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The effect of airline passenger anthropometry on aircraft emergency evacuations

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ABSTRACT

This paper demonstrates the impact of passenger anthropometry on the emergency egress for both single aisle and double aisle aircraft. A demographic model of passenger anthropometry based on Body Mass Index (BMI) categories was developed building upon data retrieved from an online database. Knowing that the prevalence of obesity is becoming greater at a global scale, various obesity condition were simulated to explore the effects of an increased number of obese/overweight passenger on-board medium and large aircrafts. Verification of the software used in egress simulations was carried out by undertaking a trial mimicking a real-life evacuation. The simulated results show that for current levels of BMI prevalence the time to evacuate an aircraft is 76.6 s (95% CI, 76.2–76.9) for a narrow-body and 87.1 s (95% CI, 86.7–87.7) for a wide-body aircraft. Leaving current prevalence of BMI categories unchanged but increasing overall obesity by just 5% can lead to an increase of the egress time of approximately 2 s for the wide-body aircraft scenario. The egress time is significantly increased when greater percentages of obese passengers are considered. The results show that the egress time for a population with a demographic distribution similar to that expected in the next 30 years exceeds the current time limit of 90 s considered by aviation authorities for certification purposes of passenger aircraft.

1. Introduction

As airlines continue to squeeze an increasing number of passengers into their aircraft, the evacuation of passengers from the aircraft in an emergency is a pressing issue owing to the risks associated with this practice. With competitive airfares, air travel has been made accessible to new markets and passengers from different demographics. Coupled to this, the anthropometric characteristics of these passengers and the world population have been changing over time, in particular, obesity. In fact, over the last fifty years, the average weight and the proportion of obese and/or overweight individuals have been increasing. Current global estimates place 60% of the world's population at a Body Mass Index (BMI) over 25 (NCD Risk Factor Collaboration, 2016b).

Airlines across the world are pushed by increasing competition and business pressures to find new ways to increase passenger loads with their fixed aircraft cabin capacity. They have to balance customer expectations for high levels of service while striving to maintain profitability and market share. This situation is further complicated by a need for continual safety and efficiency improvements. These factors have led to substantial research into technologies that predominantly strive to make aircraft operations more efficient such as bio-fuels, lightweight materials, better aerodynamic designs and advancements in air traffic management. Notwithstanding this, Melis (2019) and Melis et al. (2017) have highlighted that there is limited research being conducted to explore the issues associated with anthropometrical changes of commercial aviation passengers. The main thrust of research and studies in this domain is limited to the passenger's perceptions of comfort.

1.1. Global obesity trends

It is noted that the average person's weight has been increasing making obesity a global problem especially in developed regions (NCD Risk Factor Collaboration, 2016b; Wang and Lim, 2014; Finucane et al., 2011). The World Health Organisation noted that worldwide obesity prevalence tripled between 1975 and 2016 (WHO, 2016). Beginning in 2016, there is a high prevalence of BMI > 25 in many Westernised nations together with an average BMI greater than 25 prevalence of 65%. This is most notable in the United States of America (USA) and the United Kingdom (UK) where BMI > 25 prevalence is 70% and 66% respectively.

Further, a prevalence of 61% BMI above 25 is seen in Latin America and the Caribbean region and 57% and 59% is seen in the Pacific and Central and East European regions respectively. In Central Asia, Middle East and North Africa the average prevalence is 63%, while, the rest of

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Africa and South Eastern Asia have a prevalence of BMI greater than 25 less than 35% (NCD Risk Factor Collaboration, 2017). Increasing body weight has many social implications, especially in health. The management and prevention of direct health effects associated with increased body weights can be costly to society. People with a higher body mass potentially become more susceptible to diseases such as diabetes, vascular disorders or muscular-skeletal problems. In an emergency situation these secondary health effects have the potential to be exacerbated during egress (Ananthapavan et al., 2014; Hammond and Levine, 2010).

1.2. Current regulatory context

Evacuations from an aircraft are comparatively rare events in today's aviation industry, but it is an essential process from the safety perspective in an emergency. All aircraft manufacturers are required to demonstrate that they meet the evacuation requirements set by their respective aviation certification authority. The current Federal Aviation Administration (FAA) regulation §25.803(c) requires aircraft to be evacuated in less than 90 s in darkness and only using half the exits (FAA, 1990b). The total evacuation time is determined when the last occupant reaches the ground using the inflatable slides. Furthermore, Title 14 Part 25 states that participants must be of normal health, with 40% being female and 35% being over 50 years old (FAA, 1990a). Full-scale evacuations are generally only performed once for certifi,cation purposes due to the number of resources required. A cost-effective solution is to perform computer simulations to understand evacuation dynamics. In a recent article published by the Royal Aeronautical Society, they highlighted the changes needed to improve emergency evacuation procedures and regulations (Butcher et al., 2018). The importance placed on increased realism has been noted to provide enhanced training for cabin crews in crowd control and passenger management (Read, 2018). Existing aviation regulations emphasise the cabin layout such as the number and location of emergency exits, passenger density and existence of obstacles that might restrict the flow of passengers (Martínez-Val and Hedo, 2000). However, the regulations have a minimum focus on changes in passenger anthropometrics and impact of passenger mobility during egress. Studies focusing on aircraft cabin layout predominantly explore the overwing exits and cabin aisle.

1.3. Evacuation computer simulation

Computer simulations have the advantage of allowing researchers to carry out different scenarios in their studies such as smoke in the cabin (Zhang et al., 2014), passenger emotions and behaviour (Du et al., 2014; Miyoshi et al., 2012) or different cabin/aircraft configurations (Galea et al., 2010). There are some evacuation software packages available with varying analysis capabilities as shown in Table 1. However, minimal information is available on egress simulations considering the effects of passengers' anthropometry. Liu et al. (2014) and Wang et al. (2012) research highlighted simulations involving physical characteristics of passengers, noting that waist-size and age of passengers can cause a considerable impact on the variance of evacuation times produced by simulations.

Table 2 shows six of the prominent simulations model products tailored to aircraft evacuations studies. The GPSS (General Purpose Simulation System) and AvatarSim models have been developed to verify the 90 s rule. However, airEXODUS, MACEY, VacateAir, and DEM (Discrete Element Method) models can simulate both the 90 s rule scenario and different accident scenarios, e.g. number of doors in use, cabin layout or passenger behaviour. These four models use fine mesh and are better at representing cabin area accurately than coarse mesh. Further, many of these existing evacuation models rely on anthropometric data ranging from the 1950s to 1980s, which do not reflect current demographics (Thompson et al., 2015).

Table 1
Emergency Evacuation simulation model summary Source: (Hedo and Martinez-Val, 2011; Hedo et al., 2019).

Model Name	Year	Institution	Purpose	Simulation Typology Model	Reference
GPSS	1978–1980	CAMI-FAA	Certification	Network-rule based Model	Folk (1972); Chandler et al. (1978)
FIREVAC	1984	NASA/Simulation Tech, Inc.	Fire accident reconstruction	Network Model	Middleton (1984)
GA	1987–1992	FAA/Gourary Associates	Accident reconstruction	Network Model	Gourary (1994a, 1994b)
AIREVAC AIRCEVAC	1991–1994	ATA/South West Research Institute	Certification	Agent based	Schroeder and Turtle (1991); Grant and Turtle (1992)
airEXODUS	1993–	Greenwich University	Certification, accident reconstruction and design	Network type with single-occupancy cells/rule-based behaviour	Owen et al. (1998); Galea et al. (2003); Galea (2006)
RAM	1994–1996	Cranfield University	Certification and accident reconstruction	Network, deterministic model, with rule-based behaviour	Macey and Cordey-Hayes (1995); Macey and Cordey-Hayes (1996)
DEM	2001–	Strathclyde University	Certification (psychological aspects)	Deterministic model	Robbins and McKee (2001)
AvatarSim	2008-	Bowie State University	Certification and accident reconstruction	Multi-agent based model	Sharma et al. (2008); Sharma (2009)
VacateAir	2008–	State University of New York at Buffalo	Certification and design	Particle-Swarm multi-agent stochastic model	Xue, DesJardin and Bloebaum (2007); Xue and Bloebaum (2008a); Xue and Bloebaum (2008b)
ETSIA	2009–	Universidad Politecnica de Madrid	Certification and accident reconstruction	Agent-based computer model	Hedo and Martinez-Val (2010); Hedo and Martinez-Val (2011); Martínez-Val et al. (2017))

Table 2
Evacuation time of various aircraft for the 90 s test and simulation verification Source: (Chen et al., 2014).

Model	Airplane Type		Number of Evacuees	Test Time (s)	Simulation Time (s)
GPSS	B747		527	66.2	84
	L-1011		356	82	84.9
	L-1011		411	89.7	79.6
MACEY	A320		179	79	85
	A321		224		81.2
	B757		219	73.5	77.8
	B737-800		189		91.8
DEM	B737-300			75	81
VacateAir	B737-200 Cabin	Straight Aisle	51	40.87	37.73
	Simulator	Non Straight Aisle		42.58	39.92
airEXODUS	Wide-Body	2-3-2	255	83.7	86.6
		2-3-2	285	72.6	70.4
		2-4-2	351	71.7	68.2
		3-4-3	440	74.4	76.9
	Narrow-Body	3-3	149	64.1	70.5
		3-3	188	78.5	73
Avatarsim	A319		149\138	64.1	60.13

1.4. Passenger behaviour during emergency evacuation

The behaviours of passengers during an evacuation are not consistent. Passengers may feel overwhelmed by emotions and disorientated during an evacuation. There are limited studies available exploring the influence of psychological behaviour on the evacuation time. Frightened passengers behave inconsistently during egress and it has been demonstrated that an emotionally and disorientated state could lead to increased evacuation time (Miyoshi et al., 2012). Unlike simulations, real evacuations see greater complexities and variations of behaviour. It has been shown that the evacuation time decreases with a competitive emphasis compared to evacuation times where a non-competitive emphasis is employed (Muir et al., 1996). To mimic these behaviours, participants of evacuation trials can be manipulated by financial enticements, verbal commands or other motivation incentives (McLean and George, 1995; Muir et al., 1992). A survey by Chang and Yang (2011) of passengers after experiencing a real-life aircraft evacuation revealed that passengers rely highly on cabin crew directions and that they have concerns over specific aspects of cabin design, such as the width of aisles.

1.5. Aircraft cabin design aspects

Developments in cabin safety addressing the design of aisles, seats, and cabin dividers was a key outcome after the accident involving British Airtours Flight 28 M (AAIB, 1988). Flight 28 M caught fire during take-off and resulted in 55 fatalities due to smoke and the inability of passengers to egress the aircraft. Recommendations from this accident saw changes made to the regulations governing the aisle, emergency exits and cabin materials to allow for greater access of the passenger waist and hips to pass through with ease.

