	Walk Rt (m/s)	FWalk Rt (m/s)	**End Node**	CWT (s)
7	Female	51	128	Person_128	**1**	0.54	1.08	**R1**	0.41
Distance (m)	**PET (s)**	PEE	ExtDelay	T opt	PAXCon.R	Near Ext	#Push	RspRatio	CWTRatio
4.69	**12.64**	96.77	0.10	5.46	0.07	No	0	0.079	0.032
TrvRatio	AllSeats. Duration (s)	AllSeats. TimeIn (s)	AllSeats. TimeOut (s)	L1-Area. Duration (s)	L1-Area. TimeIn (s)	L1-Area. TimeOut (s)	R1-Area. Duration (s)	R1-Area. TimeIn (s)	R1-Area. TimeOut (s)
0.889	2.06	0	2.06	11.42	0	11.42	12.64	0	12.64
L4R4-Area. Duration (s)	L4R4-Area. TimeIn (s)	L4R4-Area. TimeOut (s)	L2L3Pax. Duration (s)	L2L3Pax. TimeIn (s)	L2L3Pax. TimeOut (s)	L1R1Pax. Duration (s)	L1R1Pax. TimeIn (s)	L1R1Pax. TimeOut (s)	LugCollZone. Duration (s)
-1	-1	-1	-1	-1	-1	2.06	0	2.06	2.06
LugCollZone. TimeIn (s)	**LugCollZone. TimeOut (s)**	**LugNodesZone.Duration (s)**	**LugNodesZone. TimeIn (s)**	**LugNodesZone. TimeOut (s)**	LugDataZone01. Duration (s)	LugDataZone01. TimeIn (s)	LugDataZone01. TimeOut (s)	LugDataZone02. Duration (s)	LugDataZone02. TimeIn (s)
0	**2.06**	**7.07**	**2.06**	**9.13**	9.13	0	9.13	-1	-1
LugDataZone02. TimeOut (s)	LugDataZone03.Duration (s)	LugDataZone03.TimeIn (s)	LugDataZone03.TimeOut (s)	LugDataZone04.Duration (s)	LugDataZone04. TimeIn (s)	LugDataZone04. TimeOut (s)	LugDataZone05. Duration (s)	LugDataZone05. TimeIn (s)	LugDataZone05. TimeOut (s)
-1	-1	-1	-1	-1	-1	-1	-1	-1	-1

Note: The table has been adapted for presentation in this report. Within the simulation output file, these data appear as a single row of data. For each agent in the simulation, EXODUS produces a similar row of data (variables in bold are described in the text).

Luggage Passing Data

Pos	Person	Label	Start Node	Label	Lug Person	Label	Lug Node	Label	Pass Prb	Spd Rdt	Start(s)	End (s)	Passed
1	Person_37	37	Seat_D_19	100	Person_43	43	Row_18	205	0.51	0.14	5.42	10.63	1
2	Person_83	83	Seat_D_22	109	Person_103	103	Row_21	208	0.44	0.49	6.58	8.60	1

Luggage Failed Passing Data

Pos	Person	Label	Start Node	Label	Lug Person	Label	Pass Prb	Failed Node	Label	Lug Node	Label	Wait (s)	Delay(s)	Time(s)
1	Person_115	115	Seat_C_17	132	Person_141	141	0.40	Seat_C_17	132	Row_17	204	25.75	9.28	1.75
2	Person_73	73	Seat_B_11	79	Person_129	129	0.31	Seat_C_11	78	Row_11	199	2.74	2.40	2.58

Figure 25: Two PAXs managed to overtake luggage retrievers P_{LC} (top table), while two others attempted to overtake P_{LCs} but failed to do so (lower table).

Note: This information is found in the simulation output file in the Luggage Passing Data and Luggage Failed Passing Data sections located after the overall evacuation results.

Information summarising agent performance within each of the identified compartment zones is presented in the simulation output file in the *LugDataZoneXX* sections, which can be found in the Compartment Zone Performances located after the exit performance results (see Figure 27). The first person originating from the region Zone 01 (i.e., the zone where the luggage collector P_{LC} is located) (see Figure 26) to leave the Zone 01 region did so at 7.3 seconds (see *Min Duration*, Figure 27), and the last person to leave Zone 01 did so at 87.3 seconds (see *Max Duration*, Figure 27). The average time for agents starting in Zone 01 to leave Zone 01 was 51.1 seconds (see *Avg Duration*, Figure 27). There were 25 luggage collector agents within Zone 01 (see *Number of luggage collectors in Zone*, Figure 27). Finally, there was one luggage collector agent from the adjacent zone, Zone 02, that traversed Zone 01 (see Passing Through, Figure 27).

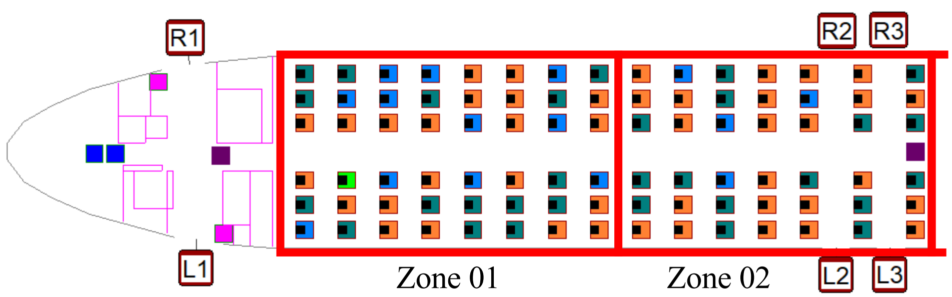


Figure 26: Data regarding effect of luggage collection can be retrieved from any user-defined region of the cabin. Here, two such regions are shown: Zone 01 and Zone 02.

```
LugDataZone01   Max Density:   48
Number Entering:   49  First In:   0.00 (s) Last :  30.41 (s) Avg PPM :  96.66
Flow Time:  30.41 (s) No Flow Time:  29.91 (s) MNS :  98.36 (%)
Number Leaving:   49  First Out:   7.28 (s) Last :  87.29 (s) Avg PPM :  36.75
Flow Time:  80.01 (s) No Flow Time:  58.04 (s) MNS :  72.55 (%)
Number Initially in Zone:   48  Min Duration:    7.28 (s) Max  Duration:  87.29 (s) Avg  Duration:  51.05 (s)
Exit Times Starting in Zone - First :  11.74 (s) Last :  99.30 (s) Avg :  57.95 (s)
Not in Zone - Min Duration:  38.87 (s) Max Duration:  38.87 (s) Avg Duration:  38.87 (s)
All - Min Duration:    7.28 (s) Max Duration:  87.29 (s) Avg Duration:  50.80 (s)
Number of Luggage Collectors In Zone:   25 Passing Through:    1
Number of Push Pasts In Zone: 5 Number Failed to Push Past: 36 Number Failed in Aisle: 5 Number Failed in Seats: 31
```

Figure 27: Data collected for Zone 01 located in the Compartment Zone Performance located after the exit performance results.

For a full description of the nature of data recorded regarding luggage collection on an individual or zone basis, see Section 5.2.

5.4 Scenario 1 Results — 0% Luggage Retrieval, Including Zone Data Results

The following results are for Scenario 1 and are similar to the results presented in Section 3. Scenario 1 was repeated using the modified software and includes the newly defined zone performance data that may be useful to define a base case to compare and assess the impact of luggage retrieval on evacuation performance. Another difference between these simulations and those presented in Section 3 is that the population represents a different 1000 populations generated to that used in Section 3.

It is noted that the simulation results presented here differ slightly from those in Section 3, but the difference is considered small and insignificant. For example, the 95th percentile case has TET (Total Evacuation Time (out-of-aircraft)) and PET (Personal Evacuation Time (out-of-aircraft)) values for the original set of results are 129.5 s and 58.6 s, respectively, compared with 127.7 s and 60.3 s for the modified software. This represents a difference of -1.4% in TET and 2.9% in PET. Furthermore, the distributions for TET and the exit curves for both sets of simulations clearly display the same trends in evacuation performance. Thus, the same conclusions concerning the performance of the aircraft configuration for this scenario would be made regardless of which set of 1000 repeat simulations was selected.

These small differences in results for the two sets of 1000 simulation are to be expected for several reasons. Firstly, the airEXODUS software is stochastic in nature, so each time the software is run, slightly different results are generated, depending on the behaviour of the agents, their attributes, and the natural variation in exiting behaviour, even if exactly the same population and scenario conditions are used. Thus, if two lots of 1000 simulations are run, we would expect to observe some small differences in the nature of the distribution produced. Finally, several optimisations to the scenario specification implemented during the development of the luggage collection capabilities may have also contributed to the small variation between the two sets of 1000 simulations.

For completeness, the full set of results for Scenario 1 are presented here, and the results presented in Section 3 should not be referred to. The discussion of the results follows that as presented in Section 3.

Presented in Table 21 is a summary of key data from Scenario 1 (0% luggage retrievers). The results are from the 1000 repeat simulations and represent the results from the simulations producing the minimum, median and maximum total evacuation time (TET). In this analysis, the TET is defined as the out-of-aircraft time (not the on-ground time). Thus, from the 1000 repeat simulations, the minimum TET is 110.1 s, the median TET is 120.9 s, maximum TET is 138.5 s, and the 95th percentile TET is 127.7 s. Also presented in the table are CWT (cumulative wait time), Average Distance Travelled, and Average Personal Evacuation Time (PET). The CWT is a measure of how much time each agent in the simulation wastes in congestion. This is defined as being stationary or travelling at a slower speed than their maximum walk speed. Within a simulation, the CWT is determined for each agent and averaged over all the agents within that simulation to produce the 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 average distance travelled. The PET is the personal evacuation time for an agent. It measures the time from the start of the simulation to the point where the agent has exited the aircraft. The PET can be determined for all agents in a simulation and then averaged over all agents in the simulation. Thus, for the simulation producing the maximum TET (138.5 s), the average PET was 61.9 s and, on average, passengers wasted 45.8 s in congestion and travelled 7.8 m to exit. Clearly, the aircraft layout considered in this analysis, with two forward Type-C exits and two left Type-III exits available (representing 50% of the available exits) and with the passengers seeking to exit via their nearest exit, does not satisfy the 90 s requirement, with a minimum evacuation time of 110 s and a maximum evacuation time of 139 s.

Table 21: Summary performance data for Scenario 1 (0% luggage retrievers) for the simulations producing the minimum, median, maximum, and 95th percentile evacuation time.

Scenario 1 (0% luggage retrievers)	Avg. CWT (s)	Avg. Distance (m)	Avg. PET (s)	TET (s)
Min sim	36.6	7.6	52.1	110.1
Median* sim	40.6	7.7	56.2	120.9
Max sim	45.8	7.8	61.9	138.5
95th% sim	44.3	7.7	60.3	127.7
*Note: Simulations are ordered by out-of-aircraft time, with Min sim being the fastest evacuation simulation and Max sim being the slowest evacuation simulation. *Median sim is the 501st simulation from the 1000 repeat simulations ranked in ascending TET.*				

Presented in Table 22 is a summary of the minimum, mean, maximum, and 95th percentile values from all the simulations. This is intended to simply provide a measure for the spread in values for each parameter. The values in Table 22 are not necessarily derived from the same simulation but represent the range of values derived from all 1000 simulations. Thus, the minimum value is the smallest value of a particular parameter generated by all 1000 simulations. Thus, the smallest Average CWT observed was 35.8 s, while the largest was 45.8 s.

Table 22: Summary performance data for Scenario 1 (0% luggage retrievers) representing the minimum, mean, maximum, and 95th percentile values for key simulation parameters.

Scenario 1 (0% luggage retrievers)	Avg. CWT (s)	Avg. Distance (m)	Avg. PET (s)	TET (s)
Min value	35.8	7.6	51.6	110.1
Mean value	40.2	7.7	55.9	121.1
Max value	45.8	8.0	61.9	138.5
95th% value	43.2	7.8	59.0	127.7
Note: The data in the table are simulation-independent, i.e., the values are not necessarily from the same simulation.				

The distribution of the TET for all 1000 repeat simulations is presented in Figure 28. Each repeat simulation produces a different TET due to a different population being generated for each simulation; thus, there is a different agent seated in each seat for each simulation. Furthermore, even if the simulation was repeated with the same agents in the same seating location, the results describing the evacuation performance would still not be identical, as an agent will not necessarily do the same thing if the simulation is repeated, as some of the behaviours are stochastic in nature. This includes the passenger exit selection.

As can be seen in Figure 28, all 1000 repeat simulations for Scenario 1 produce TETs in excess of 90 s. The TET varies from 110.1 s to 138.5 s, with the corresponding average personal evacuation time (PET) varying from 52.1 s to 61.9 s (note that the absolute range of average PET varies from 51.6 s to 61.9 s). By 90 s, between 86% (159) and 70% (129) of the 185 occupants or an average of 146.2 (79%) have evacuated.

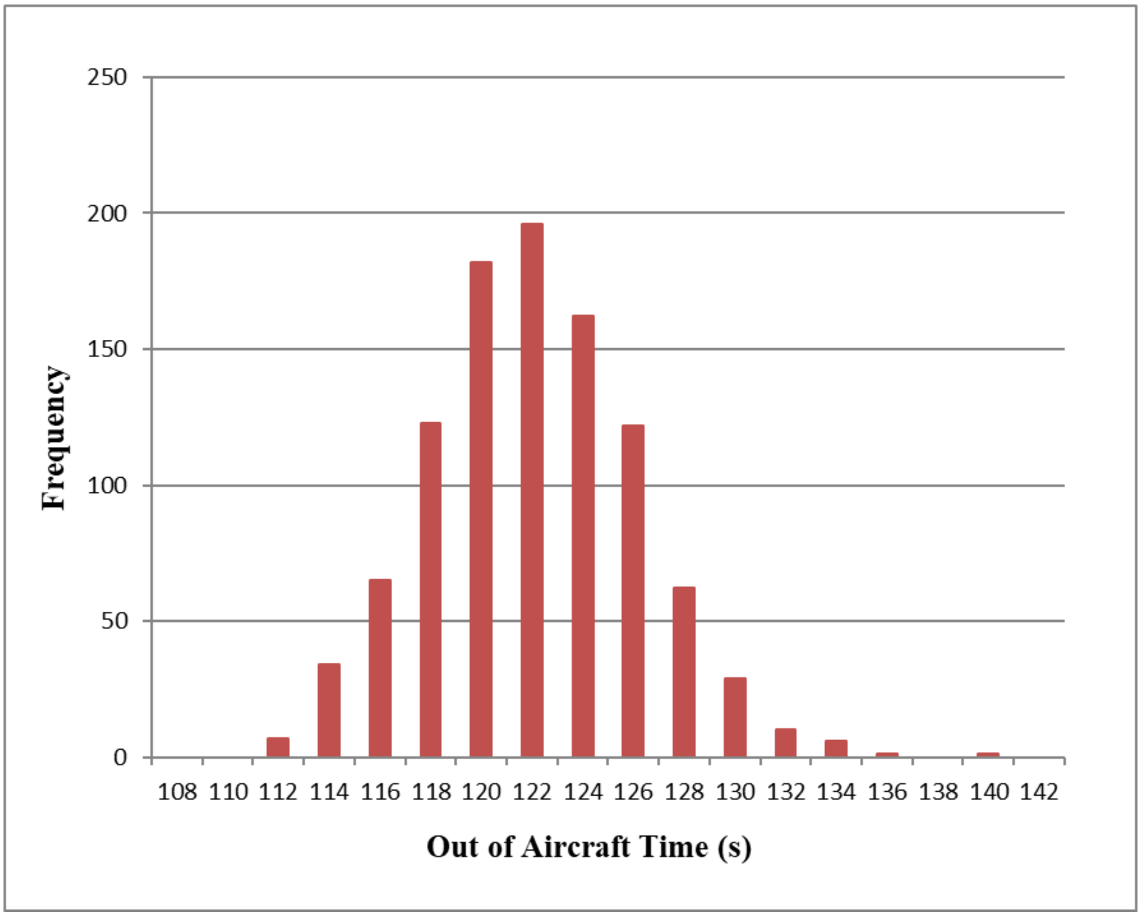


Figure 28: Distribution of TET for Scenario 1 (0% luggage retrievers).

The exit usage and flows produced for Scenario 1 are presented in Table 23 and Table 24. The minimum, mean, and maximum number passengers attempting to use L1/R1 are approximately equal, as seen in Table 23. This is also true for L2/L3 usage. The slight imbalance in the number of passengers using particular exit pairs (i.e., L1/R1 and L2/L3) will result in inefficiencies in exiting and, hence, lead to longer evacuation times. The imbalance in the numbers of passengers using the various exits will also impact the exit flows achieved, in particular the forward Type-C exits, given that the number of passengers using these exits is low.

Table 23: Minimum, mean, maximum, and 95th percentile values for exit flow and exit usage for Scenario 1 (0% luggage retrievers).

Scenario 1 (0% luggage retrievers)	L1 Avg.PPM	L1 No. Used	R1 Avg.PPM	R1 No. Used	L2 Avg. PPM	L2 No. Used	L3 Avg. PPM	L3 No. Used
Min value	15.4	13	18.1	11	32.4	63	32.7	63
Mean value	37.3	22	38.7	21	38.9	71	39.8	71
Max value	63.4	31	61.5	30	44.9	78	45.6	80
95th% value	51.0	17*	51.2	16*	42.2	67*	42.7	67*

Note: The data in the table are simulation-independent, i.e., the values are not necessarily from the same simulation.
** For these data, it shows that 95% of the time it was this amount or higher.*

The number of passengers using each exit and the achieved flows for the minimum, median, maximum, and 95th percentile simulations are presented in Table 24. The simulation producing minimum TET generally achieves higher flows at each exit, while the maximum TET generally achieves lower flows at each exit.

Table 24: Exit flow and exit usage for Scenario 1 (0% luggage retrievers) for the simulations producing the minimum, median, maximum, and 95th percentile evacuation time.

Scenario 1 (0% luggage retrievers)	L1 Avg.PPM	L1 No. Used	R1 Avg.PPM	R1 No. Used	L2 Avg.PPM	L2 No. Used	L3 Avg.PPM	L3 No. Used	All Exits Avg. PPM
Min Sim	53.0	25	36.0	18	43.3	71	43.1	71	46.5
*Median Sim	36.8	19	48.9	23	38.2	69	40.4	74	38.5
Max Sim	25.9	17	41.6	26	35.5	75	33.3	67	31.5
95th% Sim	39.7	23	37.1	20	36.0	69	37.8	73	37.8

Note: Simulations are ordered by out-of-aircraft time, with Min sim being the fastest evacuation simulation and Max sim being the slowest evacuation simulation.
**Median sim is the 501st simulation from the 1000 repeat simulations ranked in ascending TET.*

It is clear from Table 23 that there is a large spread in exit flow achieved by the various exits, with the Type-C and Type-III exits varying from approximately 15 to 63 ppm and 32 to 46 ppm, respectively. While the Type-III exits are performing as may be expected compared to their rated performance, the Type-C exits are significantly underperforming. The poor performance of the Type-C exits is due to the nature of the scenario and, in particular, the supply of passengers to the two exits. Essentially, the single cabin aisle cannot supply sufficient passengers to enable both Type-C exits to operate at their full capacity. This situation is compounded by the relatively small number of passengers that are able to use the two Type-C exits in this scenario (nearest exit). In contrast, the Type-III exits, which have a significantly lower flow capability than the Type-C exits (mean flow for Type-III is just 57% of the mean flow for Type-C), can be adequately supplied with passengers by the single cabin aisle. Indeed, the flow produced by the single cabin aisle is able to support both Type-III exits, so these exits operate in almost ideal conditions.

The times for each exit to finish for the simulations producing the minimum, median, maximum, and 95th percentile simulations are presented in Table 25. Clearly, the forward L1/R1 exits finish well before the overwing L2/L3 exits due to the smaller number of passengers available in the nearest exit scenario. The forward L1/R1 exits dry up after 37 s to 46 s, depending on the particular simulation.

Table 25: Time for last person to exit from each door for Scenario 1 (0% luggage retrievers) for the simulations producing the minimum, median, maximum, and 95th percentile evacuation times.

Scenario 1 (0% luggage retrievers)	L1 Last Out (s)	R1 Last Out (s)	L2 Last Out (s)	L3 Last Out (s)
Min Sim	35.6	36.6	109.6	110.1
*Median Sim	37.7	35.6	119.4	120.9
Max Sim	45.6	44.6	138.5	132.2
95th% Sim	41.5	38.9	125.9	127.7
*Note: Simulations ordered by out-of-aircraft time, with Min sim being the fastest evacuation simulation and Max sim being the slowest evacuation simulation. *Median sim is the 501st simulation from the 1000 repeat simulations ranked in ascending TET.*				

Finally, the exit curves for Scenario 1 (0% luggage retrievers) are presented in Figure 29 and Figure 30. For approximately the first 36 s to 46 s (see Table 25), the evacuation is proceeding with maximum exit flow produced by all four exits working together. However, after between approximately 37 s and 46 s, the Type-C exits are no longer working, as they have exhausted their supply of passengers, and only the Type-III exits are operating. At this time, the exit flow has significantly decreased, resulting in a reduction in the slope of the curves. As can clearly be seen in Figure 29 and Figure 30, all 1000 simulations produce TETs at least 23% (21 s) greater than the critical regulatory requirement of 90 s. Of the 185 occupants, only 129 (70%), 136 (74%), 145 (78%), and 157 (85%) occupants are evacuated at 90 s in the simulations producing the maximum, 95th percentile, median, and minimum TET simulations, respectively.

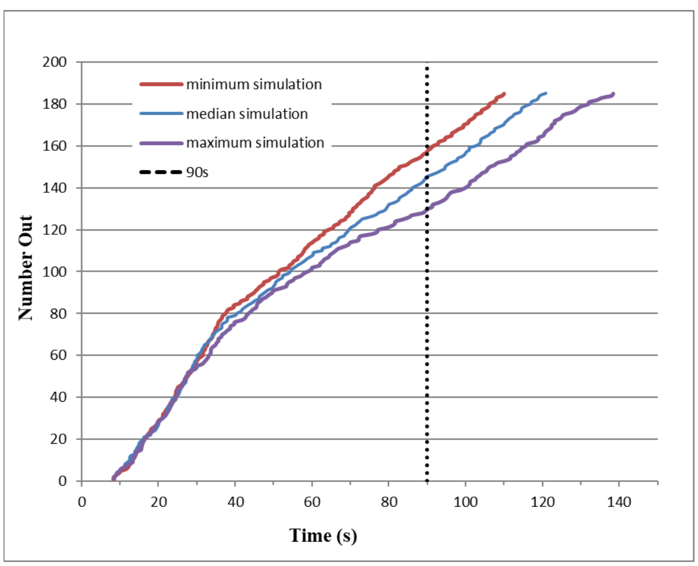


Figure 29: Scenario 1 (0% luggage retrievers) exiting curves for simulations producing the minimum, median, and maximum TETs, where the dotted line represents the 90 s mark.

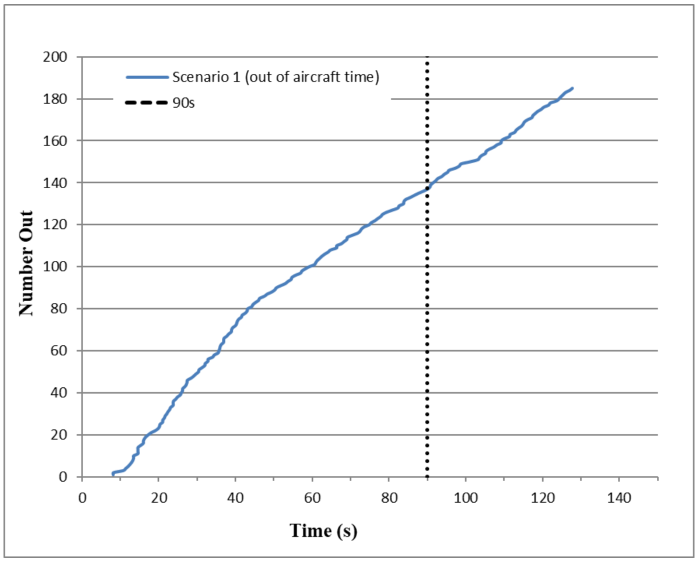


Figure 30: Scenario 1 (0% luggage retrievers) exiting curve for the simulation producing the 95th percentile TET, where the dotted line represents the 90 s mark.

As described in Section 5.3(c), to better understand the impact that luggage collection has on the overall evacuation performance, five compartment zones were defined within the aircraft configuration (see Figure 21). Note that Zone 01 is at the front of the aircraft, while Zone 05 is in the rear of the aircraft. For each compartment zone, additional information can be recorded to assess the impact of luggage retrieval on other passengers. Until the analysis of the luggage retrieval scenarios begins, it is not clear what additional parameters will be informative, so here, various key zone data are presented for the case without luggage retrieval. Other data may need to be extracted from Scenario 1 (base case) once the analysis of the luggage retrieval scenarios begins, for example, the zonal data for specific simulations, such as the simulation producing the median, 95th percentile, or maximum evacuation time.

Presented in Table 26 is the average along with the minimum and maximum (min – max) values from the 1000 sims of the Min Duration, Max Duration, and Avg Duration of the time spent by agents within their starting zone. The time duration an agent spends in a zone is also referred to as 'dwell time'. The dwell time (duration) is simply determined by airEXODUS as the time duration an agent remains in a zone from the start of the simulation. For a given simulation, airEXODUS identifies the minimum duration, the maximum duration, and an average duration for each zone. The average duration is the simple average of all the individual durations associated with agents in a particular zone for a given simulation. Presented in Table 26 are the average values for each of these three parameters across all 1000 simulations. The numbers in brackets represent the minimum and maximum values of the parameter. So, for the 'Min Duration', 2.6 s represents the average of the minimum duration in Zone 01 across all 1000 simulations, while 1.3 s represents the minimum of the minimum durations across all 1000 simulations, and 5.9 s represents the maximum of the minimum durations across all 1000 simulations. Similarly, for the 'Avg Duration', 19.8 s represents the average of the average durations across all 1000 simulations, while 14.3 s represents the minimum of the average durations across all 1000 simulations, and 26.1 s represents the maximum of the average durations across all 1000 simulations.

Also presented are the number of agents (PAXs) starting within each zone. Thus, for example, in Zone 05, the zone located in the rear of the aircraft, for the 36 agents initially located in that zone, on average, the first PAX to leave the zone exited after 4.4 s (and this varied from 1.6 s to 21.8 s in the 1000 simulations), and the last PAX to leave the zone exited after 95 s (varied from 77 s to 111 s). The average exit time for the 36 PAXs located in Zone 05 was 65 s (the average time varied from 47 s to 83 s).

Table 26: Dwell Time (s) spent by agents in their zone of origin for Scenario 1 (0% luggage retrievers).

Zone	Min Dwell Time (s)	Max Dwell Time (s)	Avg Dwell Time (s)	Number of PAXs
1	2.6	48.1	19.8	48
	(1.3 - 5.9)	(28.1 - 79)	(14.3 - 26.1)	
2	3.8	81.7	40.1	36
	(1.8 - 12.5)	(52.2 - 129.4)	(27.9 - 57.9)	
3	3.9	89.2	38.3	30
	(1.7 - 14.6)	(42.5 - 128.1)	(23.7 - 62.5)	
4	4.3	92.7	51.4	30
	(1.6 - 42.7)	(59.4 - 118.4)	(34.1 - 71.5)	
5	4.4	95.0	65.0	36
	(1.6 - 21.8)	(76.9 - 110.8)	(46.6 - 82.6)	

Presented in Table 27 is the average and the minimum and maximum (min - max) values from the 1000 sims of the Minimum Personal Evacuation Time (PET) (Min Evac Time), Maximum PET (Max PET), and Average PET (Avg PET) for the agents starting from each zone. Also presented are the number of agents (PAXs) starting within each zone. Thus, for example, in Zone 05, the zone located in the rear of the aircraft, for the 36 agents initially located in that zone, on average, the first PAX to evacuate the aircraft exited after 64.1 s (and this varied from 29 s to 96 s over the 1000 simulations), and the last PAX to evacuate the aircraft exited after 120 s (varied from 106 s to 138 s). The average PET for the 36 PAXs located in Zone 05 was 99 s (the average PET varied from 81 s to 113 s).

Table 27: PET (s) based on zone of origin for Scenario 1 (0% luggage retrievers).

Zone	Min PET (s)	Max PET (s)	Avg PET (s)	Number of PAXs
1	8.4	81.7	30.1	48
	(8.1 - 10.6)	(50.2 - 125.1)	(24.8 - 37.4)	
2	13.0	90.9	44.5	36
	(12 - 16.6)	(60.1 - 131)	(31.9 - 60.7)	
3	13.0	98.1	43.3	30
	(11.9 - 19.9)	(46.2 - 132.4)	(29 - 68.5)	
4	31.5	111.1	72.8	30
	(15.1 - 63.6)	(82.3 - 138.5)	(55.7 - 91.3)	
5	64.1	120.2	99.0	36
	(29 - 96.3)	(106.4 - 138.1)	(80.6 - 113.1)	

Presented in Table 28 is the average and the minimum and maximum (min – max) values from the 1000 sims of the Minimum Dwell Time (Min Dwell Time), Maximum Dwell Time (Max Dwell time), and Average Dwell Time (Avg Dwell Time) for ALL agents passing through each zone. Also presented are the number of agents (PAXs) passing through each zone. Thus, for example, the data for Zone 03 includes all the agents from Zone 05, Zone 04, and Zone 03 that pass through Zone 03 to exit the aircraft. In this case, on average, 103.8 PAXs pass through Zone 03, and this varied between 97 PAXs and 113 PAXs. Furthermore, the average dwell time within Zone 03, based on all the PAXs that passed through Zone 03, was 21.1 s, and this varied from 16.1 s to 30.0 s. It is noted that this time is less than the dwell time for PAXs that started in Zone 03, which is an average of 38.3 s (see Table 26) since when the PAXs from Zone 05 (and, to a lesser extent, Zone 04) pass through Zone 03, the density within the zone is reduced, so the PAXs spend less time in the zone.

Table 28: Dwell Time (s) spent by all agents in zones for Scenario 1 (0% luggage retrievers).

Zone	Min Dwell Time (s)	Max Dwell Time (s)	Avg Dwell Time (s)	Number of PAXs*
1	1.9	48.1	19.5	48.8
	(0.3 - 5.9)	(28.1 - 79)	(13.8 - 25.8)	(48 - 56)
2	2.9	81.7	25.0	78.1
	(0.3 - 5.7)	(52.2 - 129.4)	(16.4 - 37.4)	(69 - 88)
3	3.4	89.2	21.1	103.8
	(0.3 - 6.3)	(42.5 - 128.1)	(16.1 - 30)	(97 - 113)
4	3.2	92.7	30.1	67.1
	(0.3 - 8.2)	(59.4 - 118.4)	(22.7 - 41.3)	(67 - 70)
5	3.3	95.0	60.1	39.8
	(0.3 - 4)	(76.9 - 110.8)	(44.2 - 76.9)	- 48)

5.5 Key Findings: Software Enhancement

Key Finding 5.1 Enhancements to airEXODUS to represent luggage retrieval: airEXODUS software has been enhanced to represent passengers retrieving luggage during evacuation and the impact that they have on the evacuation of other passengers.

The modified software has the following new capabilities:

- Ability to represent a specified number of PAXs designated as luggage retrievers
- Delay the evacuation of the designated luggage retrievers once they enter the aisle from their seat for a duration of time derived from a luggage retrieval time distribution.
- Allow other PAXs in the aisle to attempt to by-pass the luggage retriever based on a by-pass probability. However, the PAX will attempt to by-pass only if there is sufficient space on the other side of the luggage retriever; otherwise, they will wait until space is available. As the PAX by-passing the luggage retriever is hindered by the obstacle created by the presence of the luggage retriever, their walk speed is reduced by an amount derived from the speed reduction distribution.
- Additional simulation output parameters have been defined to characterise the performance of the PAXs when interacting with luggage collectors.
- Ability to quantify PAX-based luggage retrieval parameters and evacuation performance over user-defined spatial zones.

5.6 Key Findings: Scenario 1 (0% Luggage Retrievers) with Enhanced Software

The base case, Scenario 1 (0% luggage retrievers) for the narrow-body aircraft configured with two forward Type-C exits and two left Type-III exits available (representing 50% of the available exits) and with the passengers seeking to exit via their nearest exit (see Key Finding 3.1) was rerun using the modified software. The results produced using the modified are consistent with those produced in Section 3 but include additional results (concerning Zones), so are considered to constitute the baseline results for comparison purposes.

Key Finding 5.2 Scenario 1, Overall Evacuation performance:

- The Total Evacuation Time (TET) varied from approximately 110.1 s to 138.5 s (with an average of 121.1 s) and, on average, with 79% (146.2) of the 185 occupants evacuated by 90 s. The average PET varies from 51.6 s to 61.9 s.
- Given the nature of the evacuation scenario, including the location of the available exits, clearly, this configuration does not satisfy the 90 s requirement in this scenario.

Key Finding 5.3, Scenario 1, Specific Evacuation performance:

- It is more informative to consider the evacuation performance of several key simulations, such as the simulations producing the minimum, median, and maximum TET.
- For the simulation producing the ***minimum TET***, the TET is 110.1 s, and the average PET is 52.1 s.
- For the simulation producing the ***median TET***, the TET is 120.9 s, and the average PET is 56.2 s.
- For the simulation producing the ***maximum TET***, the TET is 138.5 s, and the average PET is 61.9 s.
- However, when assessing the impact of luggage retrievers on evacuation performance, it is inappropriate to simply consider typical global evacuation parameters such as TET or average PET, as this may not reveal the significant localised impact of luggage retrieval on specific groups of passengers.

Key Finding 5.4, Scenario 1, Localised Evacuation performance:

- A deeper understanding of the impact of luggage retrievers on the overall evacuation can be derived from investigating localised evacuation parameters, such as zonal dwell times and zonal evacuation times.
- In S1, for those passengers starting in Zone 01 (the front eight seat rows),
  - the average Zone 01 dwell time is 19.8 s.
  - the average Zone 01 evacuation time is 30.1 s.
- In S2, with 25% of the passengers retrieving luggage, for those passengers starting in Zone 05 (rear six seat rows),
  - the average Zone 05 dwell time is 65.0 s.
  - the average Zone 05 evacuation time is 99.0 s.
  - the average evacuation time for passengers in Zone 05 exceeds 90 s.

Key Finding 5.5, Scenario 1, Overall evaluation:

- In S1, the overall evacuation times (110.1 s to 138.5 s, with an average of 121.1 s) are well in excess of 90 s. By 90 s, on average, only 146.2 (79%) occupants have evacuated, with 38.8 remaining onboard. As is to be expected, passengers located in the rear of the aircraft (Zone 05) have the greatest evacuation times with an average of 99.0 s. They also have a large zonal dwell time of 65.0 s. While half the normally available exits are used in the evacuation scenario, as is required by FAR 28.803, the available exits are not optimally located as used in the certification trial, i.e., one from each exit pair dispersed along the length of the aircraft. The two largest exits (Type-C), located at the front of the aircraft, are available, and the pair of left small overwing exits (Type-III) located in the centre of the aircraft are available. As passengers will tend to use their nearest exit, most of the passengers attempt to exit via the overwing exits. This, along with the greater travel distances, contributes to the long evacuation times. In addition, given the nature of the scenario, both pairs of exits are utilised sub-optimally. For the front pair of Type-C exits, the single cabin aisle cannot supply passengers quickly enough to satisfy the capability of the two Type-C exits. Thus, the exits operate sub-optimally. For the overwing exits, the majority of the supply of passengers is from the rear, and so the supply of passengers to the dual Type-III exits is predominately from one side, which preferentially supplies the first of the exits (i.e., 3L) encountered by the passenger flow. This can result in sub-optimal usage of both exits, with gaps occurring in the exiting flow of both exits.

