An investigation of the changing commercial airline passenger anthropometry and its effects on aircraft safety and performance

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

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I dedicate this thesis to my family.

My mother Omega, father Robin, sister Stephanie and grandmother Eileen.

In particular, my grandfather Rutgerus, who passed away before he could see his grandson accomplish this prestigious achievement.

Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

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List of Publications

This section outlines the author's related works that have contributed to the field of aerospace and aviation performance and safety during the course of his candidature. The following peer-reviewed publication outputs have resulted from this candidature research:

Refereed Journal Articles

- **Melis, D. J.**, Silva, J. M., Silvestre, M. A., & Yeun, R. C. K. (2019). *The effects of changing passenger weight on aircraft flight performance*. Journal of Transport & Health, 13, 41–62. https://doi.org/10.1016/j.jth.2019.03.003
- **Melis, D. J.**, Silva, J. M., & Yeun, R. C. K. (2018). *Impact of biometric and anthropometric characteristics of passengers on aircraft safety and performance*. Transport Reviews, 38(5), 602–624. https://doi.org/10.1080/01441647.2017.1396264
- **Melis, D. J.**, Silva, J. M., Yeun, R. C. K., & Wild, G. (2019). *The airline passenger anthropometry, the increasing prevalence of obesity and aircraft emergency evacuations*. Safety Science. (Reviewed not yet accepted at time of submission for examination.)

Refereed Conference Papers

- **Melis, D. J.**, Silva, J. M., & Yeun, R. C. K. (2019). *Aircraft safety and passenger anthropometry—evaluating emergency egress times of different passenger profiles*. 18th Australian Aerospace Congress, Melbourne, Australia.
- **Melis, D. J.**, Silva, J. M., Silvestre, M. A., & Clothier, R. (2017). *Characterisation of the anthropometric features of airline passenger and their impact on fuel usage in the Australian domestic aviation sector*. 17th Australian Aerospace Congress, Melbourne, Australia.
- **Melis, D. J.**, Silva, J. M., & Clothier, R. (2015). *The changing size of commercial aviation passenger and its potential impact on the aviation industry*. 7th Asia-Pacific International Symposium on Aerospace Technology, 25–27 November, Cairns, Australia.

Conference Presentations

The author has presented at three conferences over the course of his candidature:

- Oral presentation, 18th Australian International Aerospace Congress, 25–26 February 2019, Melbourne, Australia.
- Oral presentation, 17th Australian International Aerospace Congress, 26–28 February 2017, Melbourne, Australia.
- Poster presentation, 7th Asia-Pacific International Symposium on Aerospace Technology, 25–27 November 2015, Cairns, Australia.

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List of Abbreviations

ATR	Avions de Transport Regional
BMI	Body mass index
CAA UK	Civil Aviation Authority, United Kingdom
CASA	Civil Aviation Safety Authority
CDC	Centers for Disease Control and Prevention
DEM	Discrete Element Method
DVT	Deep vein thrombosis
EASA	European Aviation Safety Authority
FAA	Federal Aviation Administration
FIFO	Fly in, fly out
GPSS	General Purpose Simulation System
HFES	Human Factors and Ergonomics Society
ICAO	International Civil Aviation Organisation
NCD	Non-communicable Diseases
NHANES	National Health and Nutrition Examination Survey
OEW	Operational empty weight
PAYW	Pay As You Weigh
PRM	Passengers with reduced mobility
PSFC	Power-specific fuel consumption
ROC	Rate of climb
ROD	Rate of descent
SD	Standard deviation
SIPRI	Stockholm International Peace Research Institute
SR	Specific range
TSFC	Thrust-specific fuel consumption
UK	United Kingdom
US	United States
WHO	World Health Organization
ZFW	Zero fuel weight

Abstract

At first glance, anthropometry and aviation would appear to be unrelated to one another; however, an important relationship exists between them. Aircraft are vehicles that are primarily designed to transport people across long distances, and new aircraft types with enhanced design features are continually being developed, built then entering the aviation market for global airline service. These enhancements to human–machine interfaces ensure continued safety and efficiency, improve performance and prolong the life cycle of components. However, they often do not consider the effect of the changing anthropometric characteristics of the passenger. The media and the medical literature have identified increasing global trends in the average weight and height of passengers, as well as other anthropometrical and biometrical measures. However, the majority of these studies have been limited to exploring the ramifications primarily from the perspective of passengers' experience.

This thesis is the first to explore the explicit relationship between commercial passengers' anthropometry and aircraft safety, design and performance. It highlights the importance of considering passengers' anthropometric characteristics from a holistic perspective, and it identifies gaps for future research. A thorough search of the available literature shows that this topic has received little attention, thereby demonstrating the need for this research. Most literature to date has revealed that there is limited knowledge regarding the ramifications of changes in passengers' anthropometry. The two main areas of focus of this research are aircraft performance and aircraft safety.

Aircraft Performance

All aircraft are designed to ensure optimal performance during flight, with key flight characteristics interacting and changing depending on the aircraft's weight. However, the correct estimation of the passenger component of that weight is often overlooked when compared with the weight of freight or fuel. Passenger weight is typically set to a predetermined value by aviation regulators; therefore, it does not reflect the true weight of the passengers onboard. In some cases, the standard weights issued by the regulator are out of date and do not reflect current society trends in obesity. Hence, the research component that addresses aircraft performance explores the effect of passenger weight attributes and obesity on several aircraft performance characteristics.

The numerical performance analysis uses spreadsheets to calculate the various performance objectives related to specific phases in the flight. The performance literature shows that similar methods have been used to analyse data, predominantly for studies regarding aircraft flight attributes. The key benefit of spreadsheets is that they allow changes to be made to initial base parameters such as passenger weight, aircraft data and initial conditions.

It was concluded that Western countries with a higher prevalence of obesity and lower standard passenger weights might overestimate performance characteristics such as fuel usage, range, landing and take-off performance. Similarly, countries (predominantly African) with lower obesity prevalence underestimate these performance characteristics because they rely on standard weights from the Federal Aviation Administration, European Aviation Safety Authority and Civil Aviation Authority United Kingdom. Overall performance characteristics for any aircraft type considered in this study will be significantly affected if existing obesity growth forecasts for the next few decades are proven to be accurate. This justifies the need for more accurate regulations and improved flight operational procedures.

Safety—Emergency Egress

The design of commercial passenger aircraft must take into consideration the certification requirement that all occupants should be able to evacuate from the cabin within 90 seconds in an emergency. Manufacturers are required to demonstrate compliance with this regulatory requirement using the aircraft to be certified. There is a significant risk of injury to participants when conducting evacuation tests. To determine whether passengers can evacuate safely from the aircraft within 90 seconds, manufacturers may use computer-aided simulations to mitigate risks to participants. This has an added benefit of allowing customisation of the profiles of the individual models used.