Aircraft exit type depends on the aircraft designed capacity and size. Details of these specifications are found in FAR §25.807(a) (FAA, 1990b). The exit size plays an important role in the effectiveness of an aircraft evacuation. A smaller exit increases the time required for traversing the exit. A wider exit door allows for increased flow rates as the opening may accommodate two passengers simultaneously to negotiate egress. Small commuter-sized aircraft through to large narrow-body aircraft often incorporate a Type-III door over the wing. Unlike larger exit door types, Type-III exits require the passenger to manually remove the exit hatch and deposit the hatch away from the exit opening. Studies of accidents and experiments have shown that in an emotionally disorienting state of mind a passenger might dispose of the hatch in an inappropriate location, obstructing the exit (Wilson and Muir, 2010; McLean and Corbett, 2004; McLean et al., 2002). Similarly, obstructions in the cabin aisle such as baggage can hinder passenger evacuation flow. Narrower aisle dimensions lead to increased congestion, decreasing flow rates, thus longer egress times (Huang et al., 2018a, Huang et al., 2018b). Further obstructions can occur due to passenger behaviour such as blocking the aisle while retrieving carry-on luggage during the evacuation (Read, 2016).

Muir and Thomas (2004) brought attention to passenger safety in the very large aircraft environment. Factors exploring behaviours of passenger and crew are central to ensure an orderly evacuation, while cabin design including the location and size of exits, aisles and cross aisles for many wide-body aircraft are important to evacuation flow. With most wide-body commercial aircraft cabins situated approximately 5 m off the ground, an additional second full-length deck has required innovative changes to evacuation procedures and equipment; e.g. longer slides. Zhang et al. (2014) explore the effect of fire on egress time for a large aircraft cabin with two levels. Importantly, it demonstrates the use of the egress software "Pathfinder" on aircraft evacuation applications. Additionally, egress studies looking at novel cabin layouts, such as the blended wing-body aircraft concept do not demonstrate accurate demographic modelling for when these aircraft types are introduced in the future (Galea et al., 2010).

Very little is known on how anthropometric trends will affect aircraft evacuation. This paper addresses this issue by introducing models that take into consideration passengers' physical attributes in emergency egress. The paper aims to demonstrate that the current regulatory requirements for certification, using typical aircraft cabin layouts, under the changing obesity trends can effect evacuation time.

2. Methodology

The study proposed in this paper was conducted according to the following phases: (1) data sourcing (see Section 2.1); (2) development for demographic composition model and regression model (see Section 2.2); (3) simulation modelling of a narrow and a wide-body aircraft (see Section 2.3); (4) egress simulations in pathfinder (see Section 2.4); (5) delay sensitivity analysis (see Section 2.5); (6) verification[1] of results (see Section 2.6).

2.1. Anthropometric data phase

2.1.1. Anthropometric data

For this study, the 2013–2014 National Health and Nutrition Examination Survey (NHANES) (CDC, 2015) data from the Centre for Disease Control in the USA was used. The NHANES contains a large sample of current data pertaining to physical characteristics such as height, weight, BMI and age. For this data to be used for this research, it was sorted by age and BMI categories. BMI is calculated by the weight (kilograms) of a person divided by the square of the person's height (meters). The NHANES data also shows that a person's height and waist/shoulder diameters vary within the prescribed profiles within Table 3. Either shoulder breadth was used over waist diameter when the latter was considered to be the smaller dimension. The NHANES data contained 5,229 sample individuals with usable data, of which 47.5% and 53.5% are male and female respectively (CDC, 2015).

A person's size determines the speed at which they can move. For the purposes of this paper, a person size is described by weight and

[1] The term "verification" has been used in the context of this paper in line with the taxonomy adopted by the IEEE (1991), i.e., verification is considered *"A test of a system to prove that it meets all its specified requirements at a particular stage of its development."*

Table 3
Age and BMI Categories with associated regression model input variable value.

Age Group (Years)	Regression Model Variable Value	BMI Category	BMI Range (kg/m^2)	Regression Model Variable Value (k)
18–24	21	Underweight	Under 18.5	1
25–34	30	Normal weight Cat. 1	18.5–19.99	2
35–44	40	Normal weight Cat. 2	20–24.99	3
45–54	50	Overweight Cat.1	25–29.99	4
55–64	60	Obese Cat.1	30–34.99	5
65–74	70	Obese Cat. 2	35–39.99	6
75+	80	Morbidly Obese	40+	7

height. Waist-size and BMI are therefore dependent on the aforementioned physical attributes and change with these attributes when describing a person's size. The characteristics used in Pathfinder, describe a person's size; these descriptors being height, speed and shoulder and waist diameter and were considered to characterise the BMI categories along with age and gender. Each passenger dataset created in Pathfinder relied on anthropometrical attributes generated from statistical distributions. These data are subsequently used to create the demographic profile based on age, gender and BMI category as shown in Table 3. An example of a passenger profile could be a "Female", "Age 45 to 50 years old" with a "Normal BMI" and "Normal Weight Cat.1".

2.1.2. Occupant gait speed

Walking (gait) speed is the measure of a person's ability to travel longitudinally. Gait speed depends on several factors. A person's weight (BMI) is a contributing factor to gait speed (Windham et al., 2017; Pataky et al., 2014; Sheehan and Gormley 2013). However, a person's height also plays a pivotal role in determining gait stride and speed, as taller people generally have longer legs allowing for greater stride length at a lower cadence.

Gait speed was introduced into the Pathfinder profile models. The method presented in Samson et al. (2001) provides regression equations (Eq. (1), Eq. (2)) correlating an individual's age (A), height (h) and weight (W) with the gait speed (V). The data regarding these variables were obtained from NHANES. Thus, the calculated gait speed is therefore indicative of the individual within the NHANES data set.

$$V_{female} = -0.001(A) + 0.879(h) - 0.003(W) + 0.316 \tag{1}$$

$$V_{male} = -0.001(A) + 0.486(h) - 0.001(W) + 0.72 \tag{2}$$

In an emergency egress scenario, a passenger will endeavour to move at a faster pace. These calculated speeds represent a normal gait. However, increasing gait speed will cause an increase in stride length and frequency (Browning and Kram, 2007). A gait speed factor is applied to the calculated normal speed of a person to obtain a faster gait speed, Table 4. This factor is derived from the percentage increase of normal to fast gait speed from data found in Bohannon (1997).

2.1.3. Sit-to-stand delay time

The time taken by each passenger to evacuate during an emergency is influenced by their own ability to respond to visual and audio cues from the cabin crew. The response time of a passenger, from when they hear the evacuation call to the mental decision to stand up, is minuscule. This response time is encompassed in the sit-to-stand time which captures the time the person starts moving purposely to the exit from the time they begin to leave their seat. This response time of comprehension by the passenger is not considered as a time delay in this study as human emotions can cause variabilities in response time under different scenarios. Once evacuation cues given by cabin crew have been activated, there will be a short time required for the passenger to unstrap their seat belt and stand up from their seat to prepare for egress. The time for each passenger to stand from a seated position varies depending on gender, age and body size (weight and height). In particular, the weight factor has a direct impact on the time taken to stand. A higher weight will increase the time needed. Pataky et al. (2014) noted that people with a normal weight (BMI $<$ 25) took 8.28 $\pm$ 1.42 s to complete five consecutive sit-to-stand actions whilst people in the obesity category took 11.29 $\pm$ 3.14 s. Further, it was also determined that the timings did not change significantly between people in the higher BMI categories. Similarly, when exiting from their seats, elderly passengers will support themselves by holding on to the seat chair frames whilst youthful passengers can stand up without any additional support (Lijmbach et al., 2014).

Therefore, it is necessary to include a time delay into Pathfinder to simulate the sit-to-stand motion of the passengers. Pathfinder's mechanics do not allow for an occupant to begin from a seated position. To overcome this limitation, a time delay was implemented based on the research by Bohannon et al. (2010) to the Pathfinder behaviour mechanics to replicate the sit-to-stand phase. Since delay times cannot be added to each individual profile, a mean delay of 1.56 s with a standard deviation of 0.41 s following a normal distribution is implemented, with a range of 1.20 s–2.16 s (Bohannon et al., 2010). This time delay is applied to all passengers as the sit-to-stand times reflect the age range explored in Bohannon et al. (2010) study of 18 to 75+ years.

Table 4
Factor used to increase normal gait speed to a fast gait speed.

Age	18–24	25–34	35–44	45–54	55–64	65–74	75+
Male	1.82	1.75	1.68	1.58	1.45	1.49	1.56
Female	1.75	1.70	1.59	1.48	1.40	1.37	1.38

2.2. Model phase

2.2.1. Passenger demographic model

The NHANES data is sorted into several age categories to determine the proportion (P_i) of the given population size (n) that has the specific BMI category i (Table 3). Additionally, FAA regulations relating to emergency evacuation certification stipulate the following requirements. (1) at least 40% of the passenger load must be female, (2) at least 35% of the passenger load must be over 50 years of age and (3) at least 15% of the passenger load must be female and over 50 years of age (FAA, 1990a). For a given age group and gender (A,G), the number of elements of that (A,G) is divided by the total number of elements in the population as shown by Eq. (3).

$$P_{i(A,G)} = \frac{n_{i(A,G)}}{\sum n_{(A,G)}} \tag{3}$$

The effects of passenger weight changes explored in this paper depend on the prevalence of obesity being modelled. The total percentage of BMI greater than 25 for gender is given by $(P^j_{BMI>25})_{(G)}$ in Eq. (4), where K is the reference percentage value calculated from NHANES and j represents the obesity prevalence in percentage. The same equation is used to evaluate the percentage of BMI $<$ 25.

$$(P^j_{BMI>25})_{(G)} = (P^K_{BMI>25})_{(G)}\left(\frac{P^j_{BMI>25}}{P^K_{BMI>25}}\right)_{Total} \tag{4}$$