6 SCENARIO 2 (25% LUGGAGE RETRIEVERS) RESULTS AND ANALYSIS

In this section, the impact of 25% of the passengers attempting to retrieve their luggage (i.e., Scenario 2) on overall evacuation efficiency is explored. As in all the evacuation scenarios considered in this analysis, the narrow-body, single-aisle cabin layout presented in Section 3.1 is used, and all the passengers attempt to evacuate via their nearest serviceable exit, i.e., either of the two forward Type-C exits or the left pair of Type-III overwing exits.

The initial seating allocation for luggage collectors is defined within the model by the Luggage Collectors' Zone as described in Section 5.3(a). Throughout this analysis, this is defined to encompass the seat blocks as shown in Figure 19. Note that seat rows that lead to an exit are not included in the luggage collectors' zone. Furthermore, to better understand how the luggage collection behaviour impacts the overall evacuation performance, five compartment zones are defined as described in Section 5.3(c) and shown in Figure 21. For each compartment zone, the additional information that is recorded and exported into the simulation data output file includes the time that a PAX entered the zone, the time a PAX left the zone, and the dwell time (i.e., duration they spend inside that zone).

The chosen aircraft cabin layout accommodates 180 passengers, 3 cabin crew, and 2 flight deck crew in total. As two rows of seats are excluded from containing luggage retrievers (last row of Zone 02 and first row of Zone 03) this reduces the number of potential Luggage Collectors to 168. Thus, for the scenarios involving luggage retrievers, the following number of passengers are designated as luggage retrievers:

- Scenario 2: In total, 25% or 42 of the passengers are luggage retrievers,
- Scenario 3: In total, 50% or 84 of the passengers are luggage retrievers,
- Scenario 4: In total, 75% or 126 of the passengers are luggage retrievers.

Prior to commencing the analysis, the push-past probability and speed reduction distribution introduced to represent the impact of the luggage collectors on evacuation performance (described in Section 5.1 (see Table 19) are defined, and a sensitivity analysis around these chosen values is performed.

6.1 Scenario 2: Defining Parameters Required by the Luggage Collection Model

The luggage retrieval model developed in Section 5 included two user-defined parameters to describe how passengers attempt to by-pass a luggage retriever (see Table 19 for details). Ideally, data derived from accident analysis or controlled experimentation would be used to define these parameters. However, as this is not available, engineering judgement is used to suggest plausible estimations of these parameters. The two parameters and the values used in the simulations are:

- **Probability that a passenger will attempt to by-pass a luggage retriever:** In the model, a normal distribution is used to describe the by-pass probability (BPP) (producing BPP values between 0.0 and 1.0), with mean 0.5 and standard deviation of 0.12, as depicted in Figure 31.

- **Walking speed reduction factor during by-pass:** In the model, a uniform random distribution between 0.1 and 0.5 is used to describe the walking speed reduction factor. This means that walk speed during by-pass will be uniformly reduced by between 90% and 50%.

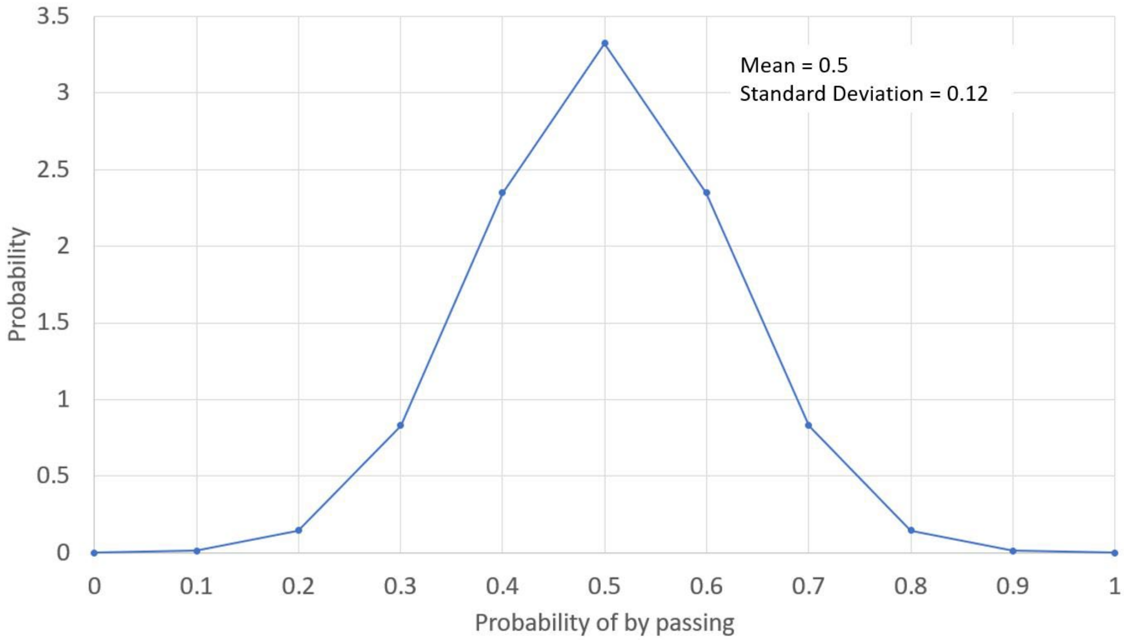


Figure 31: By-pass probability distribution.

In the next section, a sensitivity study is performed to evaluate the impact of these estimated parameters.

6.2 Sensitivity Analysis for Luggage Collection Model

Prior to commencing the analysis of Scenario 2, the sensitivity of the model to various luggage retrieval parameters is assessed. The sensitivity analysis is undertaken assuming 25% of the passengers will attempt to retrieve luggage. Each case is repeated 1000 times, with a new population generated for each repeat simulation. Thus, the location and nature of the luggage retrievers are changed for each repeat simulation.

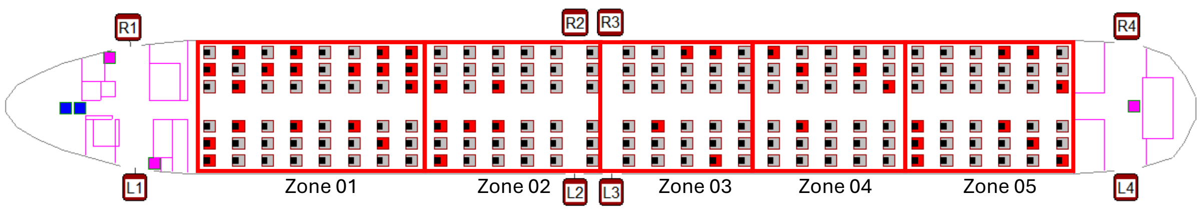
Four sensitivity studies are considered, as described below:

- Sensitivity case 1, no by-pass
- Sensitivity case 2, 100% by-pass with walking speed reduction factor of 0.4
- Sensitivity case 3, 100% by-pass with walking speed reduction factor of 0.5
- Sensitivity case 4, 100% by-pass with walking speed reduction factor of 0.6

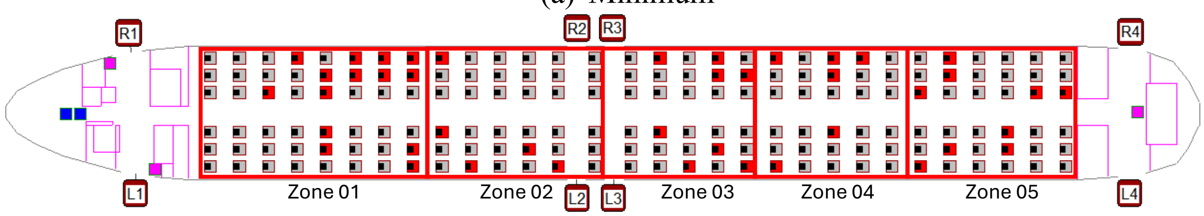
NOTE: The modified walking speed is determined by multiplying the original walking speed by the reduction factor, so a reduction factor of 0.6 results in a larger walking speed than the resulting speed with a reduction factor of 0.4.

(a) Sensitivity case 1, no by-pass.
In this sensitivity case (SC), none of the passengers can by-pass another passenger who is retrieving their luggage (by-pass probability (BPP) of 0%). This sensitivity case, therefore, represents the worst conceivable outcome, assuming that 25% of the passengers attempt to retrieve their luggage. The results for Scenario 2 are expected to be not as severe as passengers have a non-zero probability of passing the luggage retriever.

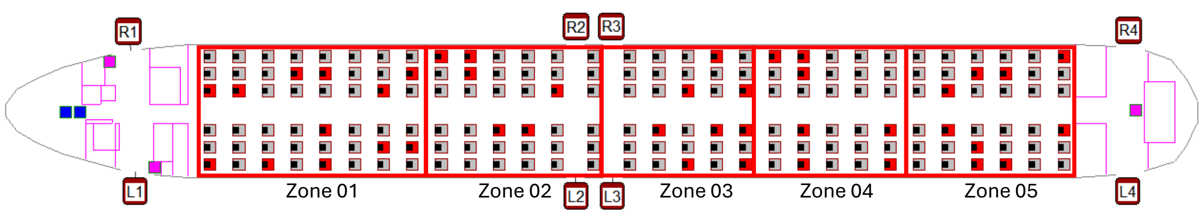
Presented in Figure 32 are the seating locations for the luggage retrievers in SC1 for the simulations producing the minimum (Figure 32a), median (Figure 32b), and maximum (Figure 32c) total evacuation times. This demonstrates that the seating locations for the luggage retrievers change with each repeat simulation.



(a) Minimum



(b) Median



(c) Maximum

Figure 32: Seating location of luggage retrievers in SC1 for the (a) minimum, (b) median, and (c) maximum evacuation time.

Presented in Table 29 are the number of luggage retrievers in each zone for the minimum, median, maximum, and 95th percentile simulations for SC1, while presented in Table 30 are the minimum, average, and maximum number of luggage retrievers in each zone across the 1000 simulations. Clearly, the distribution of luggage retrievers will impact the overall evacuation times and the performance of passengers within each zone. As seen in Table 30, there can be a larger variation in the number of luggage retrievers in each zone over the 1000 repeat simulations; for example, in Zone 05, the number varies from 2 to 15, with an average of 9.

Table 29: Number of luggage retrievers in each zone for various repeat simulations for SC1.

	Zone 01	Zone 02	Zone 03	Zone 04	Zone 05	Total
Min sim	18	6	4	5	9	42
***Median sim**	14	5	8	6	9	42
Max sim	12	6	8	7	9	42

*Median sim is the 501st simulation

Table 30: Minimum number, average, and maximum number of luggage retrievers in each zone across all 1000 repeat simulations for SC1.

	Zone 01	Zone 02	Zone 03	Zone 04	Zone 05
Min	5	2	1	2	2
Average	12	7.4	6	7.5	9
Max	20	16	12	15	15

Presented in Figure 33 are the exit curves for Scenario 1 and SC1 for the simulations producing the minimum, median, and maximum simulations, while key simulation parameters are reported in Table 31. It is clear from both Figure 33 and Table 31 that the impact of the luggage retrievers in SC1 is not uniform throughout a simulation (early part of the evacuation can be more or less impacted than the final part of the evacuation) and can vary significantly between repeat simulations.

For the simulations producing the minimum Total Evacuation Time (TET) for Scenario 1 and SC1, the TET is increased by only 2.3% (see Table 32) when luggage retrievers are included. However, the early stages of the evacuation result in significantly longer TET for SC1, e.g., by the time 80 passengers have evacuated, the TET is some 32.5% longer for SC1 (see ANNEX B). Furthermore, the average personal evacuation time (PET) is some 11.9% longer in the minimum simulation when luggage collectors are included (see Table 32). **Thus, in the *minimum simulation*, while the TET has increased only marginally (2.3%), the average PET has increased by a large (11.9%) amount.**

For the simulations producing the maximum TET for Scenario 1 and SC1, the TET increases by 35.5% (see Table 32) when luggage retrievers are included. However, in the early stages of the evacuation, there are smaller increases in evacuation times for SC1, e.g., by the time 40 passengers have evacuated, the evacuation time is some 21.1% longer for SC1, and when 80 passengers have evacuated, the increase in evacuation time is only 5.3% (see ANNEX B). Furthermore, the average PET is some 19.2% longer in the maximum simulation when luggage collectors are included (see Table 32). **Thus, in the *maximum simulation*, both the TET and PET times are significantly longer (35.5% and 19.2%, respectively) with luggage retrievers.**

For the simulations producing the median TET for Scenario 1 and SC1, the TET increases by 13.5% (see Table 32) when luggage retrievers are included. However, in the early stages of the evacuation, there are smaller increases in evacuation times for SC1, e.g., by the time 40 passengers have evacuated, the evacuation time is some 6.2% longer for SC1, and when 80 passengers have evacuated, the increase in evacuation time is 12.3% (see ANNEX B). Furthermore, the average PET is only 3.6% longer in the median simulation when luggage collectors are included (see Table 32).

Thus, in the *median simulation*, while the TET has increased by a large amount (13.5%), the average PET is only marginally longer (3.6%).

Thus, when assessing the impact of luggage retrievers on evacuation performance, it is inappropriate to simply consider total evacuation time for any one particular simulation, e.g., median simulation, maximum simulation, or minimum simulation. The difficulty with simply using the total evacuation time to assess the impact of luggage retrievers on evacuation performance is that parts of the cabin and resulting evacuation may be impacted significantly, while the overall total evacuation time is not significantly affected. While the number of luggage retrievers is constant for all 1000 repeat simulations, their distribution can vary widely from simulation to simulation, as shown in Table 29 and Table 30. The number of luggage retrievers within each zone can vary significantly, as does their seating locations. It is thus also inappropriate to simply base the analysis on any one simulation because, as has been shown, depending on which simulation from the 1000 repeat simulations is selected, the results can vary widely. It is thus more appropriate to consider the impact on the entire evacuation process and to consider the impact on several meaningful simulations, e.g., simulations producing the minimum, median, and maximum evacuation times.

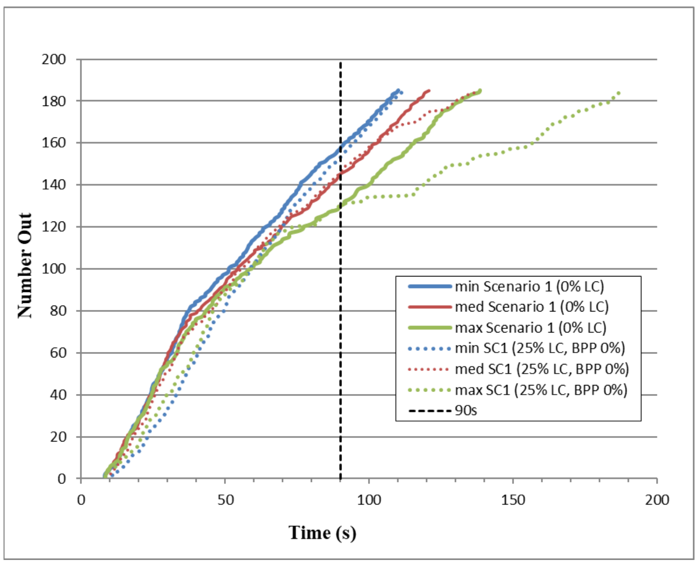


Figure 33: Evacuation curves for Scenario 1 (0% luggage retrievers) and SC1.

Table 31: Simulation parameters from Scenario 1 and SC1 for the simulations producing the minimum, median, maximum, and 95th percentile evacuation times.

Sim	Avg. CWT (s)		Avg. Distance (m)		Avg. PET (s)		TET (s)	
	S1 0% LC	SC1 25% LC SR 0	S1 0% LC	SC1 25% LC SR 0	S1 0% LC	SC1 25% LC SR 0	S1 0% LC	SC1 25% LC SR 0
Min Sim	36.6	40.5	7.6	8.0	52.1	58.3	110.1	112.6
***Median Sim**	40.6	40.3	7.7	8.0	56.2	58.2	120.9	137.2
Max Sim	45.8	54.7	7.8	8.2	61.9	73.8	138.5	187.6
95th% Sim	44.3	47.4	7.7	8.3	60.3	66.1	127.7	165.9

**Median sim is the 501st simulation.*

Table 32: Increase in average out-of-aircraft time and total evacuation time for Scenario SC1 compared with Scenario 1.

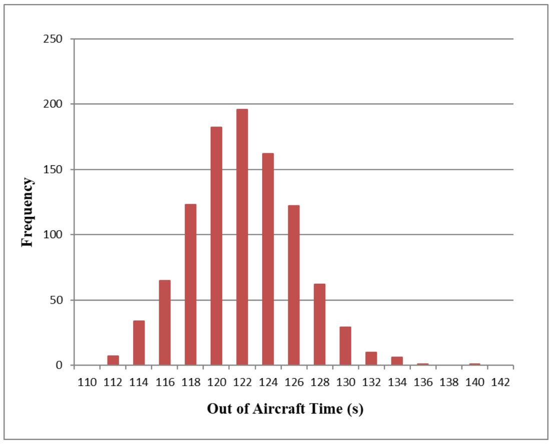
Sim	Increase in Avg. PET (%)	Increase in TET (%)
Min Sim	11.9	2.3
***Median Sim**	3.6	13.5
Max Sim	19.2	35.5
95th% Sim	9.6	29.9

**Median sim is the 501st simulation.*

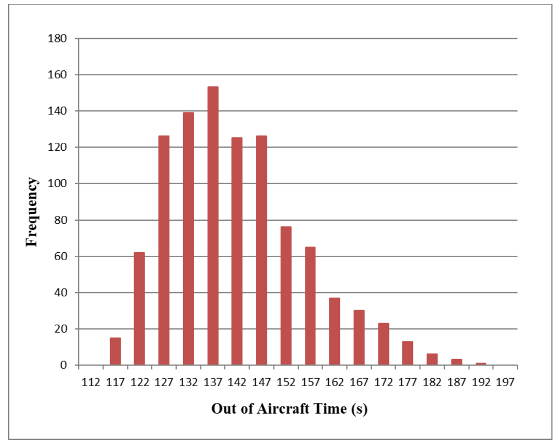
Presented in Figure 34 are the frequency distributions for Scenario 1 (a), SC1 (b) and Scenario 1 combined with SC1 (c). Clearly, having 25% of passengers retrieve their luggage can significantly impact overall evacuation time. Without luggage retrieval, only approximately 2% (18) of the simulations have a total evacuation time in excess of 130 s, while with 25% luggage retrieval, almost 72% (718) exceed 130 s, and 43% (433) exceed 140 s.

A deeper understanding of the impact of luggage retrievers on the overall evacuation can be derived from investigating zonal dwell times. Dwell times provide a measure of how long passengers remain in a particular spatial zone during their evacuation. The shorter the zonal dwell times, the more efficient the evacuation, as this suggests that passengers are making progress towards an exit. Long zonal dwell times suggest that the evacuation of the individual is being hampered or delayed. While long zonal dwell times can be due simply to congestion associated with the evacuation, which, in turn, is related to the number and location of the available exits, passenger behaviour may also adversely impact dwell times. For example, luggage retrieval can increase both individual passenger dwell times and average zonal dwell times by delaying the movement of passengers that cannot by-pass the luggage retriever. Increased zonal dwell times lead to more inefficiency and can result in longer evacuation times.

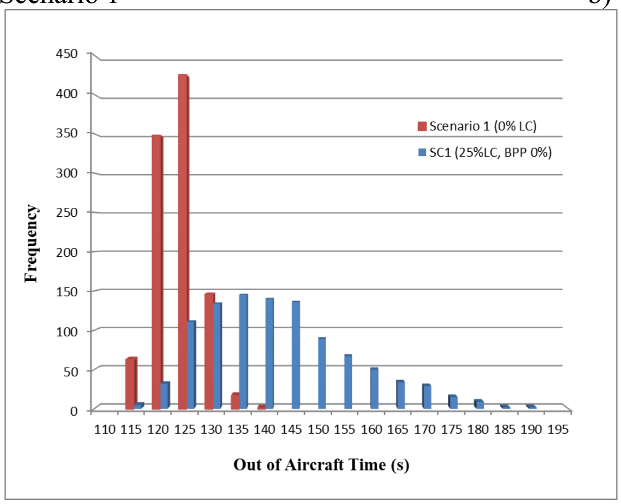
Regardless of whether luggage retrievers are present, passengers in Zone 05 typically have the longest evacuation times, as they have the longest distance to travel to reach a viable exit, and the closest exits available to them are a pair of Type-III exits, i.e., relatively small and slow exits. They are also impacted by the behaviour of more passengers than those originating in other zones as they are affected by the behaviour of passengers in Zone 03, Zone 04, Zone 05, and potentially Zone 02. They, therefore, will experience the greatest delays resulting from luggage retrievers, as there are likely to be a greater number of luggage retrievers in their evacuation path. For example, in the median simulation, there are 23 luggage retrievers in these three zones (see Table 29), while on average, there are 22.5 luggage retrievers (see Table 30). This represents considerably more luggage retrievers than experienced by passengers in any other zone.



a) Scenario 1



b) SC1



c) Scenario 1 and SC1

Figure 34: Evacuation time frequency distribution for (a) Scenario 1 (0% luggage retrievers), (b) SC1, and (c) Scenario 1 and SC1.

In contrast, passengers in Zone 01 have the shortest evacuation times, as they have amongst the shortest travel distances to reach a viable exit, and the exits available to them are a pair of Type-C exits, i.e., relatively large and fast exits. They are also impacted only by the other passengers in their zone of origin, i.e., Zone 01. They are, therefore, likely to be impacted by the least number of luggage retrievers on their exit path, 14 in the median simulation (see Table 29) and 12, on average (see Table 30).

In addition, the significance of increased average zonal dwell times is dependent not only on the magnitude of the increase but also on the location of the zone and the nature of the scenario. To evaluate the potential significance of increases in zonal dwell time, consider a post-crash fire that gains access to the cabin interior during the evacuation. In the evacuation scenario considered in this analysis, only the front exits and one pair of overwing exits are considered viable. This exit availability is likely to result from a post-crash external fire initially impacting the rear of the aircraft (resulting in the rear exits not being available). In such a scenario, it is likely that the fire first gains access to the rear of the cabin, as in the 1985 Manchester B737 [4, 20] and the 2019 Sheremetyevo Sukhoi Superjet-100 [21, 22, 23] fatal accidents involving post-crash fires. In this type of fire scenario, passengers in the rear of the aircraft, particularly those in Zone 05, are at greatest risk due to their proximity and duration of exposure to the fire. Conversely, passengers in the front of the aircraft, particularly those in Zone 01, will be at least risk from the developing fire due to their distance from hazards and relatively shorter expected exposure duration.

Presented in Table 33 are the average minimum, maximum, and average ***dwell times*** for passengers originating in each zone. The values represent the average from the 1000 simulations of the minimum zonal dwell time, the maximum zonal dwell time and the average zonal dwell time. For Scenario 1, the average dwell time (across all 1000 simulations) in Zone 05 is 65.0 s. This is determined by calculating the average dwell time in Zone 05 for all the passengers starting in Zone 05 in a simulation and then averaging this across all 1000 simulations.

Table 33: Average (across 1000 simulations) minimum, maximum, and average dwell time incurred by agents in their zone of origin for Scenario 1 and SC1.

Zone	Scenario	Min Dwell Time (s) (min - max)	Max Dwell Time (s) (min - max)	Avg Dwell Time (s) (min - max)	Number of PAXs
1	1	2.6 (1.3 - 5.9)	48.1 (28.1 - 79.0)	19.8 (14.3 - 26.1)	48
	SC1	3.0 (1.3 - 11.8)	65.9 (42.9 - 107.0)	32.9 (21 - 56.6)	48
2	1	3.8 (1.8 - 12.5)	81.7 (52.2 - 129.4)	40.1 (27.9 - 57.9)	36
	SC1	3.8 (1.8 - 13.5)	77.1 (47.5 - 121.1)	38.9 (25.9 - 58.1)	36
3	1	3.9 (1.7 - 14.6)	89.2 (42.5 - 128.1)	38.3 (23.7 - 62.5)	30
	SC1	3.8 (1.8 - 12.5)	66.4 (38.7 - 117.9)	33.0 (22.4 - 54.1)	30
4	1	4.3 (1.6 - 42.7)	92.7 (59.4 - 118.4)	51.4 (34.1 - 71.5)	30
	SC1	10.3 (1.6 - 57.9)	89.9 (60.3 - 140.2)	58.4 (37.6 - 97.5)	30
5	1	4.4 (1.6 - 21.8)	95.0 (76.9 - 110.8)	65.0 (46.6 - 82.6)	36
	SC1	7.3 (1.6 - 34.8)	120.0 (84.8 - 169.9)	87.8 (59.1 - 132.1)	36

Similarly, the minimum time a passenger spent in Zone 05 across all 1000 simulations was 1.6 s, the average minimum time was 4.4 s, the maximum time was 110.8 s, and the average maximum time was 95.0 s. In comparison, in SC1, the average dwell time in Zone 05 was 87.8 s, with the minimum time a passenger spent in Zone 05 being 1.6 s, the average minimum time was 7.3 s, the maximum time was 169.9 s, and the average maximum time was 120.0 s. Thus, across the 1000 simulations, with 25% of the population retrieving their luggage, passengers in Zone 5 spend, on average, an additional 22.8 s (35%) exposed to the conditions of Zone 05.

In the event of a serious post-crash fire that gains access to the rear of the cabin, the large increase in average dwell time for passengers in Zone 05 resulting from luggage retrievers can represent a significant additional exposure to fire hazards, which can have fatal consequences.

In contrast, for Scenario 1, the average dwell time in Zone 01 is 19.8 s, while the minimum time a passenger spent in Zone 01 across all 1000 simulations is 1.3 s, the maximum time is 79.0 s, and the average maximum time is 48.1 s. In comparison, in SC1, the average dwell time in Zone 01 is 32.9 s, with the minimum time a passenger spent in Zone 01 being 1.3 s and the maximum time being 107.0 s, while the average maximum time is 65.9 s. Thus, across all the 1000 simulations, with 25% of the population retrieving their luggage, passengers in Zone 01 spend, on average, an additional 13.1 s (66%) exposed to the conditions of Zone 01. While this is a large percentage increase in average dwell time for Zone 01, the dwell time is reasonably small and so is not expected to be significant. In the event of a serious post-crash fire that gains access to the rear of the cabin (consistent with this scenario), passengers in the front of the cabin are furthest away from high concentrations of fire hazards that are likely to be located in the rear of the cabin. Thus, the increase in dwell time for passengers in Zone 01, while relatively large, is not expected to have significant consequences.

In Zone 02 the difference between the average dwell time is just 3%, but with SC1 being faster than Scenario 1. While the difference is small, on the surface, this is an odd result, as the scenario with luggage retrievers is faster. Similarly, for Zone 03, the difference between the average dwell times is 14%, somewhat larger, but again, with SC1, the case with luggage retrievers is quicker. As both these zones predominately utilise the two Type-III overwing exits, it could be that the presence of luggage retrievers preferentially slows the flow to one of the heavily congested Type-III exits from one zone, allowing passengers from the other zone to make full use of both exits and resulting in a slightly lower average dwell time.

Presented in Table 34 are the average minimum, maximum, and average ***evacuation times*** for passengers originating in each zone. The values represent the average from the 1000 simulations of the minimum zonal evacuation time, the maximum zonal evacuation time, and the average zonal evacuation time. For Scenario 1, the average evacuation time in Zone 05 is 99 s. This is determined by calculating the average evacuation time for all the passengers starting in Zone 05 in a simulation and then averaging across all 1000 simulations. Similarly, the average minimum time a passenger spent evacuating from Zone 05 across all 1000 simulations is 64.1 s, while the minimum time a passenger spent evacuating from Zone 05 across all 1000 simulations is 29 s, and the maximum time is 138.1 s. In comparison, in SC1, the average evacuation time for passengers starting in Zone 05 is 114 s, with an average minimum evacuation time from Zone 05 of 78.5 s and a maximum time of 187.6 s.

Thus, across all 1000 simulations, with 25% of the population retrieving their luggage, passengers in Zone 05 spend an additional 15 s (15%), on average, evacuating compared to the situation without luggage retrievers. While this increase in average Zone 05 evacuation time does not seem significant, recall that the passengers in Zone 05 spend an additional 22.5 s (35%) exposed to the conditions of Zone 05. While these two times may appear contradictory, they can be explained by the nature of the delays incurred. Passengers in Zone 05 are greatly delayed from leaving Zone 05 by the luggage retrievers in Zones 03, 04, and 05. This results in an additional average 22.5 s incurred in exiting

Zone 05. However, with this delay, the conditions ahead of Zone 05 have cleared, making the rest of the evacuation easier; hence, the overall delay in evacuating the aircraft incurred by passengers in Zone 05 is only 15 s. However, the longer average dwell time in Zone 05 can be significant, as it potentially exposes the passengers to hazardous conditions that may develop in this zone resulting from a post-crash fire.

For Scenario 1, the average evacuation time in Zone 01 is 30.1 s. The average minimum time a passenger spent evacuating from Zone 01 across all 1000 simulations is 8.4 s, while the minimum time a passenger spent evacuating from Zone 01 across all 1000 simulations is 8.1 s, and the maximum time is 125.1 s. In comparison, in SC1, the average evacuation time for passengers starting in Zone 01 is 42.1 s, with an average minimum evacuation time from Zone 01 across all 1000 simulations of 9.2 s and a maximum time of 123.7 s.

Table 34: Average (across 1000 simulations) minimum, maximum, and average PET based on zone of origin for Scenario 1 and SC1.

Zone	Scenario	Min PET (s) (min - max)	Max PET (s) (min - max)	Avg PET (s) (min - max)	Number of PAXs
1	1	8.4 (8.1 - 10.6)	81.7 (50.2 - 125.1)	30.1 (24.8 - 37.4)	48
	SC1	9.2 (8.2 - 22.8)	86.0 (58.9 - 123.7)	42.1 (29.7 - 64.7)	48
2	1	13 (12 - 16.6)	90.9 (60.1 - 131)	44.5 (31.9 - 60.7)	36
	SC1	13.1 (11.9 - 16.7)	83.9 (51.6 - 130.1)	43.4 (31.8 - 64.6)	36
3	1	13.0 (11.9 - 19.9)	98.1 (46.2 - 132.4)	43.3 (29 - 68.5)	30
	SC1	13.0 (11.9 - 16.3)	75.1 (41.9 - 132.5)	37.7 (27.2 - 58.3)	30
4	1	31.5 (15.1 - 63.6)	111.1 (82.3 - 138.5)	72.8 (55.7 - 91.3)	30
	SC1	38.5 (16.1 - 75.3)	105.0 (77.5 - 146.2)	75.7 (57.3 - 107.8)	30
5	1	64.1 (29 - 96.3)	120.2 (106.4 - 138.1)	99.0 (80.6 - 113.1)	36
	SC1	78.5 (30.9 - 124.7)	138.3 (111.5 - 187.6)	114.0 (91.3 - 160.6)	36

Thus, across all 1000 simulations, with 25% of the population retrieving their luggage, passengers in Zone 01 spend an additional 12.0 s (40%), on average, evacuating compared to the situation without luggage retrievers. While this increase in average Zone 01 evacuation time seems significant, the evacuation time is still small, being just 42 s on average.

It is also noted that the average evacuation times for passengers in Zones 02 and 03 for the scenario with the luggage retrievers is less than that for the scenario without luggage retrievers. Again, while a surprising result, this is possibly due to the better use of the heavily congested Type-III exits that luggage retrieval enables by preferentially allowing one zone to fully utilise both exits momentarily throughout the evacuation.

Finally, note that the minimum evacuation time for Zone 05 is quite small, 29.0 s for Scenario 1 and 30.9 s for SC1. These surprisingly small evacuation times can be explained by passengers seated on the boundary between Zone 04 and Zone 05 with very short response times and large walking speeds.

It is important to note that in SC1, it was assumed that NO passengers are able to by-pass luggage retrievers. As identified in Section 5.1, this is an overly pessimistic assumption, so it is likely that the impact of luggage retrievers on evacuation performance will not be as severe as suggested in this analysis. In the next section, we explore the impact of having everyone pass, while in Section 6.4, an arguably more realistic scenario is explored.

(b) Sensitivity cases 2-4, 100% BPP, speed reduction factors of 0.4, 0.5 and 0.6
Sensitivity cases SC2 (speed reduction [SR] 0.4), SC3 (SR 0.5), and SC4 (SR 0.6) are intended to demonstrate the impact of the speed reduction factor on the walking speed of passengers as they overtake a passenger attempting to retrieve their luggage. Thus, unlike in SC1, ALL passengers can overtake a passenger retrieving their luggage, and all overtaking passengers have a fixed speed reduction factor representing the reduced walking speed incurred when passengers overtake someone retrieving their luggage.

It is expected that all of these cases will produce shorter total evacuation times than those generated for SC1 and, as shown in Table 35, this is indeed the case. This is most clearly shown in the average value for the average personal evacuation time (PET) and the total evacuation time (TET).

Table 35: Key evacuation parameters (CWT, PET, and TET) for all four sensitivity cases for the simulations producing the minimum, median, and maximum evacuation times and the average value across all 1000 repeat simulations.

Scenario	Parameter	Min Sim	*Median Sim	Max Sim	Average value
SC1: LC25% BPP0%	Avg. CWT	40.5	40.3	54.7	43.6
	Avg. PET	58.3	58.2	73.8	61.6
	TET	112.6	137.2	187.6	139.3
SC2: LC25% BPP100% SR0.4	Avg. CWT	34.3	41.1	48.0	40.2
	Avg. PET	52.2	60.0	66.4	58.4
	TET	110.2	126.7	176.6	129.5
SC3: LC25% BPP100% SR0.5	Avg. CWT	36.0	37.8	53.4	39.9
	Avg. PET	53.8	56.0	71.6	58.0
	TET	110.4	126.1	180.5	128.9
SC4: LC25% BPP100% SR0.6	Avg. CWT	32.7	38.2	52.5	39.9
	Avg. PET	51.5	56.1	71.5	57.8
	TET	111.1	126.4	177.9	129.4

**Median sim is the 501st simulation.*

It is also noted that there is little difference in the average values for the average PET and TET, as the SR varies from 0.4 (representing travelling at 40% of the walking speed while overtaking) to 0.6 (representing travelling at 60% of the walking speed). Thus, the overall results do not appear to be overly sensitive to the SR, at least for SR in the range of 0.4 to 0.6.

Presented in Figure 35, Figure 36, and Figure 37 are the evacuation curves for the minimum, median, and maximum evacuation times, respectively, for all four sensitivity cases. As can be seen, the total evacuation time for SC2, SC3, and SC4 are all shorter than for SC1. Furthermore, throughout most of the evacuation, times for a given number of passengers to have evacuated are shorter than for SC1. Throughout the evacuation, while there is some small variation between cases SC2, SC3, and SC4, this variation is generally small, suggesting that the evacuation outcome is not strongly dependent on the SR in the range of 0.4 to 0.6.

Presented in Figure 38, Figure 39, and Figure 40 are the frequency distributions of the evacuation times for SC1 and SC2, SC1 and SC3, and SC1 and SC4, respectively. Clearly, allowing **ALL** passengers to overtake luggage retrieving passengers produces a higher frequency of simulations with shorter evacuation times and fewer simulations with higher evacuation times. This is to be expected, as in SC1, all passengers are effectively blocked by passengers attempting to retrieve their luggage, so no one is able to bypass the luggage retriever, resulting in longer evacuation times.

The sensitivity study suggests that while it is important to enable passengers to by-pass luggage retrievers in the process of retrieving their luggage, the results are not sensitive to the precise value of the minimum speed reduction factor (upper limit of range), with reduction factors of 0.4, 0.5, and 0.6 producing similar results. The minimum speed reduction factor implemented in the remaining analysis is therefore set at 0.5, with a range of 0.1 to 0.5, as described in Section 6.1.