The research component in this study involved simulations using two aircraft types: narrow-body (180 seats) and wide-body (399 seats) aircraft. Both aircraft are modelled using the multi-application egress simulation software package Pathfinder. Multiple scenarios are explored and consist of different levels of obesity prevalence ranging from the control parameter of 55% to higher levels of obesity prevalence that mirror obesity growth forecasts. These scenarios form three situations in which different body mass index (BMI) groups have greater prevalence in society: overweight (25<BMI<30), obese (30<BMI<40) and morbid obesity (BMI>40).

A total of 98 different anthropometric profiles based on age, gender and BMI were created. Data from the National Health and Nutrition Examination Survey were used for the model in this study. A total of 40 repeated simulations were conducted for each scenario. The results showed that when obesity prevalence increases, the evacuation time of both aircraft types also increases. Increasing overall obesity by just 5% can lead to an increase in the egress time of approximately two seconds for the wide-body aircraft scenario. Further, regression analysis for both aircraft demonstrated that the variables of BMI and distance to exit have strong statistical significance for overall evacuation time.

A sensitivity study was conducted for delay time, which represents the sit-to-stand time of the occupant. This study was needed because Pathfinder could not allocate delay times to individual profiles, but only to the overall occupant population. The control scenario formed the basis of this study, and the control delay time standard deviation was used as a factor to change the delay time. The results showed that the delay time did not affect the egress time, except for the highest delay time scenario of six standard deviations above the control time. A bus emergency egress exercise was conducted in August 2018 to validate the model. This exercise involved conducting several evacuations from a bus and then replicating the trials in Pathfinder. The results were consistent between the simulations and the experimental exercise and showed that the model has an uncertainty interval of −4.5% to 6.5%.

Chapter 1: Introduction

1.1 Background and Significance

As a result of cheaper airfares, population growth and increasing wealth, commercial aviation demand is expected to grow between 4.4 - 4.6% over the next few decades (Airbus 2018; Boeing 2019). Airlines are meeting this demand by expanding and upgrading their fleet with increased capacity and new technologies such as biofuels, light-weight materials and improved aerodynamic designs. However, their focus is often centred on the aircraft and associated technologies, and they seldom consider the effect of passengers' anthropometric characteristics such as weight and size. The media has highlighted concerns regarding the issue of obesity and air travel - in particular, the effect of obesity on legroom relative to seat pitch and other passenger comfort issues (Adler 2008; Veldhuis & Holt 2012a; Hunter 2013; Reese 2013; Platt 2015; Levin 2017; Vasel 2017). In light of the media coverage, the judicial system in the United States (US) has ordered a review of aircraft seat design (Wattles 2017) while the Human Factors and Ergonomic Society (HFES) have issued an airline seat policy statement in 2019 (HFES 2019).

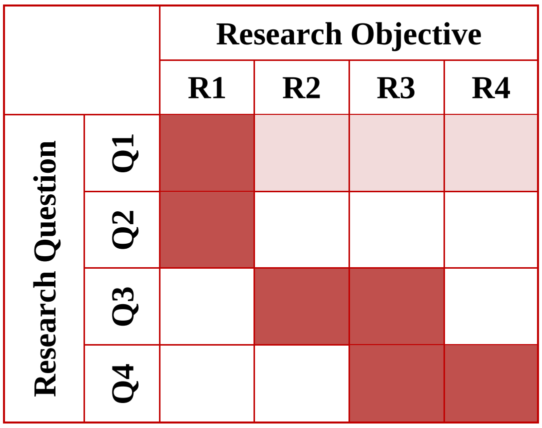
Worldwide, aircraft manufacturers and airlines are grappling with challenges relating to anthropometrical changes in passengers - in particular, average passenger weight. A recent global survey of obesity noted that there are more obese people in the world than underweight people (NCD Risk Factor Collaboration 2016c). Globally, one-third of adults are considered overweight (Lobstein 2015). The World Health Organization (WHO) has declared obesity a global-scale pandemic. In 2008, it reported that obesity had nearly doubled worldwide between 1980 and 2008, with 35% of adults considered obese - that is, with a body mass index (BMI) greater than 25 $\mathrm{kg{\bullet}m^{-2}}$ (WHO 2016). The importance of this global problem has led many researchers to undertake anthropometrical studies to investigate the epidemiology of the causes of 'the obesity epidemic'.

The heightened media interest in issues concerning obesity and overweight populations has primarily focused on health and society implications, and little has been explored in the transport setting. In particular, research in the aviation sector with a focus on anthropometry is limited to ergonomics, and areas such as safety and performance are often not considered. The primary goal of this thesis is to understand the implications for aircraft operations resulting from the increasing prevalence of obesity and overweight passengers.

1.2 Research Objectives and Questions

In 2014, the Civil Aviation Safety Authority (CASA) in Australia issued various research sponsorship themes and requested a review of the current standards for passenger and baggage weights (CASA 2014). Further questions arose regarding the implications of passenger weight changes for other aspects of aircraft operations. An initial literature survey was conducted to determine the potential paths for the present research. From this initial survey, the research questions were devised (see Section 1.2.1), and the research objectives were then established to answer these questions (see Section 1.2.2).

The research scope focuses on two areas: aircraft performance and emergency egress of commercial passenger aircraft. In both areas, only passenger anthropometry - in particular, passenger weight - is considered at different levels of BMI prevalence, with a focus on higher levels of obesity and overweight passengers. This thesis does not consider studies that focus on other anthropometrical factors that have an indirect bearing on safety and performance. Figure 1-1 outlines the relationship between the research questions and objectives. Some objectives (e.g., R1) seek to answer two different questions, and some questions (e.g., Q3 and Q4) are answered by multiple objectives. Since Q1 refers to an understanding of the literature; Q1 is, in part, answered by all research objectives.



		Research Objective			
		R1	**R2**	**R3**	**R4**
Research Question	**Q1**	■	▨	▨	▨
	Q2	■			
	Q3		■	■	
	Q4			■	■

Figure 1-1 Relationship between research objectives and questions

1.2.1 Research Questions

This research aims to answer the following research questions:

Q1) What are the potential ramifications of airline passengers' anthropometric changes for aircraft design from a safety and performance point of view?

Q2) How have airline passengers' anthropometric changes been considered by both aircraft manufacturers and regulators over time?

Q3) What is the effect of airline passengers' anthropometric changes on the efficiency of airline operations?

Q4) What are the future outcomes of passengers' anthropometric changes for air safety and aircraft performance if current trends in anthropometry and air travel demand continue at the current rates?

1.2.2 Research Objectives

According to the four objectives derived from the above research questions, this thesis will:

R1) explore current knowledge and research relating to the relationship between aircraft safety/performance and passenger anthropometry

R2) assess the effect of passengers' weight changes and fuel consumption on the Australian commercial passenger aviation sector and the consequences for airlines and the environment

R3) determine the performance degradation resulting from passengers' weight changes for transport aircraft over a generic flight profile

R4) incorporate passengers' anthropometric features in current available models to simulate an emergency egress with changing physical characteristics and population densities.