Using the same process as Eq. (4), the proportion of a new estimated

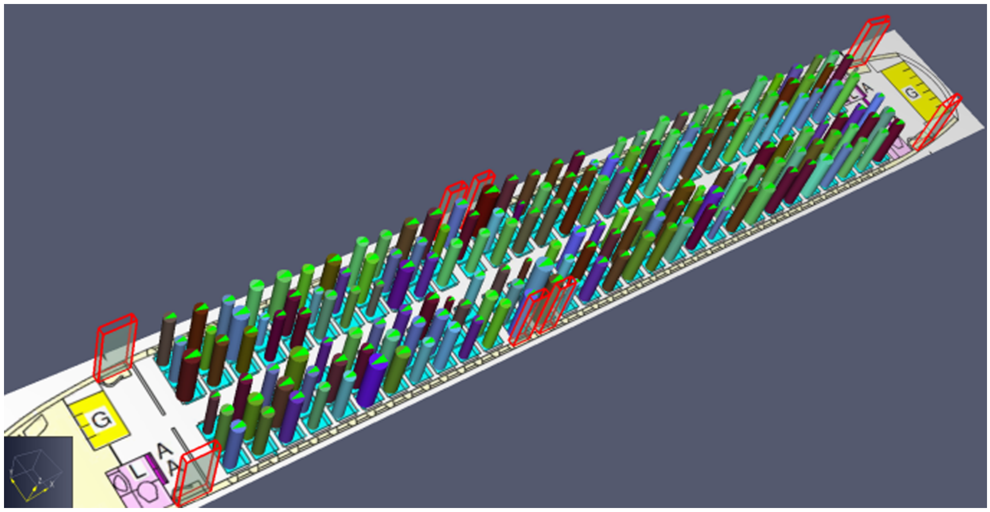

Fig. 1. Narrow-body aircraft Pathfinder model featuring 180 passengers in single class layout.

sample size j can be determined with Eq. (5), where K denotes the reference value calculated from NHANES.

$$P^{j}_{i(A,G)} = (P^{j}_{BMI>25})_{(G)}\left(\frac{P_{i(A,G)}}{(P_{BMI>25})_{(G)}}\right)_{K} \tag{5}$$

2.2.2. Regression model

Regression modelling is conducted to establish evacuation times for each aircraft simulated in this study. This paper presents two models to determine the evacuation time of an individual based on a combination of the following attributes: gender (G), age group (A), BMI category (BMI_k), where k is the Regression Model Variable Value in Table 3 and distance to closest exit (X) for an occupant. Eq. (6) corresponds to Model 1 (t_{M1}) encompassing all variables, whereas Eq. (7) presents a Model 2 (t_{M2}) with variables for age, BMI and distance only. Where, the coefficients α, β, γ, and δ are for each variable for a particular scenario and C is the model constant. The inputs for the regression models *M1* and *M2* variables for age group and BMI category are shown in Table 3. The input values for gender in *M1* are 1 and 0 for male and female respectively. The age input values and the BMI category input values are shown in Table 3.

$$t_{M1} = \alpha(G_i) + \beta(A_j) + \gamma(BMI_k) + \delta(X) + C_{M1} \tag{6}$$

$$t_{M2} = \beta(A_j) + \gamma(BMI_k) + \delta(X) + C_{M2} \tag{7}$$

The third model (Eq. (8)) presented in this paper conveys the total egress time for an aircraft. In this model, the relationship between evacuation time is determined from the percentage of obesity of the passenger demographics and the BMI categories of overweight (BMI25-30), obese (BMI30-40) and morbidly obese (BMI40+). Where, θ and ξ are the coefficients relating to BMI percentage and category respectively. The $BMI_{percentage}$ variable has inputs of 5% intervals while the $BMI_{category}$ variable has inputs of 27.5, 35 and 45 corresponding to mean values in Table 3 for overweight, obese and morbidly obese BMI categories respectively.

$$t_{M3} = \theta(BMI_{percentge}) + \xi(BMI_{category}) + C_{M3} \tag{8}$$

2.3. Simulation modelling phase

The simulation modelling phase is conducted in two parts: the creation of the aircraft models and the creation of the occupant models. The simulation models are developed using the evacuation software Pathfinder. This software package was selected on the basis that it is free to use for academic purposes. Many of the other evacuation software, e.g. airEXODUS, are not provided for third party uses that are external to their developers.

2.3.1. Aircraft parameters

2.3.1.1. Model geometry characteristic. Two aircraft types were considered in this paper; a narrow and a wide-body aircraft with a capacity of 180 and 339 passengers respectively, with only an economy class configuration. To create the basic model in which the simulation mesh is applied, Pathfinder allows for imports of images or computer-aided drafting (CAD) files. In this study, an image detailing the utilised cabin layout was imported. The cabin layouts were sourced from Airbus Technical document publicly available from the Airbus website (Airbus, 2014; Airbus, 2015). The geometry for the models was then built upon a cabin layout image (Fig. 1 and Fig. 2) consisting of floor, wall and door elements. Note that these figures are just examples of two simulations scenarios; other passenger distributions have been considered for the same aircraft types. Seat pitch in the narrow-body aircraft is 73–78 cm (29–31 in.) with an aisle width of 61 cm. Additionally, the seat pitch at the over-wing exits is 88 cm (34 in.). The wide-body aircraft has a seat pitch of 76–81 cm (30–32 in.) with an aisle width of 51 cm.

2.3.1.2. Exit types characteristic. Exits are added to the model and characterised by the width, flow rate and opening delay. These characteristics are implemented as shown in Table 5 (McLean and Corbett, 2004; McLean et al., 2002). The narrow-body aircraft has four Type-I and four Type-III doors whereas the wide-body aircraft has six Type A and two Type-I doors. In an emergency situation, all doors may not be used for various reasons. For example, a door may not be used if it is damaged or faulty, the emergency slides improperly deployed or when there are hazards and obstructions directly in front of the exit (such as fire, debris or water). Therefore, the certification requirements necessitate that only half the total number of doors on an aircraft are used and that the evacuation be conducted in darkness.

2.3.2. Occupant parameters

2.3.2.1. Occupant seeding. Occupants are seeded into a position that represents a seat in the aircraft; each occupant is allocated a colour based on their profile. The seeded occupants are then grouped. The relevant demographic profiles, as derived in Section 2.2.1, are entered into Pathfinder using the group property interface. Heights, diameters and speeds of occupants follow a normal distribution; data relating to the maximum, minimum, standard deviation and mean are determined from the NHANES database. Occupants are modelled as cylindrical elements where the governing diameter is determined by the waist

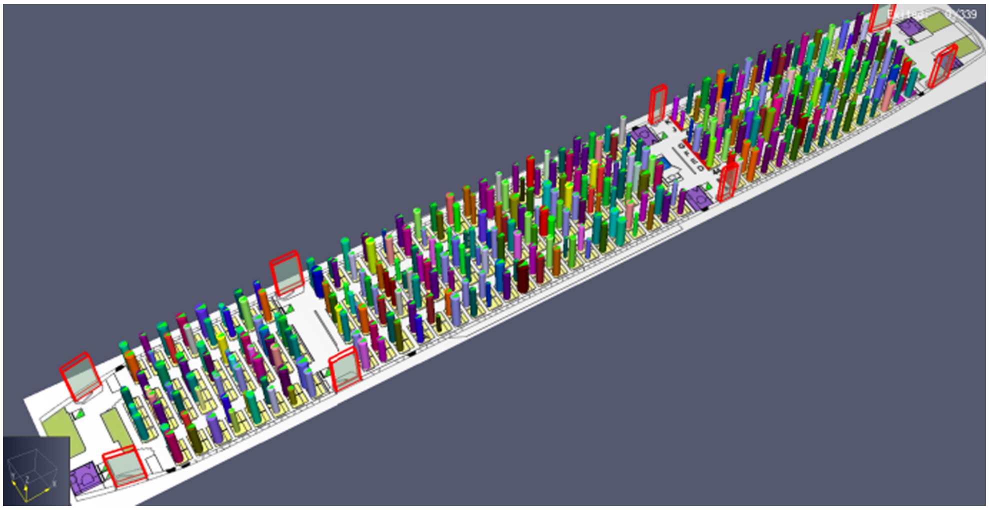

Fig. 2. Wide-body aircraft Pathfinder model featuring 339 passengers in single class layout.

Table 5
Aircraft Door types and Characteristics.

Exit Type	Type-I	Type-III	Type A
Width (cm)	60.9	50.8	106.7
Flow Rate (person/s)	0.780	0.640	2.105
Time to open exit (s)	4.61	5.27	2.25

diameter or shoulder breadth. The shoulder diameter is used whenever the specific profile of an occupant has a waist diameter smaller than the shoulder; this is the case for BMI profiles < 25.

2.3.2.2. Occupant behaviour. Passenger behaviour represents a challenge to simulate. Behaviours vary with the situation; passengers will experience greater levels of anxiety and a sense of urgency in a real evacuation (McLean and Corbett, 2004). Further, an individual's behavioural response will be different from the next person. In this respect, this study's model simplified the passengers' behaviour by assuming all passengers have similar behavioural tendencies and priority levels. These psychological behaviours use the default settings as provided by Pathfinder. Each occupant has a behaviour assigned to them in the user interface and dictates a sequence of goals that the occupant must achieve during the simulation. There are two main types of goals in Pathfinder: idle goals and seek goals (Thunderhead Engineering, 2016). Idle goals are ones in which an occupant must wait at a location until an event occurs. In this study, this equates to the time delays mimicking the time it takes for a passenger to get up from the seat. Seek goals are ones in which an occupant moves towards a destination, such as a waypoint or an exit. For this study, waypoints are used to move occupants to the nearest available door. This action prevents occupants from travelling against the flow towards an irrelevant door. Additionally, replicating the compression behaviour of the passenger in a queue, due to passengers urgency to evacuate, was also incorporated into the model by allowing occupant partial overlap in the model. Without this behaviour, the occupants in the model would jam against other occupants and the surrounding cabin interior.

2.4. Egress simulations phase

The egress simulations were conducted with different scenarios of BMI prevalence as outlined in Table 6. To ensure that the results are statistically significant, a total or 40 simulation runs were made for each scenario. Pathfinder provides a function to randomise attributes, according to a selected distribution method for each occupant within a specific profile. A normal distribution was used for this study. Each simulation run was made with the following randomised attributes except for the occupant location: occupant gait speed, height, waist-diameter and delay time.

2.4.1. Simulation scenarios

A control scenario has been utilised to compare against the scenarios consisting of higher BMI > 25 level. The control scenario comprises of NHANES data (with 55% obesity) adjusted to meet the FAA evacuation requirements (FAA, 1990a). Though all aircraft are expected to meet these FAA requirements, obesity prevalence varies in different countries. Hence, this study explores the various situations in which the obesity prevalence scenario changes.