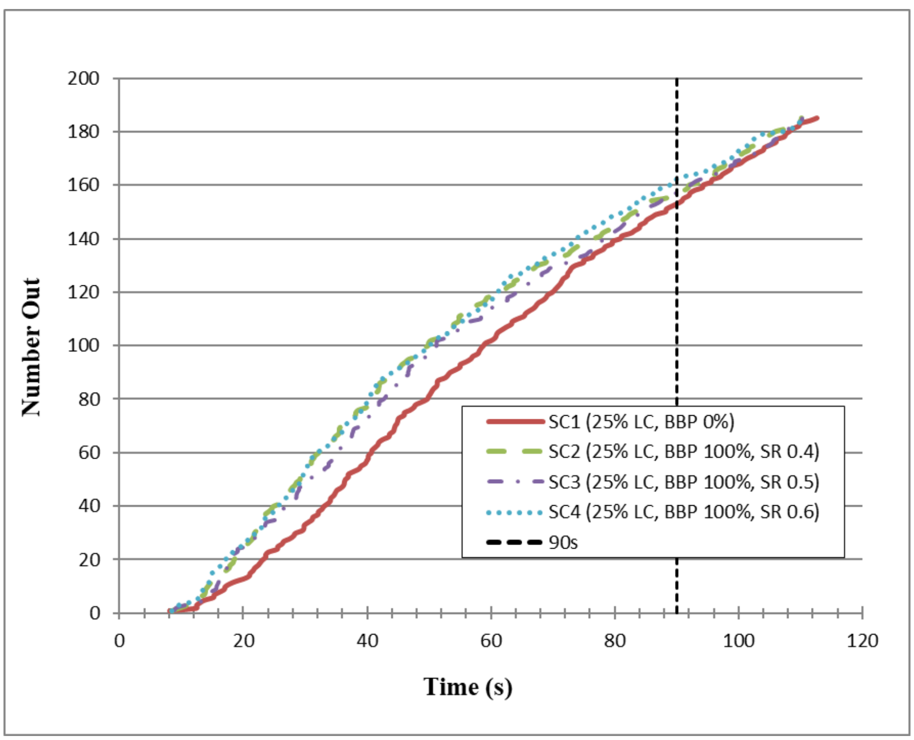


Figure 35: Evacuation curves for the minimum evacuation time case for the four sensitivity cases.

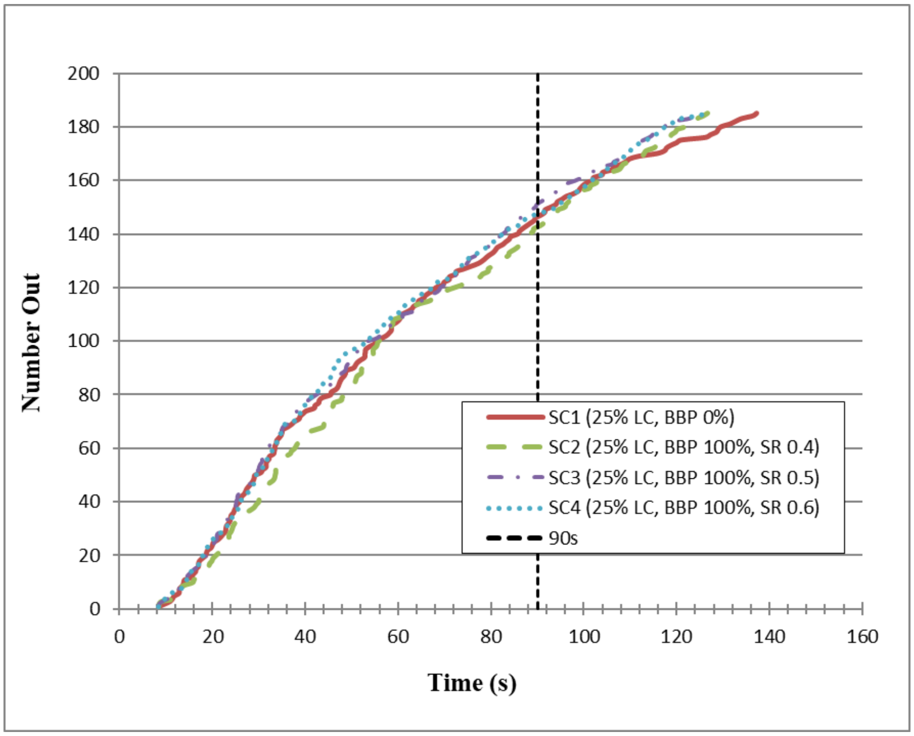


Figure 36: Evacuation curves for the median evacuation time case for the four sensitivity cases.

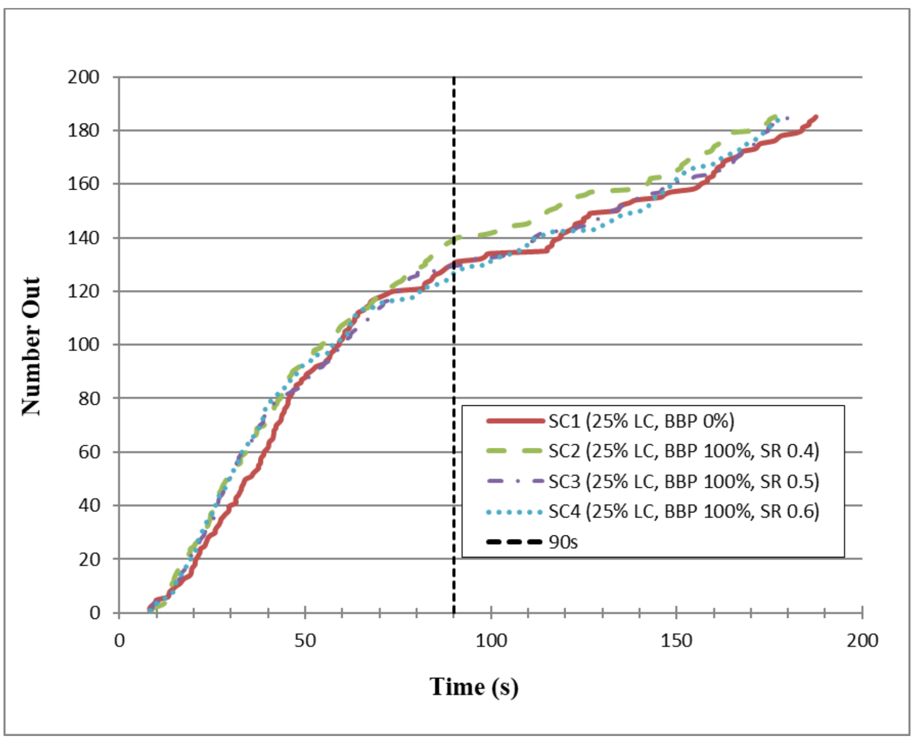


Figure 37: Evacuation curves for the maximum evacuation time case for the four sensitivity cases.

Also, it is important to note that in SC2, SC3, and SC4, it was assumed that ALL passengers can by-pass luggage retrievers. As identified in Section 5.1, this is an overly optimistic assumption, so it is likely that the impact of luggage retrievers on evacuation performance will be more severe than suggested in this analysis. Indeed, it is expected that the reality falls somewhere between the two extremes of SC1 and SC2. In Section 6.3, an arguably more realistic scenario is explored.

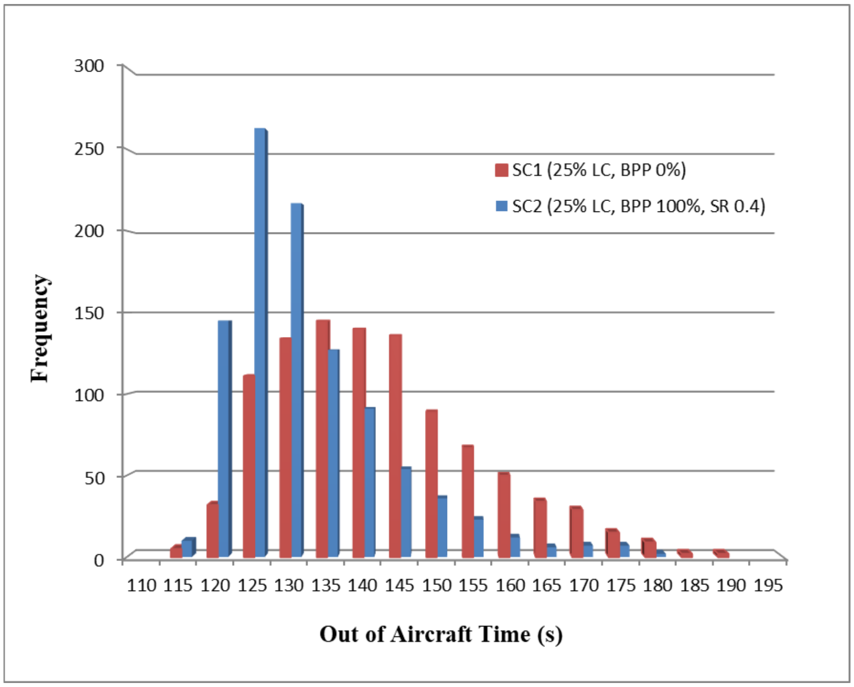


Figure 38: Evacuation time frequency distribution for SC1 and SC2.

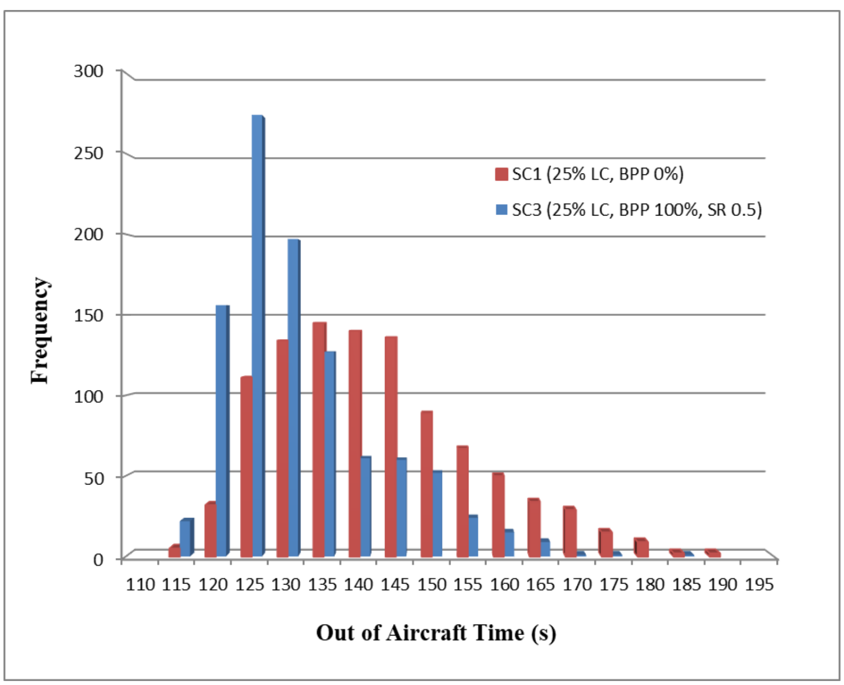


Figure 39: Evacuation time frequency distribution for SC1 and SC3.

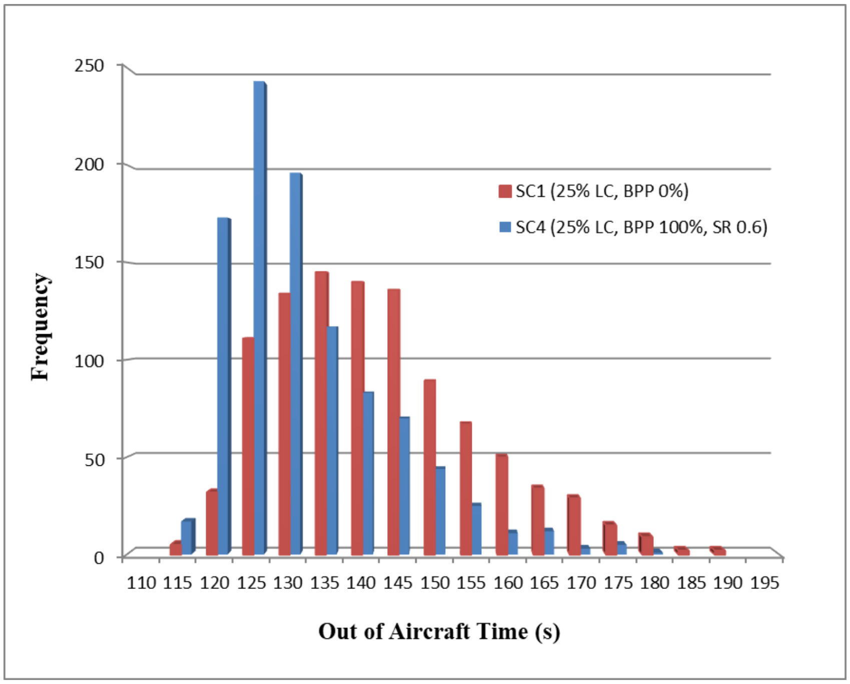
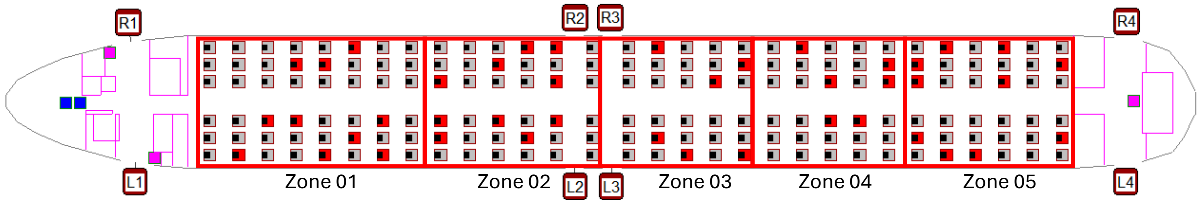


Figure 40: Evacuation time frequency distribution for SC1 and SC4.

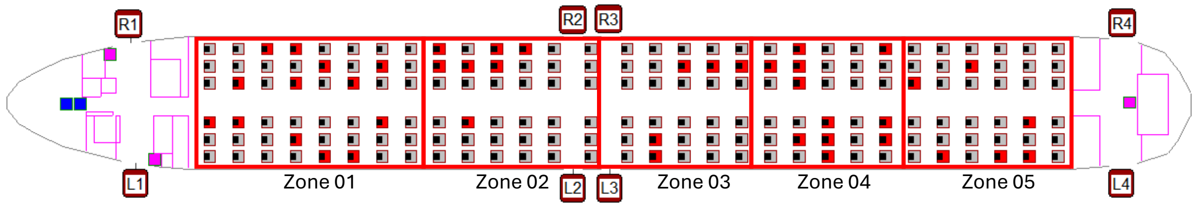
6.3 Scenario 2 Setup — Seating Location of Luggage Retrievers

As two rows of seats are excluded from containing luggage retrievers (last row of Zone 02 and first row of Zone 03), this reduces the number of potential luggage collectors from 180 passengers to 168. Thus, for Scenario 2, with 25% luggage collectors, there are 42 passengers attempting to retrieve their luggage.

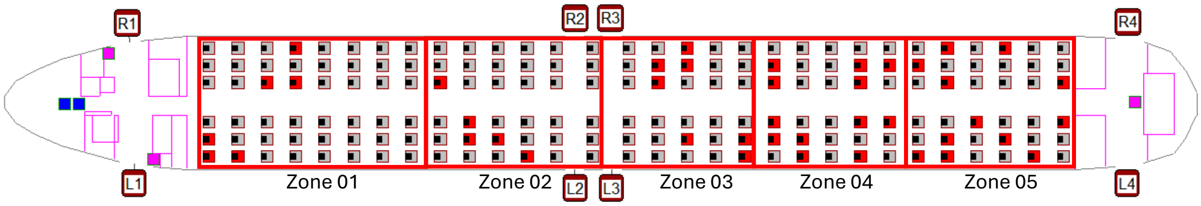
Presented in Figure 41 is the seating location for the luggage retrievers (red coloured seats) for the simulations producing the minimum, median, and maximum Total Evacuation Time (TET). Note that some seat rows have up to four luggage retrievers.



(a) Minimum



(b) Median



(c) Maximum

Figure 41: Seating locations of luggage retrievers in Scenario 2 (red-coloured seats) for the (a) minimum, (b) median, and (c) maximum evacuation time.

Presented in Table 36 are the number of luggage retrievers in each zone for the minimum, median, and maximum simulations for Scenario 2, while presented in Table 37 are the minimum, average, and maximum number of luggage retrievers in each zone across the 1000 simulations. Clearly, the distribution of luggage retrievers will impact the overall evacuation times and the performance of passengers within each zone. As seen in Table 37, there can be a large variation in the number of luggage retrievers in each zone over the 1000 repeat simulations; for example, in Zone 05, the number varies from 3 to 16, with an average of 9. While the range in the number of luggage retrievers across all 1000 simulations is similar to that in SC1 (see Table 30), the precise number of luggage retrievers in each zone for the minimum, median, and maximum scenarios in Scenario 2 (see Table 36) is quite different to that in SC1 (see Table 29).

Table 36: Number of luggage retrievers in each zone for various repeat simulations for Scenario 2.

	Zone 01	Zone 02	Zone 03	Zone 04	Zone 05	Total
Min sim	10	10	6	6	10	42
***Median sim**	13	7	5	11	6	42
Max sim	6	5	7	12	12	42

**Median sim is the 501st simulation.*

Table 37: Minimum number, average, and maximum number of luggage retrievers in each zone across all 1000 repeat simulations for Scenario 2.

	Zone 01	Zone 02	Zone 03	Zone 04	Zone 05
Min	5	1	1	1	3
Average	12	7.6	5.9	7.5	9
Max	21	15	11	14	16

6.4 Scenario 2 (25% Luggage Retrievers) Results and Analysis

Here, the results for Scenario 2 are presented. In this scenario, 25% of the passengers (i.e., 42) attempt to retrieve their luggage and incur a delay time derived from the distribution presented in Section 4.3, Table 18. The probability that passengers will attempt to by-pass the luggage retriever is approximated by the normal distribution presented in Section 6.1 Figure 31, while the by-pass speed reduction factor is based on a uniform random distribution between 0.1 and 0.5 described in Section 6.1.

(a) Scenario 2 (25% luggage retrievers) general results and analysis

Presented in Figure 42 are the exit curves for Scenario 2 (25% luggage retrievers) together with those for Scenario 1 (no luggage retrievers) for the simulations producing the minimum, median, and maximum simulations, while key simulation parameters are reported in Table 38.

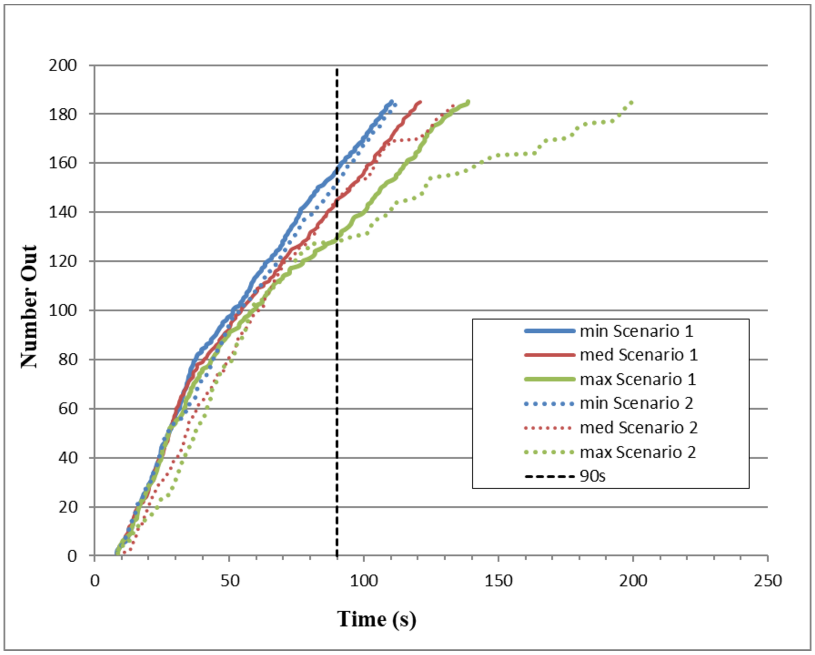


Figure 42: Evacuation curves for Scenario 1 (base case) and Scenario 2.

From Table 38, we note that over the 1000 repeat simulations, the TET for Scenario 2 varies from 111.7 s to 200.2 s (with an average of 136.8 s), with the corresponding average personal evacuation time (PET) varying from 54.5 to 74.6 s (note that the absolute range of average PET varies from 54.2 s to 74.6s). By 90 s, between 84% (155) and 65% (120) of the 185 occupants or an average of 143 (77%) have evacuated. Furthermore, it is clear from both Figure 42 and Table 38 that the impact of the luggage retrievers in Scenario 2 is not uniform throughout a simulation (early part of the evacuation can be more or less impacted than the final part of the evacuation) and can vary significantly between repeat simulations.

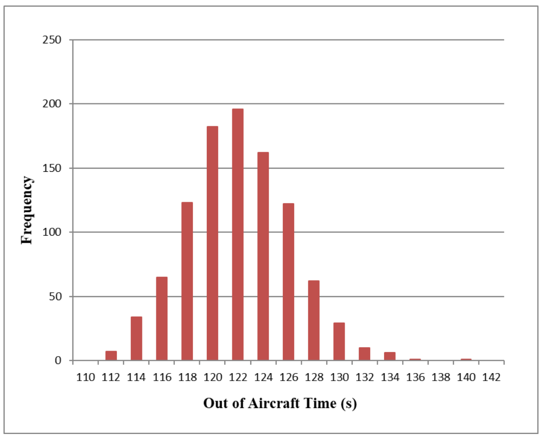
Presented in Figure 43 are the TET frequency distributions for Scenario 1 (a), Scenario 2 (b), and Scenario 1 and Scenario 2 (c). Clearly, having 25% of passengers retrieve their luggage can significantly impact TET. Without luggage retrieval, only approximately 2% (18) of the simulations have a total evacuation time in excess of 130 s, while with 25% luggage retrieval, almost 67% (667) exceed 130 s, and 37% (365) exceed 140 s.

From Figure 43c, it is clear that the two simulations producing the longest evacuation times are outliers, with the maximum simulation producing an evacuation time of 200.2 s, the next longest producing an evacuation time of 195.6 s, and the next longest producing an evacuation time of 181.2 s. While the last two simulations may be outliers in terms of the total evacuation time produced, the evacuation behaviours exhibited by the agents within the simulations are not unusual or anomalies but plausible responses given the conditions within these simulations.

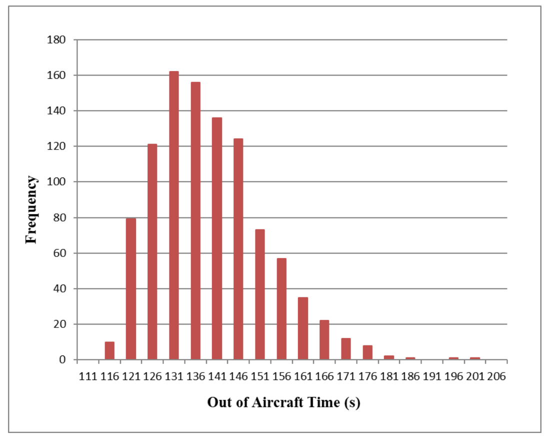
Table 38: Simulation parameters from Scenario 1 and Scenario 2 for the simulations producing the minimum, median, maximum, and 95th percentile evacuation times.

Sim	Avg. CWT (s)		Avg. Distance (m)		Avg. PET (s)		TET (s)	
	S1 0% LC	S2 25% LC	S1 0% LC	S2 25% LC	S1 0% LC	S2 25% LC	S1 0% LC	S2 25% LC
Min Sim	36.6	37.1	7.6	7.9	52.1	54.5	110.1	111.7
***Median Sim**	40.6	43.2	7.7	8	56.2	61.1	120.9	135.0
Max Sim	45.8	54.6	7.8	8.5	61.9	74.6	138.5	200.2
95th% Sim	44.3	43.4	7.7	8	60.3	61.5	127.7	160.2

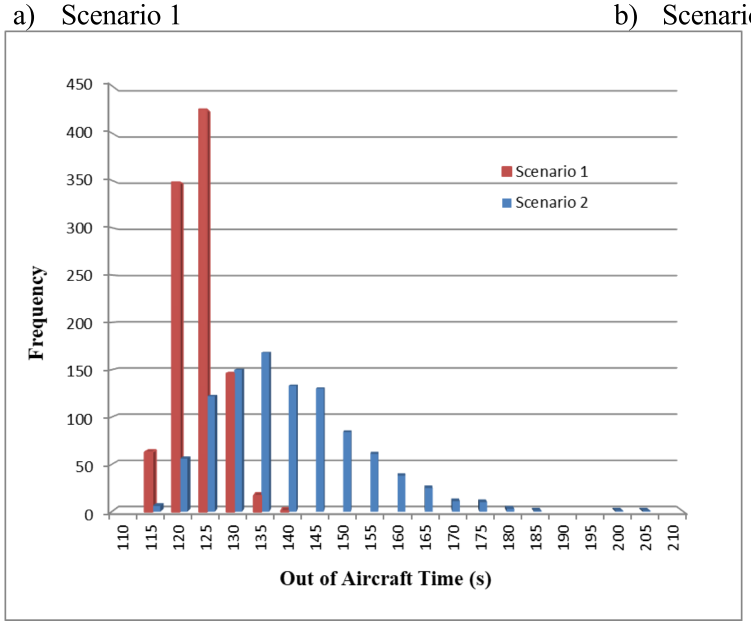
**Median sim is the 501st simulation.*



a) Scenario 1



b) Scenario 2



c) Scenario 1 and Scenario 2

Figure 43: TET frequency distribution for (a) Scenario 1 (0% luggage retrievers), (b) Scenario 2 (25% luggage retrievers), and (c) Scenario 1 and Scenario 2.

Consider the exit curve for the simulation producing the maximum evacuation time (see Figure 44). It is clear that there are several plateaux that form during the second phase of the evacuation when only the two Type-III exits are functioning (i.e., portion of the curve with a sharp reduction in gradient, signifying front two Type-I exits are no longer being used). These plateaux are formed by significant reductions in exit flow resulting from few, if any, passengers exiting through the Type-III exits due to aisle blockages formed by passengers retrieving cabin luggage in the rear part of the aircraft (Zones 04 and 05). The first plateau consists of two intervals from 80.7 s to 100.8 s. The first interval is from 80.7 s (127 people have exited) to 88.9 s (128 people have exited), and the second interval is from 88.9 s to 100.8 s (131 people have exited). Over the first interval of 8.2 s, one person has exited, while over the second interval of 11.9 s, three have exited.

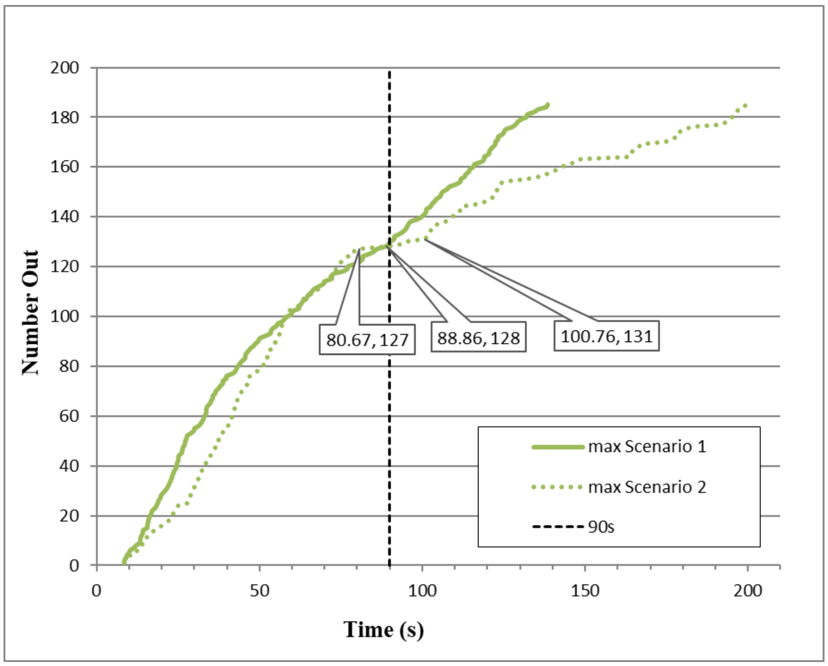
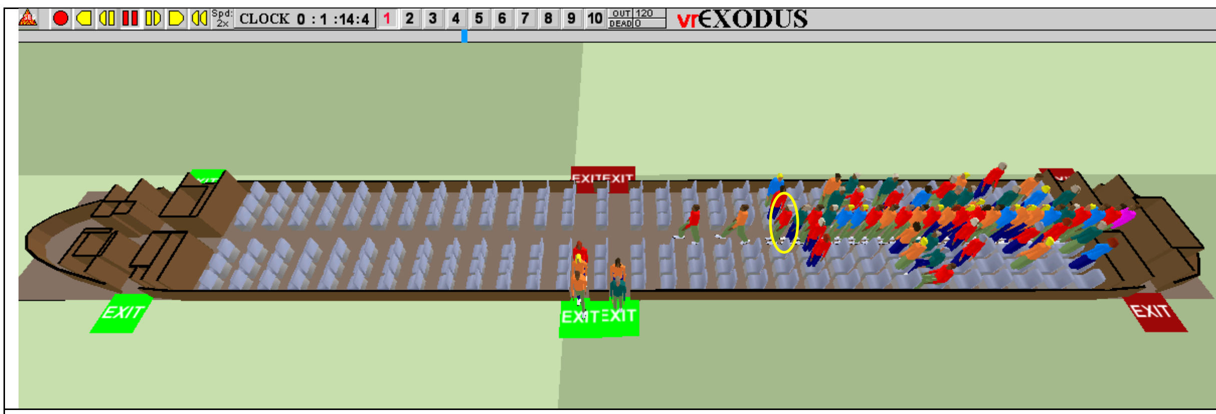


Figure 44: Evacuation curves for Scenario 1 (base case) and Scenario 2 maximum evacuation time.

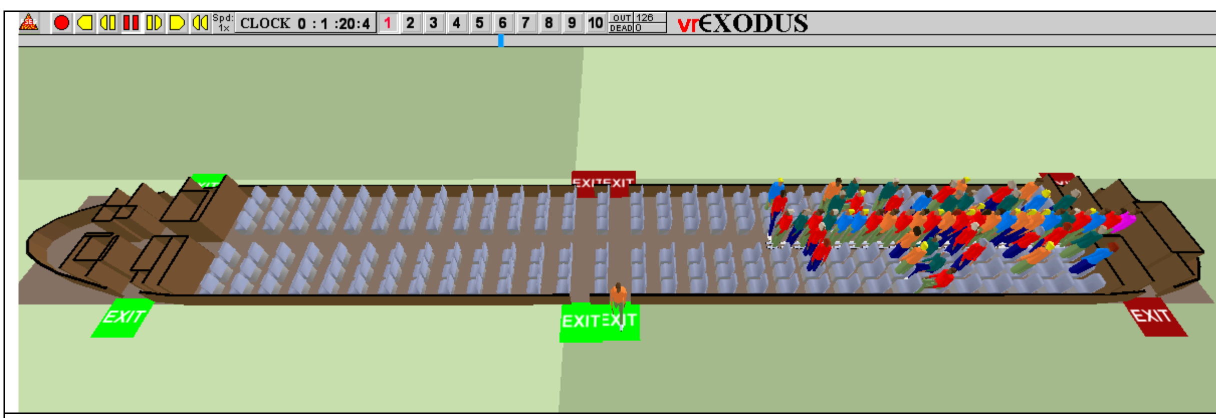
The first plateau interval is caused by the luggage collector seated in 20D (first row of Zone 04) who starts to retrieve their luggage at 74.4 s (see Figure 45a). They are allocated a luggage retrieval delay time of 6.2 s, with a pass probability of 0.45 and a passenger overtaking speed reduction of 0.12. At about 80.4 s, the luggage collector has completed retrieving their luggage, and as no passengers have managed to overtake them (given the low pass probability), the aisle ahead is clear (see Figure 45b). At this time, the last person prior to the start of the plateau exits using the rear overwing exit, marking the start of the first interval (see Figure 45b).

At 82.3 s, the first luggage collector is walking down the clear aisle to exit via the overwing exit (see Figure 45c), while a second luggage collector from seat 20E blocks the aisle to retrieve their luggage. Furthermore, as the second luggage collector was in the adjacent seat to the first luggage collector, no one has managed to follow the first luggage collector down the aisle before the second luggage collector blocks the aisle, potentially creating another gap behind the first luggage collector (see Figure 45c). The second luggage collector has a luggage retrieval delay time of 3.5 s, with a pass probability of 0.58 and a passenger overtaking speed reduction of 0.16. At 85.2 s, the second luggage collector has completed their luggage retrieval, and no one has managed to overtake them (see Figure 45d). At this time, the first luggage collector is approaching the overwing exit. At 88.1 s, the first luggage collector (from seat 20D) is about to exit via the rear overwing exit and will eventually exit at 88.9 s, marking the end of the first plateau (see Figure 45e).

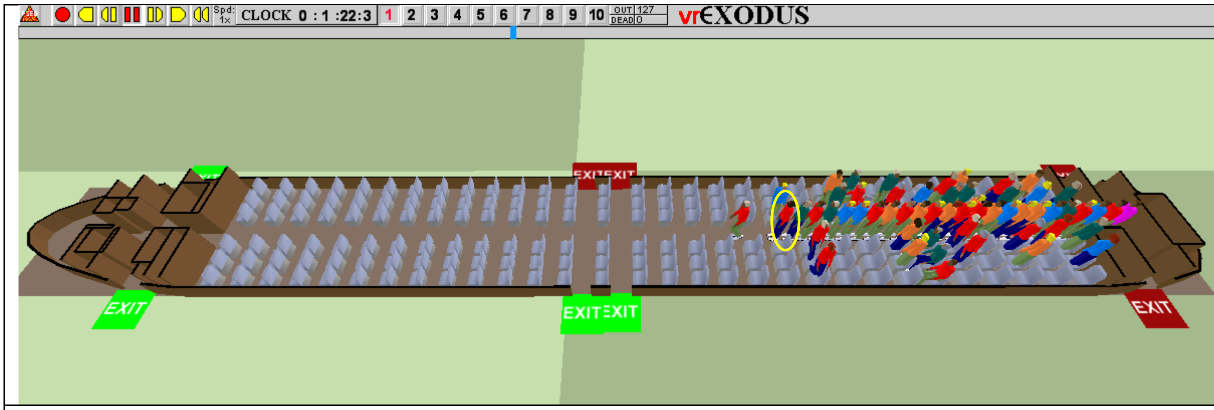
The first interval of the first plateau in the exit curve resulted from having three luggage collectors in the same row attempting to retrieve their luggage at similar times (20B at 62.6 s, 20D at 74.4 s, and 20E at 82.3 s), located towards the rear of the aircraft and in the second phase of the evacuation when the forward exits are no longer being used (hence, maximising the impact of these events). Furthermore, no one managed to overtake the luggage collectors from seats 20D and 20E. It is also noted that for the simulation producing the maximum evacuation time, 24 luggage collectors were in Zones 04 and 05, while in the simulation producing the minimum evacuation time, only 16 luggage collectors were in these zones (see Table 36). Thus, it is an unfortunate combination of random factors that produced the maximum evacuation time, but clearly, a combination that can result from 1000 repeat simulations.