1.3 Research Methodology Overview

1.3.1 Review Methodology

The literature review process began with a conceptualisation of the relationship through a systematic approach centred on mind mapping and using keyword association. To conduct the review, literature was sourced from databases including, but not limited to, SCOPUS, Web of Science, Science Direct and Google Scholar. Current niche studies are also reviewed in this chapter and were obtained from academic journals, technical papers and reports from relevant aviation organisations. The process became iterative as new relationships developed between passenger anthropometry and aircraft/aviation from the resulting database searches.

The review process employs a mind mapping (Figure 1-2) process to enable a clear visualisation of the various elements stemming from the central relationship between biometrics and aviation. The literature was then categorised into four sections related to the aviation industry: passenger experience, airline economics, safety aspects and regulatory constraints. Each study outlined in this review focused on a single aspect or element, thereby introducing a new branch in the mind map. Figure 1-2 illustrates the three aspects that make up biometrics: anthropometry, which explores direct measurements of anatomy; metabolic rate, which relates to bodily functions that affect aircraft systems; and biomechanics, which explores both the movement of people and the forces involved with those movements within an aircraft cabin environment.

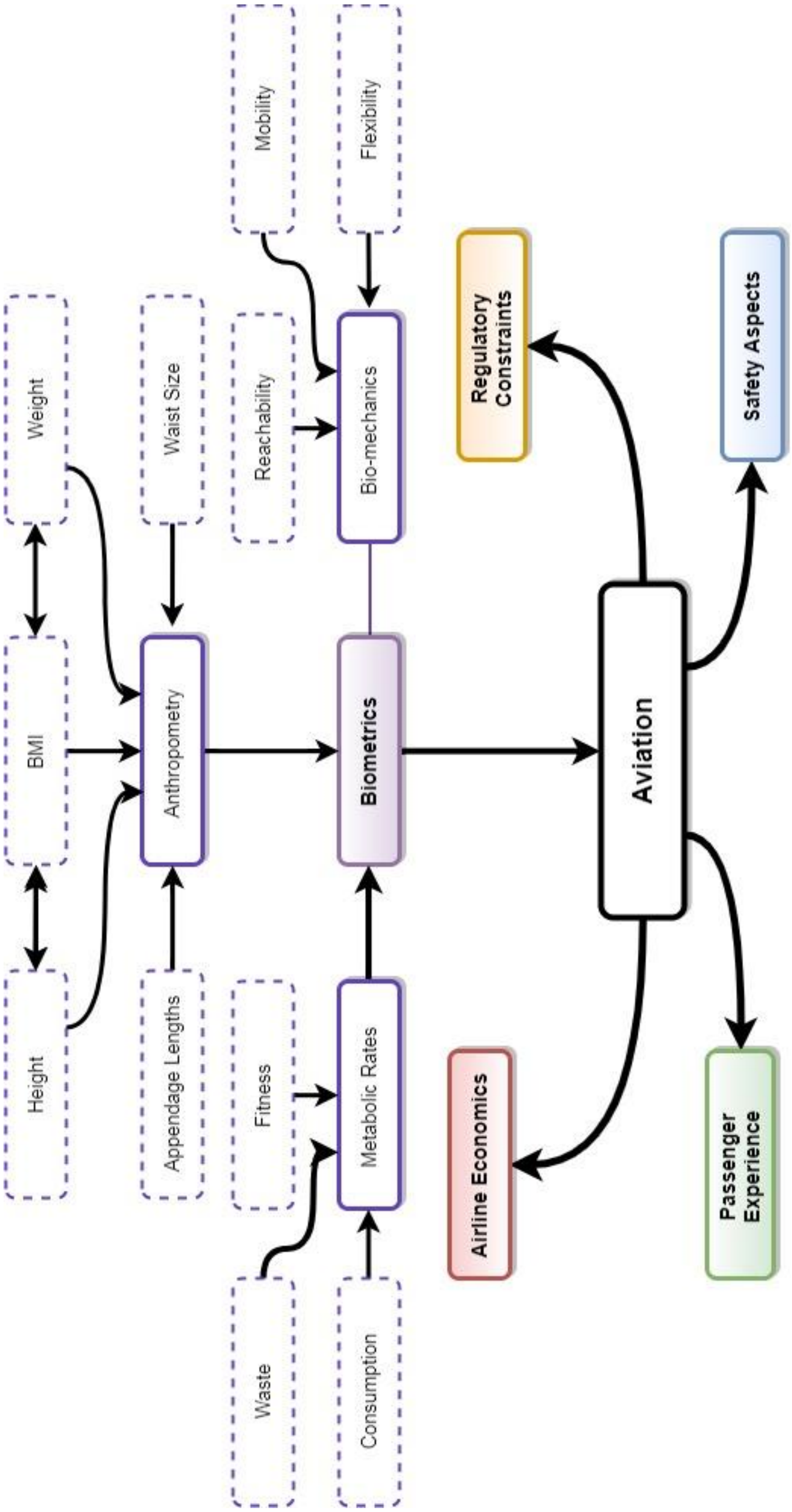


Figure 1-2 Influences of passengers' biometrics on performance, safety, economics and regulatory framework in aviation

1.3.2 Aircraft Performance Methods

The numerical analysis research method follows a quantitative approach. Performance analysis using spreadsheets was extensively used to calculate the research objectives. The literature shows that the non-code method has predominantly been used to analyse data in studies regarding aircraft performance. The key benefit of spreadsheets is that they allow changes to be made to initial base parameters (e.g., anthropometric parameters and aircraft data). This results in the manipulation of successive calculations, which changes the results. Flight performance formulae have been used to explore the effect of passenger payload changes resulting from anthropometric trends for commuter, regional and large transport aircraft. The passenger payload model uses the demographic makeup of the source data from the National Health and Nutrition Examination Survey (NHANES) 2013–2014. Although these data are applicable to the US, the reason behind their use in this study is that obesity relevancies are manipulated to demonstrate various trends that are exhibited around the world and are not specific to the US.

1.3.3 Aircraft Safety Methods

The safety study exploring the aircraft emergency evacuation used numerical and experimental approaches, both of which are considered quantitative methods. The numerical analysis hinged on computer simulations. The multi-application egress simulation software package used in this study was Pathfinder, which was available at no cost from the developer. Although the software is predominantly used to build egress simulations, it can also be used for aircraft evacuations.

The results from the numerical approach were used in the regression analysis, which used three models to determine whether gender, age, BMI or distance to exit can be considered as significant factors. The experimental component validates the models by replicating real-life evacuations of a bus. The reason for using a bus rather than an aircraft was due to the unavailability of an aircraft cabin mock-up despite the many contacts with potential interested parties.

1.4 Thesis Overview

1.4.1 Introduction

This thesis is structured in three parts: introduction of anthropometry and review of current passenger anthropometry within the aviation sector (Chapters 2 and 3); aircraft performance: a study of passenger weight changes (Chapters 5); and aircraft safety: a study of the effect of passenger anthropometry changes on aircraft evacuations (Chapter 6). The layout of this thesis is presented in Figure 1-3. As shown, the performance and evacuation components of this research are independent of each other but linked by the initial chapters, making it possible to read this thesis with or without either of the performance or evacuations parts.