The scenarios in Table 6 consist of the control with BMI greater than 25 at 55% prevalence followed by three sets of scenarios, corresponding to higher prevalence of overweight (25 < BMI < 30) and obese (30 < BMI < 40) categories, beginning at 65% and increasing with increments of 5% until reaching BMI greater than 25 at 90% prevalence. The following obesity scenarios with BMI greater than 25 prevalence rates of 65%, 70% and 80% from each of the three scenarios are considered for regression analysis. Additionally, an extreme scenario where the demographic is predominantly morbidly obese (BMI40+) with a BMI above 25 prevalence rate of 65% is considered. All the simulations used only half the available doors for each cabin configuration; all starboard doors remained closed. A completed egress time is considered when an occupant exits the door; slides are not considered in this study as they cannot be modelled in Pathfinder.

2.4.2. Pathfinder software behaviour mechanics

Pathfinder is an agent-based egress simulator that uses steering behaviours to model occupant motion. It consists of three modules: a graphical user interface, the simulator, and a 3D results viewer. Pathfinder provides two primary options for occupant motion: a model developed by the Society of Fire Protection Engineers (SFPE) and a steering mode. For this study, the steering mode is used. The steering mode is based on the idea of inverse steering behaviours. Steering behaviours were first presented in Reynolds (1999) and later refined into inverse steering behaviours in a study presented in Amor et al. (2006). Pathfinder's steering mode allows the more complex behaviours to naturally emerge as a by-product of the movement algorithms, thus eliminating the need for explicit door queues and density calculations.

Table 6
List of all the simulations conducted; outlining the obesity level and scenarios considered for regression analysis.

	Scenarios						
	Obesity %						
Aircraft Type	55%*	65%	70%	75%	80%	85%	90%
A320	RM1, RM2	O,Ob,OM, RM1,RM2	O,Ob,OM, RM1,RM2	O,Ob,OM	O,Ob,OM, RM1,RM2	O,Ob,OM	O,Ob,OM
A332	RM1, RM2	O,Ob,OM, RM1,RM2	O,Ob,OM, RM1,RM2	O,Ob,OM	O,Ob,OM, RM1,RM2	O,Ob,OM	O,Ob,OM
A380	RM1, RM2						
Legend							
O	Scenario where Overweight (BMI25-30) is predominant						
Ob	Scenario where Obese (BMI30-40) is predominant						
MO	Scenario where Morbidly Obese (BMI40+) is predominant						
RM1	Regression Model 1						
RM2	Regression Model 2						
*	Control Scenario						

2.5. Delay sensitivity analysis phase

Delay times (representing the sit-to-stand movement) discussed in Section 2.1.3 highlights that the individuals assume a different delay time taken from a normal distributed time delay that was applied to the entire passenger population. Implementing a time delay cannot be applied to an individual occupant profile because of a limitation in the Pathfinder software. Therefore, additional analysis has been conducted to investigate the consequences of variations in sit-to-stand time within the simulations.

2.5.1. Method

Exploring the differences with an increase or decrease in the time delay on the evacuation time are considered using five different alternative scenarios; two scenarios below and three above the control setting. The control scenario used the results from the narrow-body aircraft (FAA requirements) where the obesity level is set to 55%. To create these new scenarios representing varying degrees of delay time, a factor was introduced to shift the existing normally distributed delay time. The factor chosen was a standard deviation (0.41 s) of the control delay time. This factor was selected as it shifted the delay distribution along with the standard deviation of the control scenario.

Fig. 3 illustrates the shifting delay time distribution for the different scenarios considered. Shifting the distribution in this manner allows for the spread and probability of the data to remain the same over the differing scenarios. The initial delay for the various sensitivity scenarios is shown in Table 7. The analysis considered the repeats of the 40 simulations conducted for the control group (55% obesity prevalence). Each of the 40 simulations of the control scenario has a corresponding simulation among the five alternative delay scenarios. Thereby, ensuring that all the control simulations attributes and parameters are retained for each alternative scenario. This then, guarantees that the delay time was the only variable being changed.

Table 7
Delay sensitivity analysis input time settings for higher and lower delay times and control settings.

Time (s)	3 SD Below	1.5 SD Below	Control	2 SD Above	4 SD Above	6 SD Above
Mean	0.33	0.95	1.56	2.38	3.20	4.02
SD	0.41	0.41	0.41	0.41	0.41	0.41
Max	0.93	1.55	2.16	2.98	3.80	4.62
Min	0.00	0.59	1.20	2.02	2.84	3.66

2.6. Verification phase

A verification process has been used to check that Pathfinder has the ability to conduct evacuation simulations of narrow aisle passage ways, as seen on commercial passenger transports; such as aircraft or buses. Verification of the simulation model resorting to a scenario involving narrow aisles and confined space was conducted using two methods. The first involved conducting a real-life evacuation simulation trial

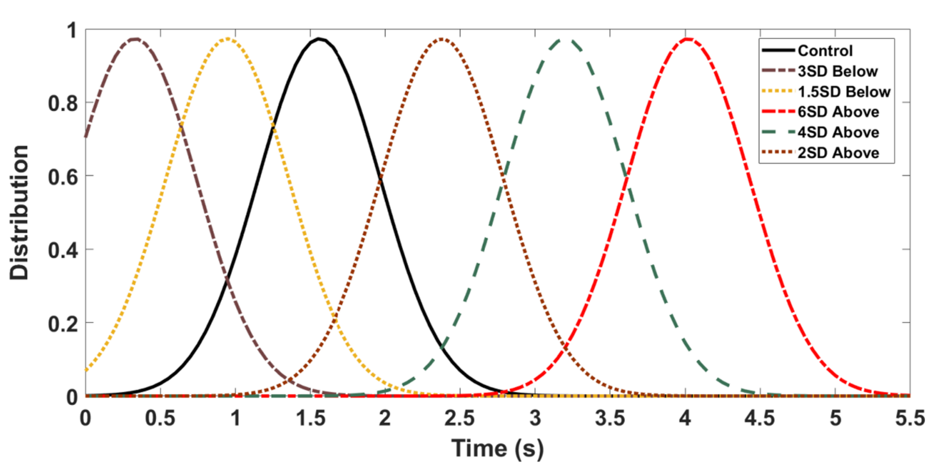

Fig. 3. Distribution of Delay Time against the control scenario.

using a 57 seater coach bus. The second method centred on replicating the reported evacuation time of the Airbus A380 where the published evacuation time is 78.04 s (Daly 2006).

2.6.1. Coach bus evacuation trial

An evacuation trial using a coach bus with a similar interior to a narrow-aisle aircraft with seats facing forward on either side of the aisle was used to verify the numerical results. Past research studies using bus evacuations include Purswell and Dorris (1978) and Matolcsy (2009) exploring the design of both emergency doors and windows. Similarly to other aircraft studies, human performance is also examined in studies such as those by Cook and Southall (2000), Pollard and Markos (2009) and Abulhassan et al. (2016). These studies conducted partial or full evacuation experiments to explore their goals; e.g. exit accessibility, bus interior layout, passenger behaviour and use of specific exits. Liang et al. (2018) successfully demonstrated the evacuation time of a commuter bus using evacuation software to replicate experimental evacuations.

2.6.1.1. Experimental format. The coach bus evacuations for this study consisted of three trials requiring the participating volunteers to exit the bus rapidly. Ethical approval was obtained prior to the evacuation trials. The primary reason for the utilisation of a bus evacuation was due to resource constraints; airlines and cabin training simulators facilities when sought were not available for this study. As such, the authors opted for the next best option for this research paper.

A total of 21 random adult participants took part in this exercise comprising of 12 males and 9 females. Participants were measured for their anthropometric attributes (Table 8) and assigned a seat to be used for each trial. The participants had a mean age of 22.2 years and an average BMI of 22.3. The vehicle used in this study was a bus with a capacity of 57 passengers.

Each trial was initiated by the phrase “EVACUATE, EVACUATE, EVACUATE” (Fig. 4). Participants were not made aware when each evacuation order would be given, thus providing a sense of surprise and removal of readiness similar to the conditions experienced in a real emergency situation. An additional motivation was introduced by repeating some supporting phrases to instil urgency towards the behaviour of the participants.

2.6.1.2. Bus simulation model. Following the bus trials, a model was created within Pathfinder to replicate the same conditions, both in terms of cabin layout and participant anthropometric features (Fig. 5). Using video footage taken during the trials, individual egress times and the exit sequence in which each participant evacuated was obtained. In comparison to the aircraft study, each occupant seed placed in the corresponding seat was characterised by the matching participant’s anthropometric attributes. The shoulder breaths and waist diameter were used as the limiting model factors for the occupants. For example, if a participant had a shoulder breadth greater than their waist diameter than their corresponding occupant model would use their shoulder breadth as the model factor. Furthermore, each occupants speed was calculated for each trail from the associated participant exit time and distance travelled, it should be noted that the speeds of an individual participant differ in each trial.

Fig. 4a. Bus evacuation trial interior.

Fig. 4b. Bus evacuation trial main exit.

2.6.2. A380 aircraft comparison

The introduction of the A380 aircraft saw a new revolution in aviation with the advent of an ultra-high-capacity aircraft used for commercial passenger transport. With a capacity of over 800 in a single cabin layout configuration, the A380 raised concerns on the observance of the 90 s requirement due to a large number of passengers. It should be noted though most A380 operators do not operate single class configurations but instead, they configure their aircraft around 500 passengers in a multi-class double-aisle configuration. Notwithstanding this, the A380 was required to demonstrate egress abilities for a single class configuration during initial certification. The goal of this comparison was to verify that Pathfinder and the models are capable of simulating a real aircraft evaluation.

2.6.2.1. The scenario. It has been widely publicised that the A380 evacuation time is 78.04 s (Daly, 2006), including a video recording of the evacuation being uploaded to popular video streaming sites. Other than the total egress time resulting from the only trial conducted by airbus for certification purposes of the A380, information on the demographics of the participants (e.g. anthropometric characteristics, individual responses times, etc.) was not found in any source available in the public domain. Therefore, the model created in this study utilises the Control Scenario demographic composition to compare the real trials as the certification process only dictates for a cross-section of the general public. However, the media reported that over 1,000

Table 8
Characteristics of the participants involved in the bus evacuation trials.