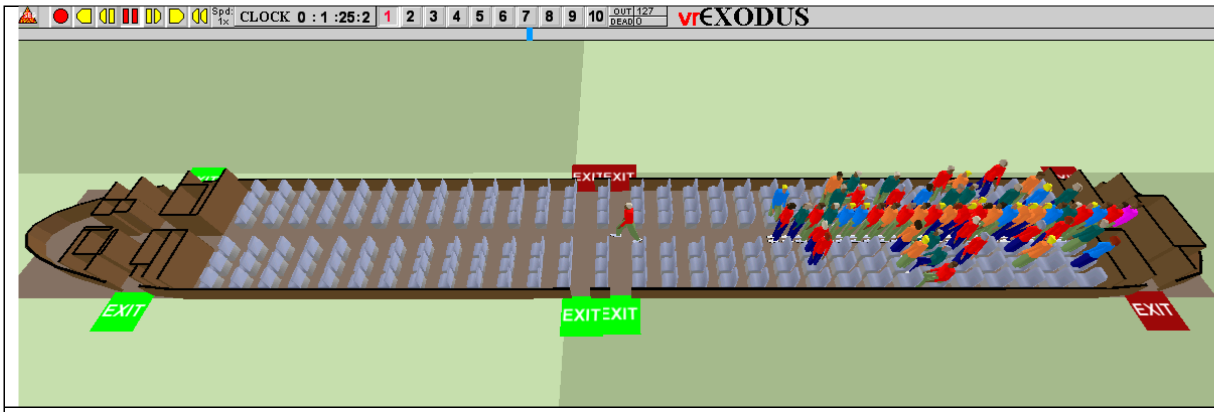
(a) Luggage collector from seat 20D (red agent highlighted in yellow oval) starts luggage retrieval at approximately 74.4 s.



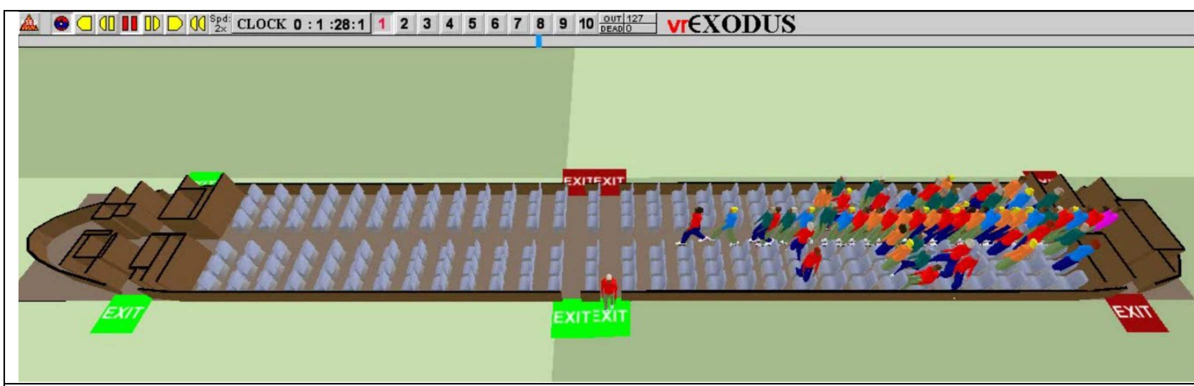
(b) Luggage collector from seat 20D completes luggage collection at 80.4 s and begins to walk down the aisle.



(c) Luggage collector from seat 20D is walking towards the overwing exits with no one in front of them, while another luggage collector from seat 20E (red agent highlighted in yellow oval) starts to retrieve their luggage at 82.3 s.



(d) Luggage collector from seat 20E completes luggage collection at 85.2 s and begins to walk down the aisle. The luggage collector from seat 20D is about to turn into the exit aisle and exit via the rear Type-III overwing exit.



(e) Luggage collector from seat 20D is about to exit at 88.1 s, with the next person in the aisle being the luggage collector from 20E.

Figure 45: Images from vrEXODUS for the simulation producing the maximum evacuation time and showing luggage retrieval process contributing to the first interval (80.7 s to 88.9 s) in the first plateau in the exit curve.

However, the nature of the model has also contributed to how these events played out. For example, if the by-pass probability distribution (see Figure 31 in Section 6.1) was biased towards increased probability of producing higher by-pass probabilities, this situation may have been resolved by randomly generating and allocating a higher by-pass probability to the passengers attempting to pass the luggage collectors from seats 20D and 20E. Furthermore, if the model allowed multiple attempts at performing a by-pass manoeuvre for a single encounter, the situation could have been resolved.

(b) Impact of 25% luggage retrievers on evacuation time
For the simulations producing the minimum TET for Scenario 1 and Scenario 2, the TET is increased by only 1.5% (see Table 39) when luggage retrievers are included. However, the early stages of the evacuation result in significantly longer evacuation times for Scenario 2, e.g., by the time 80 passengers have evacuated, the evacuation time is some 17.3% longer for Scenario 2 (see ANNEX C). By 90 s, 157 (85%) occupants have evacuated in Scenario 1, and 151 (82%) occupants have evacuated in Scenario 2. Furthermore, the average PET is some 4.6% longer in the minimum simulation when luggage collectors are included (see Table 38 and Table 39).

To correctly interpret simulation results, it is important to recall two key model assumptions: first, passengers located in seat rows cannot by-pass a luggage retriever, and secondly, aisle by-pass is only possible if there is sufficient space ahead of the luggage retriever (see Section 5.1).

In the minimum simulation, the 42 luggage retrievers directly impacted 44 potential by-pass events: 14 in the aisle that could have occurred as there was sufficient space and 30 located in seat rows (see Table 38). However, the seated passengers involved in the 30 seat row events are not able to by-pass the luggage collector, so they are effectively trapped until the luggage collector has retrieved their luggage. Of the 14 possible aisle by-pass events, 6 (or 43%) were successfully implemented.

Thus, for the simulation producing the *minimum TET*, with 25% (42) of the passengers attempting to retrieve their luggage, 6 of the 14 (43%) attempts to by-pass luggage retrievers in the aisle were successful, with the TET increasing marginally from 110.1 s to 111.7 s (1.5%) and the average PET also increasing by a relatively small amount from 52.1 s to 54.5 s (4.6%).

For the simulations producing the maximum TET for Scenario 1 and Scenario 2, the TET increases by 44.5% (see Table 38) when luggage retrievers are included. In the early stages of the evacuation, there are also large increases in evacuation times for Scenario 2, e.g., by the time 40 passengers have evacuated, the evacuation time is some 36.7% longer for Scenario 2, and when 80 passengers have evacuated, the increase in evacuation time is 18% (see ANNEX C). By 90 s, 129 (70%) occupants have evacuated in Scenario 1, and 128 (69%) occupants have evacuated in Scenario 2. Furthermore, the average PET is some 20.5% longer in the maximum simulation when luggage collectors are included (see Table 38).

In the maximum simulation, the 42 luggage retrievers directly impacted 86 potential by-pass events: 46 in the aisle that could have occurred, as there was sufficient space, and 40 located in seat rows (see Table 38). However, the seated passengers involved in the 40 seat row events are not able to by-pass the luggage collector, so they are effectively trapped until the luggage collector has retrieved their luggage. Of the 46 possible aisle by-pass events, 24 (52%) were successfully implemented.

Thus, for the simulation producing the *maximum TET*, with 25% (42) of the passengers attempting to retrieve their luggage, 24 of the 46 (52%) attempts to by-pass luggage retrievers in the aisle were successful, with the TET increasing significantly from 138.5 s to 200.2 s (44.5%), and the average PET also increasing significantly from 61.9 s to 74.6 s (20.5%).

For the simulations producing the median TET time for Scenario 1 and Scenario 2, the TET increases by 11.7% (see Table 38) when luggage retrievers are included. However, in the early stages of the evacuation, there are larger increases in evacuation times for Scenario 2, e.g., by the time 40 passengers have evacuated, the evacuation time is some 22.6% longer for Scenario 2, and when 80 passengers have evacuated, the increase in evacuation time is 22.2% (see ANNEX C). By 90 s, 145 (78%) occupants have evacuated in Scenario 1 and 145 (78%) occupants have evacuated in Scenario 2. Furthermore, the average PET is only 8.7% longer in the median simulation when luggage collectors are included (see Table 39Table 38).

In the median simulation, the 42 luggage retrievers directly impacted 53 potential by-pass events: 18 in the aisle that could have occurred, as there was sufficient space, and 35 located in seat rows (see Table 38). However, the seated passengers involved in the 35 seat row events are not able to by-pass the luggage collector, so they are effectively trapped until the luggage collector has retrieved their luggage. Of the 18 possible aisle by-pass events, 7 (39%) were successfully implemented.

Thus, for the simulation producing the *median TET*, with 25% (42) of the passengers attempting to retrieve their luggage, 7 of the 18 (39%) attempts to by-pass luggage retrievers in the aisle were successful, with the TET increasing by a large amount from 120.9 s to 135.0 s (11.7%) and the average PET increasing by a slightly smaller amount from 56.2 s to 61.1 s (8.7%).

It is noted that not many passengers appear to successfully by-pass the 42 luggage collectors. In the simulations producing the minimum, median, and maximum evacuation times, there were 6, 7, and 24 successful by-pass events, respectively, by aisle passengers (see Table 39). The small numbers of passengers by-passing luggage collectors is due to several issues. Passengers cannot by-pass luggage collectors in a congested aisle, i.e., in situations where there is not sufficient clear space on the other side of the luggage collector. This will particularly be an issue early in the evacuation when the aisle is heavily congested.

Table 39: Increase in average PET and TET for Scenario 2 compared with Scenario 1.

Sim	Increase in Avg. PET (%)	Increase in TET (%)	Number of successful by-pass events	Number of unsuccessful by-pass events
Min Sim	4.6	1.5	6	38 (A8, S30)
***Median Sim**	8.7	11.7	7	46(A11, S35)
Max Sim	20.5	44.5	24	62(A22, S40)
95th% Sim	2	25.5	23	48(A16, S32)

**Median sim is the 501st simulation. A: aisle-located passenger, S: seat row-located passenger.*

Furthermore, each luggage collector is randomly assigned a by-pass probability that varies from 0.0 to 1.0 (see Section 6.1 Figure 31) and if this probability is low, there is less chance that a passenger will be able to by-pass the luggage collector. For example, consider the two luggage collectors described in Figure 45 who have entered the aisle late in the evacuation. These have been randomly assigned by-pass probabilities of 0.48 and 0.58, and while the aisle ahead of them was clear, no one was able to by-pass them during the luggage retrieval process. For each of these luggage collectors, there were two attempts at by-passing, but given the magnitude of the by-pass probability assigned (approximately a 50% chance that a passenger will be able to by-pass), they were all unsuccessful. However, in the simulations producing the minimum, median, 95th percentile, and maximum evacuation times, the successful by-pass rate is 43%, 39%, 59%, and 52%. These are reasonably high success rates that are consistent with the by-pass probability distribution presented in Figure 31.

(c) The impact of 25% luggage retrievers on zonal dwell times

A deeper understanding of the impact of luggage retrievers on the overall evacuation can be derived from investigating zonal dwell times. As described previously (see Section 6.2(a)), regardless of whether luggage retrievers are present, passengers in Zone 05 typically have the longest evacuation times, as they have the longest distance to travel to reach a viable exit, and the closest exits available to them are a pair of Type-III exits, i.e., relatively small and slow exits. They are also impacted by the behaviour of more passengers than those originating in other zones, as they are affected by the behaviour of passengers in Zone 03, Zone 04, Zone 05, and potentially Zone 02. They, therefore, will experience the greatest delays resulting from luggage retrievers, as there are likely to be a greater number of luggage retrievers in their evacuation path. In contrast, passengers in Zone 01 have the shortest evacuation times, as they have amongst the shortest travel distances to reach a viable exit, and the exits available to them are a pair of Type-C exits, i.e., relatively large and fast exits. They are also impacted only by the other passengers in their zone of origin, i.e., Zone 01. They are, therefore, likely to be impacted by the least number of luggage retrievers on their exit path.

Presented in Table 40 are the average minimum, maximum, and average ***dwell times*** for passengers originating in each zone. The values represent the average from the 1000 simulations of the minimum zonal dwell time, the maximum zonal dwell time, and the average zonal dwell time. For Scenario 1, the average dwell time (across all 1000 simulations) in Zone 05 is 65.0 s. This is determined by calculating the average dwell time in Zone 05 for all the passengers starting in Zone 05 in a simulation and then averaging this across all 1000 simulations.

Similarly, the minimum time a passenger spent in Zone 05 across all 1000 simulations is 1.6 s, the average minimum time is 4.4 s, the maximum time is 110.8 s, and the average maximum time is 95.0 s. In comparison, in Scenario 2, the average dwell time in Zone 05 is 85.1 s, with the minimum time a passenger spent in Zone 0 being 1.6 s, the average minimum time is 6.5 s, the maximum time is 177.6 s, and the average maximum time is 117.5 s. Thus, across the 1000 simulations, with 25% of the population retrieving their luggage, passengers in Zone 05 spend, on average, an additional 20.1 s (31%) exposed to the conditions of Zone 05. In the event of a serious post-crash fire that gains access to the rear of the cabin (see Section 6.2(a)), the large increase in average dwell time for passengers in Zone 05 resulting from luggage retrievers can represent a significant additional exposure to fire hazards, which can have fatal consequences.

In contrast, for Scenario 1, the average dwell time in Zone 01 is 19.8 s, while the minimum time a passenger spent in Zone 01 across all 1000 simulations is 1.3 s, the maximum time is 79.0 s, and the average maximum time is 48.1 s. In comparison, in Scenario 2, the average dwell time in Zone 01 is 31.5 s, with the minimum time a passenger spent in Zone 01 being 1.3 s and the maximum time being 96.0 s, while the average maximum time is 64.1 s. Thus, across all the 1000 simulations, with 25% of the population retrieving their luggage, passengers in Zone 01 spend, on average, an additional 11.7 s (59%) exposed to the conditions of Zone 01. While this is a large percentage increase in average dwell time for Zone 01, the dwell time is reasonably small, so it is not expected to be significant. In the event of a serious post-crash fire that gains access to the rear of the cabin (consistent with this scenario), passengers in the front of the cabin are furthest away from high concentrations of fire hazards that are likely to be located in the rear of the cabin. Thus, the increase in dwell time for passengers in Zone 01, while relatively large, is not expected to have significant consequences.

Table 40: Average (across 1000 simulations) passenger dwell time incurred by agents in their zone of origin for Scenario 1 and Scenario 2.

Zone	Scenario	Min Dwell Time (s) (min - max)	Max Dwell Time (s) (min - max)	Avg Dwell Time (s) (min - max)	Number of PAXs	Avg. Number of Luggage Collectors (min - max)
1	1	2.6 (1.3 - 5.9)	48.1 (28.1 - 79.0)	19.8 (14.3 - 26.1)	48	0
	2	3.0 (1.3 - 15.9)	64.1 (40.3 - 96.0)	31.5 (20.0 - 51.2)	48	12 (5 - 21)
2	1	3.8 (1.8 - 12.5)	81.7 (52.2 - 129.4)	40.1 (27.9 - 57.9)	36	0
	2	3.8 (1.7 - 14.8)	77.8 (44.6 - 118.9)	38.9 (26.1 - 62.5)	36	7.6 (1 - 15)
3	1	3.9 (1.7 - 14.6)	89.2 (42.5 - 128.1)	38.3 (23.7 - 62.5)	30	0
	2	3.9 (1.8 - 12.5)	67.6 (37.4 - 117.5)	33.1 (21.6 - 48.4)	30	5.9 (1 - 11)
4	1	4.3 (1.6 - 42.7)	92.7 (59.4 - 118.4)	51.4 (34.1 - 71.5)	30	0
	2	7.9 (1.6 - 61.8)	89.1 (54.4 - 137.7)	57.3 (36.4 - 91.0)	30	7.5 (1 - 14)
5	1	4.4 (1.6 - 21.8)	95.0 (76.9 - 110.8)	65.0 (46.6 - 82.6)	36	0
	2	6.5 (1.6 - 31.2)	117.5 (86.5 - 177.6)	85.1 (51.9 - 128.5)	36	9 (3 - 16)

In Zone 02, the difference between the average dwell time is just 3%, but with Scenario 2 being faster than Scenario 1. While the difference is small, on the surface, this is an odd result, as the scenario with luggage retrievers is faster. Similarly, for Zone 03, the difference between the average dwell times is 14%, somewhat larger, but again, with Scenario 2, the case with luggage retrievers being quicker. As both these zones predominantly utilise the two Type-III overwing exits, it could be that the presence of luggage retrievers preferentially slows the flow to one of the heavily congested Type-III exits from one zone, allowing passengers from the other zone to make full use of both exits and resulting in a slightly lower average dwell time.

Thus, in evacuation scenarios involving only three available exits, the two front exits and two overwing exits located on one side of the aircraft, even with just one in four passengers attempting to retrieve cabin luggage, there can be a significant increase in dwell times incurred by some passengers (i.e., those in the rear of the aircraft (Zone 05)) and in total evacuation times for the aircraft, at least for some of the 1000 repeat simulations. However, this is strongly dependent on the random distribution of passengers attempting to retrieve luggage. Furthermore, passengers in the rear of the aircraft are more significantly impacted by luggage collectors than those seated in the front or centre parts of the cabin. Thus, in the event of a serious cabin post-crash fire, the increase in dwell times for passengers in the rear of the aircraft (Zone 05) due to luggage collectors is likely to decrease passenger survivability by increasing passenger exposure to hazardous fire products.

(d) The impact of 25% luggage retrievers on zonal evacuation times

Presented in Table 41 are the average, minimum, maximum, and average PET for passengers originating in each zone. The values represent the average from the 1000 simulations of the minimum zonal evacuation time, the maximum zonal evacuation time, and the average zonal evacuation time. For Scenario 1, the average PET in Zone 05 is 99.0 s. This is determined by calculating the average PET for all the passengers starting in Zone 05 in a simulation and averaging this across all 1000 simulations. Similarly, the average minimum time a passenger spent evacuating from Zone 05 across all 1000 simulations is 64.1 s, while the minimum time a passenger spent evacuating from Zone 05 across all 1000 simulations is 29.0 s, and the maximum time is 138.1 s. In comparison, in Scenario 2, the average PET for passengers starting in Zone 05 is 111.9 s, with an average minimum PET from Zone 05 of 75.8 s and a maximum time of 198.2 s.

Thus, across all 1000 simulations, with 25% of the population retrieving their luggage, passengers in Zone 05 spend an additional 12.9 s (13%) on average evacuating compared to the situation without luggage retrievers. While this increase in average Zone 05 PET does not seem significant, recall that the passengers in Zone 05 spend an additional 20.1 s (31%) exposed to the conditions of Zone 5. While these two times may appear contradictory, they can be explained by the nature of the delays incurred. Passengers in Zone 05 are greatly delayed from leaving Zone 05 by the luggage retrievers in Zones 03, 04, and 05. This results in the additional average of 20.1 s incurred in exiting Zone 05. However, with this delay, the conditions ahead of Zone 05 have cleared, making the rest of the evacuation easier; hence, the overall delay in evacuating the aircraft incurred by passengers in Zone 05 is only 12.9 s. However, the longer average dwell time in Zone 05 can be significant, as it potentially exposes the passengers to hazardous conditions that may develop in this zone resulting from a post-crash fire.

For Scenario 1, the average PET in Zone 1 is 30.1 s. The average minimum time a passenger spent evacuating from Zone 01 across all 1000 simulations is 8.4 s, while the minimum time a passenger spent evacuating from Zone 01 across all 1000 simulations is 8.1 s, and the maximum time is 125.1 s. In comparison, in Scenario 2, the average PET for passengers starting in Zone 01 is 41.1 s, with an average minimum PET from Zone 01 across all 1000 simulations of 9.0 s and a maximum time of 132.4 s.

Thus, across all 1000 simulations, with 25% of the population retrieving their luggage, passengers in Zone 01 spend an additional 11.0 s (37%), on average, evacuating compared to the situation without luggage retrievers. While this increase in average Zone 01 PET seems significant, it is noted that the evacuation time is still small, being just 41.1 s on average.

It is also noted that the average PET for passengers in Zones 02 and 03 for the scenario with the luggage retrievers is less than that for the scenario without luggage retrievers. Again, while a surprising result, this is possibly due to the better use of the heavily congested Type-III exits that luggage retrieval enables by preferentially allowing one zone to fully utilise both exits momentarily throughout the evacuation.

Table 41: PETs based on zone of origin for Scenario 1 and Scenario 2.

Zone	Scenario	Min PET (s) (min - max)	Max PET (s) (min - max)	Avg PET (s) (min - max)	Number of PAXs
1	1	8.4 (8.1 - 10.6)	81.7 (50.2 - 125.1)	30.1 (24.8 - 37.4)	48
	2	9.0 (8.2 - 19.8)	84.9 (60.2 - 132.4)	41.1 (29.1 - 62)	48
2	1	13.0 (12 - 16.6)	90.9 (60.1 - 131)	44.5 (31.9 - 60.7)	36
	2	13.0 (11.9 - 16.9)	85.0 (49.5 - 127.8)	43.6 (29.9 - 66)	36
3	1	13.0 (11.9 - 19.9)	98.1 (46.2 - 132.4)	43.3 (29 - 68.5)	30
	2	13.0 (12 - 16.4)	76.2 (41.2 - 122.9)	37.9 (26.5 - 52.8)	30
4	1	31.5 (15.1 - 63.6)	111.1 (82.3 - 138.5)	72.8 (55.7 - 91.3)	30
	2	36.1 (15.2 - 69.6)	104.5 (79.9 - 145.5)	75.1 (55.3 - 104.4)	30
5	1	64.1 (29.0 - 96.3)	120.2 (106.4 - 138.1)	99.0 (80.6 - 113.1)	36
	2	75.8 (34.6 - 123.7)	135.7 (111.7 - 198.2)	111.9 (89.6 - 158.5)	36

Finally, note that the minimum of the minimum PET for Zone 05 is quite small, 29.0 s for Scenario 1 and 34.6 s for Scenario 2. These surprisingly small evacuation times can be explained by passengers seated on the boundary between Zone 04 and Zone 05 with very short response times and large walking speeds.

(e) Analysis of the by-pass probability — comparing Scenario 2 with SC1 and SC3

To assess the significance of the by-pass probability (BPP) distribution imposed on these simulations, we can compare the results produced by Scenario 2 (S2), which uses the user-defined BPP distribution (see Section 6.1, Figure 31), with the results produced by Sensitivity Case 1 (SC1), which prevents ALL passengers from by-passing, i.e., BPP of 0.0 and Sensitivity Case 3 (SC3), which allows ALL passengers to by-pass, i.e., BPP of 1.0 (with speed reduction of 0.5). However, for a passenger to overtake a luggage collector obstructing the aisle (in both S2 and SC3), there first must be sufficient space on the other side of the luggage collector for the overtaking passenger to move into.

As SC1 does not allow passengers to overtake luggage collectors (BPP of 0.0), it is expected to produce not only the longest evacuation times but also a higher frequency of simulations generating longer evacuation times. In contrast, SC3, which allows all eligible passengers to overtake (BPP of 1.0), is expected to produce the shortest evacuation times and also a higher frequency of simulations generating shorter evacuation times. S2, which incorporates the more realistic BPP distribution, is expected to produce evacuation times and evacuation performance between the two extremes. Presented in Table 42 are the average PET and average TET derived from the 1000 repeat simulations for SC1, S2, and SC3, along with the results for Scenario 1 (S1), which do not include the effect of luggage collectors. Clearly, S1 should produce the smallest evacuation times, as there are no luggage collectors delaying the evacuation of others, and this is indeed the case (see Table 42). Furthermore, the performance of S2 falls between that of SC1 and SC3, as is to be expected, and produces evacuation performance slightly closer to that of SC1 with no by-pass than to SC3, with all passengers able to by-pass.

Table 42: Average PET and average TET values (from the 1000 simulations) for various by-pass probability scenarios (SC1, S2, SC3) and the scenario without luggage retrievers (S1).

	SC1 (BPP=0.0)	**S2 (BPP = distrib)**	**SC3 (BPP=1.0)**	**S1 (0% luggage retrievers)**
Avg. PET (s)	61.6	60.9	58.0	55.9
Avg. TET (s)	139.3	136.8	128.9	121.1

Presented in Figure 46 is the frequency distribution for total evacuation times (TETs) for SC1 (BPP=0), S2 (BPP distribution), and SC3 (BPP=1.0). As can be seen, in SC3, with all passengers able to by-pass the luggage collector, passengers are able to exit the aircraft sooner than in SC1, where none of the passengers are able to by-pass luggage collectors. As a result, in SC3, there are considerably more simulations that produce lower TETs and fewer that produce higher TETs than in SC1. This is also reflected in the lower average TET and average PET for SC3 compared to SC1, shown in Table 42. This trend is also reflected in the results for S2 (BPP distribution), although clearly not as pronounced as in SC3, so the frequency distribution is closer to that of SC1 than SC3. Again, this is supported by the average TET and average PET values for S2 being closer to SC1 than SC3 in Table 42.

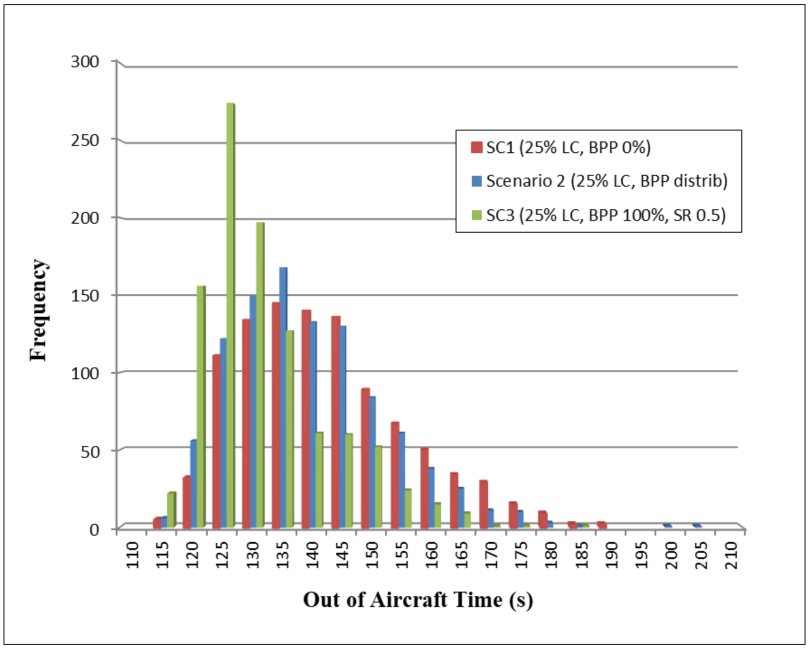


Figure 46: Frequency distribution of TET for 1000 repeat simulations of SC1 (BPP=0.0), S2 (BPP distribution), and SC3 (BPP =1.0).

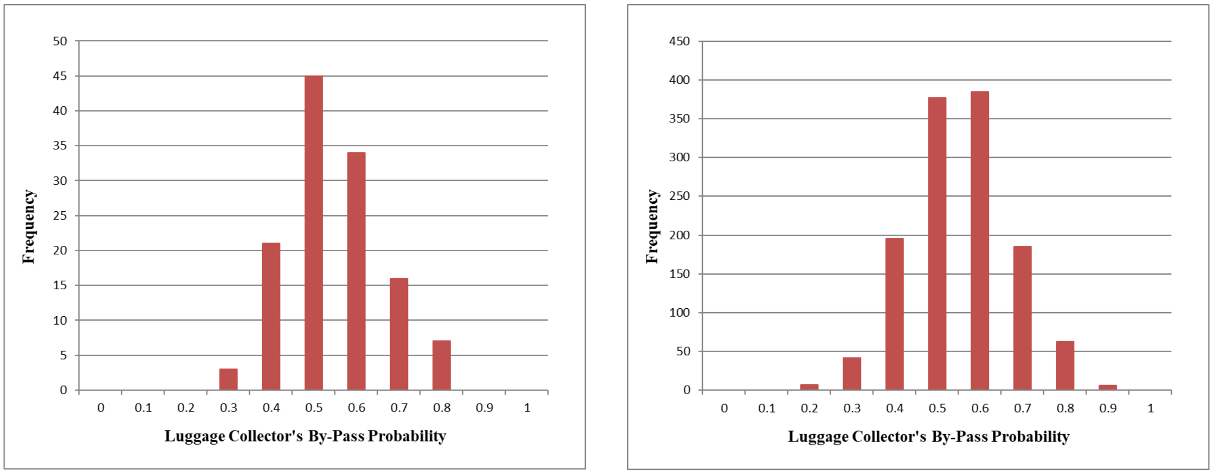
Given the nature of the BPP distribution used in S2 (see Section 6.1, Figure 31), it is perhaps surprising that these simulations more closely resemble SC1 with no by-pass than SC3, where everyone can by-pass. This could be due to the number of passengers that successfully by-pass luggage collectors. Presented in Table 43 are the number of successful by-pass events generated in S2 and SC3 for the minimum, median, maximum, and 95th percentile simulations. Clearly, there are significantly more by-pass events generated in SC3 compared to S2. As all passengers can by-pass a luggage collector in SC3, it is not surprising that the number of by-pass events is high. As the luggage collectors don't significantly impact the evacuation (note that passengers by-passing the luggage collector still incur a speed reduction during the by-pass), the average PET and TET in SC3 are less than those for S2.

Table 43: By-pass and evacuation performance values for Scenario 2 and Sensitivity Case 3.

Sim	Scenario 2 (BPP=distrib)				SC3 (BPP =1.0)			
	Avg. PET (s)	TET (s)	# of times PAXs overtake LC	# of times PAXs fail to overtake LC	Avg. PET (s)	TET (s)	# of times PAXs overtake LC	# of times PAXs fail to overtake LC
Min Sim	54.5	111.7	6	38 (A8, S30)	53.8	110.4	87	42 (A0, S42)
***Median Sim**	61.1	135.0	7	46(A11, S35)	56.0	126.1	81	38(A0, S38)
Max Sim	74.6	200.2	24	62(A22, S40)	71.6	180.5	33	28(A0, S28)
95th% Sim	61.5	160.2	23	48(A16, S32)	58.7	150.1	39	29(A0, S29)

**Median sim is the 501st simulation. A: aisle-located passenger, S: seat row-located passenger.*

However, the comparatively low number of successful by-pass events in S2 may appear surprising. To explore the legitimacy of the small number of successful by-pass events in S2, first, we consider if the by-pass probabilities are being correctly allocated by the software. This can be verified by producing a frequency distribution of allocated by-pass probabilities. Presented in Figure 47 is the BPP distribution generated for Scenario 4 (75% luggage collectors or 126 passengers) from one simulation (see Figure 47a) and 10 simulations (see Figure 47b).



a) Data from 1 simulation (126 data points) b) Data from 10 simulations (1260 data points)

Figure 47: By-pass probability generated for Scenario 4 (126 luggage collectors) by airEXODUS for (a) one simulation and (b) 10 simulations.

As can be seen, airEXODUS is reproducing reasonably accurately the BPP distribution given the relatively small number of luggage collectors within a single simulation (126 allocated probabilities). After 10 simulations (1260 allocated probabilities), the original BPP distribution is more accurately represented. Thus, we conclude that airEXODUS is accurately reflecting the nature of the imposed BPP distribution.

Next, we consider whether the number of successful by-pass events reflects the expected outcome given the nature of the imposed BPP distribution. The success of a by-pass event is dependent on the by-pass probability randomly allocated to the luggage collector based on the user-defined BPP distribution described in Figure 31. The peak of the BPP distribution is at 50% success, and the BPP then drops significantly for higher and lower probabilities and is practically zero for by-pass probabilities less than 0.1 or greater than 0.9. Presented in Figure 48 is the distribution of successful by-pass events generated from the 1000 repeat simulations for S2. As can be seen, the distribution of successful by-pass events is consistent with the BPP distribution imposed on the simulation (see Section 6.1, Figure 31).

Finally, we consider if the small number of successful by-pass events is related to the number of by-pass opportunities. In S2 and SC3, each time a passenger is adjacent to a luggage retriever in the process of retrieving their luggage, a by-pass event is possible, so long as there is space on the other side of the luggage collector for the passenger who wishes to by-pass. In SC3, when the first passenger in the queue behind a luggage collector passes the luggage collector, the next passenger in the queue can by-pass if the first by-passing passenger has moved on, and then the next, and so on until the luggage collector has completed their retrieval task. Thus, there can be many by-pass events, all of which will be successful (assuming the by-passing passengers are able to move on, freeing the space adjacent to the luggage retriever), as demonstrated in Table 43.

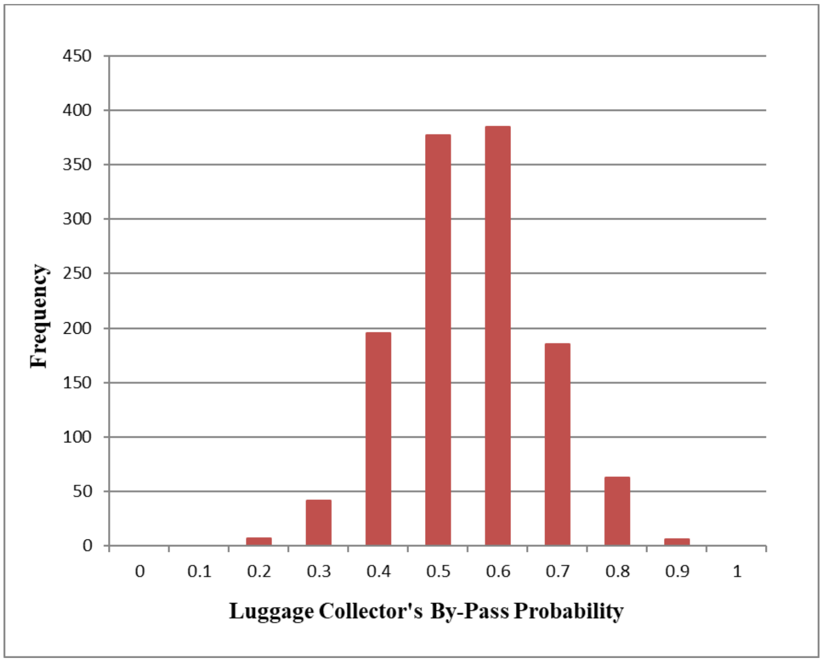


Figure 48: Successful by-pass events for Scenario 2 for the 1000 simulations.

However, in S2, the success of a by-pass event is dependent on the by-pass probability randomly allocated to the luggage collector, so a by-pass attempt may fail, even if there is sufficient space for the by-passing passenger to move into. Once a passenger has failed to by-pass the luggage collector, they effectively prevent all the other passengers waiting behind them from attempting to by-pass the luggage collector. With the exception of situations involving luggage retrievers, the passenger behaviour model within airEXODUS does not represent passengers pushing past each other in the aisle, so a passenger that has failed to by-pass a luggage retriever effectively blocks the aisle, preventing other passengers from pushing past. This is consistent with the behavioural logic of the model, as the blockage preventing other passengers from progressing past the luggage retriever is effectively caused by two passengers who are unable to resolve their conflict, i.e., the luggage retriever and the passenger that has attempted the by-pass the luggage retriever.

Another consequence of the imposed by-pass model behaviour is that gaps may occur in evacuation flow within the main cabin aisle, as failed by-pass events prevent passengers behind the luggage retriever from progressing down the aisle to an exit. These gaps in aisle flow may also result in gaps in exit flows. It is noted that gaps in exit flow are often observed in actual accident situations, albeit resulting from unknown conditions within the cabin, not necessarily related to luggage retrieval.

For example, depicted in Figure 49 is the situation 18 s into the evacuation producing the median TET for Scenario 1 with no luggage retrievers (top image) and Scenario 2 with 25% luggage retrievers (bottom image). At this time, there are no significant gaps formed in Scenario 1; however, in Scenario 2, there are two significant gaps created by luggage retrievers — one in the front of the aircraft (highlighted by the red ellipse and one just aft of the overwing exits highlighted by the black ellipse. The blockage at the front of the aircraft is caused by a luggage retriever and passenger that failed to by-pass sometime after approximately 16 s. By 18 sec, a sizeable gap has formed between the luggage retriever and the passengers ahead who are exiting the aircraft through both Type-C exits. As a result, between approximately 22 s and 27 s, there is no flow through either Type-C exit. By 23 s, the blockage is resolved, and the aisle flow resumes, and by 27 s, both Type-C exits are again in use by exiting passengers.