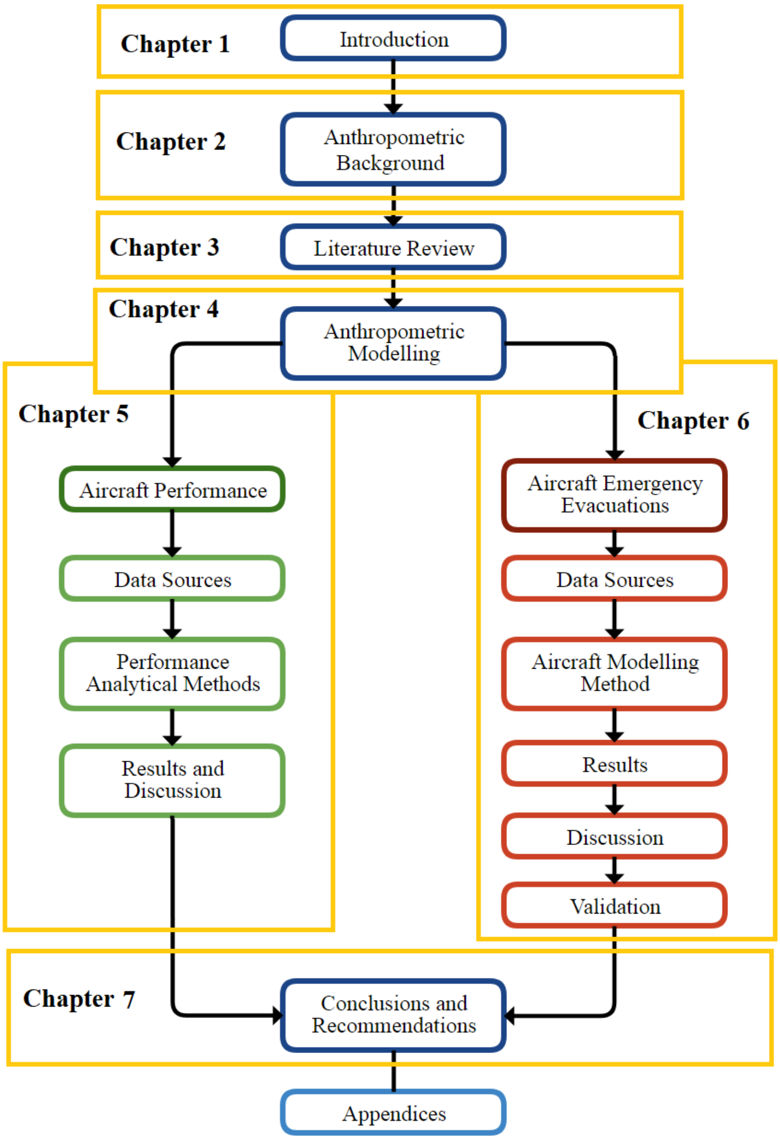


Figure 1-3 Thesis structure

1.4.2 Chapter 2: Anthropometry - Background and Application

Chapter 2 outlines the anthropometry fundamentals for this study. An explanation of the development of BMI is provided, along with the various anthropometric attributes that are often cited in the literature. These attributes - in particular, BMI - are discussed from a global viewpoint in terms of its implications for society. Additionally, global obesity is discussed in terms of BMI to provide an understanding of the current global situation and potential outlook, which are discussed in later chapters.

1.4.3 Chapter 3: Literature Review

Chapter 3 examines the limited body of knowledge in the field of passenger anthropometry and its ramifications in areas such as cabin design, aircraft efficiency and design safety. The work carried out in this chapter has been presented at a conference in 2015 and published in the journal *Transport Reviews* in 2018. Four key areas are identified that are susceptible to the biometric and anthropometric characteristics of airline passengers, namely passenger experience, airline economics, safety aspects and regulatory constraints of the aviation sector. These key areas are discussed in the following section and are supported by schematic representations that highlight both the current facets being explored in the literature and the existing knowledge gaps in these areas. This chapter addresses research objective R1 (and, to an extent, the remaining objectives) and answers research questions Q1 and Q2.

1.4.4 Chapter 4: Anthropometrical Data and Passenger Model

Chapter 4 introduces two aspects of research used in both the performance and safety chapters. The first aspect is a discussion of the primary source of anthropometrical data used in these studies. The second aspect is a discussion of the development of a model to describe changes to BMI prevalence in a sample demographic population.

1.4.5 Chapter 5: Aircraft Performance and Passenger Anthropometry

Chapter 5 investigates changes to selected aircraft performance characteristics based on the effects of increasing passenger weight payloads on the key performance characteristics of commercial aircraft. The passenger demographic model from Chapter 4 is used to model various scenarios of BMI prevalence. The work carried out in these two chapters has been published in the *Journal of Transport and Health* in 2019. Aircraft performance characteristics are determined from traditional analytical methods to examine three aircraft types. Comparisons are made between standard passenger weights from key aviation regulators around the world with scenarios reflecting various degrees of obesity prevalence. These scenarios are further compared with global variations across different regions around the world. This chapter addresses research questions Q3 and Q4 by addressing research objective R3 and, to some extent, R2. Objective R2 was achieved using a case study of the Australian domestic commercial aviation sector using a modified model by Tom et al. (2014). This case study was presented at a conference in 2017, and the paper can be viewed in Appendix 12.

1.4.6 Chapter 6: Emergency Evacuations and Passenger Anthropometry

Chapter 6 demonstrates the effect of passenger anthropometry on emergency egress for both single-aisle and double-aisle aircraft. The work carried out in this chapter has been presented at a conference in 2019. It has been reviewed and pending a decision for publication by the journal *Safety Science* in 2019. Evacuation software packages are discussed, and simulations are carried out using the Pathfinder software developed by Thunderhead Engineering. A demographic model of passenger anthropometry from Chapter 4 is used to model the various scenarios of BMI prevalence. Verification is also discussed in this chapter. This process involves three separate methods to demonstrate the model's validity. The three methods are simulated through a real-life bus evacuation exercise and by corroborating the A380 certification trial. This chapter addresses research objectives R3 and R4 and answers research question Q4.

1.4.7 Chapter 7: Conclusion and Recommendations

Chapter 7 presents the answers to the research questions via the conclusions from the performance and safety aspects of the research conducted. Recommendations and further research opportunities are also presented.

Chapter 2: Anthropometry Background

2.1 Introduction

This chapter discusses anthropometry and highlights its application to society. The purpose of this chapter is to provide background information on what anthropometry is, with particular emphasis on BMI and its effects around the world. The chapter covers the following topics:

- First, it highlights various anthropometric attributes that are the focus of this research.
- Second, BMI and the various approaches used to create this index relating to body frame and adiposity are discussed.
- Third, reasons for using BMI in this research and its limitations in society are explored.
- Fourth, current and past trends in the prevalence of overweight and obesity for various regions around the world are examined to demonstrate changes in body shape.