	Age	Shoulder Breadth (cm)	Waist Circumference Size (cm)	Waist Diameter (cm)	Height (cm)	Weight (kg)	BMI
Mean	22.6	45.4	87.5	31.7	171.6	66.1	22.3
Standard Deviation	5.0	2.7	21.1	7.7	6.0	14.4	3.7
Confidence Level (95%)	2.3	1.2	9.6	3.5	2.8	6.6	1.7
Minimum	18.0	40.0	64.0	24.0	162.0	44.1	16.8
Maximum	38.0	50.0	162.0	60.7	184.5	98.3	31.0

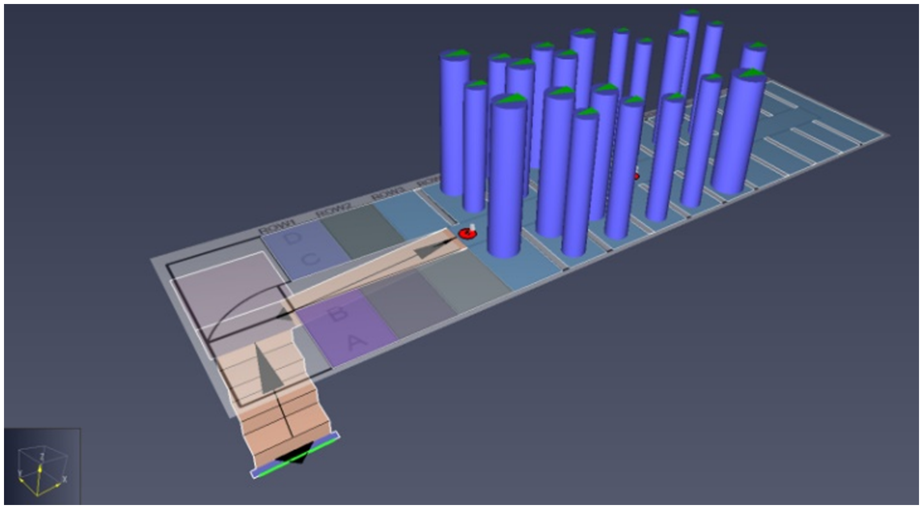

Fig. 5. Pathfinder bus simulation model.

participants were chosen through a vetting process of able-bodied persons after they completed a warm-up exercise. These participants were employees of Airbus and random people from the local gymnasiums (Daly, 2006). The aircraft was configured for a full high-capacity economy cabin with 10 abreast (3-4-3) seating and 8 abreast (2-4-2) seating for the lower and upper deck respectively.

2.6.2.2. The model. The model presented in this paper considered an aircraft with 853 occupants seated in a single class layout (Fig. 6). Both the upper and lower decks have a cabin layout consisting of two 60 cm width aisles and a seat pitch of 76–83 cm (31–33 in.). There are 367 and 486 occupants seated on the upper and lower decks respectively. The demographics in the scenario mirrors the control scenario passenger's demographic model derived from the NHANES data used for the FAA narrow and wide bodied aircraft scenarios. Further, only the left-hand side doors were considered in the simulations and egress time was measured when the last occupant exited the aircraft. A total of 40 simulation runs were carried out. The final evacuation times are then compared with the real evacuation time as per the certification requirements.

3. Results from the simulation modelling

3.1. Simulation scenario Statistics

Increasing the prevalence of overweight and obese passengers has shown to increase evacuation times in certain scenarios for both aircraft types. The statistical descriptions of the data for the narrow-body and wide-body aircraft are shown in Table 9a and Table 9b respectively. The scenarios consist of the control with BMI greater than 25 at 55% prevalence followed by three sets of scenarios beginning at 65% and increasing with increments of 5% until reaching BMI greater than 25 at 90% prevalence. For each set of scenarios, the results show an increase in evacuation time. The control scenario showed a baseline evacuation mean time of 76.61 s with a standard deviation of 1.13 s for the narrow-body aircraft and 87.13 s with a standard deviation of 1.53 s for the wide-body aircraft. Both aircraft types experienced significant mean evacuation time over the 90 s certification requirement when considering the scenario with a population of BMI greater than 40 predominates. The 90-seconds threshold is also surpassed when considering a population predominantly consisting of BMI 30 to 40 for the wide-body aircraft.

This study has shown that for current levels of BMI greater than 25 (55%), a mean egress time of 76.61 s (95% CI, 76.2–76.9) and 87.13 s (95% CI, 86.66–87.60) was obtained for the narrow-body and wide-body aircraft types respectively. Liu et al. (2014) highlights that for a 180 narrow-body aircraft, their study resulted in an egress time of 79.0 s with a standard deviation of 1.7 s, while Chen et al. (2014) using two different egress software's, MACEY and airEXODUS, obtained results of 85.0 s for a 179 seat aircraft and a 73.0 s for a 188 seat aircraft respectively. Likewise, the use of GPSS and airEXODUS provided results of 84.9 s for a 356 seat and 71.7 s for a 351 seat wide-body aircraft

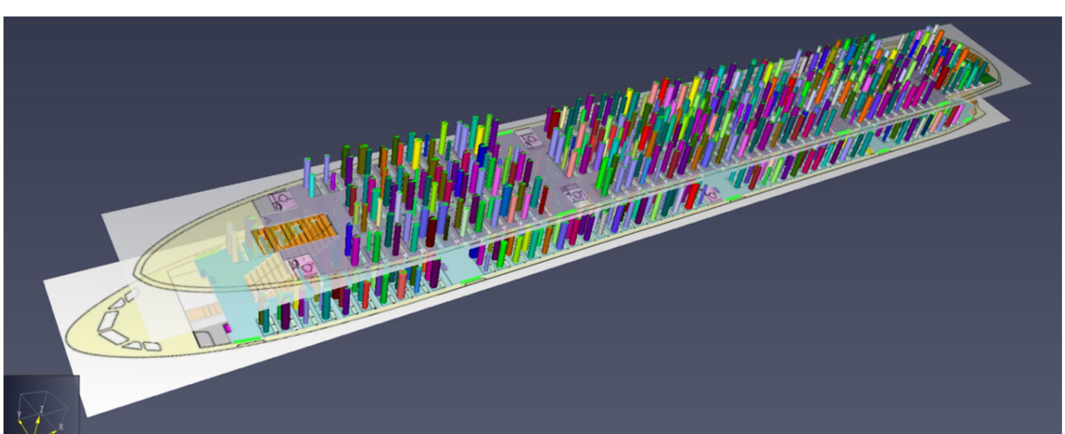

Fig. 6. A380 aircraft Pathfinder model featuring 853 passengers in single class layout.

Table 9a
Evacuation time (s) for Narrow-body aircraft descriptive statistic for all simulated scenarios of different BMI > 25 prevalence and specific BMI category predominance.

Narrow-Body Aircraft	*Control*	*Scenario where BMI25-30 is predominant*						*Scenario where BMI30-40 is predominant*						*Scenario where BMI40+ is predominant*					
BMI > 25 prevalence	*55%*	*65%*	*70%*	*75%*	*80%*	*85%*	*90%*	*65%*	*70%*	*75%*	*80%*	*85%*	*90%*	*65%*	*70%*	*75%*	*80%*	*85%*	*0.90*
Mean Time	76.61	76.63	77.19	77.14	77.16	77.34	77.27	78.38	79.68	84.51	86.78	87.97	89.26	91.56	91.87	92.68	94.14	94.57	94.87
Standard Error	0.18	0.21	0.13	0.18	0.18	0.21	0.22	0.16	0.34	0.22	0.39	0.21	0.40	0.40	0.51	0.24	0.44	0.49	0.52
Median	76.40	76.50	77.60	77.40	77.40	77.60	77.00	77.90	79.00	84.35	86.80	88.05	89.20	91.05	92.35	92.45	93.10	93.20	94.45
Standard Deviation	1.13	1.31	0.85	1.11	1.13	1.31	1.41	1.04	2.16	1.39	2.48	1.36	2.50	2.51	3.24	1.50	2.78	3.12	3.28
Variance	1.28	1.70	0.72	1.23	1.28	1.71	1.98	1.09	4.65	1.94	6.14	1.84	6.24	6.31	10.49	2.26	7.75	9.72	10.75
Kurtosis	5.59	−0.28	0.73	−0.57	0.28	−0.17	−0.71	−0.23	8.99	−0.88	−2.00	−1.30	0.97	1.52	−1.04	4.01	−0.21	−0.11	−0.08
Skewness	−0.93	−0.10	−0.52	−0.05	0.19	0.12	0.30	0.35	2.51	0.12	−0.06	−0.37	0.77	1.26	−0.28	1.21	0.72	0.95	0.64
Minimum	72.2	73.8	75.0	75.0	75.0	75.2	75.2	76.4	77.3	82.0	83.9	85.4	85.4	89.1	85.4	89.2	90.5	90.5	89.3
Maximum	79.0	79.2	79.0	79.0	80.1	80.3	80.3	80.4	89.2	87.5	89.4	89.6	97.0	99.4	96.9	98.2	101.1	102.1	103.4
Confidence Level (95%)	0.36	0.42	0.27	0.36	0.36	0.42	0.45	0.33	0.69	0.45	0.79	0.43	0.80	0.80	1.04	0.48	0.89	1.00	1.05

Table 9b
Evacuation time (s) for Wide-body aircraft descriptive statistic for all simulated scenarios of different BMI > 25 prevalence and specific BMI category predominance.

Wide-Body Aircraft	*Control*	*Scenario where BMI25-30 is predominant*						*Scenario where BMI30-40 is predominant*						*Scenario where BMI40+ is predominant*					
BMI > 25 prevalence	*55%*	*65%*	*70%*	*75%*	*80%*	*85%*	*90%*	*65%*	*70%*	*75%*	*80%*	*85%*	*90%*	*65%*	*70%*	*75%*	*80%*	*85%*	*90%*
Mean Time	87.13	88.82	89.11	89.30	89.19	89.33	88.97	91.58	93.90	94.39	94.93	95.55	96.09	96.04	98.11	98.51	99.65	100.72	102.13
Standard Error	0.24	0.29	0.48	0.38	0.42	0.59	0.48	0.69	0.74	0.76	0.63	0.72	0.80	0.97	0.78	0.75	0.76	0.84	0.78
Median	87.15	88.85	89.00	89.30	89.35	87.90	87.95	91.45	94.05	94.75	94.75	94.50	95.95	95.70	98.35	99.05	99.45	100.25	103.35
Standard Deviation	1.53	1.84	3.01	2.39	2.67	3.73	3.05	4.34	4.69	4.78	4.01	4.55	5.09	6.11	4.92	4.72	4.78	5.29	4.91
Variance	2.35	3.40	9.03	5.70	7.13	13.89	9.28	18.87	21.96	22.86	16.10	20.71	25.87	37.31	24.22	22.24	22.87	27.99	24.09
Kurtosis	−0.82	−0.90	−0.48	−0.77	−0.28	4.59	−0.61	−0.92	−0.36	−0.08	−0.73	−0.07	1.14	−0.32	−0.34	0.12	−0.01	0.13	−0.10
Skewness	−0.22	−0.22	0.23	−0.01	0.39	1.86	0.60	−0.09	−0.43	−0.31	−0.04	0.84	0.34	0.20	−0.48	−0.35	0.19	0.38	−0.75
Minimum	84.0	85.3	83.4	84.6	84.6	83.1	83.6	83.5	82.8	83.7	86.2	89.2	84.3	84.4	86.9	87.1	90.8	91.1	89.7
Maximum	89.5	91.7	95.3	93.4	94.9	102.1	95.5	99.1	102.7	103.1	102.4	106.4	111.0	109.9	106.4	108.0	110.5	114.5	109.8
Confidence Level (95%)	0.49	0.59	0.96	0.76	0.85	1.19	0.97	1.39	1.50	1.53	1.28	1.46	1.63	1.95	1.57	1.51	1.53	1.69	1.57

Table 10a
One sample T-Test results for various obesity scenarios for the narrow-body aircraft against the 90-seconds rule.