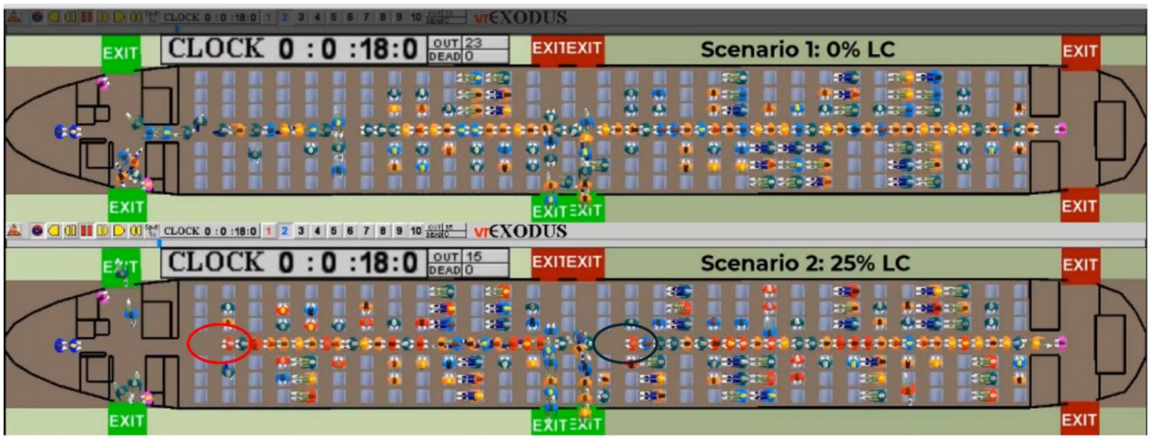


Figure 49: The predicted passenger distribution for Scenario 1 (top) and Scenario 2 (bottom) at 18 s into the simulations, producing the median TET and demonstrating gap formation.

A similar situation occurs near the overwing exits. In this case, a luggage retriever creates the blockage after approximately 16 s, and the passenger immediately behind fails to by-pass, creating the gap between the luggage collector and the Type-III exit queue. However, by 19 s, the passenger has retrieved their luggage, quickly moves on and joins the exit queue. Unfortunately, a second luggage collector enters the aisle at the same location and creates a second blockage. In this case, while gaps in the aisle form they are quickly resolved, and there is no interruption to the exit flows for either Type-III exit.

Thus, the results produced by airEXODUS for scenarios involving luggage retrievers appear to be logically consistent with the mechanism introduced to represent the by-pass process, i.e., the by-pass probability distribution and furthermore, the specific by-pass probability distribution used produces results that fall between the two extremes of no by-pass and all by-pass, albeit slightly biased to the no by-pass results. It remains to be demonstrated that the degree of overtaking produced in the simulations is a reasonable reflection of reality, but it would appear to be valid and reasonable to assume that by-passing does not and cannot occur in all situations and is strongly dependent on a number of factors, such as size of the person retrieving the luggage, size of the person attempting to overtake, dimensions of the cabin aisle, temperament of the person attempting to overtake, severity of the situation, etc., as discussed in Section 5.1.

6.5 Key Findings: Scenario 2 (25% Luggage Retrievers)

The results generated for all luggage retrieval scenarios are compared against the base case, Scenario 1 (no luggage retrieval) (S1), where the Total Evacuation Time (TET) varied from approximately 110 s to 139 s and the average personal evacuation time (PET) varied between 51.6 s and 61.9 s, with an average of 79% (146.2) of the 185 occupants evacuated by 90 s.

Scenario 2 (S2) involved 25% of the passengers (42 passengers) attempting to retrieve their luggage during the evacuation.

Key Finding 6.1, Scenario 2, Overall Evacuation performance:

- With 25% (42) of the passengers designated as luggage collectors, the TET varied from approximately 111.7 s to 200.2 s (with an average of 136.8 s) and on average with 77% (143) of the 185 occupants evacuated by 90 s. The average PET varies from 54.2 s to 74.6 s. This is a wide variation in evacuation performance, with a significant increase in the maximum TET (45%) and a large increase in the maximum average PET (21%) compared to S1.
- The impact of luggage collectors on evacuation performance is complex and varies depending on the specific seating location and the distribution of luggage collectors.

Key Finding 6.2, Scenario 2, Specific Evacuation performance:

- As the number of luggage retrievers within a spatial zone within the aircraft can vary significantly, as does their seating locations, it is inappropriate to simply base conclusions on any one simulation, e.g., a simulation producing median evacuation time, as this may provide an overly pessimistic or optimistic conclusion. It is more informative to consider evacuation performance of several key simulations, such as the simulations producing the minimum, median, and maximum TET.
- **For the simulation producing the *minimum TET*, with 25% (42) of the passengers attempting to retrieve their luggage, 6 of the 14 (43%) attempts to by-pass luggage retrievers in the aisle were successful. Compared to S1, the TET has increased marginally from 110.1 s to 111.7 s (1.5%), and the average PET has also increased by a relatively small amount from 52.1 s to 54.5 s (4.6%).**
- **For the simulation producing the *median TET*, with 25% (42) of the passengers attempting to retrieve their luggage, 7 of the 18 (39%) attempts to by-pass luggage retrievers in the aisle were successful. Compared to S1, the TET has increased by a large amount from 120.9 s to 135.0 s (11.7%), and the average PET has also increased by a slightly smaller amount from 56.2 s to 61.1 s (8.7%).**
- **For the simulation producing the *maximum TET*, with 25% (42) of the passengers attempting to retrieve their luggage, 24 of the 46 (52%) attempts to by-pass luggage retrievers in the aisle were successful. Compared to S1, the TET has increased significantly from 138.5 s to 200.2 s (44.5%), and the average PET has also increased significantly from 61.9 s to 74.6 s (20.5%).**
- In Scenario 2 for the simulation producing the median TET (135 s), there were 18 viable aisle by-pass events, of which 7 (39%) were successful. In addition, there were 35 occurrences where passengers in seat rows were prevented from by-passing the luggage collector blocking their exit from the seat row.
- **Thus, compared to S1, the simulation producing the minimum TET experienced small increases in average PET and TET, while the simulation producing the median TET experienced large increases, and the simulation producing the maximum TET experienced significant increases.**
- However, when assessing the impact of luggage retrievers on evacuation performance, it is inappropriate to simply consider typical global evacuation parameters such as TET or average PET, as this may not reveal the significant localised impact of luggage retrieval on specific groups of passengers.

Key Finding 6.3, Scenario 2, Localised Evacuation performance:

- A deeper understanding of the impact of luggage retrievers on the overall evacuation can be derived from investigating localised evacuation parameters such as zonal dwell times and zonal evacuation times.
- In S2, with 25% of the passengers retrieving luggage, for those passengers starting in **Zone 01** (the front eight seat rows),
  - the average Zone 01 dwell time is 31.5 s; thus, passengers in Zone 01 spend on average an additional 11.7 s (59%) exposed to the conditions of Zone 01 compared to S1.
  - the average Zone 01 evacuation time is 41.1 s, an increase of 11.0 s (37%) compared to S1.
  - in the event of post-crash fire gaining access to the rear of the cabin (consistent with the evacuation scenario), these dwell times and evacuation times may not pose a threat to some passengers in Zone 01, given they are far removed from the initial fire.
- In S2, with 25% of the passengers retrieving luggage, for those passengers starting in **Zone 05** (rear six seat rows),
  - the average Zone 05 dwell time is 85.1 s; thus, passengers in Zone 05 spend on average an additional 20.1 s (31%) exposed to the conditions of Zone 05 compared to S1.
  - the average Zone 05 evacuation time is 111.9 s, an increase of 12.9 s (13%) compared to S1.
  - In the event of a serious post-crash fire that gains access to the rear of the cabin (consistent with the evacuation scenario), the large average dwell time (85.1 s) and average evacuation time (111.9 s) for passengers in Zone 05 can result in significant additional exposure to fire hazards compared to S1, which can have fatal consequences.
- A consequence of the imposed by-pass model behaviour is that gaps may occur in evacuation flow within the main cabin aisle, as failed by-pass events prevent passengers behind the luggage retriever from progressing down the aisle to an exit. This, in turn, can result in periods of no flow at the exits.

Key Finding 6.4, Scenario 2, Overall evaluation:

- In S2, with 25% of the passengers attempting to retrieve luggage, there is a **large increase** in both dwell times incurred by **some** passengers and the TET for the aircraft for **some** of the 1000 repeat simulations. **These increases are of concern, as they can compromise survivability in the event of a post-crash fire gaining access to the cabin, at least for some passengers.** However, with 25% of the passengers retrieving luggage, the outcome **is strongly dependent** on the random distribution of the luggage retrievers and the seating zone of the passengers, so not all passengers are impacted equally by luggage collectors. Passengers in the rear of the aircraft are **more significantly** impacted by luggage collectors. Thus, in the event of a serious post-crash cabin fire that gains access to the rear of the cabin (consistent with the evacuation scenario), those most at risk are passengers seated in the rear of the aircraft (Zone 05) due to the **large increase** in average dwell times (85.1 s) and average evacuation times (111.9 s) resulting from passengers retrieving their luggage. The increased passenger exposure to hazardous fire products due to the incurred delays **is likely to** decrease passenger survivability. However, passengers seated in the front of the aircraft (Zone 01) and, hence, furthest removed from the initial fire are **marginally** impacted, incurring **moderate increases in** average dwell time (31.5 s) and average evacuation times (41.1 s).

6.6 Key Findings: Sensitivity Study Based on Scenario 2 (25% Luggage Retrievers)

A series of sensitivity studies were conducted to explore model sensitivity to two key parameters in the by-pass model: the speed reduction factor employed during by-pass and the by-pass probability distribution.

Key Finding 6.5, Sensitivity of model predictions to speed reduction factor:

- Model predictions are not sensitive to the precise value of the minimum speed reduction factor (upper limit of range) employed in the by-pass model, with reduction factors of 0.4, 0.5, and 0.6 producing similar results. The minimum speed reduction factor implemented in the model assumes a value of 0.5, with the range in speed reduction factors being 0.1 to 0.5.

Key Finding 6.6, Sensitivity of model predictions to by-pass probability:

- Model predictions are sensitive to the nature of the by-pass probability (BPP) distribution.
  - Assuming a BPP of 0.0 prevents all passengers from by-passing luggage retrievers, resulting in the longest evacuations as measured by global parameters such as TET, average TET, and average PET, as well as the longest local parameters, such as zonal dwell times. Using this simplified approach results in predictions that are overly pessimistic.
  - Assuming a BPP of 1.0 allows all passengers to by-pass luggage retrievers, resulting in the shortest evacuations as measured by global parameters such as TET, average TET, and average PET, as well as the shortest local parameters, such as zonal dwell times. This also results in a very large number of passengers who by-pass luggage collectors. Using this simplified approach results in predictions that are overly optimistic.
  - Assuming a BPP described by a normal distribution with a mean of 0.5 and standard deviation of 0.12 produces results that are positioned between the two extremes of no by-pass and all by-pass, albeit slightly biased to the no by-pass results. This is due to the nature of the model, which only allows the passenger attempting to by-pass one attempt and does not allow passengers from further back in the queue to push their way forward. As a result, significantly fewer passengers manage to successfully by-pass luggage retrievers than in the case with all passengers being able to by-pass.
  - While some degree of by-pass behaviour is expected in real accident situations, it remains to be demonstrated that the degree of by-pass produced in the simulations is a reasonable reflection of reality. However, it would appear to be valid and reasonable to assume that by-passing does not and cannot occur in all situations and is strongly dependent on a number of factors such as size of the person retrieving the luggage, size of the person attempting to overtake, dimensions of the cabin aisle, temperament of the person attempting to overtake, severity of the situation, etc.

7 SCENARIO 3 (50% LUGGAGE RETRIEVERS) RESULTS AND ANALYSIS

In this section, the impact of 50% of the passengers attempting to retrieve their luggage (i.e., Scenario 3) on overall evacuation efficiency is explored. As in all the evacuation scenarios considered in this analysis, the narrow-body, single-aisle cabin layout presented in Section 3.1 is used, and all the passengers attempt to evacuate via their nearest serviceable exit, i.e., either of the two forward Type-C exits or the left pair of Type-III overwing exits.

The initial seating allocation for luggage collectors is defined within the model by the *Luggage Collectors' Zone* as described in Section 5.3(a). Throughout this analysis, this is defined to encompass the seat blocks as shown in Figure 19. Note that seat rows that lead to an exit are not included in the luggage collectors' zone. Furthermore, to better understand how the luggage collection behaviour impacts the overall evacuation performance, five compartment zones are defined as described in Section 5.3(c) and shown in Figure 21. For each compartment zone, the additional information that is recorded and exported into the simulation data output file includes the time that a PAX entered the zone, the time a PAX left the zone, and the dwell time (i.e., duration they spend inside that zone).

The chosen aircraft cabin layout accommodates 180 passengers, 3 cabin crew, and 2 flight deck crew in total. As two rows of seats are excluded from containing luggage retrievers (last row of Zone 02 and first row of Zone 03), this reduces the number of potential Luggage Collectors to 168. Thus, for Scenario 3, 84 of the passengers are luggage retrievers,

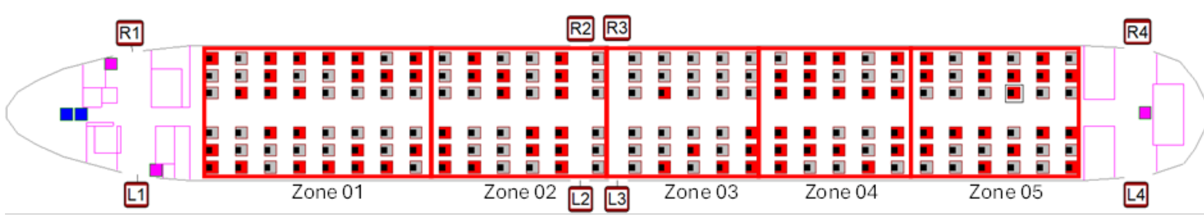
7.1 Scenario 3: Defining Parameters Required by the Luggage Collection Model

The luggage retrieval model developed in Section 5 included two user-defined parameters to describe how passengers attempt to by-pass a luggage retriever (see Table 19 for details). The two parameters and the values used in the simulations are identical to those for Scenario 2; see Section 6.1.

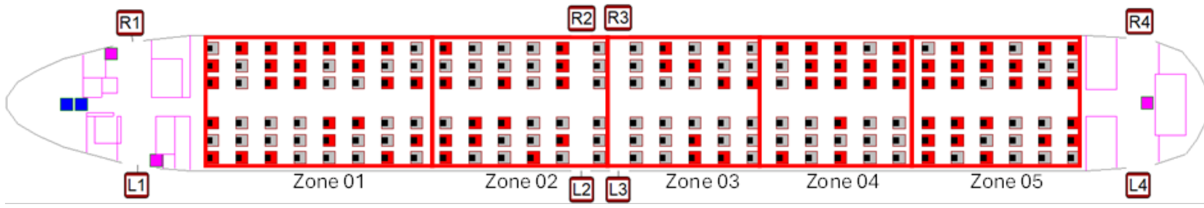
7.2 Scenario 3 Setup — Seating Location of Luggage Retrievers

As two rows of seats are excluded from containing luggage retrievers (last row of Zone 02 and first row of Zone 03), this reduces the number of potential luggage collectors from 180 passengers to 168. Thus, for Scenario 3, with 50% luggage collectors, there are 84 passengers attempting to retrieve their luggage.

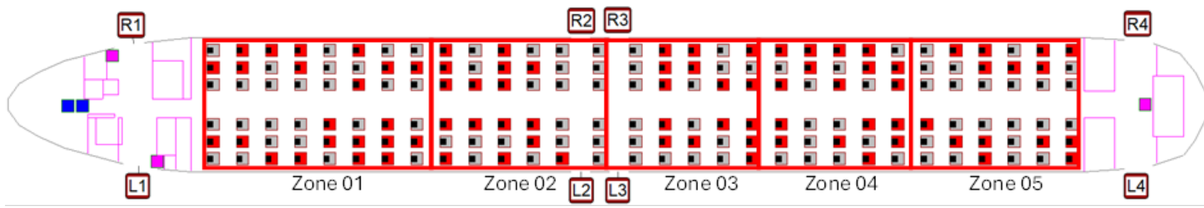
Presented in Figure 50 is the seating location for the luggage retrievers (red-coloured seats) for the simulations producing the minimum, median, and maximum Total Evacuation Time (TET). Note that some seat rows have up to five luggage retrievers, and one row in the minimum case has six.



(a) Minimum



(b) Median



(c) Maximum

Figure 50: Seating locations of luggage retrievers in Scenario 3 (red-coloured seats) for the (a) minimum, (b) median, and (c) maximum evacuation time.

Presented in Table 44 are the number of luggage retrievers in each zone for the minimum, median, and maximum simulations for Scenario 3, while presented in Table 45 are the minimum, average, and maximum number of luggage retrievers in each zone across the 1000 simulations. Clearly, the distribution of luggage retrievers will impact the overall evacuation times and the performance of passengers within each zone. As seen in Table 45, there can be a large variation in the number of luggage retrievers in each zone over the 1000 repeat simulations; for example, in Zone 05, the number varies from 9 to 27, with an average of 18.

Table 44: Number of luggage retrievers in each zone for various repeat simulations for Scenario 3.

	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Total
Min sim	24	16	7	19	18	84
***Median sim**	24	13	9	15	23	84
Max sim	22	16	15	17	14	84

**Median sim is the 501st simulation.*

Table 45: Minimum number, average, and maximum number of luggage retrievers in each zone across all 1000 repeat simulations for Scenario 3.

	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Min	15	6	6	7	9
Average	24	15.1	12	15	18
Max	32	23	19	23	27

7.3 Scenario 3 (50% Luggage Retrievers) Results and Analysis

Here, the results for Scenario 3 are presented. In this scenario, 50% of the passengers (i.e., 84) attempt to retrieve their luggage and incur a delay time derived from the distribution presented in Section 4.2, Table 18.

(a) Scenario 3 (50% luggage retrievers) general results and analysis
Presented in Figure 51 are the exit curves for Scenario 3 (50% luggage retrievers), together with those for Scenario 1 (no luggage retrievers) for the simulations producing the minimum, median, and maximum simulations, while key simulation parameters are reported in Table 46.

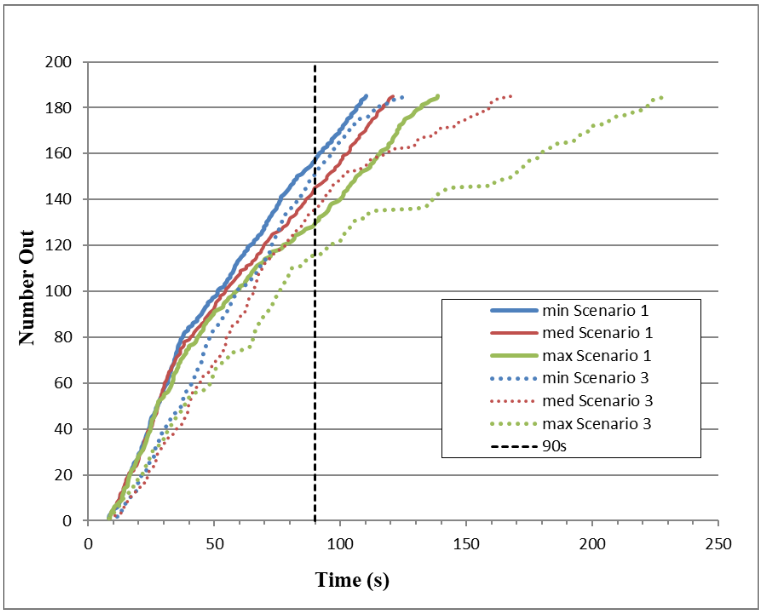


Figure 51: Evacuation curves for Scenario 1 (0% luggage retrievers) and Scenario 3 (50% luggage retrievers).

From Table 46, we note that over the 1000 repeat simulations, the total evacuation time for Scenario 3 varies from 124.7 s to 228.0 s (with an average of 168.7 s), with the corresponding average personal evacuation time (PET) varying from 59.3 to 89.1 s (note that the absolute range of average PET over all 1000 repeat simulations varies from 58.2 s to 89.1s). By 90 s, between 82% (151) and 61% (112) of the 185 occupants, or an average of 134.8 (73%), have evacuated.

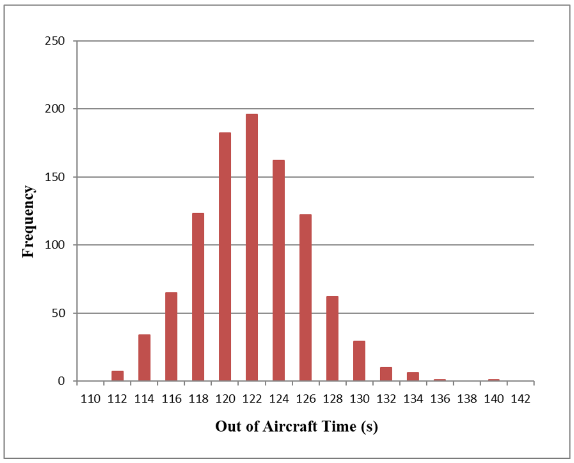
Furthermore, as with Scenario 2 (25% luggage collectors), it is clear from both Figure 51 and Table 46 that the impact of the luggage retrievers in Scenario 3 is not uniform throughout a simulation (early part of the evacuation can be more impacted than the final part of the evacuation) and can vary significantly between repeat simulations.

Table 46: Simulation parameters from Scenario 1 and Scenario 3 for the simulations producing the minimum, median, maximum, and 95th percentile TET.

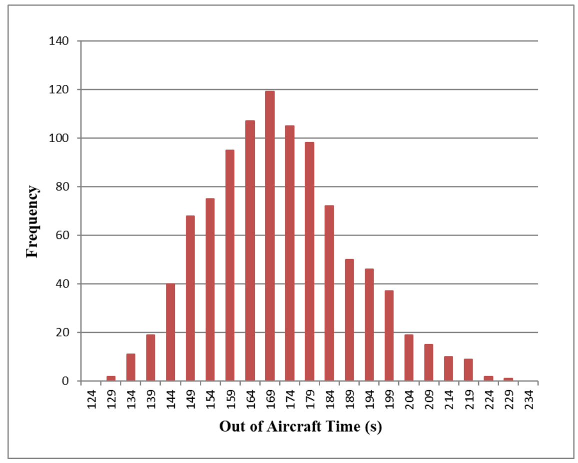
Sim	Avg. CWT (s)		Avg. Distance (m)		Avg. PET (s)		TET (s)	
	S1 0% LC	S3 50% LC	S1 0% LC	S3 50% LC	S1 0% LC	S3 50% LC	S1 0% LC	S3 50% LC
Min Sim	36.6	39.8	7.6	8.4	52.1	59.3	110.1	124.7
***Median Sim**	40.6	48.1	7.7	8.6	56.2	69.0	120.9	167.6
Max Sim	45.8	67.4	7.8	8.8	61.9	89.1	138.5	228.0
95th% Sim	44.3	53.9	7.7	8.9	60.3	75.3	127.7	201.0

**Median sim is the 501st simulation.*

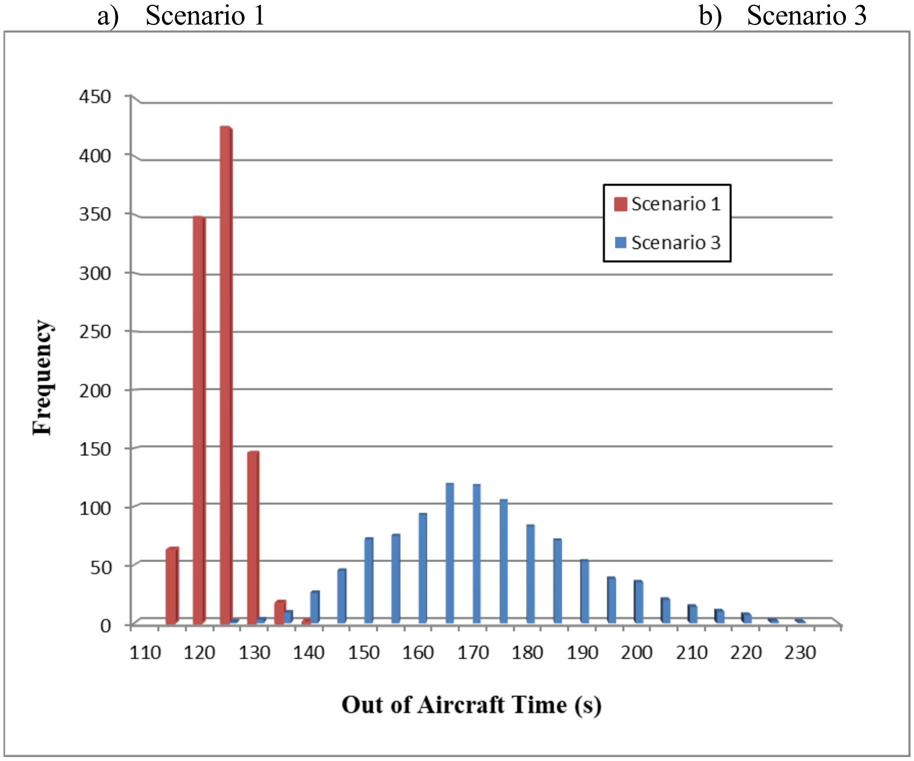
Presented in Figure 52 are the frequency distributions of evacuation times for (a) Scenario 1, (b) Scenario 3, and (c) both Scenario 1 and Scenario 3. Clearly, having 50% of passengers retrieve their luggage can significantly impact TET. Without luggage retrieval, only approximately 2% (18) of the simulations have a TET in excess of 130 s, while with 50% luggage retrieval, almost 100% (996) exceed 130 s, and 6% (61) exceed 198 s. Thus, in Scenario 3, there is virtually no overlap with Scenario 1, demonstrating that with 50% of passengers retrieving their luggage, TET is significantly increased in virtually every simulation.



a) Scenario 1



b) Scenario 3



c) Scenario 1 and Scenario 3

Figure 52: TET frequency distribution for (a) Scenario 1 (0% luggage retrievers), (b) Scenario 3 (50% luggage retrievers), and (c) Scenario 1 and Scenario 3.

(b) Impact of 50% luggage retrievers on evacuation time

For the simulations producing the minimum TET for Scenario 1 and Scenario 3, the TET is increased by 13.3% (see Table 47) when luggage retrievers are included. However, in the early stages of the evacuation, there are larger increases in evacuation times for Scenario 3, e.g., by the time 40 passengers have evacuated, the evacuation time is some 26.0% longer for Scenario 3, and when 80 passengers have evacuated, the increase in evacuation time is 28.8% (see ANNEX D). By 90 s, 157 (85%) occupants have evacuated in Scenario 1 and 151 (82%) occupants have evacuated in Scenario 3. Furthermore, the average PET is some 13.8% longer in the minimum simulation when luggage collectors are included (see Table 47).

As described in Section 6.4(b), when interpreting these results, it is important to recall the two key assumptions of the luggage retrieval model, i.e., passengers located in seat rows cannot by-pass a luggage retriever, and aisle by-pass is only possible if there is sufficient space ahead of the luggage retriever (see Section 5.1).

In the **minimum simulation**, the 84 luggage retrievers directly impacted 98 potential by-pass events, 25 in the aisle that could have occurred as there was sufficient space and 73 located in seat rows (see Table 47). However, the seated passengers involved in the 73 seat events are not able to by-pass the luggage collector and so are effectively trapped until the luggage collector has retrieved their luggage. Of the 25 attempted by-pass events occurring in the aisle, 14 (56%) were successfully implemented. Compared to Scenario 2, where there were half as many luggage retrievers, the number of possible aisle by-pass events have increased by 79% (9), the successful aisle by-pass events have increased by 133% (8), and the number of seat events has increased by 143% (43).

Thus, for the simulation producing the *minimum TET*, with 50% (84) of the passengers attempting to retrieve their luggage, 14 of the 25 (56%) attempts to by-pass luggage retrievers in the aisle were successful, with the TET increasing by a large amount from 110.1 s to 124.7 s (13.3%) and the average PET also increasing by a large amount from 52.1 s to 59.3 s (13.8%).

For the simulations producing the maximum TET time for Scenario 1 and Scenario 3, the TET increases by 64.6% (see Table 47) when luggage retrievers are included. In the early stages of the evacuation, there are also large increases in evacuation times for Scenario 3, e.g., by the time 40 passengers have evacuated, the evacuation time is some 30.2% longer for Scenario 3, and when 80 passengers have evacuated, the increase in evacuation time is 51.4% (see ANNEX D). By 90 s, 129 (70%) occupants have evacuated in Scenario 1 and 115 (62%) occupants have evacuated in Scenario 3. Furthermore, the average PET is some 43.9% longer in the maximum simulation when luggage collectors are included (see Table 47).

In the **maximum simulation**, the 84 luggage retrievers directly impacted 127 potential by-pass events, 39 in the aisle that could have occurred as there was sufficient space and 88 located in seat rows (see Table 47). However, the seated passengers involved in the 88 seat row events are not able to by-pass the luggage collector and so are effectively trapped until the luggage collector has retrieved their luggage. Of the 39 possible aisle by-pass events, 9 (23%) were successfully implemented. Compared to Scenario 2, where there were half as many luggage retrievers, the number of possible aisle by-pass events have decreased by 15% (7), the successful aisle by-pass events have decreased by 63% (15), and the number of seat events has increased by 120% (48).

Thus, for the simulation producing the *maximum TET*, with 50% (84) of the passengers attempting to retrieve their luggage, 9 of the 39 (23%) attempts to by-pass luggage retrievers in the aisle were successful, with the TET increasing significantly from 138.5 s to 228.0 s (64.6%), and the average PET also increasing significantly from 61.9 s to 89.1 s (43.9%).

For the simulations producing the median TET time for Scenario 1 and Scenario 3, the TET time increases by 38.6% (see Table 47) when luggage retrievers are included. However, in the early stages of the evacuation, there are larger increases in evacuation times for Scenario 3, e.g., by the time 40 passengers have evacuated, the evacuation time is some 43.6% longer for Scenario 3, and when 80 passengers have evacuated, the increase in evacuation time is 22.2% (see ANNEX D). By 90 s, 145 (78%) occupants have evacuated in Scenario 1 and 136 (74%) occupants have evacuated in Scenario 3. Furthermore, the average PET is 22.8% longer in the median simulation when luggage collectors are included (see Table 47).

In the **median simulation**, the 84 luggage retrievers directly impacted 142 potential by-pass events, 60 in the aisle that could have occurred as there was sufficient space and 82 located in seat rows (see Table 47). However, the seated passengers involved in the 82 seat row events are not able to by-pass the luggage collector and so are effectively trapped until the luggage collector has retrieved their luggage. Of the 60 possible aisle by-pass events, 34 (57%) were successfully implemented. Compared to Scenario 2, where there were half as many luggage retrievers, the number of possible aisle by-pass events have increased by 233% (42), the successful aisle by-pass events have increased by 386% (27), and the number of seat events has increased by 134% (47).

Thus, for the simulation producing the *median TET*, with 50% (84) of the passengers attempting to retrieve their luggage, 34 of the 60 (57%) attempts to by-pass luggage retrievers in the aisle were successful, with the TET increasing significantly from 120.9 s to 167.6 s (38.6%) and the average PET also increasing significantly from 56.2 s to 69.0 s (22.8%).

It is noted that not many passengers appear to successfully overtake the 84 luggage collectors. In the simulations producing the minimum, median, and maximum evacuation times, passengers successfully overtake luggage collectors 14, 34, and 9 times, respectively (see Table 47). The relatively small number of overtaking luggage collectors is due to several issues. Passengers cannot overtake luggage collectors in a congested aisle, i.e., in situations where there is not sufficient clear space on the other side of the luggage collector. This will particularly be an issue early in the evacuation when the aisle is heavily congested. Furthermore, each luggage collector is randomly assigned a by-pass probability that varies from 0.0 to 1.0 (see Section 6.1, Figure 31) and if this probability is low, there is less chance that a passenger will be able to overtake the luggage collector. In the simulations producing the minimum, median, 95th percentile, and maximum evacuation times, the successful by-pass rate is 56%, 57%, 45%, and 23%, respectively. With the exception of the maximum case, these are reasonably high success rates that are consistent with the by-pass probability distribution presented in Figure 31.

Table 47: Increase in average out-of-aircraft time and total evacuation time for Scenario 3 compared with Scenario 1.

Sim	Increase in Avg. PET (%)	Increase in TET (%)	Number of successful by-pass events	Number of unsuccessful by-pass events
Min Sim	13.8	13.3	14	84 (A11, S73)
***Median Sim**	22.8	38.6	34	108 (A26, S82)
Max Sim	43.9	64.6	9	118 (A30, S88)
95th% Sim	24.9	57.4	24	118 (A29, S89)

**Median sim is the 501st simulation. A: aisle-located passenger, S: seat row-located passenger.*

(c) The impact of 50% luggage retrievers on zonal dwell times

Presented in Table 48 are the average, minimum, maximum, and average dwell times for passengers originating in each zone. The values represent the average from the 1000 simulations of the minimum zonal dwell time, the maximum zonal dwell time, and the average zonal dwell time. For Scenario 1, the average dwell time in Zone 05 is 65.0 s. Similarly, the minimum time a passenger spent in Zone 05 across all 1000 simulations is 1.6 s, the average minimum time is 4.4 s, the maximum time is 110.8 s, and the average maximum time was 95.0 s.

In comparison, in Scenario 03, the average dwell time in Zone 05 is 109.8 s, with the minimum time a passenger spent in Zone 05 being 1.7 s, the average minimum time being 9.5 s, the maximum time being 210.4 s, and the average maximum time being 150.8 s. Thus, across the 1000 simulations, with 50% of the population retrieving their luggage, passengers in Zone 05 spend, on average, an additional 44.8 s (69%) exposed to the conditions of Zone 05, with the average dwell time exceeding 90 s. In the event of a serious post-crash fire that gains access to the rear of the cabin (see Section 6.2 (a)), as noted for Scenario 2, the large increase in average dwell time for passengers in Zone 05 resulting from luggage retrievers can represent a significant additional exposure to fire hazards, which can have fatal consequences.

In contrast, for Scenario 1, the average dwell time in Zone 01 is 19.8 s, while the minimum time a passenger spent in Zone 01 across all 1000 simulations is 1.3 s, the maximum time is 79.0 s, and the average maximum time is 48.1 s. In comparison, in Scenario 3, the average dwell time in Zone 1 is 41.4 s, with the minimum time a passenger spent in Zone 1 being 1.3 s and the maximum time being 117.7 s, while the average maximum time is 78.9 s. Thus, across all the 1000 simulations, with 50% of the population retrieving their luggage, passengers in Zone 01 spend, on average, an additional 21.6 s (109%) exposed to the conditions of Zone 1. In the event of a serious post-crash fire that gains access to the rear of the cabin (consistent with this scenario), passengers in the front of the cabin are furthest away from high concentrations of fire hazards that are likely to be located in the rear of the cabin. However, the average dwell time in Zone 01 (41.4 s) has increased significantly compared to Scenario 2, so in the event of post-crash fire gaining access to the rear of the cabin, these dwell times may pose a threat to some passengers in Zone 01, even though they are far removed from the initial fire.

As noted in Scenario 2, in Zone 02, the difference between the average dwell time is just 1%, with Scenario 3 being faster than Scenario 1. While the difference is small, on the surface, this is an odd result, as the scenario with luggage retrievers is faster. Similarly, for Zone 03, the difference between the average dwell times is 11.7%, somewhat larger, but again, with Scenario 3, the case with luggage retrievers being quicker. As both these zones predominately utilise the two Type-III overwing exits, it could be that the presence of luggage retrievers preferentially slows the flow to one of the heavily congested Type-III exits from one zone, allowing passengers from the other zone to make full use of both exits, resulting in a slightly lower average dwell time.