2.2 Anthropometry Attributes

Human physical characteristics have been evolving since the origin of the modern human species (Ruff 2002). These traits differ around the world and provide a level of variability and diversity among generations. From an early age through to adolescence, children’s growth is monitored by measuring their height and weight. In adulthood, weight remains a crucial metric for monitoring health. This information is used in many fields, from medicine to ergonomics. Anthropometry is a subset of biometrics (a measure of any physical characteristic) and is used to describe people’s physical dimensions. Various characteristics can be measures of anthropometry, which plays an essential role in passenger–aircraft interactions (Jurum Kipke, Baksa & Kavran 2008). These characteristics include height and appendage lengths, waist circumference, waist–hip ratio and weight. However, the most commonly discussed anthropometric term used across multiple disciplines, from the social sciences to health, is BMI.

2.2.1 Height

Every person is unique in that no one has the same height or appendage dimensions. This anthropometric measure is essential in aircraft design—particularly cabin dimensions that encompass various cabin heights, seat pitches and reachable cabin elements. Height has been shown to change with the human's environment (e.g., prosperity increases the likelihood of improved nutrition); therefore, physical attributes are likely to be higher than those of the previous generation. For example, malnourished children and adolescents or those who suffer from serious ailments are generally shorter as adults. Taller people generally live longer and are less likely to suffer from heart disease and stroke, and taller females and their children are less likely to have complications during and after birth (Cole 2003; NCD Risk Factor Collaboration 2016b).

The tallest males, according to Non-communicable Diseases (NCD) Risk Factor Collaboration (2016b), are in the Netherlands and are, on average, 183 cm tall, whereas the shortest males are in Timor-Leste and Yemen, with an average height of 159 cm. The tallest females are in the Netherlands and Latvia (168 cm and 169 cm respectively), while the shortest females are in Guatemala and the Philippines (149 cm tall). The difference between the tallest and shortest countries is about 20 cm for both males and females (NCD Risk Factor Collaboration 2016b). Over the past 100 years, height changes have differed between countries. Between 1896 and 1996, the average height of Australians increased by around 17 cm for males and 10 cm for females. In comparison, average height increased by 5 cm for both males and females in the US.

2.2.2 Weight

Weight is a crucial factor in aircraft design and safety. Passenger weight determines aircraft performance and safety load limits of cabin structures such as seats, and it can play a main role in the buoyancy requirements of life preservers. Therefore, a person's weight is an essential anthropometric attribute of aircraft–passenger interactions. Some of the heaviest people in the world are from the Pacific region and Western nations, where people weigh, on average, more than 70 kg. Conversely, those that are lighter (less than 70 kg on average) are usually from Africa and Asia (NCD Risk Factor Collaboration 2016a). An individual's weight fluctuates with time and is determined by several environmental factors (Wilding 2012; Martínez 2000) that can vary between people. These factors include seasonal changes, socioeconomic status, social influences, diet, food abundance and physical activity. Although weight gain is mutually exclusive to these factors at the individual level, it also plays a role in broader society.

2.2.3 Waist Circumference and Waist–Hip Ratio

Waist circumference and waist–hip ratio are used in seat base design (distance between armrests), aisle width (to ensure adequate space for movement), the occupied area in emergency rafts and other spatially designed cabin attributes (Quigley et al. 2001; Nadadur & Parkinson 2009; Nadadur & Parkinson 2012). Waist circumference is the most commonly used and recommended measure of central obesity. The relationship between waist circumference and central adiposity varies with age and ethnicity. The measurement is taken horizontally at the midpoint between the hips and the lower rib cage. The WHO also recommends that waist circumference be used to classify abdominal obesity because it is associated with disease risk.

As shown in Table 2-1, specified cut-off points have been established to define obesity based on high-risk waist circumferences in adults (WHO 2008). A higher BMI classification leads to an increased risk of obtaining an obesity-related illness. The WHO has prescribed a waist circumference cut-off point of 102 cm for males and 88 cm for females. A circumference that is higher than these cut-off points significantly increases the health risk compared with people below the cut-off points (WHO 2008). Additionally, the use of waist circumference measures is limited in more obese patients because it becomes increasingly difficult to determine the waistline as obesity increases.

Similar to BMI, the ratio of waist circumference to hip is used as a measure to determine the risk to a person’s health. The WHO has also provided a set of guidelines regarding the risk level for people based on their waist–hip ratio. Table 2-1 shows these values for adult males and females. A ratio of less than 1 indicates a wider waist circumference compared with the hip circumference.

Table 2-1 Waist circumference and waist–hip ratio (WHO 2008)

Anthropometric Parameter		**Not at Risk**	**Increased Risk**	**Substantially Increased Risk**
Waist Circumference	Male	Less than 94 cm	94 cm or more	102 cm or more
	Female	Less than 80 cm	80 cm or more	88 cm or more
		Not at Risk	**Increased Risk**	
Waist–Hip Ratio	Male	Less than 0.9	0.9 or more	
	Female	Less than 0.85	0.85 or more	

2.3 Body Mass Index

2.3.1 A Short History

Relative body weight and height indices have been explored since the mid nineteenth century, when it was understood that the relationship between a person's height and weight described their body shape and health consequences. When life insurance agencies observed an increase in the number of deaths of heavier policyholders, they began grouping their clients according to relative body weight. This enabled the insurance agencies to compare clients with others of a similar stature to assign an appropriate cover.

The vice president of the Metropolitan Life Insurance Company, Louis Dublin (1882–1969) was the first to develop tables of normal weight based on the average weight for a given height for use in insurance policies (Keys et al. 1972). However, Dublin noted that there was a wide range of weights for the same gender and height, and that the variation was attributable to body frame or shape. To rectify the issue, Dublin categorised the weight ranges for a given height into three distinct distributions: small, medium and large frames. He also labelled the average weights within each height and distribution category first as 'ideal weight' and later as 'desirable weight'. However, limitations in using these weight–height tables were soon recognised. For example, at the same ratio exhibited from the tables developed by Dublin, insurance agencies noticed that taller policyholders had a lower death rate compared with policyholders of a shorter stature.

Other attempts were made to rectify the inconsistent weight–height distributions, including using several measurements such as shoulder width, elbow width, knee width and ankle width. However, these modifications failed to resolve the issues. Consequently, the concept of body scaling (in which a tall person is a scaled-up version of a short person) was explored. This method has been labelled the Ponderal Index. In this concept, the body is treated as a volume of mass. Ideally, if the body had the same frame at different heights, then the weight would tend to be proportional to the height—particularly to the cube root of weight divided by height.