Scenario predominance BMI Category	*BMI > 25 Prevalence*	*One-Sample Statistics*			*One-Sample Test*				
					Test Value = 90			*95% Confidence Interval of the Difference*	
		Mean Time (s)	*Std. Deviation*	*Std. Error*	*t*	*Sig. (2-tailed)*	*Mean Difference*	*Lower*	*Upper*
Control	55%	76.61	1.13	0.18	−74.75	< 0.001	−13.40	−13.76	−13.03
BMI25-30	65%	76.63	1.31	0.21	−64.80	< 0.001	−13.38	−13.79	−12.96
BMI25-30	70%	77.19	0.85	0.13	−95.19	< 0.001	−12.82	−13.09	−12.54
BMI25-30	80%	77.16	1.13	0.18	−71.71	< 0.001	−12.84	−13.20	−12.48
BMI20-40	65%	78.38	1.04	0.16	−70.57	< 0.001	−11.63	−11.96	−11.29
BMI30-40	70%	79.68	2.16	0.34	−30.28	< 0.001	−10.32	−11.01	−9.63
BMI30-40	80%	86.78	2.48	0.39	−8.23	< 0.001	−3.23	−4.02	−2.43

(Chen et al., 2014). Using ETSIA Martínez-Val et al. (2017) determined an evacuation time of 77.8 s for a 179-seat single aisle aircraft. However, all of these cases were unclear on the demographic/anthropometric characteristics considered in the simulations.

3.2. Obesity prevalence and the 90-second requirement

Simulations conducted in this study explored the effects of various BMI above 25 prevalence scenarios on evacuation time. Several scenarios were selected for analysis using a one-sample *t*-test to determine the significance of the evacuation results concerning the 90-seconds regulatory requirement. Tables 10a and 10b present the analysis for the narrow-body and wide-body aircraft respectively. According to the *t*-test, the narrow-body aircraft fell well under the 90 s rule. The control scenario saw the greatest mean difference with this difference decreasing as the BMI prevalence increased over both predominant BMI category scenarios.

Similarly, the wide-body aircraft has a decreasing mean difference with increasing BMI prevalence. Although this difference is small, as overall BMI prevalence increases the scenario with greater overweight (BMI 25–30) prevalence becomes less significant as the egress time approaches the test value of 90 s. The reason why at 70% and 80% BMI greater than 25 is not significant is due to the *t*-test value set at 90 s; this indicates that the evacuation time in these scenarios is approaching the regulatory threshold. In the scenarios where greater obesity (BMI 30–40) is prevalent for the wide-body aircraft, the mean difference is positive as the evacuation times surpass the 90-second rule.

3.3. Regression analysis results

3.3.1. Regression analysis for determining individual evacuation time

Regression analyses for selected scenarios are presented in Table 11 and Table 12 for Model 1 and Model 2 respectively. The narrow body aircraft returned an R-square value greater than 0.9 with model significance less than 0.001. Similarly, the wide-body aircraft showed similar R-square and significance values ($0.7 < r^2 < 0.85, p < 0.001$). These results show that for both models, the various scenarios with a different predominance of BMI categories are good predictors of an individual's ability to vacate the aircraft.

The regression analysis has shown that an individual's distance to an exit is significant for all models ($p < 0.001$), whereas an individual BMI is significant in most models ($p < 0.05$). Gender and age of passengers have less significance on their egress time on a narrow body aircraft compared with the wide-body aircraft. However, there are some models where the significance level of the age and gender variables is less than 0.05, predominantly in the wide-body aircraft models.

3.3.2. Evacuation time and BMI prevalence regression

Regression Model 3 shows that the percentage of BMI greater than 25 ($p < 0.01$) and the predominant BMI category ($p < 0.01$) within an aircraft is a significant factor of the evacuation time (Table 13). The models for both the narrow and wide body aircraft have R-square values of 0.92 and 0.95 respectively, with a significance of less than 0.001. These two models well represent the evacuation time of an aircraft regarding a predominant BMI category with an overall BMI percentage greater than 25.

The model indicates that as BMI above 25 increases, so does the overall evacuation time. The two independent variables of BMI prevalence and specific BMI category predominance have positive coefficient values. A one-unit increase of BMI prevalence results in an approximate 1% increase in evacuation time for both the narrow and wide body aircraft. If the categorical variable of predominate BMI category changed for a scenario from predominantly overweight (BMI 25–30) to a scenario of obese (BMI 30–40) passengers, evacuation time would only differ by 0.87 s and 0.56 s for the narrow and wide body aircraft respectively.

Table 10b
One sample T-Test results for various obesity scenarios for the wide-body aircraft against the 90-seconds rule.

Scenario predominance BMI Category	*BMI > 25 Prevalence*	*One-Sample Statistics*			*One-Sample Test*				
					Test Value = 90			*95% Confidence Interval of the Difference*	
		Mean Time (s)	*Std. Deviation*	*Std. Error*	*t*	*Sig. (2-tailed)*	*Mean Difference*	*Lower*	*Upper*
Control	55%	87.13	1.53	0.24	−11.83	< 0.001	−2.87	−3.36	−2.38
BMI25-30	65%	88.82	1.84	0.29	−4.07	< 0.001	−1.19	−1.77	−0.60
BMI25-30	70%	89.11	3.01	0.48	−1.87	0.069	−0.89	−1.85	0.07
BMI25-30	80%	89.19	2.67	0.42	−1.92	0.062	−0.81	−1.67	0.04
BMI20-40	65%	91.58	4.34	0.69	2.30	0.027	1.58	0.19	2.97
BMI30-40	70%	93.90	4.69	0.74	5.26	< 0.001	3.90	2.40	5.39
BMI30-40	80%	94.93	4.01	0.63	7.78	< 0.001	4.93	3.65	6.22

Table 11
Model 1 regression analysis for the narrow and wide body aircraft evacuation times constituting the demographic properties of obesity percentages and predominate category.

Aircraft Type	*Scenario predominance BMI Category*	*BMI > 25 Prevalence*	*Coefficients*					*Model 1*		
			Constant	*Gender*	*Age*	*BMI*	*Distance*	*SE*	r^2	*p*
Narrow-Body	***Control***	55%	−2.751	0.477	0.032	0.336	4.620^	4.809	0.909	< 0.001
	BMI25-30	65%	−2.277	0.527	0.036	0.088	4.693^	4.046	0.911	< 0.001
		70%	−3.279*	0.231	0.009	0.801*	4.603^	3.576	0.943	< 0.001
		80%	−2.062	−0.690	0.015	0.628*	4.618^	4.292	0.931	< 0.001
	BMI30-40	65%	−3.347	0.714	0.035	0.616*	4.565^	4.253	0.914	< 0.001
		70%	−2.648	0.716	0.009	0.808*	4.309^	4.855	0.921	< 0.001
		80%	−2.614*	−0.647	0.029	0.345*	4.946^	3.094	0.964	< 0.001
	BMI40+	65%	−2.663	0.674	0.044	−0.185	5.150^	4.654	0.919	< 0.001
Wide-Body	***Control***	55%	−9.899*	−0.028	0.074*	0.798*	3.921^	4.253	0.858	< 0.001
	BMI25-30	65%	−10.643*	−1.311*	0.071*	0.387*	4.140^	3.171	0.845	< 0.001
		70%	−2.574	−1.917*	0.011	0.594	3.641^	4.596	0.773	< 0.001
		80%	−8.361*	0.069	0.078*	0.395*	3.882^	3.627	0.840	< 0.001
	BMI30-40	65%	−6.677*	−2.739*	0.056*	0.591*	3.792^	4.929	0.807	< 0.001
		70%	−5.856*	0.307	0.071*	0.609*	3.575^	5.470	0.712	< 0.001
		80%	−4.642*	0.325	0.043*	−0.169	3.918^	4.486	0.823	< 0.001
	BMI40+	65%	−11.264*	−2.780	0.086	0.497*	4.272^	4.367	0.774	< 0.001

Note: (^)$p < 0.001$; (*) $p < 0.05$.

3.4. Delay sensitivity analysis results

The results of the delay sensitivity analysis showed that the effect of the sit-to-stand time delay is not significant at times less than 6-standard deviations above the control delay time. Fig. 7 illustrates the spread of the different scenarios considered. The scenarios of 1.5Below and 2Above share similar spread properties to that of the control scenario indicating a narrower spread of evacuation times. The scenarios of 4Above, 6Above and 3Below have a wider spread of evacuation times.

The t-Test is used to determine whether the changes in delay time effect on evacuation time when compared to the control scenario. The results are shown in Table 14. The results indicate that the time taken to stand from a seated position does not affect overall egress time. In the timeframe of the entire evacuation, observations in the simulation show that delay time is suppressed by other factors such as congestion in the aisle and at the exits. Notwithstanding this, an addition 2.5 s delay (represent by the 6SD Above scenario) above the control delay time is statistically significant, $t(74) = 1.99$, $p < 0.001$. It has been shown that age increases the time to rise from a chair. Elderly (70+) persons taking 55% longer to stand from their seats when compared to people in their 20's (Bohannon et al., 2010). Similarly, a person's weight can increase the time it takes to stand. An obese person with a BMI over 35 takes 31% longer to stand than someone with a BMI less than 30 (Schmid et al., 2013). These sit-to-stand values are for the physically

Table 13
Model 3 regression analysis for the narrow and wide body aircraft evacuation times constituting the demographic properties of obesity percentages and predominate category.

	Narrow-Body Aircraft			*Wide-Body Aircraft*		
	Coefficients	*SE*	*p-value*	*Coefficients*	*SE*	*p-value*
Constant	42.867	4.411	< 0.001	65.967	2.189	< 0.001
BMI > 25 Percentage	0.142	0.053	0.017	0.109	0.026	0.001
Predominate BMI Category	0.874	0.070	< 0.001	0.555	0.035	< 0.001
Model SE	2.221			1.102		
Model R Square	0.918			0.950		
Model p-value	< 0.001			< 0.001		

Table 12
Model 2 regression analysis for the narrow and wide body aircraft evacuation times constituting the demographic properties of obesity percentages and predominate category.