Thus, in evacuation scenarios involving only four available exits, the two front exits and two overwing exits located on one side of the aircraft, with one in two (50%) passengers attempting to retrieve cabin luggage, there is a significant increase in dwell times incurred by some passengers (i.e., those in the rear of the aircraft (Zone 05)) and in total evacuation times for the aircraft. Of particular concern is that the average dwell time in Zone 05 exceeds 90 s, so passengers are forced to spend an excessive amount of time in the rear of the aircraft during the evacuation. However, this is strongly dependent on the random distribution of passengers attempting to retrieve luggage, with average dwell times for Zone 05 varying from 74.3 s to 165.2 s. In the event of a serious cabin post-crash fire, the increase in dwell times for passengers in the rear of the aircraft (Zone 05) due to luggage collectors is likely to significantly decrease passenger survivability by increasing passenger exposure to hazardous fire products.

Table 48: Average (across 1000 simulations) time spent by agents in their zone of origin for Scenario 1 and Scenario 3.

Zone	Scenario	Min Dwell Time (s) (min - max)	Max Dwell Time (s) (min - max)	Avg Dwell Time (s) (min - max)	Number of PAXs	Avg. Number of Luggage Collectors (min - max)
1	1	2.6 (1.3 - 5.9)	48.1 (28.1 - 79.0)	19.8 (14.3 - 26.1)	48	0
	3	3.7 (1.3 - 12.2)	78.9 (53.3 - 117.7)	41.4 (27.5 - 62.3)		24 (15 - 32)
2	1	3.8 (1.8 - 12.5)	81.7 (52.2 - 129.4)	40.1 (27.9 - 57.9)	36	0
	3	3.8 (1.7 - 9.3)	80.3 (48.9 - 124.8)	39.7 (25.6 - 64)		15.1 (6 - 23)
3	1	3.9 (1.7 - 14.6)	89.2 (42.5 - 128.1)	38.3 (23.7 - 62.5)	30	0
	3	4.0 (1.7 - 14.2)	68.6 (41.8 - 110.3)	33.8 (23.6 - 51.5)		12 (6 - 19)
4	1	4.3 (1.6 - 42.7)	92.7 (59.4 - 118.4)	51.4 (34.1 - 71.5)	30	0
	3	12.3 (1.6 - 68.3)	107.6 (72.1 - 166.9)	69.8 (45.3 - 115)		15 (7 - 23)
5	1	4.4 (1.6 - 21.8)	95.0 (76.9 - 110.8)	65.0 (46.6 - 82.6)	36	0
	3	9.5 (1.7 - 33.8)	150.8 (106.5 - 210.4)	109.8 (74.3 - 165.2)		18 (9 - 27)

(d) The impact of 50% luggage retrievers on zonal evacuation times

Presented in Table 49 are the average, minimum, maximum, and average evacuation times for passengers originating in each zone. The values represent the average from the 1000 simulations of the minimum zonal evacuation time, the maximum zonal evacuation time, and the average zonal evacuation time. For Scenario 1, the average evacuation time in Zone 05 is 99.0 s. Similarly, the average minimum time a passenger spent evacuating from Zone 05 across all 1000 simulations is 64.1 s, while the minimum time a passenger spent evacuating from Zone 05 across all 1000 simulations is 29.0 s, and the maximum time is 138.1 s.

In comparison, in Scenario 3, the average evacuation time for passengers starting in Zone 05 is 134.7 s, with an average minimum evacuation time from Zone 05 of 89.2 s and a maximum time of 227.1 s. Thus, across all 1000 simulations, with 50% of the population retrieving their luggage, passengers in Zone 05 spend an additional 35.7 s (36%), on average, evacuating compared to the situation without luggage retrievers. The average evacuation time for passengers in Zone 05 significantly exceeds 90 s; this, combined with the excessively long average dwell time in Zone 05, can be significant, as it potentially exposes the passengers to hazardous conditions that may develop in this zone resulting from a post-crash fire.

Table 49: Evacuation times based on zone of origin for Scenario 1 and Scenario 3.

Zone	Scenario	Min PET (s) (min - min)	Max PET (s) (min - max)	Avg PET (s) (min - max)	Number of PAXs
1	1	8.4 (8.1 - 10.6)	81.7 (50.2 - 125.1)	30.1 (24.8 - 37.4)	48
	3	9.8 (8.1 - 21.6)	91.3 (66.4 - 130.7)	50.0 (36.9 - 71.2)	
2	1	13.0 (12 - 16.6)	90.9 (60.1 - 131)	44.5 (31.9 - 60.7)	36
	3	13.0 (11.9 - 16.5)	84.3 (53.4 - 126.7)	44.0 (31.1 - 70)	
3	1	13.0 (11.9 - 19.9)	98.1 (46.2 - 132.4)	43.3 (29 - 68.5)	30
	3	13.0 (11.9 - 16.5)	72.4 (44.9 - 111.6)	37.9 (28.1 - 54.3)	
4	1	31.5 (15.1 - 63.6)	111.1 (82.3 - 138.5)	72.8 (55.7 - 91.3)	30
	3	40.7 (15 - 88.4)	118.1 (86.7 - 175.4)	83.5 (62 - 127.1)	
5	1	64.1 (29.0 - 96.3)	120.2 (106.4 - 138.1)	99.0 (80.6 - 113.1)	36
	3	89.2 (28.5 - 160.7)	167.2 (124 - 227.1)	134.7 (98.7 - 192.5)	

For Scenario 1, the average evacuation time in Zone 01 is 30.1 s. The average minimum time a passenger spent evacuating from Zone 01 across all 1000 simulations is 8.4 s, while the minimum time a passenger spent evacuating from Zone 01 across all 1000 simulations is 8.1 s, and the maximum time is 125.1 s. In comparison, in Scenario 3, the average evacuation time for passengers starting in Zone 01 is 50.0 s, with an average minimum evacuation time from Zone 1 across all 1000 simulations of 9.8 s and a maximum time of 130.7 s. Thus, across all 1000 simulations, with 50% of the population retrieving their luggage, passengers in Zone 1 spend an additional 19.9 s (66%), on average, evacuating compared to the situation without luggage retrievers. Given the proximity of Zone 01 to both forward Type-C exits, an average evacuation time of 50.0 s is significantly long and in the event of a post-crash fire, can prove hazardous for some passengers in Zone 01.

It is also noted that the average evacuation times for passengers in Zones 02 and 03 for Scenario 3 are less than those for the scenario without luggage retrievers. Again, while a surprising result, this is possibly due to the better use of the heavily congested Type-III exits that luggage retrieval enables by preferentially allowing one zone to fully utilise both exits momentarily throughout the evacuation.

7.4 Key Findings: Scenario 3 (50% Luggage Retrievers)

The results generated for all luggage retrieval scenarios are compared against the base case, Scenario 1 (no luggage retrieval) (S1), where the Total Evacuation Time (TET) varied from approximately 110 s to 139 s, and the average personal evacuation time (PET) varied between 51.6 s and 61.9 s, with an average of 79% (146.2) of the 185 occupants evacuated by 90 s.

Scenario 3 (S3) involved 50% of the passengers (84 passengers) attempting to retrieve their luggage during the evacuation.

Key Finding 7.1, Scenario 3, Overall Evacuation performance:

- With 50% (84) of the passengers designated as luggage collectors, the TET varied from approximately 124.7 s to 228.0 s (with an average of 168.7 s) and, on average, with 73% (134.8) of the 185 occupants evacuated by 90 s. The average PET varies from 58.2 s to 89.1 s. This is a wide variation in evacuation performance, with a significant increase in the maximum TET (64%) and maximum average PET (44%) compared to S1.
- The impact of luggage collectors on evacuation performance is complex and varies depending on the specific seating location and the distribution of luggage collectors.

Key Finding 7.2, Scenario 3, Specific Evacuation performance:

- As the number of luggage retrievers within a spatial zone within the aircraft can vary significantly, as does their seating locations, it is inappropriate to simply base conclusions on any one simulation, e.g., a simulation producing a median evacuation time, as this may provide an overly pessimistic or optimistic conclusion. It is more informative to consider evacuation performance of several key simulations, such as the simulations producing the minimum, median, and maximum TET.
- **For the simulation producing the *minimum TET*, with 50% (84) of the passengers attempting to retrieve their luggage, 14 of the 25 (56%) attempts to by-pass luggage retrievers in the aisle were successful. Compared to S1, the TET has increased by a large amount from 110.1 s to 124.7 s (13.3%), and the average PET has also increased by a large amount from 52.1 s to 59.3 s (13.8%).**
- **For the simulation producing the *median TET*, with 50% (84) of the passengers attempting to retrieve their luggage, 34 of the 60 (57%) attempts to by-pass luggage retrievers in the aisle were successful. Compared to S1, the TET has increased significantly from 120.9 s to**

167.6 s (38.6%), and the average PET has also increased significantly from 56.2 s to 69.0 s (22.8%).

- **For the simulation producing the *maximum TET*, with 50% (84) of the passengers attempting to retrieve their luggage, 9 of the 39 (23%) attempts to by-pass luggage retrievers in the aisle were successful. Compared to S1, the TET has increased significantly from 138.5 s to 228.0 s (64.6%), and the average PET has also increased significantly from 61.9 s to 89.1 s (43.9%).**
- Thus, compared to S1, the simulation producing the minimum TET experienced large increases in average PET and TET, while the simulations producing the median and maximum TET experienced significant increases in both average PET and TET.
- In Scenario 3 for the simulation producing the median TET (167.6 s), with twice as many luggage retrievers as in Scenario 2, there were 60 viable aisle by-pass events, of which 34 (57%) were successful. In addition, there were 82 occurrences where passengers in seat rows were prevented from by-passing the luggage collector blocking their exit from the seat row. Compared to Scenario 2, the number of possible aisle by-pass events has increased by 233% (42), the number of successful aisle by-pass events has increased by 386% (27), and the number of occurrences where passengers in seat rows are prevented from by-passing the luggage collector seat events has increased by 134% (47).
- However, when assessing the impact of luggage retrievers on evacuation performance, it is inappropriate to simply consider typical global evacuation parameters, such as TET or average PET, as this may not reveal the significant localised impact of luggage retrieval on specific groups of passengers.

Key Finding 7.3, Scenario 3, Localised Evacuation performance:

- A deeper understanding of the impact of luggage retrievers on the overall evacuation can be derived from investigating localised evacuation parameters, such as zonal dwell times and zonal evacuation times.
- In S3, with 50% of the passengers retrieving luggage, for those passengers starting in Zone 01 (the front eight seat rows),
  - the average Zone 01 dwell time is 41.4 s; thus, passengers in Zone 01 spend, on average, an additional 21.6 s (109%) exposed to the conditions of Zone 01 compared to S1.
  - the average Zone 01 evacuation time is 50.0 s, an increase of 19.9 s (66%) compared to S1.
  - in the event of post-crash fire gaining access to the rear of the cabin (consistent with the evacuation scenario), these dwell times and evacuation times may pose a threat to some passengers in Zone 01, even though they are far removed from the initial fire.
- In S3, with 50% of the passengers retrieving luggage, for those passengers starting in Zone 05 (rear six seat rows),
  - the average Zone 05 dwell time is 109.8 s; thus, passengers in Zone 05 spend on average an additional 44.8 s (69%) exposed to the conditions of Zone 05 compared to S1.
  - the average Zone 05 evacuation time is 134.7 s, an increase of 35.7 s (36%) compared to S1.
  - Both the Zone 05 average dwell time and average evacuation time significantly exceed 90 s.
  - In the event of a serious post-crash fire that gains access to the rear of the cabin (consistent with the evacuation scenario), the excessively long average dwell time (109.8 s) and average evacuation time (134.7 s) for passengers in Zone 05 can result in significant additional exposure to fire hazards compared to S1, which can have fatal consequences.

- A consequence of the imposed by-pass model behaviour is that gaps may occur in evacuation flow within the main cabin aisle, as failed by-pass events prevent passengers behind the luggage retriever from progressing down the aisle to an exit. This, in turn, can result in periods of no flow at the exits.

Key Finding 7.4, Scenario 3, Overall evaluation:

- In S3, with 50% of the passengers attempting to retrieve luggage, **there is a significant increase** in both dwell times incurred by **many** passengers and the TET for the aircraft for many of the 1000 repeat simulations. **These increases are of great concern, as they seriously compromise survivability in the event of a post-crash fire gaining access to the cabin for many passengers.** However, even with as many as 50% of the passengers retrieving luggage, the outcome **is still dependent** on the random distribution of the luggage retrievers and the seating zone of the passengers, so not all passengers are impacted equally by luggage collectors. Passengers in the rear of the aircraft are **significantly** impacted by luggage collectors. Thus, in the event of a serious post-crash cabin fire that gains access to the rear of the cabin (consistent with the evacuation scenario), those most at risk are passengers seated in the rear of the aircraft (Zone 05) due to the **significant increase** in average dwell times (109.8 s) and average evacuation times (134.7 s) resulting from passengers retrieving their luggage. The increased passenger exposure to hazardous fire products due to the incurred delays **is likely to seriously** decrease passenger survivability. Furthermore, even passengers seated in the front of the aircraft (Zone 01) and, hence, furthest removed from the initial fire are **significantly** impacted, incurring **long** average dwell times of 41.4 s and average evacuation times of 50.0 s.

8 SCENARIO 4 (75% LUGGAGE RETRIEVERS) RESULTS AND ANALYSIS

In this section, the impact of 75% of the passengers attempting to retrieve their luggage (i.e., Scenario 4) on overall evacuation efficiency is explored. As in all the evacuation scenarios considered in this analysis, the narrow-body, single-aisle cabin layout presented in Section 3.1 is used, and all the passengers attempt to evacuate via their nearest serviceable exit, i.e., either of the two forward Type-C exits or the left pair of Type-III overwing exits.

The initial seating allocation for luggage collectors is defined within the model by the *Luggage Collectors' Zone* as described in Section 5.3(a). Throughout this analysis, this is defined to encompass the seat blocks as shown in Figure 19. Note that seat rows that lead to an exit are not included in the luggage collectors' zone. Furthermore, to better understand how the luggage collection behaviour impacts the overall evacuation performance, five compartment zones are defined as described in Section 5.3(c) and shown in Figure 21. For each compartment zone, the additional information that is recorded and exported into the simulation data output file includes the time that a PAX entered the zone, the time a PAX left the zone, and the dwell time (i.e., duration they spend inside that zone).

The chosen aircraft cabin layout accommodates 180 passengers, 3 cabin crew, and 2 flight deck crew in total. As two rows of seats are excluded from containing luggage retrievers (last row of Zone 02 and first row of Zone 03), this reduces the number of potential luggage collectors to 168. Thus, for Scenario 4, 126 of the passengers are luggage retrievers,

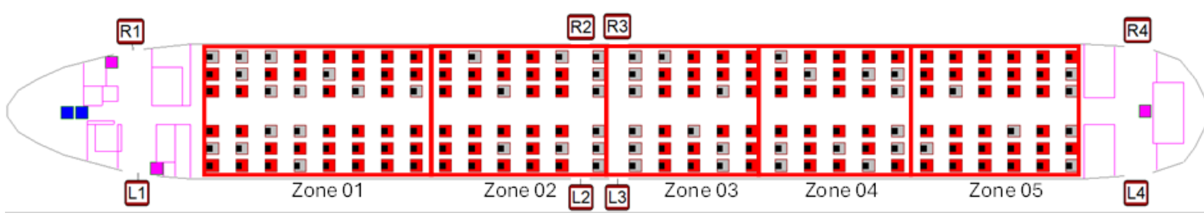
8.1 Scenario 4: Defining Parameters Required by the Luggage Collection Model

The luggage retrieval model developed in Section 5 included two user-defined parameters to describe how passengers attempt to by-pass a luggage retriever (see Table 19 for details). The two parameters and the values used in the simulations are identical to those for Scenario 2; see Section 6.1.

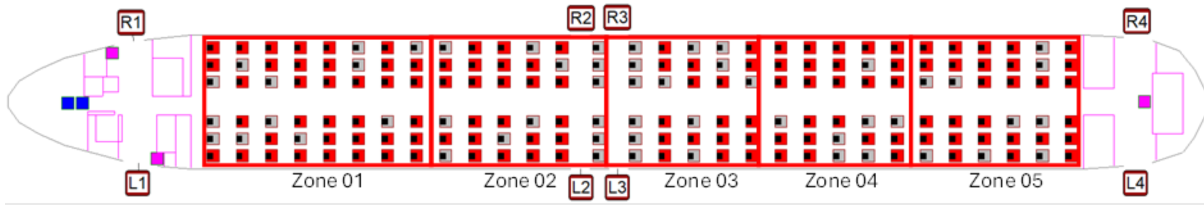
8.2 Scenario 4 Setup — Seating Location of Luggage Retrievers

As two rows of seats are excluded from containing luggage retrievers (last row of Zone 02 and first row of Zone 03), this reduces the number of potential luggage collectors from 180 passengers to 168. Thus, for Scenario 3, with 75% luggage collectors, there are 126 passengers attempting to retrieve their luggage.

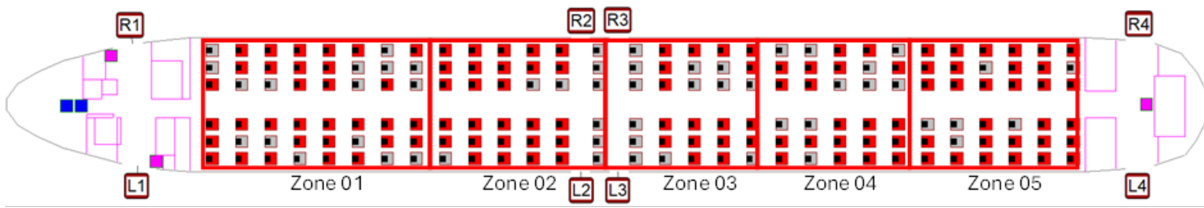
Presented in Figure 53 is the seating location for the luggage retrievers (red-coloured seats) for the simulations producing the minimum, median, and maximum Total Evacuation Times (TETs). Note that a number of seat rows have up to six luggage retrievers.



(a) Minimum



(b) Median



(c) Maximum

Figure 53: Seating location of luggage retrievers in Scenario 3 (red-coloured seats) for the (a) minimum, (b) median, and (c) maximum evacuation time.

Presented in Table 50 are the number of luggage retrievers in each zone for the minimum, median, and maximum simulations for Scenario 4, while presented in Table 51 are the minimum, average, and maximum number of luggage retrievers in each zone across the 1000 simulations. Clearly, the distribution of luggage retrievers will impact the TET and the performance of passengers within each zone. As seen in Table 51, there can be a large variation in the number of luggage retrievers in each zone over the 1000 repeat simulations; for example, in Zone 05, the number varies from 20 to 34, with an average of 27.

Table 50: Number of luggage retrievers in each zone for various repeat simulations for Scenario 3.

	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Total
Min sim	34	25	19	19	29	126
***Median sim**	36	23	17	23	27	126
Max sim	32	27	17	20	30	126

*Median sim is the 501st simulation.

Table 51: Minimum number, average, and maximum number of luggage retrievers in each zone across all 1000 repeat simulations for Scenario 3.

	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Min	28	14	12	15	20
Average	36.0	22.4	18.0	22.6	27.0
Max	44	28	24	29	34

8.3 Scenario 4 (75% Luggage Retrievers) Results and Analysis

Here, the results for Scenario 4 are presented. In this scenario, 75% of the passengers (i.e., 126) attempt to retrieve their luggage and incur a delay time derived from the distribution presented in Section 4.3, Table 18.

(a) Scenario 4 75% luggage retrievers) general results and analysis

Presented in Figure 54 are the exit curves for Scenario 4 (75% luggage retrievers), together with those for Scenario 1 (no luggage retrievers) for the simulations producing the minimum, median, and maximum simulations, while key simulation parameters are reported in Table 52.

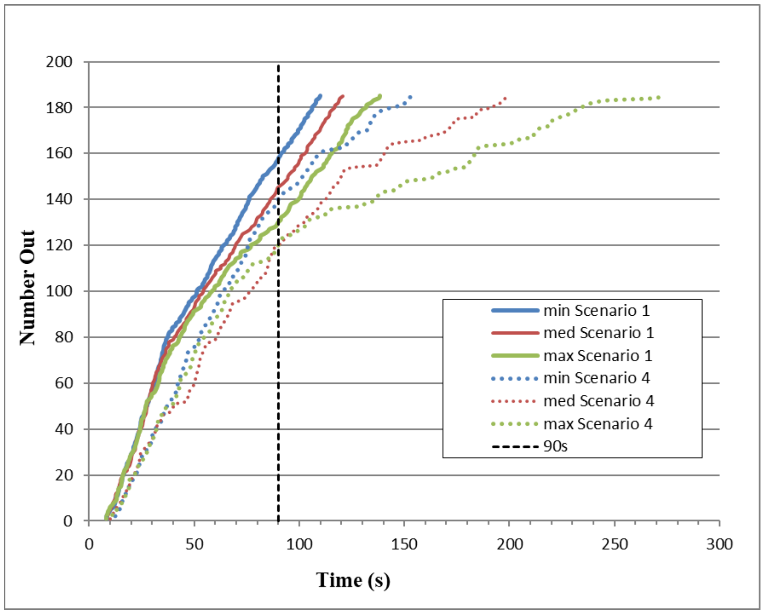


Figure 54: Evacuation curves for Scenario 1 (base case) and Scenario 4.

From Table 52, we note that over the 1000 repeat simulations, the TET for Scenario 4 varies from 153.7 s to 271.5 s (with an average of 199.7 s), with a corresponding average PET varying from 65.8 to 88.8 s (note that the absolute range of PET varies from 65.8 s to 100.7 s). By 90 s, between 77% (143) and 48% (88) of the 185 occupants or an average of 121.3 (66%) have evacuated.

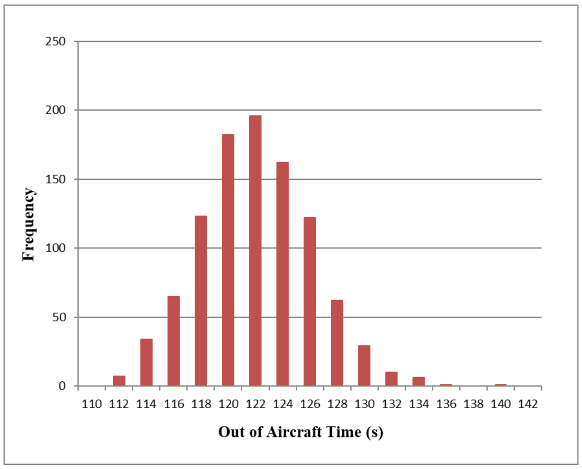
Furthermore, as with Scenarios 2 (25% luggage retrievers) and 3 (50% luggage retrievers), it is clear from both Figure 54 and Table 52 that the impact of the luggage retrievers in Scenario 4 is not uniform throughout a simulation (early part of the evacuation can be more or less impacted than the final part of the evacuation) and can vary significantly between repeat simulations.

Table 52: Simulation parameters from Scenario 1 and Scenario 4 for the simulations producing the minimum, median, maximum and 95th percentile evacuation times.

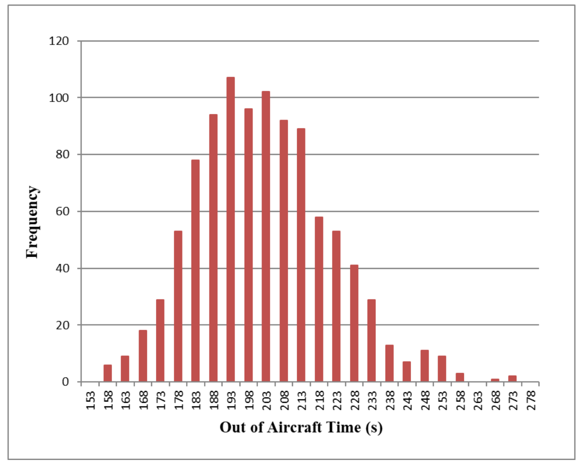
Sim	Avg. CWT (s)		Avg. Distance (m)		Avg. PET (s)		TET (s)	
	S1 0% LC	S4 75% LC	S1 0% LC	S4 75% LC	S1 0% LC	S4 75% LC	S1 0% LC	S4 75% LC
Min Sim	36.6	42.5	7.6	9.2	52.1	65.8	110.1	153.7
*Median Sim	40.6	54.6	7.7	9.5	56.2	79.1	120.9	198.6
Max Sim	45.8	64.1	7.8	9.4	61.9	88.8	138.5	271.5
95th% Sim	44.3	65.1	7.7	9.9	60.3	90.2	127.7	232.0

**Median sim is the 501st simulation.*

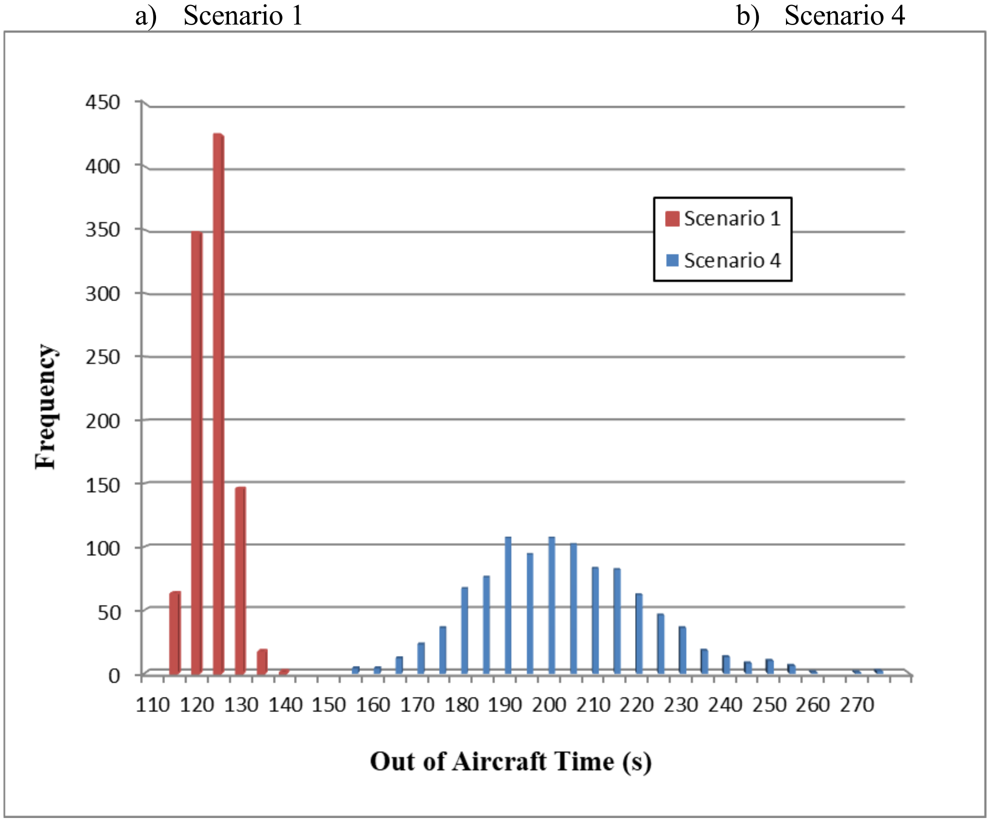
Presented in Figure 55 are the TET frequency distributions for (a) Scenario 1, (b) Scenario 4. and (c) Scenario 1 and Scenario 4. Clearly, having 75% of passengers retrieve their luggage can significantly impact TET. Without luggage retrieval, only approximately 2% (18) of the simulations have a TET in excess of 130 s, while with 75% luggage retrieval, 100% (1000) exceed 130 s, 51% (510) exceed 198 s. and 6% (59) exceed 230 s. Thus, in Scenario 4, there is no overlap with Scenario 1, demonstrating that with 75% of passengers retrieving their luggage, TET is significantly increased in every simulation.



a) Scenario 1



b) Scenario 4



c) Scenario 1 and Scenario 4

Figure 55: Evacuation time frequency distribution for (a) Scenario 1 (base case), (b) Scenario 4, and (c) Scenario 1 and Scenario 4.

(b) Impact of 75% luggage retrievers on evacuation time

For the simulations producing the minimum TET for Scenario 1 and Scenario 4, the TET is increased by 39.6% (see Table 53) when luggage retrievers are included. In the early stages of the evacuation, there are also large increases in evacuation times for Scenario 4, e.g., by the time 40 passengers have evacuated, the evacuation time is some 28.5% longer for Scenario 4, and when 80 passengers have evacuated, the increase in evacuation time is 40.0% (see ANNEX E). By 90 s, 157 (85%) occupants have evacuated in Scenario 1 and 140 (76%) occupants have evacuated in Scenario 4. Furthermore, the average PET is some 26.3% longer in the minimum simulation when luggage collectors are included (see Table 53).

As described in Section 6.4(b), when interpreting these results, it is important to recall the two key assumptions of the luggage retrieval model, i.e., passengers located in seat rows cannot by-pass a luggage retriever, and aisle by-pass is only possible if there is sufficient space ahead of the luggage retriever (see Section 5.1).

In the **minimum simulation**, the 126 luggage retrievers directly impacted 214 potential by-pass events: 80 in the aisle that could have occurred, as there was sufficient space, and 134 located in seat rows (see Table 53). However, the seated passengers involved in the 134 seat events are not able to by-pass the luggage collector and so are effectively trapped until the luggage collector has retrieved their luggage. Of the 80 attempted by-pass events occurring in the aisle, 42 (53%) were successfully implemented. Compared to Scenario 2, where there was a third of the luggage retrievers in Scenario 4, the number of possible aisle by-pass events increased by 471% (66), the successful aisle by-pass events increased by 600% (36), and the number of seat events increased by 347% (104).

Thus, for the simulation producing the *minimum TET*, with 75% (126) of the passengers attempting to retrieve their luggage, 42 of the 80 (53%) attempts to by-pass luggage retrievers in the aisle were successful, with the TET increasing by a significant amount from 110.1 s to 153.7 s (39.6%), and the average PET also increasing by a significant amount from 52.1 s to 65.8 s (26.3%).

For the simulations producing the maximum PET for Scenario 1 and Scenario 4, the PET increases by 96% (see Table 53) when luggage retrievers are included. In the early stages of the evacuation, there are also large increases in evacuation times for Scenario 4, e.g., by the time 40 passengers have evacuated, the evacuation time is some 30.5% longer for Scenario 4, and when 80 passengers have evacuated, the increase in evacuation time is 26.5% (see ANNEX E). By 90 s, 129 (70%) occupants have evacuated in Scenario 1 and 119 (64%) occupants have evacuated in Scenario 4. Furthermore, the average PET is some 43.5% longer in the maximum simulation when luggage collectors are included (see Table 53).

In the **maximum simulation**, the 126 luggage retrievers directly impacted 203 potential by-pass events: 67 in the aisle that could have occurred, as there was sufficient space, and 136 located in seat rows (see Table 53). However, the seated passengers involved in the 136 seat row events are not able to by-pass the luggage retriever and so are effectively trapped until the luggage retriever has collected their luggage. Of the 67 attempted by-pass events occurring in the aisle, 32 (48%) were successful, and the passengers were able to by-pass the luggage retriever. Compared to Scenario 2, where there was a third of the luggage retrievers in Scenario 4, the number of possible aisle by-pass events increased by 46% (21), the successful aisle by-pass events increased by 33% (8), and the number of seat events increased by 240% (96).

Thus, for the simulation producing the *maximum TET*, with 75% (126) of the passengers attempting to retrieve their luggage, 32 of the 67 (48%) attempts to by-pass luggage retrievers in the aisle were successful, with the TET increasing significantly from 138.5 s to 271.8 s (96%), and the average PET also increasing significantly from 61.9 s to 88.8 s (43.5%).

For the simulations producing the median TET for Scenario 1 and Scenario 4, the TET increases by 64.3% (see Table 53) when luggage retrievers are included. In the early stages of the evacuation, there are also large increases in evacuation times for Scenario 4, e.g., by the time 40 passengers have evacuated, the evacuation time is some 30.5% longer for Scenario 4, and when 80 passengers have evacuated, the increase in evacuation time is 50.6% (see ANNEX E). By 90 s, 145 (78%) occupants have evacuated in Scenario 1, and 120 (65%) occupants have evacuated in Scenario 4. Furthermore, the average PET is 40.7% longer in the median simulation when luggage collectors are included (see Table 53).

In the **median simulation**, the 126 luggage retrievers directly impacted 203 potential by-pass events: 66 in the aisle that could have occurred, as there was sufficient space, and 137 located in seat rows (see Table 53). However, the seated passengers involved in the 137 seat row events are not able to by-pass the luggage collector and so are effectively trapped until the luggage collector has retrieved their luggage. Of the 66 possible aisle by-pass events, 31 (47%) were successfully implemented. Compared to Scenario 2, where there was a third of the luggage retrievers in Scenario 4, the number of possible aisle by-pass events increased by 267% (48), the successful aisle by-pass events increased by 343% (24), and the number of seat events increased by 291% (102).

Thus, for the simulation producing the *median TET*, with 75% (126) of the passengers attempting to retrieve their luggage, 31 of the 66 (47%) attempts to by-pass luggage retrievers in the aisle were successful, with the TET increasing significantly from 120.9 s to 198.6 s (64.3%), and the average PET also increasing significantly from 56.2 s to 79.1 s (40.7%).

It is noted that not many passengers appear to successfully overtake the 126 luggage collectors. In the simulations producing the minimum, median, and maximum evacuation times, passengers successfully overtake luggage collectors 42, 31, and 32 times, respectively (see Table 53)). The relatively small number of overtaking luggage collectors is due to several issues. Passengers cannot overtake luggage collectors in a congested aisle, i.e., in situations where there is not sufficient clear space on the other side of the luggage collector. This will particularly be an issue early in the evacuation when the aisle is heavily congested. Furthermore, each luggage collector is randomly assigned a by-pass probability that varies from 0.0 to 1.0 (see Section 6.1, Figure 31) and if this probability is low, there is less chance that a passenger will be able to overtake the luggage collector. In the simulations producing the minimum, median, 95th percentile, and maximum evacuation times, the successful by-pass rate is 53%, 47%, 50%, and 48%. These are reasonably high success rates that are consistent with the by-pass probability distribution presented in Figure 31.

Table 53: Increase in average out-of-aircraft time and total evacuation time for Scenario 4 compared with Scenario 1.

Sim	Increase in Avg. PET (%)	Increase in TET (%)	Number of Successful by-pass	Number of unsuccessful by-pass events
Min Sim	26.3	39.5	42	172 (A38, S134)
***Median Sim**	40.7	64.3	31	172 (A35, S137)
Max Sim	43.5	96	32	171 (A35, S136)
95th% Sim	49.6	81.6	33	166 (A33, S133)

**Median sim is the 501st simulation. A: aisle-located passenger, S: seat row-located passenger.*

(c) The impact of 75% luggage retrievers on zonal dwell times

Presented in Table 54 are the average, minimum, maximum, and average dwell times for passengers originating in each zone. The values represent the average from the 1000 simulations of the minimum zonal dwell time, the maximum zonal dwell time, and the average zonal dwell time. For Scenario 1, the average dwell time in Zone 05 is 65.0 s. Similarly, the minimum time a passenger spent in Zone 05 across all 1000 simulations is 1.6 s, the average minimum time is 4.4 s, the maximum time is 110.8 s, and the average maximum time is 95.0 s.

In comparison, in Scenario 4, the average dwell time in Zone 05 is 133.6 s, with the minimum time a passenger spent in Zone 05 being 1.7 s, the average minimum time being 12.8 s, the maximum time being 256.9 s, and the average maximum time being 182.6 s. Thus, across the 1000 simulations, with 75% of the population retrieving their luggage, passengers in Zone 05 spend, on average, an additional 68.6 s (106%) exposed to the conditions of Zone 05, with the average dwell time significantly exceeding 90 s. In the event of a serious post-crash fire that gains access to the rear of the cabin (see Section 6.2 (a)), as noted for Scenarios 2 and 3, the significant increase in average dwell time for passengers in Zone 05 resulting from luggage retrievers represents a significant additional exposure to fire hazards, which can have fatal consequences.