Eventually, researchers found that Belgian scientist Lambert Adolphe Jacques Quetelet (1796–1874), who was known for his keen interest in the social and natural sciences, had investigated the Ponderal Index in the late nineteenth century. Quetelet was determined to develop a system of statistical normal distributions to describe human characteristics; he had no interest in developing his indices for determining adiposity. In 1885, Quetelet explored the relationship between people's height and weight concerning growth (i.e., from age). He explored the relationship between weight and height in terms of three indices: weight divided by height squared, weight divided by height cubed and the Ponderal Index. Quetelet noted that observations from experiments did not follow the concept that if a person increased equally in all anthropometric dimensions, their weight at different ages would be the cube of their height. Instead, the weight increase would be gradual over time, except for the first few years of life. However, after this period, the weight gain would be approximate to the height squared. Quetelet's research led him to write papers and books on the subject of human anthropometry with a focus on height and weight. In particular, he demonstrated the comparative value of statistics in the understanding of social conditions and social issues. The scientist Ancel Keys reaffirmed the correlation of the Quetelet index and is credited with coining the phrase 'body mass index' (Keys et al. 1972). Quetelet's research relied on data acquired from secondary sources, whereas Keys used data from self-administered surveys. Nevertheless, Keys pointed out that BMI poorly represents a person's body fat percentage.

2.3.2 Describing Body Mass Index

BMI is the most common method for measuring the estimated adiposity levels of an individual. Other methods (e.g., physiochemical and radio imaging) are more accurate but require more time and have associated costs. BMI provides a fast way for health practitioners to estimate adipose by measuring the relationship between a person's height and weight. BMI is calculated as a person's weight in kilograms divided by their height in square metres (Eq. 2.1). Adipose tissues are predominantly located in the trunk of the body, and a small percentage are located in the lower limbs. Quetelet and Keys explain that squaring the height of the person reduces the contribution from the leg length, thereby normalising the body's adipose mass distribution for each potential height in the population and reducing the variance in height in the relationship of weight to height.

$$BMI = \frac{weight}{height^2} \qquad \text{Eq. 2.1}$$

2.3.3 Body Mass Index Classifications

BMI is the main anthropometrical determinate associated with body fat, referred to as adiposity. The literature focusing on weight explores the prevalence of obesity in terms of epidemiological factors, health outcomes and factors exploring obesity prevention. BMI is age-independent and uses the same values for males and females. BMI may not correspond to equivalent adipose levels in different populations, partly because different body proportions are expressed by ethnic and racial variations. Further, the health risks associated with increasing BMI differ along similar lines.

BMI is one of the main decisive metrics used by researchers and health professionals to assess overweight and obesity in people. Depending on the magnitude of BMI, different weight classifications are defined according to the WHO (see Table 2-2). Seven principle categories encompass various cut-off points. The lowest category is underweight, in which an individual with a BMI of less than 18.5 kg•m^{-2} is considered at risk of malnutrition. A BMI of 18.5 kg•m^{-2} to less than 25 kg•m^{-2} is considered a normal body index. In this classification, health risks are significant compared with higher BMI. A BMI of more than 25 kg•m^{-2} to less than 30 kg•m^{-2} is considered overweight. At this level, the individual begins to develop a higher risk of health problems. However, the risk does not increase significantly until the individual reaches a BMI of more than 30 kg•m^{-2}. A person is classified as obese if their BMI is between 30 kg•m^{-2} and 40 kg•m^{-2}. A BMI of more than 40 kg•m^{-2} is classified as morbidly obese and is associated with significantly high levels of health issues ranging from diabetes to cardiovascular problems.

Table 2-2 Principle weight categories with associated BMI range values (WHO 2016)

BMI Classification	BMI Range (kg•m^{-2})
Underweight	Less than 18.5
Normal 1	18.5–19.9
Normal 2	20.0–24.9
Overweight	25.0–29.9
Obese 1	30.0–34.9
Obese 2	35.0–39.9
Morbid Obesity	Greater than 40

The WHO has introduced additional cut-off points to account for differences in ethnic groups in relation to BMI, percentage of body fat and body fat distribution. In some cases, the health risks increase below the cut-off point of 25 kg•m^{-2}, which defines overweight in the current WHO classification. Asian populations display a higher level of adipose tissue at a lower BMI classification. Similarly, African–Americans have higher optimal body fat levels. Thus, the WHO has prescribed lower cut-off points for Asian populations and higher cut-off points for African–American populations (WHO Expert Consultation 2004).

2.3.4 Limitations and Benefits of Body Mass Index as a Measure for Size v. Health Indicator

A particular problem with BMI as an index of obesity is that it does not differentiate between lean body mass and body fat mass; that is, a person with a high BMI can still have low fat mass and vice versa. From an anatomical and metabolic perspective, the term ‘obesity’ should refer to an excessive accumulation of body fat. However, the accuracy of BMI as a determinant of body fat mass has been repeatedly questioned because of its limitations in this regard. Gender, age, ethnic group and leg length are essential variables. In population-based studies, females generally have a lower BMI compared with males, even though their fat mass relative to their body build or BMI is considerably higher (Shimokata et al. 1989).

Notwithstanding the above, BMI is a less-than-ideal measure for obesity because it fails to distinguish between fat tissue mass and muscle mass (Cole 2003). Thus, it is customary for bodybuilders, weightlifters and non-endurance athletes to have a high BMI, and these demographics are often considered outliers in health-related data. Nevertheless, the global convention of employing BMI in sociodemographic research to compare different groups of people has been the standard throughout literature. Its versatility in capturing many physical attributes when not considering health matters is a result of the various attributes that constitute the BMI.

BMI is used as the main anthropometric measure for the research in this thesis because it provides an overarching measure that encompasses relationships to other primary anthropometric measures. Figure 2-1 illustrates this relationship. As mentioned previously, BMI is derived from the weight and the square of the height, which provides a single quantity that accounts for a person’s height and weight. Other correlations have been made that relate weight, waist circumference and waist–hip ratio with BMI (Chinedu et al. 2013; Walls et al. 2010).

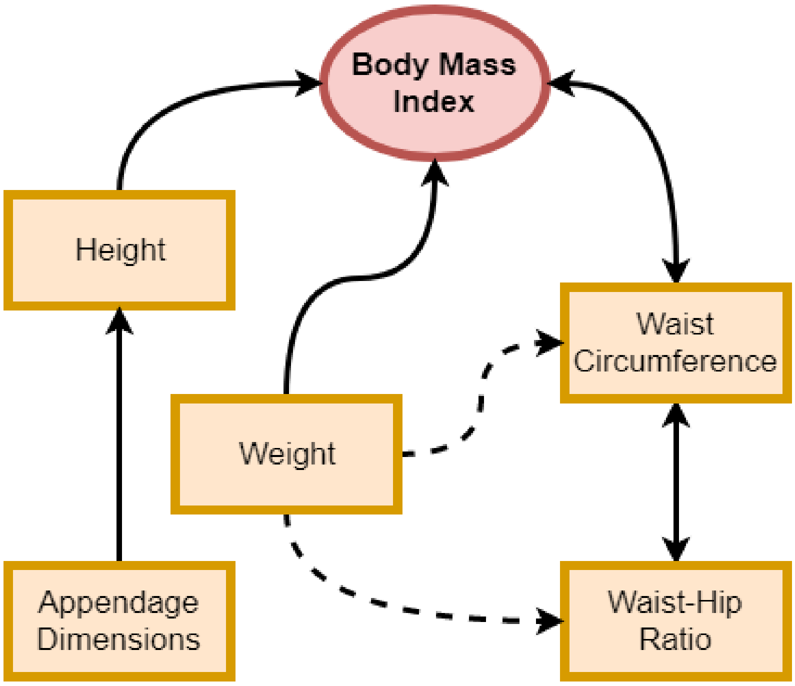


Figure 2-1 Relationship between the various anthropometric measures (solid lines indicate direct relationship, dashed lines indicate indirect relationship)