Aircraft Type	*Scenario predominance BMI Category*	*BMI > 25 Prevalence*	*Coefficient*				*Model 2*		
			Constant	*Age*	*BMI*	*Distance*	*SE*	r^2	*p*
Narrow-Body	***Control***	*55%*	−2.533	0.032	0.336	4.622^	4.790	0.909	< 0.001
	BMI25-30	*65%*	−2.140	0.036	0.086	4.712^	4.034	0.910	< 0.001
		70%	−3.183*	0.009	0.800*	4.606^	3.559	0.943	< 0.001
		80%	−2.424	0.015	0.627*	4.622^	4.283	0.930	< 0.001
	BMI30-40	*65%*	−3.202	0.035	0.608*	4.597^	4.245	0.914	< 0.001
		70%	−2.415	0.010	0.802*	4.326^	4.843	0.920	< 0.001
		80%	−2.916*	0.029	0.346*	4.943^	3.095	0.964	< 0.001
	BMI40+	*65%*	−2.620	0.045	−0.207	5.193^	4.641	0.919	< 0.001
Wide-Body	***Control***	*55%*	−9.915*	0.074*	0.798*	3.922^	4.231	0.858	< 0.001
	BMI25-30	*65%*	−11.289*	0.071*	0.387*	4.139^	3.224	0.839	< 0.001
		70%	−2.518	0.010	0.616*	3.540^	4.670	0.763	< 0.001
		80%	−8.325*	0.078*	0.395	3.881^	3.608	0.840	< 0.001
	BMI30-40	*65%*	−7.851*	0.056*	0.591*	3.773^	5.098	0.791	< 0.001
		70%	−5.721	0.071*	0.609*	3.577^	5.444	0.712	< 0.001
		80%	−4.306	0.043*	−0.170	3.902^	4.465	0.822	< 0.001
	BMI40+	*65%*	−11.330*	0.086*	0.487*	4.146^	4.563	0.751	< 0.001

Note: (^)$p < 0.001$; (*) $p < 0.05$.

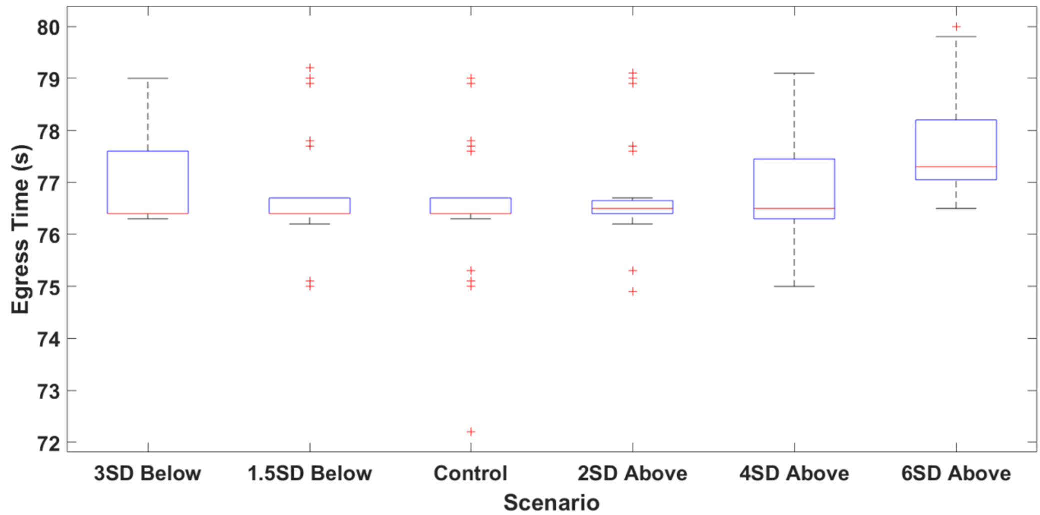

Fig. 7. Boxplot of the evacuation times for the control and alternative delay time scenario.

capable obese or overweight individual; as such these values reflect the 2SD Above scenario. However, health consequences from obesity that cause limited movement may increase the time it takes to stand.

4. Result from the verification phases

4.1. Coach bus evacuation trial results

The three bus evacuation trials have total egress times of BusT1 = 25.75 s, BusT2 = 20.36 s and BusT3 = 19.19 s. These values are very close to those obtained in the corresponding simulations, namely Pathfinder SimT1 = 24.2 s, SimT1 = 21.3 s and SimT3 = 19.6 s. Fig. 8 shows the evacuation of each of the 21 participants for the trials and simulations. Evacuation time decreased with each consecutive evacuation trial as participants become more aware and accustomed to the evacuation process. Further, each participant location determined the evacuation time as participant towards the rear of the bus had to wait for the other participants at the front to move ahead.

Analysis of the evacuation trials video footages suggests a time delay is experienced by the participants to process the evacuation order. The delay of the second trial (1.86 s) and third trial (1.65 s) showed similar consistency. The first trial (3.21 s) had a longer delay. The delay of the first trial can be attributed to the passive behaviour of the participants until encouraged to move quicker. Nevertheless, the delay times are within the range stipulated by Bohannon et al. (2010). Furthermore, it should be noted that the decrease in evacuation times over the trials can be attributed to the learned effect the participants experience with each consecutive trial. This learned effect was incorporated into Pathfinder as an effect of the key model parameters of occupant speed.

Since the purpose of these trials was to ascertain Pathfinders' capabilities for narrow aisle evacuation scenarios, analysis consisted of comparing the results of the bus exercise and the corresponding simulations using bivariate correlation test in Statistical Package for the Social Sciences (SPSS) software (Table 15). It is noted that there is a significant correlation between the egress time with the weight, BMI and distance in the trials and simulations. Furthermore, the results showed that Pathfinder provides a realistically close representation of evacuations when comparing each bus exercise with the corresponding Pathfinder simulation; BusT1-SimT1 ($r = 0.995$, $p < 0.01$), BusT2-SimT2 ($r = 0.996$, $p < 0.01$) and BusT2-SimT2 ($r = 0.998$, $p < 0.01$). The result of this analysis corroborates the appropriate use of Pathfinder to represent narrow aisle and confined cabin conditions in transport scenarios.

4.2. A380 study results

The A380 Pathfinder simulation results show an evacuation time of 81.53 s (95% CI, 81.11–81.95) with a standard deviation of 1.32 s. A t-Test analysis yielded a significance level of $t(39) = 16.18$, $p < 0.001$, indicating that the statistical results of the simulations are significant when compared to the actual evacuation time of 78.04 s. Many different factors can contribute to the slightly higher evacuation time of the simulation. The regression models discussed in Section 3.3 have also been applied in this case (Table 16). Both models are statistically significant although they capture less than 45% of the variance in the data ($r_{M1} = 0.574$; $r_{M2} = 0.569$, $p_{M1,M2} < 0.001$). As mentions Section 2.6.2.2, the exact composition of the demographics used in the real A380 evacuation is unclear as these details are not publicly available. For example, the anthropometrical attributes and behaviours of the participant compared with those used in the simulations would be different. Nevertheless, the manufactures are obligated to comply with the certification requirements that stipulate the minimum demographic composition of participants; age and gender. Should a more comprehensive understanding of the A380 trial parameters been known, a

Table 14
Results from the t-Test: Two-Sample Assuming Unequal Variances for five scenarios of time delay against the control scenario.

Scenario	*Mean Time (s)*	*SD*	*Variance*	*KS Test $D_{CRIT} = 0.215$*	*df*	*t-stat*	*p-value*	*t-value*
Control	76.61	1.13	1.28	0.269	***(2-tailed)***			
3 SD Below	76.88	0.81	0.65	0.354	70	−1.23	0.22	1.99
1.5 SD Below	76.74	0.89	0.78	0.308	74	−0.60	0.55	1.99
2 SD Above	76.74	0.87	0.75	0.313	73	−0.59	0.56	1.99
4 SD Above	76.73	0.87	0.75	0.158	73	−0.54	0.59	1.99
6 SD Above	77.67	0.89	0.80	0.215	74	−4.67	$p < 0.001$	1.99

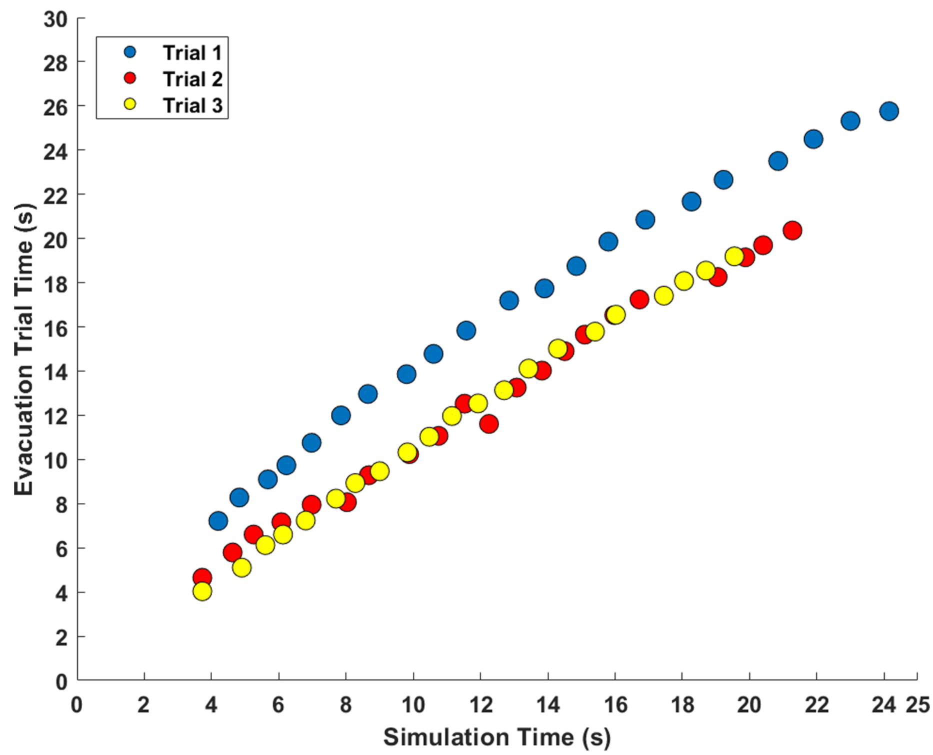

Fig. 8. Comparison of the time between Bus Evacuation Trial and simulations.

Table 15
Bus Evacuation Trial and SPSS correlation statistics.