In contrast, for Scenario 1, the average dwell time in Zone 01 is 19.8 s, while the minimum time a passenger spent in Zone 01 across all 1000 simulations is 1.3 s, the maximum time is 79.0 s, and the average maximum time is 48.1 s. In comparison, in Scenario 4, the average dwell time in Zone 01 is 50.8 s, with the minimum time a passenger spent in Zone 01 being 1.3 s and the maximum time being 131.2 s, while the average maximum time is 94.2 s. Thus, across all the 1000 simulations, with 75% of the population retrieving their luggage, passengers in Zone 01 spend, on average, an additional 31 s (157%) exposed to the conditions of Zone 1. In the event of a serious post-crash fire that gains access to the rear of the cabin (consistent with this scenario), passengers in the front of the cabin are furthest away from high concentrations of fire hazards that are likely to be located in the rear of the cabin. However, the average dwell time in Zone 01 (50.8 s) has increased significantly compared to Scenario 2, so in the event of post-crash fire gaining access to the rear of the cabin, these dwell times may pose a threat to some passengers in Zone 01, even though they are far removed from the initial fire.

The anomaly in average dwell time noted for Zone 02 in Scenarios 2 and 3 no longer persists in Scenario 4. Furthermore, the anomaly in Zone 03, where the average dwell time with luggage retrievers is smaller than average dwell time without, has reduced to just a 2.6% difference. Given the large number of luggage retrievers in Zones 2 and 3 in Scenario 4, it is likely that this effectively removes any bias in the use of both Type-III exits.

Table 54: Average (across 1000 simulations) dwell time incurred by agents in their zone of origin for Scenario 1 and Scenario 4.

Zone	Scenario	Min Dwell Time (s) (min - max)	Max Dwell Time (s) (min - max)	Avg Dwell Time (s) (min - max)	Number of PAXs	Avg. Number of Luggage Collectors (min - max)
1	1	2.6 (1.3 - 5.9)	48.1 (28.1 - 79.0)	19.8 (14.3 - 26.1)	48	0
	4	5.1 (1.3 - 16.5)	94.2 (69.8 - 131.2)	50.8 (35.6 - 76.7)		36 (28 - 44)
2	1	3.8 (1.8 - 12.5)	81.7 (52.2 - 129.4)	40.1 (27.9 - 57.9)	36	0
	4	4.0 (1.9 - 12.5)	90.7 (57.1 - 133.3)	43.3 (29.1 - 64.8)		22.4 (14 - 28)
3	1	3.9 (1.7 - 14.6)	89.2 (42.5 - 128.1)	38.3 (23.7 - 62.5)	30	0
	4	4.0 (1.8 - 13)	79.2 (47.9 - 124.4)	37.3 (24.8 - 61.3)		18 (12 - 24)
4	1	4.3 (1.6 - 42.7)	92.7 (59.4 - 118.4)	51.4 (34.1 - 71.5)	30	0
	4	17.3 (1.7 - 81.1)	129.2 (87.7 - 201.1)	84.3 (52.6 - 128.2)		22.6 (15 - 29)
5	1	4.4 (1.6 - 21.8)	95.0 (76.9 - 110.8)	65.0 (46.6 - 82.6)	36	0
	4	12.8 (1.7 - 35.9)	182.6 (136.8 - 256.9)	133.6 (93.2 - 188)		27 (20 - 34)

Thus, in evacuation scenarios involving only four available exits, the two front exits and two overwing exits located on one side of the aircraft, with one in three (75%) passengers attempting to retrieve cabin luggage, there is a significant increase in dwell times incurred by some passengers (i.e., those in the rear of the aircraft (Zone 05)) and total evacuation times for the aircraft. Of particular concern is that the average dwell time in Zone 05 significantly exceeds 90 s, so passengers are forced to spend an excessive amount of time in the rear of the aircraft during the evacuation. While the extent of the dwell time is strongly dependent on the random distribution of passengers attempting to retrieve luggage, as the average dwell times for Zone 05 vary from 93.2 s to 188.0 s, they are all significantly long. In the event of a serious cabin post-crash fire, the more than doubling in dwell times for passengers in the rear of the aircraft (Zone 05) due to luggage collectors is likely to significantly decrease passenger survivability by increasing passenger exposure to hazardous fire products.

(d) The impact of 75% luggage retrievers on zonal evacuation times

Presented in Table 55 are the average, minimum, maximum, and average evacuation times for passengers originating in each zone. The values represent the average from the 1000 simulations of the minimum zonal evacuation time, the maximum zonal evacuation time, and the average zonal evacuation time. For Scenario 1, the average evacuation time in Zone 05 is 99.0 s. Similarly, the average minimum time a passenger spent evacuating from Zone 05 across all 1000 simulations is 64.1 s, while the minimum time a passenger spent evacuating from Zone 05 across all 1000 simulations is 29.0 s, and the maximum time is 138.1 s.

In comparison, in Scenario 4, the average evacuation time for passengers starting in Zone 05 is 159.4 s, with an average minimum evacuation time from Zone 05 of 106.2 s and a maximum time of 270.4 s. Thus, across all 1000 simulations, with 75% of the population retrieving their luggage, passengers in Zone 05 spend an additional 60.4 s (61%) on average evacuating compared to the situation without luggage retrievers. The average evacuation time for passengers in Zone 05 significantly exceeds 90 s; this, combined with the excessively long average dwell time in Zone 05, can be significant, as it potentially exposes the passengers to hazardous conditions that may develop in this zone resulting from a post-crash fire.

Table 55: Evacuation times based on zone of origin for Scenario 1 and Scenario 4.

Zone	Scenario	Min PET (s) (min - max)	Max PET (s) (min - max)	Avg PET(s) (min - max)	Number of PAXs
1	1	8.4 (8.1 - 10.6)	81.7 (50.2 - 125.1)	30.1 (24.8 - 37.4)	48
	4	11.2 (8.2 - 26.7)	103.8 (75.6 - 139.7)	59.2 (44.4 - 86)	
2	1	13.0 (12 - 16.6)	90.9 (60.1 - 131)	44.5 (31.9 - 60.7)	36
	4	13.0 (12 - 17.1)	93.2 (60.6 - 137.8)	47.0 (33.1 - 67.1)	
3	1	13.0 (11.9 - 19.9)	98.1 (46.2 - 132.4)	43.3 (29 - 68.5)	30
	4	13.0 (11.9 - 16.9)	81.6 (53.5 - 125.7)	40.8 (29 - 63.6)	
4	1	31.5 (15.1 - 63.6)	111.1 (82.3 - 138.5)	72.8 (55.7 - 91.3)	30
	4	47.4 (17.5 - 98.1)	138.6 (96.6 - 211.3)	96.6 (66.8 - 141.1)	
5	1	64.1 (29.0 - 96.3)	120.2 (106.4 - 138.1)	99.0 (80.6 - 113.1)	36
	4	106.2 (44.3 - 164.8)	197.9 (150.9 - 270.4)	159.4 (119.5 - 221)	

For Scenario 1, the average evacuation time in Zone 01 is 30.1 s. The average minimum time a passenger spent evacuating from Zone 1 across all 1000 simulations is 8.4 s, while the minimum time a passenger spent evacuating from Zone 1 across all 1000 simulations is 8.1 s, and the maximum time is 125.1 s. In comparison, in Scenario 4, the average evacuation time for passengers starting in Zone 01 is 59.2 s, with an average minimum evacuation time from Zone 01 across all 1000 simulations of 11.2 s and a maximum time of 139.7 s.

Thus, across all 1000 simulations, with 75% of the population retrieving their luggage, passengers in Zone 01 spend an additional 29.1 s (97%), on average, evacuating compared to the situation without luggage retrievers. The significant increase in average Zone 01 evacuation time results in a large average evacuation time for Zone 01 (59.2 s), which is nearly double that for Scenario 1.

It is also noted that the average evacuation times for passengers in Zone 03 for Scenario 4 are less than that for the scenario without luggage retrievers. Again, while a surprising result, this is possibly due to the better use of the heavily congested Type-III exits that luggage retrieval enables by preferentially allowing one zone to fully utilise both exits momentarily throughout the evacuation.

8.4 Key Findings: Scenario 4 (75% Luggage Retrievers)

The results generated for all luggage retrieval scenarios are compared against the base case, Scenario 1 (no luggage retrieval) (S1), where the Total Evacuation Time (TET) varied from approximately 110 s to 139 s, and the average personal evacuation time (PET) varied between 51.6 s and 61.9 s, with an average of 79% (146.2) of the 185 occupants evacuated by 90 s.

Scenario 4 (S4) involved 75% of the passengers (126 passengers) attempting to retrieve their luggage during the evacuation.

Key Finding 8.1, Scenario 4, Overall Evacuation performance:

- With 75% (126) of the passengers designated as luggage collectors, the TET varied from approximately 153.7 s to 271.5 s (with an average of 199.7 s) and, on average, with 66% (121.3) of the 185 occupants evacuated by 90 s. The average PET varies from 65.8 s to 100.7 s. This is a wide variation in evacuation performance, with a significant increase in the maximum TET (96%) and maximum average PET (63%) compared to S1. Furthermore, the average PET exceeded 90 s for some simulations.
- The impact of luggage collectors on evacuation performance is complex and varies depending on the specific seating location and the distribution of luggage collectors.

Key Finding 8.2, Scenario 4, Specific Evacuation performance:

- As the number of luggage retrievers within a spatial zone within the aircraft can vary significantly, as does their seating locations, it is inappropriate to simply base conclusions on any one simulation, e.g., a simulation producing a median evacuation time, as this may provide an overly pessimistic or optimistic conclusion. It is more informative to consider evacuation performance of several key simulations, such as the simulations producing the minimum, median, and maximum TET.
- **For the simulation producing the *minimum TET*, with 75% (126) of the passengers attempting to retrieve their luggage, 42 of the 80 (53%) attempts to by-pass luggage retrievers in the aisle were successful. Compared to S1, the TET has increased by a significant amount from 110.1 s to 153.7 s (39.6%), and the average PET has also increased by a significant amount from 52.1 s to 65.8 s (26.3%).**
- **For the simulation producing the *median TET*, with 75% (126) of the passengers attempting to retrieve their luggage, 31 of the 66 (47%) attempts to by-pass luggage retrievers in the aisle were successful. Compared to S1, the TET has increased significantly from 120.9 s to 198.6 s (64.3%), and the average PET has also increased significantly from 56.2 s to 79.1 s (40.7%).**

- **For the simulation producing the *maximum TET*, with 75% (126) of the passengers attempting to retrieve their luggage, 32 of the 67 (48%) attempts to by-pass luggage retrievers in the aisle were successful. Compared to S1, the TET has increased significantly from 138.5 s to 271.8 s (96%), and the average PET has also increased significantly from 61.9 s to 88.8 s (43.5%).**
- Thus, compared to S1, the simulations producing the minimum, medium, and maximum TET experienced significant increases in average PET and TET.
- In Scenario 4, for the simulation producing the median TET (198.6 s) with three times as many luggage retrievers as in Scenario 2, there were 66 viable aisle by-pass events, of which 31 (47%) were successful. In addition, there were 137 occurrences where passengers in seat rows were prevented from by-passing the luggage collector blocking their exit from the seat row. Compared to Scenario 2, the number of possible aisle by-pass events increased by 267% (48), the number of successful aisle by-pass events increased by 343% (24), and the number of occurrences where passengers in seat rows are prevented from by-passing the luggage collector seat events increased by 291% (102).
- However, when assessing the impact of luggage retrievers on evacuation performance, it is inappropriate to simply consider typical global evacuation parameters,, such as TET or average PET, as this may not reveal the significant localised impact of luggage retrieval on specific groups of passengers.

Key Finding 8.3, Scenario 4, Localised Evacuation performance:

- A deeper understanding of the impact of luggage retrievers on the overall evacuation can be derived from investigating localised evacuation parameters, such as zonal dwell times and zonal evacuation times.
- In S4, with 75% of the passengers retrieving luggage, for those passengers starting in Zone 01 (the front eight seat rows),
  - the average Zone 01 dwell time is 50.8 s; thus, passengers in Zone 01 spend on average an additional 31 s (157%) exposed to the conditions of Zone 01 compared to S1.
  - the average Zone 01 evacuation time is 59.2 s, an increase of 29.1 s (97%) compared to S1. This is almost double that of S1.
  - in the event of post-crash fire gaining access to the rear of the cabin (consistent with the evacuation scenario), these dwell times and evacuation times may pose a threat to some passengers in Zone 01, even though they are far removed from the initial fire.
- In S4, with 75% of the passengers retrieving luggage, for those passengers starting in Zone 05 (rear six seat rows),
  - the average Zone 05 dwell time is 133.6 s; thus, passengers in Zone 05 spend, on average, an additional 68.6 s (106%) exposed to the conditions of Zone 05 compared to S1. This is more than double that of S1.
  - the average Zone 05 evacuation time is 159.4 s, an increase of 60.4 s (61%) compared to S1.
  - Both the Zone 05 average dwell time and average evacuation time significantly exceed 90 s.
  - In the event of a serious post-crash fire that gains access to the rear of the cabin (consistent with the evacuation scenario), the excessively long average dwell time (133.6 s) and average evacuation time (159.4 s) for passengers in Zone 05 can result in significant additional exposure to fire hazards compared to S1, which is highly likely to have fatal consequences.
- A consequence of the imposed by-pass model behaviour is that gaps may occur in evacuation flow within the main cabin aisle, as failed by-pass events prevent passengers behind the luggage

retriever from progressing down the aisle to an exit. This, in turn, can result in periods of no flow at the exits.

Key Finding 8.4, Scenario 4, Overall evaluation:

- In S4, with 75% of the passengers attempting to retrieve luggage, **there is a significant increase** in both dwell times incurred by **most** passengers and the TET for the aircraft for most of the 1000 repeat simulations. **These increases are of great concern, as they seriously compromise survivability in the event of a post-crash fire gaining access to the cabin for most passengers.** However, even with as many as 75% of the passengers retrieving luggage, the outcome **is still somewhat dependent** on the random distribution of the luggage retrievers and the seating zone of the passengers, so not all passengers are impacted equally by luggage collectors. Passengers in the rear of the aircraft are **significantly** impacted by luggage collectors. Thus, in the event of a serious post-crash cabin fire that gains access to the rear of the cabin (consistent with the evacuation scenario), those most at risk are passengers seated in the rear of the aircraft (Zone 05) due to the **significant increase** in average dwell times (133.6 s) and average evacuation times (159.4 s) resulting from passengers retrieving their luggage. The increased passenger exposure to hazardous fire products due to the incurred delays **will seriously** decrease passenger survivability. Furthermore, even passengers seated in the front of the aircraft (Zone 01) and, hence, furthest removed from the initial fire are **significantly** impacted, incurring **very long** average dwell times of 50.8 s and average evacuation times of 59.2 s.

9 DISCUSSION

The configuration considered in this analysis was a narrow-body aircraft equipped with a pair of forward Type-C exits, two pairs of overwing Type-III exits, and a pair of aft Type-C exits. The configuration seated 180 passengers with 3 cabin crew and 2 flight deck crew, resulting in 185 occupants in total. The configuration is typical of the B737/A320 class of aircraft. The purpose of this analysis was to explore the impact on evacuation performance of passengers retrieving cabin luggage. The relevance and realism of the modelled scenario were strengthened with a number of conditions 'typical' of accidents. Only half of the normally available exits were used, similar to the FAR 25.803. However, unlike the regulatory requirement, the available exits were not located optimally with one exit from each exit pair but consisted of both forward Type-C exits and the left pair of Type-III overwing exits. Furthermore, the simulated passengers within the simulation (agents) exhibited typical passenger behaviour that is found in many accidents in which passengers attempted to utilise their nearest exit.

The exit availability and passenger behaviour assumed in this analysis are based on studies of previous accidents [10,11,12]. For example, the adopted exit availability is similar to two noteworthy fatal incidents involving post-crash fires: the 1985 Manchester B737 [4, 20] and the 2019 Sheremetyevo Sukhoi Superjet-100 [21, 22, 23]. In the Manchester incident, both forward exits and an overwing exit, representing 50% of the normally available exits, were viable [4, 20]. In the 2019 Sheremetyevo Sukhoi Superjet-100 [21, 22, 23] incident, only the two front exits were available for evacuation, also representing 50% of the normally available exits, as this aircraft did not have overwing exits. In both incidents, an external post-crash fuel fire gained access to the cabin interior at the rear of the aircraft; hence, the rear exits were not viable for evacuation. Thus, while not fully representing conditions found in aircraft accidents, the modelled scenario is considerably more representative and challenging than the typical certification scenario.

9.1 Implications of the Base Case Scenario (Scenario 1, 0% Luggage Retrievers)

The first scenario (Scenario 1 or S1) considered was the base case that did not involve any luggage retrievers. From the 1000 repeat simulations of S1, the model predicts total evacuation times (TETs) of between 110.1 s and 138.5 s, with an average TET of 121.1 s, well in excess of the regulatory 90 s requirement (see Table 56). However, the average personal evacuation time (PET) for the aircraft is 55.9 s, indicating that many passengers are able to evacuate before 90 s. Nevertheless, by 90 s, on average, only 146.2 (79%) of the occupants have evacuated, with 38.8 remaining onboard. As would be expected, passengers located towards the rear of the aircraft (Zone 05, i.e., the six rear seat rows) have the greatest PET, with an average of 99.0 s. They also have a large zonal dwell time of 65.0 s.

While half the normally available exits are used in the evacuation scenario, as is required by FAR 25.803, the available exits are not optimally located like in a certification trial, where one from each exit pair is available along the length of the aircraft. Within S1, the available exits consist of the front pair of Type-C exits (the largest exit type available on the aircraft) and the pair of left overwing Type-III exits (the smallest exit type available on the aircraft). As passengers will tend to use their nearest exit, most attempt to exit via the pair of overwing exits. This, and the greater travel distances incurred in this scenario, contribute to the long evacuation times compared with the expected certification scenario. In addition, given the nature of the scenario, both pairs of exits are utilised sub-optimally. For the front pair of Type-C exits, the single cabin aisle cannot supply passengers quickly enough to utilise their capacity. For the overwing exits, the majority of passengers come from one side, the rear, so the aft Type-III exit (3L) is naturally supplied preferentially. This can result in sub-optimal usage of both exits, as conflicts between passengers arise when they decide which of the two exits to use. This, in turn, can disrupt the supply to and exiting flow through both exits, creating momentary gaps in the flows.

9.2 Implications of Luggage Retrievers on the Formation of Gaps in Aisle and Exit Flows

As described in Section 6.4(e), a consequence of the imposed by-pass model behaviour is that gaps may occur in evacuation flow within the main cabin aisle, as failed by-pass events prevent passengers behind the luggage retriever from progressing down the aisle to an exit. These gaps in aisle flow may also result in gaps in exit flows. For example, depicted in Figure 56 is the situation 74 s into the evacuation producing the median TET for each of the four scenarios. At this time, there is a small gap in the rear of the cabin in Scenario 1. While this is not caused by luggage retrievers, it results from conflicts between passengers attempting to enter the aisle from both the left and right seat rows and the passenger in the aisle. This conflict is rapidly resolved, and the gap disappears seconds later. At this time, there are no gaps in the aisle or exit flows for Scenario 2; however, there are multiple gaps in Scenario 3 and 4, with the gap in the front of the cabin in Scenario 4 disrupting the exit flow through the front Type-C exits. In Scenario 4, the last passenger to exit from the forward Type-C exits prior to 74 s exited at 67 s, with the next passenger to exit following the gap depicted in Figure 56 and exiting at 82 s. Thus, there was a 15 s gap in exit flow for the forward Type-C exits in Scenario 4 due to the luggage collection.

It is noted that gaps in exit flow are often observed in actual accident situations, albeit resulting from unknown conditions within the cabin and not necessarily related to luggage retrieval.

Figure 56: The predicted passenger distribution for the four scenarios (first image is Scenario 1) at 74 s into the simulations producing the median TET and demonstrating gap formation.

9.3 Implications of the Luggage Retrieval Scenarios

For scenarios involving luggage retrieval, the number of passengers designated as luggage retrievers is as follows:

- Scenario 2 (S2): 25% or 42 of the passengers
- Scenario 3 (S3): 50% or 84 of the passengers
- Scenario 4 (S4): 75% or 126 of the passengers

To interpret the simulation results correctly, it is important to recall two key model assumptions: firstly, that passengers located in seat rows cannot by-pass a luggage retriever, and secondly, that aisle by-pass is only possible if there is sufficient space ahead of the luggage retriever (see Section 5.1).

In S2, with 25% luggage retrievers, the TET varies from 111.7 s to 200.2 s, with an average TET of 136.8 s, representing an increase of 13% compared to S1. The average PET is 60.9 s, an increase of 8.9%. While these increases may appear modest, they represent the average increase. Many of the 1000 simulations have more significant increases in both TET and PET (see Figure 57). For example, the simulation producing the maximum TET has a 44.5% (200.2 s compared to 138.5 s) increase in TET and a 20.5% (74.6 s compared to 61.9 s) increase in PET (see Table 56).

Table 56: Key evacuation parameters for Scenarios 1 – 4 for the simulations producing the minimum, median, and maximum TET, along with the average values.

Scenario	Parameter	Min Sim (% increase)	Median Sim (% increase)	Max Sim (% increase)	Average Value (% increase)
Scenario 1: 0% luggage retrievers	avg PET (s)	52.1 (-)	56.2 (-)	61.9 (-)	55.9 (-)
	TET (s)	110.1 (-)	120.9 (-)	138.5 (-)	121.1 (-)
Scenario 2: 25% luggage retrievers	avg PET (s)	54.5 (4.6%)	61.1 (8.7%)	74.6 (20.5%)	60.9 (8.9%)
	TET (s)	111.7 (1.5%)	135.0 (11.7%)	200.2 (44.5%)	136.8 (13%)
Scenario 3: 50% luggage retrievers	avg PET (s)	59.3 (13.8%)	69.0 (22.8%)	89.1 (43.9%)	69.4 (24.2%)
	TET (s)	124.7 (13.3%)	167.6 (38.6%)	228.0 (64.6%)	168.7 (39.3%)
Scenario 4: 75% luggage retrievers	avg PET (s)	65.8 (26.3%)	79.1 (40.7%)	88.8 (43.5%)	80.1 (43.3%)
	TET (s)	153.7 (39.6%)	198.6 (64.3%)	271.5 (96%)	199.7 (64.9%)

**Median sim is the 501st simulation.*

In S3, with 50% luggage retrievers, the TET varies from 124.7 s to 228.0 s, with an average TET of 168.7 s, representing an increase of 39.3% compared to S1. The average PET is 69.4 s, an increase of 24.2%. While these increases in both TET and PET are large, they only represent the average, and so many simulations produce even larger increases (see Figure 57). Furthermore, even the simulation producing the smallest increase generates a moderate increase in both TET and PET. For example, the simulation producing the minimum TET has a 13.3% (124.7 s compared to 110.1 s) increase in TET and a 13.8% (59.3 s compared to 52.1 s) increase in PET (see Table 56).

In S4, with 75% luggage retrievers, both the average TET and PET are significantly increased. The TET varies from 153.7 to 271.5 s, with an average TET of 199.7 s, representing an increase of 64.9% compared to S1. The average PET is increased by 43.3% to 80.1 s. These significant increases in both TET and PET only represent the average, and so many simulations produce even greater increases. Indeed, all 1000 simulations have significant increases in both TET and PET (see Figure 57). For example, the simulation producing the minimum TET has a significant increase in both TET and PET, with TET increasing by 39.6% (153.7 s compared to 110.1 s) and PET increasing by 26.3% (65.8 s compared to 52.1 s) (see Table 56).

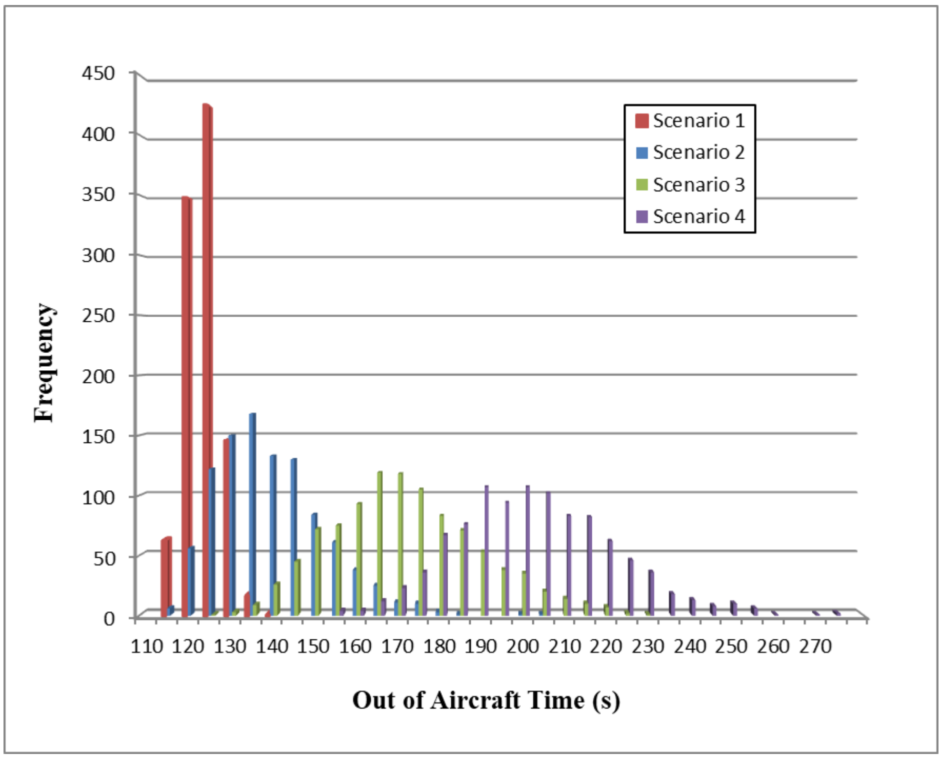


Figure 57: TET distribution for Scenario 1 (0% luggage collectors), Scenario 2 (25% luggage collectors), Scenario 3 (50% luggage collectors), and Scenario 4 (75% luggage collectors).

Thus, even with one in four (25%) of the passengers retrieving luggage, the TET and PET can increase significantly, at least for some of the simulations (see Table 57 and Figure 57). In the event of a post-crash fire gaining access to the passenger cabin during the evacuation (e.g., Manchester B737 [4, 20] and Sheremetyevo Sukhoi Superjet-100 [21, 22, 23]), this significant increase in TET and average PET could decrease the probability of surviving a post-crash fire for some passengers.

As the number of luggage retrievers increases, the TET and average PET increase, further reducing the probability of surviving.

From the simulation results, it is clear that as the number of randomly distributed luggage retrievers increases, there is not only a corresponding significant increase in the average TET and PET but also the number of simulations producing prolonged evacuations (see Table 57 and Figure 57). The significant increase in TET and PET increases the likely severity of exposure to potentially hazardous conditions for some passengers as the fire intensifies over time. Furthermore, the higher number of simulations producing significantly large TET and PET increases the likelihood that passengers will be involved in a prolonged evacuation with greater exposure to potentially hazardous conditions.

Table 57: Number of simulations exceeding specified times for each scenario.

Scenario	>=110 (s)	>=130 (s)	>=140 (s)	>=198 (s)	>=230 (s)	>=270 (s)
Scenario 1: 0% luggage retrievers Max TET: 138.5 s	1000	18	0	0	0	0
Scenario 2: 25% luggage retrievers Max TET: 200.2 s	1000	667	365	1	0	0
Scenario 3: 50% luggage retrievers Max TET: 228.0 s	1000	996	961	61	0	0
Scenario 4: 75% luggage retrievers Max TET: 271.5 s	1000	1000	1000	510	59	2

To explore whether a given number of randomly distributed luggage retrievers disadvantage all passengers equally or whether there are regions of the passenger cabin affected more severely, the cabin was divided into five seating zones. The front eight seat rows were defined as Zone 01, the rear six seat rows as Zone 05, and the space in between as Zones 02, 03, and 04 (see Figure 21). For the exit scenario investigated in this study, Zone 01 was immediately adjacent to the available two forward Type-C exits, Zone 02 and Zone 03 each contained one of the available Type-III exits, Zone 04 was adjacent to Zone 03, and Zone 05, in the rear of the aircraft, had no functioning exits and was not adjacent to a zone with a functioning exit. Thus, the passengers in Zone 05 were the furthest away from a functioning exit. Two additional parameters were defined to assess the evacuation performance of passengers originating within each zone: the zonal dwell time and zonal evacuation time. In a simulation, the zonal dwell time for a passenger is simply the time the passenger remains in the zone before moving into a neighbouring zone or exiting the aircraft. For a given simulation, the zonal average dwell time is then simply the average dwell time for all passengers starting in that zone. For a given scenario, the average zonal dwell time is simply the average of all 1000 simulation average zonal dwell times. The zonal evacuation time (i.e., zonal PET) is a measure of the personal evacuation time for passengers starting in a particular zone.

For S1 (0% luggage retrievers), the average passenger dwell time in Zone 05 (rear six seat rows) across all 1000 simulations is 65.0 s (see Table 58), and their average PET is 99.0 s (see Table 55).

In contrast, the average passenger dwell time in Zone 01 (front eight seat rows) across all 1000 simulations is 19.8 s (see Table 58), and their average PET is 30.1 s (see Table 55).

Table 58: Average (across 1000 simulations) dwell time incurred by agents in their zone of origin (Zone 01 and Zone 05) for Scenarios 1, 2, 3, and 4.

Zone	Scenario	Min Dwell Time (s) (min - max)	Max Dwell Time (s) (min - max)	Avg Dwell Time (s) (min - max)	Number of Passengers	Avg. Number of Luggage Collectors (min - max)
1	1	2.6 (1.3 - 5.9)	48.1 (28.1 - 79.0)	19.8 (14.3 - 26.1)	48	0
	2	3.0 (1.3 - 15.9)	64.1 (40.3 - 96.0)	31.5 (59%) (20.0 - 51.2)	48	12 (5 - 21)
	3	3.7 (1.3 - 12.2)	78.9 (53.3 - 117.7)	41.4 (109%) (27.5 - 62.3)	48	24 (15 - 32)
	4	5.1 (1.3 - 16.5)	94.2 (69.8 - 131.2)	50.8 (157%) (35.6 - 76.7)	48	36 (28 - 44)
5	1	4.4 (1.6 - 21.8)	95 (76.9 - 110.8)	65 (46.6 - 82.6)	36	0
	2	6.5 (1.6 - 31.2)	117.5 (86.5 - 177.6)	85.1 (31%) (51.9 - 128.5)	36	9 (3 - 16)
	3	9.5 (1.7 - 33.8)	150.8 (106.5 - 210.4)	109.8 (69%) (74.3 - 165.2)	36	18 (9 - 27)
	4	12.8 (1.7 - 35.9)	182.6 (136.8 - 256.9)	133.6 (105%) (93.2 - 188)	36	27 (20 - 34)

In S2 (25% luggage retrievers), S3 (50% luggage retrievers), and S4 (75% luggage retrievers), the average dwell time in Zone 05 across all 1000 repeat simulations is 85.1 s (an increase of 20.1 s or 31%), 109.8 s (an increase of 44.8 s or 69%), and 133.6 s (an increase of 68.6 s or 105%), respectively (see Table 58). The average Zone 05 dwell time in S2 is almost 90 s, and in S3 and S4, it greatly exceeds 90 s, with the average dwell time in S4 more than double that of S1. Similarly, the average PET for Zone 05 in S2, S3, and S4 (see Table 41, Table 49, and Table 55, respectively) is 111.9 s (increase of 13%), 134.7 s (increase of 36%), and 159.4 s (increase of 61%), respectively.

In contrast, while passengers in Zone 01 also experience increased zonal dwell and evacuation times, these times are considerably shorter than those in Zone 05. In S2 (25% luggage retrievers), S3 (50% luggage retrievers), and S4 (75% luggage retrievers), the average dwell time in Zone 01 across all 1000 repeat simulations is 31.5 s (an increase of 59%), 41.4 s (an increase of 109%), and 50.8 s (an increase of 157%), respectively (see Table 58). The average PETs for Zone 01 for S2, S3, and S4 are 41.1 s, 50.0 s, and 59.2 s, respectively. Thus, while the average PETs for Zone 01 have increased with an increased number of luggage collectors, these times are significantly shorter than for Zone 05.

The introduction of randomly located passengers retrieving luggage into the evacuation increases dwell time and PET for all passengers in all zones but with the most significant consequences for those in Zone 05 and the least significant consequences for those in Zone 01. Furthermore, the increase in both dwell and evacuation times is strongly dependent on the number of passengers retrieving their luggage.

Thus, the evacuation performance of passengers in the various zones is not impacted equally by the randomly seated luggage retrievers. The zone(s) most severely affected is likely to be dependent on the nature of the exit distribution available for the evacuation, so it is likely to be scenario-specific. For example, for a scenario in which both rear exits were available, passengers in Zone 05 would likely experience similar evacuation performance to those in Zone 01 in the current scenario. Furthermore, if the evacuation scenario resembled the ideal (optimal) FAR 25.803 scenario in which one exit from each exit pair was available, the zonal dwell times, zonal evacuation times, TETs, and average PETs are likely to be considerably shorter than those reported in this analysis.

Thus, for individual passengers, the outcome of an evacuation in which passengers attempt to retrieve luggage is strongly dependent not only on the number of passengers attempting to retrieve luggage but also on the random distribution of luggage retrievers, the seating location of the passenger, and the nature of the evacuation scenario.

While this study did not include a simulated fire or the effect it would have on the evacuation dynamics, it is possible to postulate, in broad terms, the likely impact a post-crash cabin fire would have on these evacuation scenarios. Of particular significance, the possible consequences of the increases in zonal dwell and evacuation times on passenger survivability can be assessed.

As suggested previously, given the exit availability considered in this study (two forward exits and a pair of left overwing exits), a plausible fire scenario would be similar to that in the 1985 Manchester B737 [4, 20] and the 2019 Sheremetyevo Sukhoi Superjet-100 [21, 22, 23] fatal post-crash fire incidents. These accidents, in common with the exit scenario in this study, only had 50% of exits available, with no rear exits available. In both these historic cases, the external fire initially impacts the rear of the aircraft. In these incidents (and it is suggested more generally for the exit scenario investigated in this study), the external fire eventually gains access to the rear of the aircraft cabin, allowing external fire hazards (radiative and convective heat from the external flames, visibility-obscuring smoke, and toxic narcotic and irritant fire gases) to initially impact those in the rear. Eventually, the fire spreads to interior cabin materials, and fire hazards from the external and internal fire spread throughout the cabin. Initially, the passengers in the rear of the aircraft, particularly those in Zone 05, are at greatest risk due to their proximity to the region where the fire initially gains access to the cabin and their consequent exposure to the highest concentration of fire hazards for the longest period of time. Conversely, passengers in the front of the aircraft, particularly those in Zone 01, will initially be at the lowest risk from the developing fire due to their distance from hazards, shorter expected evacuation times, and shorter expected exposure duration to the fire hazards.

In the event of a serious post-crash fire that gains access to the cabin interior, the significant increases in average dwell time for passengers in Zone 05 resulting from luggage retrievers could cause significant additional exposure to fire hazards. With 75% luggage retrievers, the average dwell time in Zone 05 more than doubles relative to S1 (i.e., no luggage retrievers). This, in turn, is likely to more than double passenger exposure to heat and toxic gases, greatly increasing their inhaled Fractional Effective Dose (FED) of hazardous fire products and raising the likelihood of fatalities and the expected number of fatalities. Even in S2 (25% luggage retrievers), while the overall average

Zone 05 dwell time is 85.1 s, average dwell times amongst the 1000 repeat simulations vary from 51.9 s to 128.5 s, so some of the 1000 repeat simulations produce dangerously long dwell times (almost doubling the average dwell time for S1).