2.4 Body Mass Index in a Global Context

Understanding the presence of BMI in the global context is essential for later chapters, which explore the performance and egress of aircraft. These later chapters (Chapter 5 and Chapter 6) discuss the prevalence of BMI at different levels, which then relate to equivalent BMI prevalence levels expressed by different nations around the world. Additionally, a brief discussion is presented in this chapter, of the effect of the increased prevalence of obesity and overweight on society and individuals' health. This discussion highlights how issues relating to BMI affect different industry sectors.

2.4.1 Global Body Mass Index Prevalence and Changes in Body Mass Index Categories

Globally, there was a steady increase in average BMI between 1975 and 2014, as shown in Figure 2-2. Over this period, BMI increased from 21.7 to 24.7 $\text{kg}\bullet\text{m}^{-2}$ for males and 22.1 to 24.4 $\text{kg}\bullet\text{m}^{-2}$ for females (NCD Risk Factor Collaboration 2017). Although these global averages indicate that most of the global population remains within a normal BMI range, there is a concern that the trend is increasing. Further, these figures account for higher levels of underweight and normal weight persons that reside in countries with low obesity prevalence, such as Africa and Asia, thus lowering the overall mean BMI.

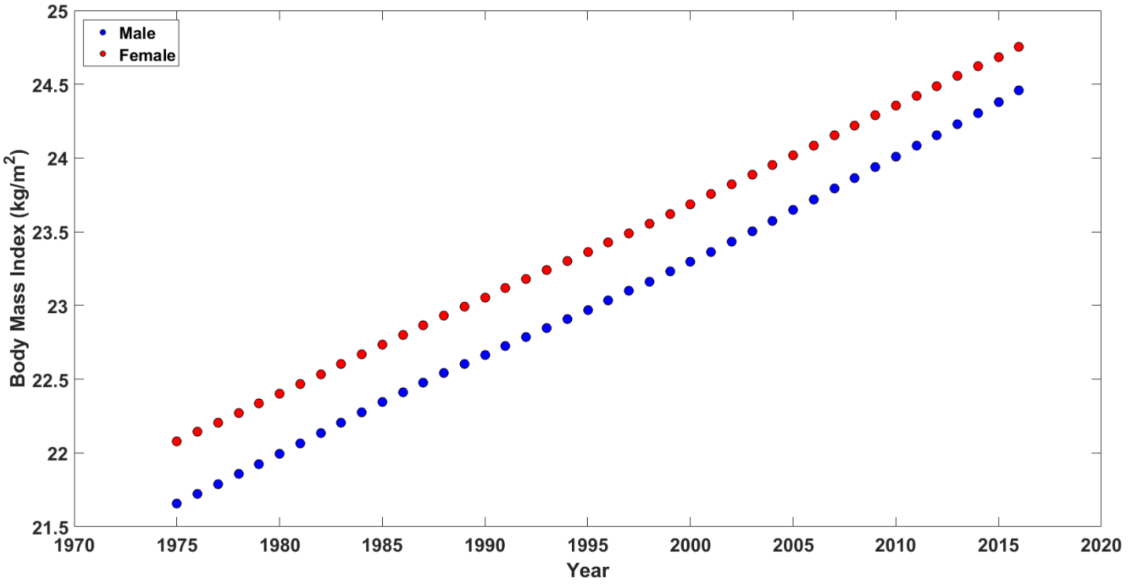


Figure 2-2 World average BMI for males and females (NCD Risk Factor Collaboration 2017)

Figure 2-3 shows a similar upward trend to describe the prevalence of overweight and obese males and females around the world. Accounting for all demographics, encompassing ethnicity, race and socioeconomic status, the global prevalence of BMI greater than 25 kg•m^{-2} increased from 20.8% to 39.9% in males and 23.6% to 40.5% in females over the period 1975–2016 (NCD Risk Factor Collaboration 2017). This trend demonstrates that obesity will become increasingly prevalent among global populations. Although BMI prevalence provides a semi-positive outlook, these trends highlight the global context. The prevalence of BMI greater than 25 kg•m^{-2} varies across countries. There is a strong prevalence of overweight and obese populations in Europe and the Americas; however, countries in the Pacific exhibit the greatest prevalence of BMI greater than 25 kg•m^{-2}.

Global demographics change periodically as a result of trends increasing and decreasing. In the instance of the WHO's BMI categories, Figure 2-4 and Figure 2-5 illustrate the periodic trends of increasing and decreasing prevalence of each category for males and females respectively. Since 1975, the prevalence of normal weight (18<BMI<25) has been in decline. In that year, the normal weight prevalence was 66% for males and 62% for females. However, in 2016, these values decreased to 51% and 50% respectively. Between 1975 and 2016, the prevalence of overweight (25<BMI<30) increased from 18% to 28% for males and 17% to 25% for females. Since 1975, obesity (30<BMI<40) has increased by 9% and 5% for males and females respectively, while morbid obesity (BMI>40) has increased from 0.2% to 1.3% for males and females globally.

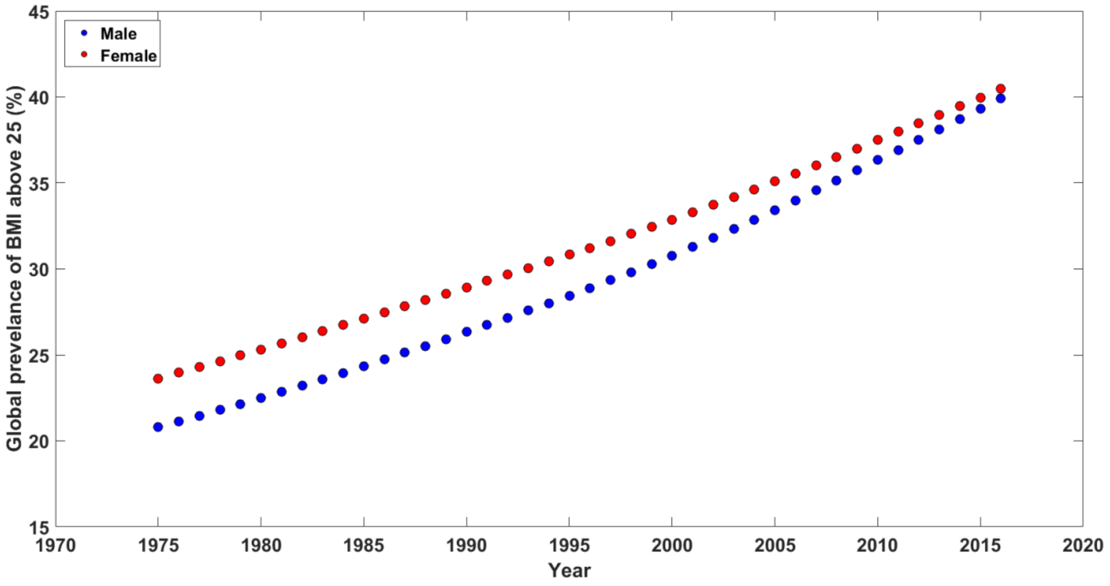


Figure 2-3 World prevalence of BMI greater than 25 kg•m^{-2} for males and females (NCD Risk Factor Collaboration 2017)