		Weight	*BMI*	*Distance*
BusT1	*Pearson Correlation*	−0.578*	−0.607*	0.983*
	Sig. (2-tailed)	0.006	0.004	0.000
BusT2	*Pearson Correlation*	−0.563*	−0.592*	0.990*
	Sig. (2-tailed)	0.008	0.005	0.000
BusT3	*Pearson Correlation*	−0.571*	−0.592*	0.984*
	Sig. (2-tailed)	0.007	0.005	0.000
SimT1	*Pearson Correlation*	−0.544*	−0.580*	0.986*
	Sig. (2-tailed)	0.011	0.006	0.000
SimT2	*Pearson Correlation*	−0.557*	−0.584*	0.987*
	Sig. (2-tailed)	0.009	0.005	0.000
SimT3	*Pearson Correlation*	−0.560*	−0.584*	0.985*
	Sig. (2-tailed)	0.008	0.005	0.000

* Correlation is significant at the 0.01 level (2-tailed).

Table 16
Regression analysis for the A380 evacuation consisting of the control demographic properties.

	Model 1			*Model 2*		
	Coefficients	*SE*	*p-value*	*Coefficients*	*SE*	*p-value*
Constant	3.132	2.982	0.296	3.111	2.981	0.299
Gender	0.988	0.997	0.324			
Age	−0.003	0.025	0.891	−0.003	0.025	0.895
BMI	0.268	0.246	0.276	0.262	0.246	0.288
Distance	3.040	0.291	2.17E-17	3.098	0.284	2.31E-18
Model SE	4.831			4.830		
Model R Square	0.574			0.569		
Model p-value	< 0.001			< 0.001		

comparison between the simulations and real trial would then add additional information on the effect of the anthropometrical characteristics participants considering the entire evacuation process (e.g. individual response times).

4.3. Verification and uncertainty

Section 4 of this paper has endeavoured to demonstrate that the numerical simulations provide a satisfactory method for analysing emergency evacuations in transport vehicles with narrow aisles and seat pitches. Relative uncertainty (U_R) is taken as the simulated egress time (V_s) minus the corresponding measured egress time (V_m) divided by the measured egress time (V_m), (Eq. (9)). Overall there is a good match between the bus simulation modelling and the bus evacuation trials. The bound of uncertainty established by conducting the bus egress trials [−4.5%, 6.2%] is small enough to be considered an acceptable margin. The uncertainty stems from the fact that passengers exhibit complex or unexpected behaviours that limit the simulation models potential for precise reproduction of real conditions. The first bus simulation showed a 6.2% faster egress time over the bus trial. Contrastingly, the second simulation showed a 4.5% slower egress time compared to the second trial similarly; the third simulation was slower by 1.9%.

$$U_R = \frac{V_s - V_m}{V_m} \tag{9}$$

For example, the A380 analysis showed that the model in this paper produced a 4.4% slower egress time than the actual evacuation time and this is within the margin of uncertainty stated previously. All aircraft evacuation certification trials are conducted as a single egress event and potentially also prone to uncertainty. Aircraft manufacturers aim to certify their aircraft for the maximum number of cabin configurations possible. However, only a single situation can be tested due to the high number of resources involved in egress trials. Manufacturers conducting multiple evacuation trials would show variations in the egress time. However, if the evacuation trials do not meet the 90 s rule, modifications can be made to the aircraft to meet these certification requirements.

The simulations for the coach bus evacuation trials demonstrate that the level of uncertainty between the bus evacuation trials and the simulation is minimal. Therefore, the models considered in this study when using Pathfinder are verified that the simulated aircraft egress times lie between a slower 4.5% or faster 6.5% interval.

5. Consequences of anthropometric and demographic change on evacuation time

The successful evacuating of an aircraft in less than 90-seconds is one of the key requirements of the aircraft certification process. Not meeting this requirement means the aircraft will not be certified for commercial use. Manufacturers need to ensure that measures are taken to replicate an emergency situation as close as possible with actual real-life scenarios. These might include evacuation in the dark, having obstructions within the cabin, not disclosing the exits to be used during the evacuation tests and to in some cases, the simulation of smoke in the cabin. Although these certification tests are conducted only once, additional analysis can be carried out by the use of computer software simulations. These simulations have the ability to explore conditions that cannot be conducted during certification, e.g., smoke hazard and varying passenger behaviours. Notably, variations in anthropometry have not been investigated thoroughly, particularly BMI prevalence in an airline passenger's population.

5.1. Anthropometry and regulation

FAA regulations Title 14 Part 25 on transport aircraft airworthiness standards provide details on the key design and safety requirements for commercial aircraft, in particular, rules on the evacuation of aircraft. These rules expand on how to conduct evacuations and which door types are to be used and demographic requirements, amongst others. However, other than stipulating that the participants in an evacuation trial be of normal health, of particular gender and age, there are no guidelines on the anthropometrical requirements for the participants. This gap in the regulations which aims at providing randomness in the population paves the way for realistic evacuations with the potential for unrealistic demographic scenarios. The use of physically fit individuals from local gyms and employees of the aircraft manufacturer as highlighted by Daly (2006) does not realistically demonstrate the typical aircraft passenger composition. The variability in passenger demographics is broad when considering that most global regulators rely primarily on accepting certification from either the USA or European regulators. Notwithstanding this, each airline is required to successfully conduct and pass the aircraft emergency evacuation tests stipulated by their own national aviation regulator using the same demographic requirements and standards. Though the demographic data from NHANES used in this study is representative of the USA, characteristics relating to BMI for those demographics can be inferred to other nations with adequate corrections. It is estimated by 2025 global obesity ($30 < \text{BMI} < 40$) prevalence will reach 18% in men and surpass 21% in women; severe obesity ($\text{BMI} < 40$) will surpass 6% in men and 9% in women (NCD Risk Factor Collaboration, 2016b). The majority of the concern is in the nations of Europe, the Americas and Pacific, where obesity has a greater presence then Africa or Asia. Furthermore, air travel has higher patronage and frequency in markets where obesity is expected to grow.

5.2. Age, gender and gait speed

The regression analysis in this study has also shown that age and gender have a less significant effect on egress time with most models. The age component led to an increase of the egress time by less than 0.1 s whereas, BMI and distance to the nearest exit increase the time by less than 1 s and 5 s respectively. The models also indicate that under specific scenarios, the passenger's weight contributes significantly to the egress time. Therefore, these changes in demographics may reduce existing occupant flow models. With flow being a product of speed and density, an ageing population constitutes a less mobile population. Passengers with a larger waist diameter (those with higher BMI) have a higher area footprint as they take up greater area in the aisle. Conversely, passengers with lower BMI have less area footprint and can form higher density queues by having more passengers per unit area. By having more passengers with a higher area footprint, it implies that the queue in the aisle will be less dense i.e. less passenger in the aisle. The simulated scenarios where the BMI was greater had occupants in the rows of seats as they waited for the queue to clear or a large enough gap to be present before moving into the aisle resulting in slowing the evacuation rate and increasing the time. In scenarios where the BMI was lower, the passengers managed to queue in higher densities due to the smaller area footprints allowing more passengers to be in the aisle at the same time, making the evacuation process faster as observed in the simulations. Not exploring and considering the effects of BMI in terms of waist-size as a key occupant input parameter for other evacuation software packages potentially may fail to represent a realistic scenario. Further research would be needed to have a better understanding of the effect of the passenger footprint on the aisle flow considering the entire evacuation process.

Having a BMI greater than 25 is not necessarily a predictor of a person's mobility function. However, maintaining a normal BMI can improve a person's chance to retain mobility function, particularly gait speed. Increasing BMI by 1%/year over 25 years decreases gait speed by 4.5 cm/s (Windham et al., 2017). Passengers with disabilities have not been explored in this study. In an emergency, passengers with reduced mobility would require the aid of either their fellow passengers or the cabin crew. Passengers with disability make up less than 3% of travellers between the ages of 18 to 64. Nevertheless, varying levels of disabled passengers have shown to increase evacuation times (Liu et al., 2014).

5.3. The sit-to-stand factor

Furthermore, the time it takes a person to get up from the seat varies between individuals. Age has shown to be a factor that increases the time it takes to stand up from a seated position. Bohannon et al. (2010) demonstrate that people under 40 years of age take approximately 6 s to complete five repetitions of sit-to-stand action compared to persons over the age of 80 who take approximately 8 s to complete the same task. This is a difference of approximately 0.4 s for a single sit-to-stand movement, equivalent to one standard deviation of time delay set in this study. Similarly, it has been shown that people with higher BMIs also take longer to stand (Schmid et al., 2013; Kamaruddin et al., 2012). In most emergency simulation packages, a generalised sit-to-stand delay time is applied to simulated occupants. The analysis in Pathfinder shows that the time taken to reach a standing position has little bearing on the overall evacuation time. The control scenario, with a mean delay time of 1.56 s (SD = 0.41 s), had the lowest evacuation time compared to the alternative scenarios. The behaviours of passengers moving within the cabin have greater weight on the overall time to exit. Some passengers will remain standing in their seat until the path is clear for them to move as they wait for others to pass by while others will block pathways trying to retrieve hand-luggage. Similarly, if a passenger seated in the aisle was slower to stand compared to a passenger in the adjacent window or middle seat, the added time will most certainly impede on the evacuation of the blocked passenger.

6. Conclusion

There is limited research currently being undertaken regarding the relationship between anthropometry and aircraft egress. This study has shown there is a significant increase in emergency egress time as the prevalence of BMI above 25 within a population increases. According to the regression analysis, gender is less of a contributing factor to egress time. The control scenario representing the FAA regulations and incorporating current obesity trends ($\text{BMI} > 25$ of 55%) reveal that weight seems not to play a significant role into egress time compared to other factors, such as passengers distance from the nearest exit. However, assuming obesity prevalence increases in the future as per the forecasts of the WHO, the maximum egress time stipulated by current aviation regulations for certification purposes might not be achievable, as demonstrated by the greater significance of the BMI in the egress time over the other variables considered in the simulations discussed in this paper. Further research is needed to assess other constraints to emergency egress, such as the evacuation of disabled passengers and the behaviour regarding passengers carrying cabin baggage. Additionally, further non-conventional aircraft cabin designs which have been proposed at a conceptual level for next-generation transport aircraft (e.g., blended wing body concept) should take into consideration changes in passenger BMI demographics to ensure the emergency egress of all passengers can be carried out within the 90 s rule irrespective of their anthropometric characteristics. This study thus highlights the need for aviation main stakeholders, most notably regulators and manufacturers, to incorporate more realistic passenger anthropometrical trends into existing aircraft design and operational standards and regulations to warrant the safety of all airline passengers.

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