Passengers seated in the front of the aircraft (Zone 01) and, hence, furthest removed from the initial effects of the fire are less impacted by luggage collectors, at least if there are relatively few of them. However, as the number of luggage retrievers increases, even passengers in Zone 01 are adversely impacted. With 50% of the passengers collecting luggage (S3), the average dwell time in Zone 01 is increased to 41.4 s, and with 75% luggage collectors, the average dwell time is 50.8 s.

Thus, in the event of a serious post-crash cabin fire, increasing the number of luggage retrievers will increase average dwell times, which, in turn, is likely to decrease the survivability of passengers, particularly in Zone 05, by increasing their exposure to hazardous fire products. Furthermore, the increased exposure to toxic fire products, heat, and the obscuration effects of smoke will adversely impact the ability of exposed passengers to evacuate, further increasing their dwell time in Zone 05 and, hence, their exposure to severe fire hazards. This downward spiral is likely to result in a significant increase in the expected number of fatalities.

It is important to note that implicit in this analysis is the assumption that the number of luggage retrievers is fixed throughout the simulation and is not dependent on the nature and severity of the fire. It could be that as conditions deteriorate due to the developing fire, those passengers originally assigned to retrieve their luggage in the rear of the aircraft (i.e., Zone 04 and Zone 05) and who are yet to do so decide not to do so. This would speed up the tail of the evacuation, especially for those in the rear zones.

9.4 Comparative Analysis

To evaluate the impact of an evacuation scenario on passenger survivability in the event of a post-crash fire, it is necessary to couple both the fire and evacuation analysis, as demonstrated in the analysis of the Manchester B737 fatal fire [4]. In the previous section, an attempt was made to evaluate the impact of extended evacuation times caused by passengers retrieving luggage on passenger survivability in the event of a post-crash fire. This was based on a postulated likely fire scenario and how the predicted evacuation performance might impact passenger survivability. However, as a fire was not simulated and imposed on the evacuation, it was not possible to quantify the expected impact.

Another approach to evaluating the impact of passenger luggage retrieval on survivability is to undertake a comparative analysis, where the evacuation performance with luggage retrieval is compared with an accepted standard without luggage retrieval. Clearly, the industry-standard FAR 25.803 provides an evacuation standard that must be met by passenger aircraft; however, in the base case analysis (S1), the aircraft configuration investigated did not meet the required 90 s evacuation performance for the selected exit scenario. As described previously, this is because the exit distribution, while representing 50% of the available exits, as required by FAR 25.803, is more challenging and more representative of typical accident scenarios than the optimal exit distribution assumed in FAR 25.803, i.e., one exit from each exit pair.

As a result, S1 (0% luggage retrievers) achieved a TET of between 110.1 s and 138.5 s, with an average TET of 121.1 s (see Table 56). Clearly, this is well in excess of 90 s for the reasons previously explained. Consequently, by 90 s, only between 129 (70%) and 159 (86%) of the 185 people on board are successfully evacuated. On average, 146.2 (79%) people are evacuated, resulting in 38.8 people, on average, remaining on board after 90 s. This number of passengers remaining on board after 90 s could be considered the cost of this exit scenario for this aircraft configuration. The cost of evacuation delays arising from luggage retrieval with various numbers of luggage retrievers could then be similarly evaluated for this exit configuration. Analysis suggests that for S2 (25% luggage retrievers), S3 (50% luggage retrievers), and S4 (75% luggage retrievers), the average cost of the evacuation delays introduced by luggage retrievers for this exit configuration is 41.7 passengers, 50.2 passengers, and 63.7 passengers, respectively (see Table 59).

While the aircraft configuration with the exit availability specified in S1 fails to achieve the 90 s requirement by a significant margin, the aircraft configuration comfortably achieves the required FAR 25.803 evacuation performance for the evacuation scenario specified in the regulations. If, by implication, the evacuation performance achieved by the aircraft configuration with the more challenging and realistic exit configuration in S1 is assumed acceptable, it could form the basis for quantifying excess costs associated with unacceptable performance. Using this approach as a basis for determining cost for a given scenario, the excess number of passengers remaining on board the aircraft after 90 s, when compared with S1, could be considered the cost of the scenario.

This suggests that for S2 (25% luggage retrievers), S3 (50% luggage retrievers), and S4 (75% luggage retrievers), the cost of the evacuation delays introduced by luggage retrievers results in an excess cost of 2.9 passengers, 11.4 passengers, and 24.9 passengers, respectively (see Table 59).

Table 59: Number of persons evacuated within 90 s for Scenario 1 to 4 over 1000 repeat simulations.

	S1 **0% Luggage retrievers**	**S2** **25% Luggage retrievers**	**S3** **50% Luggage retrievers**	**S4** **75% Luggage retrievers**
Avg. Evacuation Time (min - max) (s)	121.1 (110.1 - 138.5)	136.8 (111.7 - 200.2)	168.7 (124.7 - 228.0)	199.7 (153.7 - 271.5)
# passengers evacuated within 90 s	159 - 129 (86% - 70%)	155 - 120 (84% - 65%)	151 - 112 (82% - 61%)	143 - 88 (77% - 48%)
Avg. # passengers evacuated within 90 s	146.2 (79%)	143.3 (77%)	134.8 (73%)	121.3 (66%)
Avg. # passengers remaining after 90 s	38.8	41.7	50.2	63.7
Avg. excess # passengers remaining over S1	-	2.9	11.4	24.9

9.5 Key Findings from Discussion

Given the exit availability considered in this study (two forward exits and a pair of left overwing exits), a plausible fire scenario associated with the evacuation scenario would be similar to that in the 1985 Manchester B737 [4, 20] and the 2019 Sheremetyevo Sukhoi Superjet-100 [21, 22, 23] fatal post-crash fire incidents. In both these cases, the external fire initially impacts the rear of the aircraft and eventual gains access to the rear of the aircraft cabin, allowing external fire hazards to initially impact those in the rear before spreading to cabin materials and to the front of the cabin. Initially, the passengers in the rear of the aircraft are at greatest risk, while passengers in the front of the aircraft are at least initial risk.

Key Finding 9.1, Overall Evacuation performance:
It is clear that as the number of randomly distributed luggage retrievers increases, there is not only a corresponding significant increase in the average TET and PET but also the number of simulations producing prolonged evacuations. The significant increase in TET and PET increases the likely severity of passenger exposure to potentially hazardous conditions for some passengers. Furthermore, the higher number of simulations producing significantly large TET and average PET increases the likelihood that passengers will be involved in a prolonged evacuation and, hence, the likelihood that passengers will experience greater exposure to potentially hazardous conditions.

Key Finding 9.2, Impact of luggage collection on individual passengers:
For individual passengers, the outcome of an evacuation in which passengers attempt to retrieve luggage is strongly dependent not only on the number of passengers attempting to retrieve luggage but also on the nature of the evacuation scenario (i.e., exit availability), the seating location of the passenger, and the random distribution of luggage retrievers. The last point contributes to the variability of evacuation performance for a particular scenario.

Key Finding 9.3, Localised Evacuation performance:
Passengers seated in the front of the aircraft (Zone 01) and, hence, furthest removed from the initial effects of the fire are less impacted by luggage collectors, at least if there are relatively small numbers of luggage collectors. However, as the number of luggage retrievers increases, even passengers in Zone 01 are adversely impacted. With 50% of the passengers collecting luggage (S3), the average dwell time in Zone 01 is increased to 41.4 s, and with 75% luggage collectors, the average dwell time is 50.8 s.

With 75% luggage retrievers, the average dwell time in Zone 05 is more than double that in S1. This, in turn, is likely to more than double passenger exposure to heat and toxic gases and so greatly increase their inhaled Fractional Effective Dose of hazardous fire products, raising the likelihood of fatalities and the expected number of fatalities. Even in S2 (25% luggage retrievers), while the overall average Zone 05 dwell time is 85.1 s, average dwell times amongst the 1000 repeat simulations vary from 51.9 s to 128.5 s, and so some of the 1000 repeat simulations produce dangerously long dwell times (almost doubling the average dwell time for S1).

The introduction of randomly located passengers retrieving luggage into the evacuation increases dwell time and PET for all passengers in all zones but with more significant consequences for those in Zone 05. In the event of a serious cabin post-crash fire, increasing the expected number of luggage retrievers will increase average dwell times, which, in turn, is likely to decrease the survivability of passengers in all zones, particularly in Zone 05, by increasing their exposure to the hazardous fire products. Furthermore, the increased exposure to toxic fire products, heat and the obscuration effects of smoke will adversely impact the ability of exposed passengers to evacuate, further increasing their dwell time in Zone 05 and, hence, their exposure to severe fire hazards. This downward spiral is likely to result in a significant increase in the expected number of fatalities.

Key Finding 9.4, Cost of Overall Evacuation performance:
A comparative cost of luggage retrieval on emergency evacuation outcome can be estimated by determining, for a given scenario, the additional number of passengers remaining on board after 90 s, compared with a base case scenario involving no luggage retrieval (i.e., S1). Using this approach, for the exit scenario and narrow-body aircraft considered in this study, the incremental cost associated with 25% (S2), 50% (S3), and 75% (S4) of the passengers attempting to retrieve cabin luggage during evacuation is 2.9 passengers, 11.4 passengers, and 24.9 passengers, respectively.

10 PROJECT LIMITATIONS

It is accepted that any modelling exercise is an approximation to 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 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:

(1) Passengers are not modelled carrying retrieved luggage.

Once the passenger has retrieved their luggage, they are likely to transport it to the exit, where it may be discarded or carried by the passenger out of the aircraft. The process of transporting the retrieved luggage to an exit was not included in the modelling primarily because of a lack of data to characterise the associated behaviours (see Section 5.1). As all of the behaviours associated with carrying luggage are expected to adversely impact evacuation efficiency, omission of these factors means that model predictions should be viewed as optimistic.

(2) Nature of aisle by-pass model.

Passengers located in the aisle will only attempt to by-pass a luggage retriever if there is sufficient space on the other side of the passenger retrieving their luggage. In reality, it may be possible for a passenger to attempt to by-pass a luggage retriever even if there is insufficient space for the by-passing passenger to move into. However, in such cases, this may result in passenger conflicts with passengers pushing each other, resulting in a chaotic situation. Evidence from past accidents suggests that this is not the case [10,11,12], so this is considered a reasonable assumption (see Section 5.1 and Section 6.4(e)).

Another aspect of the aisle by-pass model is that assuming a by-pass event is possible, only a single attempt is made by the passenger to by-pass the luggage retriever. If this fails, the passenger is not given another chance to by-pass the luggage retriever. To a certain extent, this issue is associated with the nature of the user-defined by-pass probability (BPP) distribution (see (3)); however, the BPP distribution is intended to consider the overall probability that a passenger will by-pass the luggage retriever during the luggage retrieval event (see Section 5.1). Nevertheless, the model could be modified to allow the passenger attempting to by-pass the luggage retriever several attempts at by-passing.

Finally, it also assumed that only the passenger adjacent to the luggage retriever is able to attempt to by-pass the luggage retriever, while other passengers in the queue cannot attempt to by-pass multiple passengers and then attempt to by-pass the luggage retriever. This, again, is considered a reasonable assumption given the space available, particularly in a narrow-body aircraft (see Section 6.4(e)). Also, there is currently insufficient evidence from actual accidents to support such behaviour (see Section 5.1). Nevertheless, the model could be modified to allow the next passenger in the queue to by-pass the passenger ahead of them (who failed to by-pass the luggage retriever), and then they would be given the opportunity to by-pass the luggage retriever. Within the model, this is essentially allowing the passenger second in the queue to swap locations with the first passenger in the queue and then attempt to by-pass the luggage retriever.

If a by-pass event is possible but fails, this will result in gaps in the aisle flow, which may also result in gaps in exit flows (see (3) and (4)). It is noted that gaps in exit flow are often observed in actual accident situations, albeit resulting from unknown conditions within the cabin and not necessarily related to luggage retrieval.

(3) Nature of the by-pass probability distribution.
The likelihood that a by-pass event is successful is dependent on the user-defined by-pass probability (BPP) distribution. In the analysis, this has been assumed to be described by a normal distribution with a mean of 0.5 and a standard deviation of 0.12. Using this BPP distribution produces evacuation performances that are positioned between the two extremes of no by-pass and all by-pass, albeit slightly biased to the no by-pass results (see Section 6.4(e)). Without data on which to base an estimation of the BPP distribution, engineering judgement was used to define an appropriate distribution to use in this analysis. If the number of by-pass events is not considered sufficient or representative of what is likely to occur, the BPP distribution could be biased towards higher probabilities of success, which would make the luggage retrieval scenarios more efficient, reducing TET, average PET, and zonal evacuation parameters. This may not have a significant effect, as demonstrated by the data in Table 42, at least for S2 (25 % luggage retrievers); however, it may have a more significant impact in scenarios with more luggage retrievers.

(4) Passengers blocked in seat rows.
In the current model, it is assumed that passengers in a seat row impacted by a passenger attempting to retrieve their luggage are not able to by-pass the luggage retriever. The rationale for this is that the luggage retriever effectively blocks the available space for the passenger attempting to exit the seat row (see Section 5.1). Furthermore, if the seated passenger were to push past the luggage retriever, this would interfere with and, hence, delay the luggage retrieval process, increasing luggage retrieval times. In addition, the passenger from the seat row would compete with the passenger in the aisle attempting to by-pass the luggage retriever passenger for the available space ahead of the luggage collector. So, a situation resulting in a win for the seat row passenger could result in further delay for the aisle passengers.

There are a large number of passengers impacted in seat rows by the luggage retriever. For example, consider the simulation producing the median evacuation time. In S2 (25% luggage retrievers), the median TET is 135 s, and there were 18 viable aisle by-pass events, of which 7 (39%) were successful. In addition, there were 35 occurrences where passengers in seat rows were prevented from by-passing the luggage collector blocking their exit from the seat row. In S3 (50% luggage retrievers), the median TET was 167.6 s, and there were 60 viable aisle by-pass events, of which 34 (57%) were successful. In addition, there were 82 occurrences where passengers in seat rows were prevented from by-passing the luggage collector blocking their exit from the seat row. Compared to S2, the number of possible aisle by-pass events has increased by 233% (42), the number of successful aisle by-pass events has increased by 386% (27), and the number of occurrences where passengers in seat rows are prevented from by-passing the luggage collector seat events has increased by 134% (47). In S4 (75% luggage retrievers), the median TET was 198.6 s, and there were 66 viable aisle by-pass events, of which 31 (47%) were successful. In addition, there were 137 occurrences where passengers in seat rows were prevented from by-passing the luggage collector. Compared to S2, the number of possible aisle by-pass events has increased by 267% (48), the number of successful aisle by-pass events has increased by 343% (24), and the number of occurrences where passengers in seat rows are prevented from by-passing the luggage collector seat events has increased by 291% (102).

Thus, it is not clear how, if seated passengers were allowed to by-pass the luggage collector, this capability would impact the model results. While excluding seated passengers from pushing past luggage retrievers is considered a reasonable assumption for a narrow-body aircraft, in future work, the model could be modified to allow passengers located in seat rows to push past the luggage retriever, as do passengers in the main cabin aisle. The model could be extended to enable this by providing a BPP distribution for seated passengers (different from that for aisle passengers) and allowing the model to function in a similar manner to the aisle by-pass model.

(5) Luggage retrieval time data set.
Two viable luggage retrieval data sets are available for use in the modelling presented in this analysis. Both have their inherent strengths and weaknesses, and neither data set is ideal (see Sections 4.1, 4.2, and 5.1). Given the small size of the data sets and that neither data set was collected in real or simulated emergency evacuation conditions, in particular with other passengers (aisle or seat row located) attempting to by-pass the luggage retriever during the retrieval process, it is possible that the data set used under-represents the time required to collect luggage during emergency evacuation conditions. Thus, the results generated using the luggage retrieval time data set could be optimistic.

(6) Location of luggage retrieval events.
To simplify the analysis and reduce the number of confounding parameters, luggage was assumed to be stored immediately above the seat of the luggage retriever. In reality, luggage could be stowed in any location, not necessarily locations close to the seating location of the luggage retriever. In particular, luggage could be stowed in a location requiring the luggage retriever to move in contraflow to the evacuation flow. Such a situation would greatly disrupt the evacuation process, leading to longer evacuation times. Thus, the results generated using this simplifying assumption could be optimistic.

(7) Luggage retrieval in life-threatening emergencies
While it is clear that passengers have a tendency to retrieve luggage even in emergency evacuation situations, it is not necessarily realistic to assume that as many as 75% of the passengers will attempt to retrieve luggage. Furthermore, it is not clear if luggage retrieval is likely to continue throughout the evacuation, even in the later stages of the evacuation when conditions within the aircraft have seriously deteriorated or in regions of the aircraft that are likely to be most severely impacted by the worsening conditions. Thus, the likelihood of passengers retrieving luggage could be dependent on the phase of the evacuation, with large numbers of passengers attempting to retrieve luggage throughout the aircraft during the early stages of the evacuation. As the situation worsens, the proportion of passengers retrieving luggage could decrease and be limited to those zones less impacted by the developing hazardous environment.

(8) Exit hesitation times impacted by luggage.
The passenger exit hesitation times that determine the flow achieved by the aircraft exits are likely to be negatively influenced by passengers carrying luggage through the exit. As no data exist to define this, it is ignored in the analysis, so the predicted exit flows may be optimistic.

11 CONCLUSIONS AND RECOMMENDATIONS

11.1 Concluding Comments

The analysis presented in this report quantifies the impact of passengers retrieving carry-on luggage on aircraft evacuations using the airEXODUS agent-based aircraft evacuation modelling tool. The study is based on a single-aircraft configuration consisting of a single-aisle narrow-body cabin layout typical of the popular B737/A320 models. The geometry consisted of:

- Two pairs of Type-C exits, one pair located in the front and the other pair in the aft of the aircraft,
- Two pairs of Type-III overwing exits, and
- Seating for 180 passengers with 2 flight deck and 3 cabin crew.

The evacuation scenario employed in the analysis was similar to that in the industry standard evacuation certification trial as described by FAR 25.803, consisting of half the normally available exits. However, to make the evacuation more challenging and representative of exit combinations typically found in real accidents, the available exit configuration utilised in this study consists of the following 50% of the normally available exits, namely the front pair of Type-C exits and the left pair of Type-III overwing exits. Furthermore, passenger behaviour was such that passengers attempted to utilise their nearest viable exit.

Utilising this underlying scenario setup, four scenario variations were investigated:

- Scenario 1 (S1), Base Case. In this scenario, no passengers attempt to retrieve their luggage, and so this serves as the base case against which all other scenarios are compared.
- Scenario 2 (S2), 25% (42) of the passengers retrieve luggage.
- Scenario 3 (S3), 50% (84) of the passengers retrieve luggage.
- Scenario 4 (S4), 75% (126) of the passengers retrieve luggage.

As part of this work, an evidence base of typical cabin luggage retrieval times was established that could be used in the modelling analysis. The airEXODUS evacuation simulation software was then modified to enable the simulated agents to retrieve luggage as part of the evacuation process.

To interpret the simulation results correctly, it is important to note two key model assumptions: firstly, that passengers located in seat rows cannot by-pass a luggage retriever, and secondly, that aisle by-pass is only possible if there is sufficient space ahead of the luggage retriever. Furthermore, it is important to note that as with any computer model, there are a number of limitations associated with the nature of the by-pass model, particularly that passengers are not modelled carrying retrieved luggage, how representative the luggage retrieval delay time data set imposed on the simulation is of retrieval times in emergency situations, and the appropriateness of the by-pass probability distribution imposed on the simulation.

Analysis of simulation results demonstrated that as the number of luggage retrievers within a specific region or spatial zone within the aircraft can vary significantly, as does their seating locations, it is inappropriate to simply base conclusions on any one simulation, e.g., a simulation producing median evacuation time, as this may provide an overly pessimistic or optimistic conclusion. It is more informative to consider the evacuation performance of several key simulations, such as the simulations producing the minimum, median, and maximum total evacuation time (TET).

Furthermore, for a deeper understanding of the impact of luggage retrievers on the overall evacuation, it is also necessary to consider localised evacuation parameters, such as zonal average dwell times and zonal average personal evacuation times (PETs). The zonal average dwell time is the time that passengers remain within a specific region or zone during their evacuation (dwell time), and PET is the personal evacuation time for passengers from a specific region.

It is clear that as the number of randomly distributed luggage retrievers increases, there is not only a corresponding significant increase in the average TET and average PET but also in the number of simulations producing prolonged evacuations. For example, with 0% (S1), 25% (S2), 50% (S3), and 75% (S4) luggage retrievers, the TET for the simulation producing the ***median*** TET is 120.9 s, 135.0 s (an increase of 11.7%), 167.6 s (an increase of 38.6%), and 198.6 s (an increase of 64.3%), respectively. And while none of the 1000 repeat simulations in S1 produce a TET in excess of 140 s, in S2, S3, and S4, there are 365, 961, and 1000, respectively. The significant increase in TET and average PET increases the likely severity of passenger exposure to potentially hazardous conditions for some passengers. Furthermore, the higher the number of simulations producing significantly large TET and average PET, the higher the likelihood that passengers will be involved in a prolonged evacuation with greater exposure to potentially hazardous conditions.

For individual passengers, the outcome of an evacuation in which passengers attempt to retrieve luggage is strongly dependent not only on the number of passengers attempting to retrieve luggage but also on the random distribution of luggage retrievers, the seating location of the passenger, and the nature of the evacuation scenario (i.e., exit availability).

To estimate the cost, in terms of risk to life of passengers attempting to retrieve luggage, consider a post-crash fire imposed on the evacuation scenario investigated in this study. A plausible fire scenario would be similar to that in the 1985 Manchester B737 and the 2019 Sheremetyevo Sukhoi Superjet-100 fatal post-crash fire incidents. In both these cases, the external fire initially impacts the rear of the aircraft and eventually gains access to the rear of the aircraft cabin.

Passengers seated in the front of the aircraft (Zone 01, consisting of the front eight seat rows) and, hence, furthest removed from the initial effects of the fire are less impacted by luggage collectors, at least if there are relatively small numbers of luggage collectors. However, as the number of luggage retrievers increases, even passengers in Zone 01 are adversely impacted. With 50% of the passengers collecting luggage (S3), the average dwell time in Zone 01 is increased from 30.1 s (S1) to 41.4 s, and with 75% luggage collectors (S4), the average dwell time is 50.8 s.

With 75% luggage retrievers (S4), the average dwell time in Zone 05 (rear six seat rows) more than doubles (133.6 s in S4 and 65.0 s in S1). This, in turn, is likely to more than double passenger exposure to heat and toxic gases, greatly increasing their inhaled Fractional Effective Dose (FED) of hazardous fire products and raising the likelihood of fatalities and the expected number of fatalities.
(Note: The FED is a measure of the ratio of the dose of fire hazards received to the dose required to cause an effect, e.g., incapacitation or death). Even in S2 (25% luggage retrievers), while the overall average Zone 05 dwell time is 85.1 s, average dwell times amongst the 1000 repeat simulations vary from 51.9 s to 128.5 s, so some of the 1000 repeat simulations produce dangerously long dwell times (almost doubling the average dwell time for S1).

The introduction of randomly located passengers retrieving luggage into the evacuation increases dwell time and PET for all passengers in all zones but with more significant consequences for those in Zone 05. In the event of a serious cabin post-crash fire, increasing the expected number of luggage retrievers will increase average dwell times, which, in turn, is likely to decrease the survivability of passengers in all zones, particularly in Zone 05, by increasing their exposure to the hazardous fire products. Furthermore, the increased exposure to toxic fire products, heat and the obscuration effects of smoke will adversely impact the ability of exposed passengers to evacuate, further increasing their dwell time in Zone 05 and, hence, their exposure to severe fire hazards. This downward spiral is likely to result in a significant increase in the expected number of fatalities.

A comparative cost of luggage retrieval on emergency evacuation outcome can be estimated by determining, for a given scenario, the additional number of passengers remaining on board after 90 s compared with a base case scenario involving no luggage retrieval (i.e., S1). Using this approach, for a narrow-bodied aircraft with 185 occupants and an evacuation scenario involving 50% exit availability, excluding exits in the rear, the average incremental cost associated with 25% (S2), 50% (S3), and 75% (S4) of the passengers attempting to retrieve luggage during the evacuation is 2.9 passengers, 11.4 passengers, and 24.9 passengers, respectively.

11.2 Recommendations for Additional Analysis to Assist the Regulatory Process

While this work has addressed the key project questions concerning the likely impact of luggage retrieval on passenger evacuation in a narrow-body aircraft configuration, to further support the regulatory process, it is recommended that additional analysis be undertaken to better represent the impact of luggage retrievers on the evacuation process and to explore other relevant scenarios.

(1) Repeat the evacuation analysis for other exit availability scenarios. As only a single exit availability option was investigated, it is not clear how severe the impact of luggage retrieval will be on evacuation outcomes in other situations.
(2) Repeat the evacuation analysis for wide-body aircraft. Clearly, wide-body aircraft, while larger and accommodating more passengers than narrow-body aircraft, also offer additional evacuation routes. Thus, for wide-body aircraft, the impact of luggage retrievers on evacuation performance could be significantly different to that for narrow-body aircraft.
(3) Repeat the evacuation analysis for narrow-body aircraft using coupled fire-evacuation analysis as in [4]. To establish the cost in terms of likely additional injuries and fatalities resulting from luggage retrieval, the analysis could be repeated, including a fire scenario. Furthermore, the luggage retrieval model could be modified to take into consideration the impact of fire conditions, for example, preventing luggage retrieval attempts once the hazard level reaches a critical value.
(4) Enhance the model describing luggage retrieval. This could take into account a number of currently employed simplifying assumptions, such as:
    a. Enable passengers in seat rows to by-pass luggage retrievers.
    b. Extend the ability for aisle passengers to by-pass luggage retrievers to include additional passengers in the aisle queue.
    c. Include a representation of passengers carrying luggage during the evacuation.

d. Allow luggage retrieval from locations other than directly adjacent to the seat row of the luggage retriever.
e. Modify BPP distribution to enhance the likelihood of achieving a successful by-pass in line with informed engineering judgement or data from experimental trials (see (5)) or accident analysis (see (6)).

(5) Experimental data collection campaign to collect a reliable evidence base that can be used for evacuation modelling. This could include data related to luggage retrieval times under simulated emergency evacuation conditions, the ability for aisle and seated passengers to by-pass luggage retrievers, and aisle movement rates for passengers encumbered with luggage. The collection of this data would support the development of enhanced passenger behaviour models.

(6) Establish an evidence base of passenger experience of real evacuations involving luggage retrieval. This could be established by extracting relevant human factors information from previous interviews conducted for accident human factors reports following major aviation accidents. Additional information could be collected from recent and future accidents by interviewing passengers using a specific interview protocol designed to collect the relevant information. Data may also be available from passenger video footage, for example, as in the 2024 Haneda JAL A350 accident [24, 25]. The database could be based on the AASK database [10,11,12].

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ANNEX A 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 airEXODUS, buildingEXODUS, maritimeEXODUS, railEXODUS, matEXODUS, and urbanEXODUS for applications in the aviation, built, maritime, rail, security and urban environments, respectively. airEXODUS is designed for use in aircraft design, compliance with 90-second certification requirements, crew training, development of crew procedures, resolution of operational issues, and accident investigation.

The EXODUS software takes into consideration people–people, people–fire, and people–structure interactions. It comprises five core interacting sub-models: the **Passenger, Movement, Behaviour, Toxicity, and Hazard** sub-models (see Figure 58). 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.

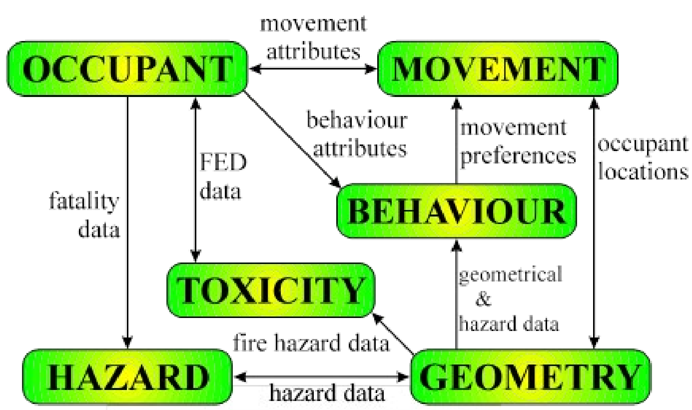

Figure 58: EXODUS sub-model interaction.

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 neighbouring 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 [1,2], 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 such as 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.

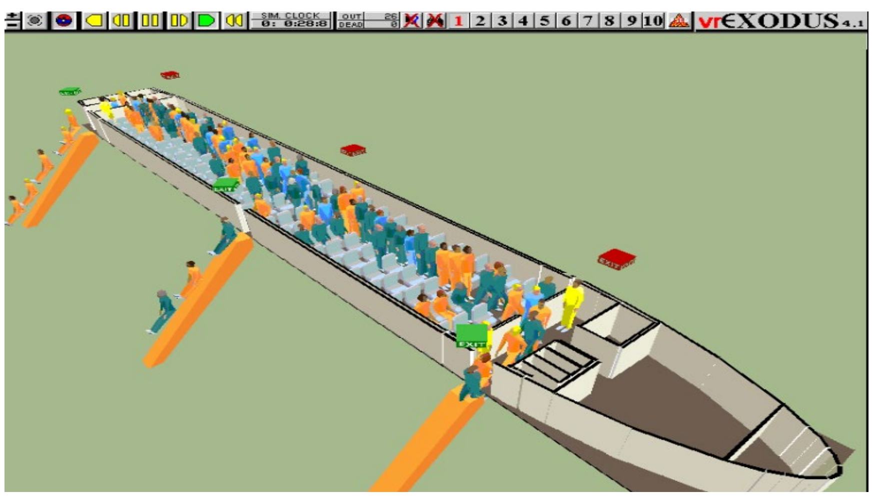

Figure 59: airEXODUS evacuation simulation depicted in the vrEXODUS software.

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 59). There has been extensive validation of the airEXODUS software. A report produced for the UK CAA presents results from an extensive validation exercise [5].

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,* as well as parameters for all the exits, must be specified. Extensive data has been extracted by FSEG from past certification data [3,4,5], 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 [3].

(b) Passenger Exit Delay Time

One 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 outstretched 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 mainly 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 processes 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), which 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 [3,4,5] (as an example, see Figure 60). 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.

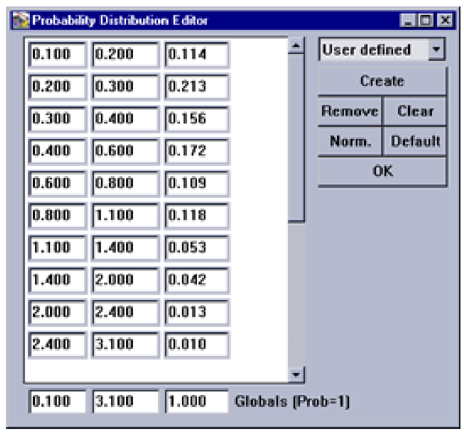

Figure 60: Example of passenger exit delay time distribution specification in airEXODUS.

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 60. 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.

(c) 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 end point). 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 [3]. Within airEXODUS, the Slide-Time is assigned using a random distribution of the values 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).

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ANNEX B Difference in exiting times between Scenario 1 and SC1

Here, the differences in exiting times for given numbers of passengers for Scenario 1 (0% luggage retrievers) and SC1 (25% luggage retrievers and BPP of 0) from Section 6 are presented. Data from three simulations are presented: the minimum, median, and maximum simulations from the 1000 repeat simulations for each scenario.

Table 60: S1 and SC1 Minimum Simulation.

No. People Out	Scenario 1:LC0%	SC1:LC25%PP0%	Difference
40	24.2	33.0	36.4%
80	37.5	49.7	32.5%
130	70.7	73.7	4.2%
185	110.1	112.6	2.3%

Table 61: S1 and SC1 Median Simulation.

No. People Out	Scenario 1:LC0%	SC1:LC25%PP0%	Difference
40	24.3	25.8	6.2%
80	40.5	45.5	12.3%
130	79.3	78.2	-1.4%
185	120.9	137.2	13.5%

Table 62: S1 and SC1 Maximum Simulation.

No. People Out	Scenario 1:LC0%	SC1:LC25%PP0%	Difference
40	24.5	29.7	21.1%
80	43.4	45.7	5.3%
130	90.2	89.9	-0.3%
185	138.5	187.6	35.5%

ANNEX C Difference in exiting times between Scenario 1 and Scenario 2

Here, the differences in exiting times for given numbers of passengers for Scenario 1 (0% luggage retrievers) and Scenario 2 (25% luggage retrievers) from Section 6 are presented. Data from three simulations are presented: the minimum, median, and maximum simulations from the 1000 repeat simulations for each scenario.

Table 63: S1 and S2 Minimum Simulation.

No. People Out	Scenario 1:LC0%	Scenario 2:LC25%	Difference
40	24.2	23.8	-1.7%
80	37.5	44.0	17.3%
130	70.7	74.0	4.7%
185	110.1	111.7	1.5%

Table 64: S1 and S2 Median Simulation.

No. People Out	Scenario 1:LC0%	Scenario 2:LC25%	Difference
40	24.3	29.8	22.6%
80	40.5	49.5	22.2%
130	79.3	79.8	0.6%
185	120.9	135.0	11.7%

Table 65: S1 and S2 Maximum Simulation.

No. People Out	Scenario 1:LC0%	Scenario 2:LC25%	Difference
40	24.5	33.5	36.7%
80	43.4	51.2	18.0%
130	90.2	95.3	5.7%
185	138.5	200.2	44.5%

ANNEX D Difference in exiting times between Scenario 1 and Scenario 3

Here, the differences in exiting times for given numbers of passengers for Scenario 1 (0% luggage retrievers) and Scenario 3 (50% luggage retrievers) from Section 7 are presented. Data from three simulations are presented: the minimum, median, and maximum simulations from the 1000 repeat simulations for each scenario.

Table 66: S1 and S3 Minimum Simulation.

No. People Out	Scenario 1:LC0%	Scenario 3:LC50%	Difference
40	24.2	30.5	26.0%
80	37.5	48.3	28.8%
130	70.7	76.8	8.6%
185	110.1	124.7	13.3%

Table 67: S1 and S3 Median Simulation.

No. People Out	Scenario 1:LC0%	Scenario 3:LC50%	Difference
40	24.3	34.9	43.6%
80	40.5	54.8	35.3%
130	79.3	85.7	8.1%
185	120.9	167.6	38.6%

Table 68: S1 and S3 Maximum Simulation.

No. People Out	Scenario 1:LC0%	Scenario 3:LC50%	Difference
40	24.5	31.9	30.2%
80	43.4	65.7	51.4%
130	90.2	105.5	17.0%
185	138.5	228.0	64.6%

ANNEX E Difference in exiting times between Scenario 1 and Scenario 4

Here, the difference in exiting times for given numbers of passengers for Scenario 1 (0% luggage retrievers) and Scenario 4 (75% luggage retrievers) from Section 8 are presented. Data from three simulations are presented: the minimum, median, and maximum simulations from the 1000 repeat simulations for each scenario.

Table 69: S1 and S4 Minimum Simulation.

No. People Out	Scenario 1:LC0%	Scenario 4:LC75%	Difference
40	24.2	31.1	28.5%
80	37.5	52.5	40.0%
130	70.7	81.8	15.7%
185	110.1	153.7	39.6%

Table 70: S1 and S4 Median Simulation.

No. People Out	Scenario 1:LC0%	Scenario 4:LC75%	Difference
40	24.3	31.7	30.5%
80	40.5	61.0	50.6%
130	79.3	102.2	28.9%
185	120.9	198.6	64.3%

Table 71: S1 and S4 Maximum Simulation.

No. People Out	Scenario 1:LC0%	Scenario 4:LC75%	Difference
40	24.5	32.2	31.4%
80	43.4	54.9	26.5%
130	90.2	104.5	15.9%
185	138.5	271.5	96.0%