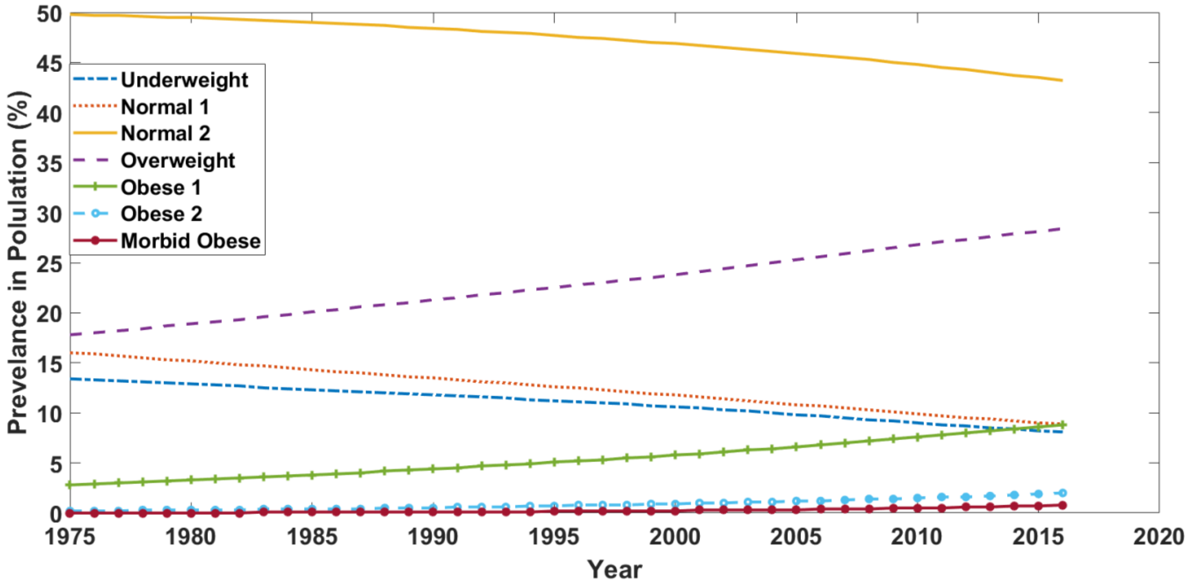


Figure 2-4 Global periodic changes in BMI category for adult males from 1975 to 2017 (NCD Risk Factor Collaboration 2017)

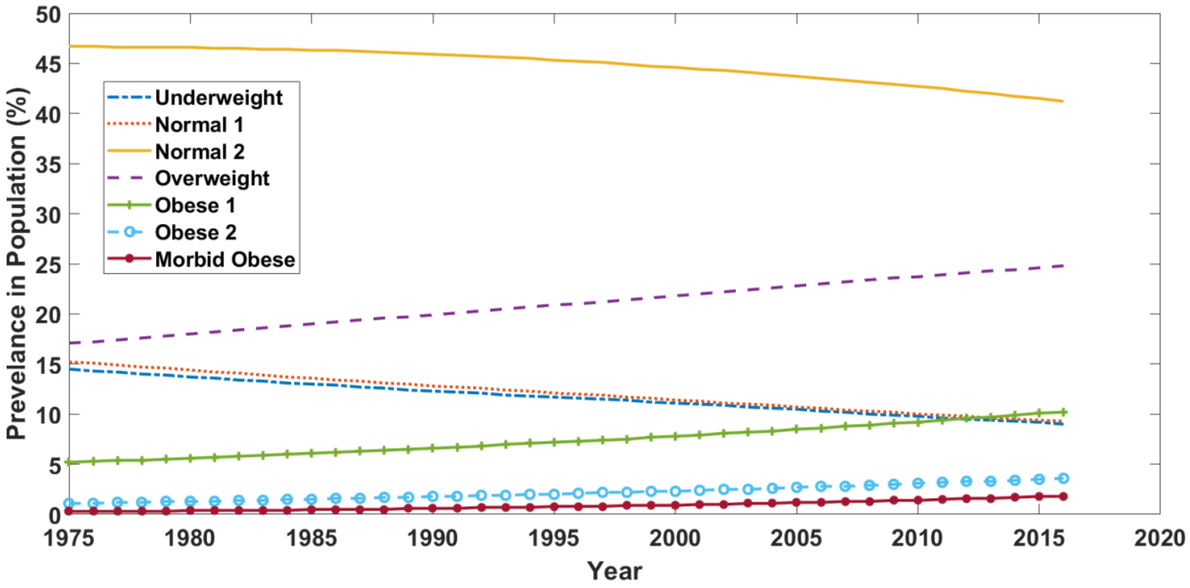


Figure 2-5 Global periodic changes in BMI category for adult females from 1975 to 2017 (NCD Risk Factor Collaboration 2017)

2.4.2 Obesity and Overweight Prevalence in Various Regions

The NCD Risk Factor Collaboration has categorised countries into nine regions based on geo-economical location. These regions are employed in this thesis to discuss aspects such as the relationship between aircraft performance and passenger payload (see Chapter 5:) and the simulations of emergency evacuations for different BMI demographics (see Chapter 6:).

Further, individual countries are referenced to draw comparisons and highlight the overall prevalence of BMI greater than 25 kg•m^{-2}. A list of detailed data outlining the 2016 BMI category prevalence for each country for a given region is presented in Appendix 2 for females and Appendix 3 for males. These BMI data are sourced from the NCD Risk Factor Collaboration adiposity data for countries.

Anthropometric characteristics change with the human environment. For example, high-income or developed countries typically have higher BMIs, with a prevalence of overweight that is more than double that of low-income and lower middle-income countries. Prosperity may increase nutritional intake levels, which directly affects changes in physical attributes (Cole 2003; McLaren 2007). Ford, Mokdad and Giles (2003), Sturm (2007), McDowell et al. (2008) and Pomerantz et al. (2013) explore obesity in the US population by using anthropometric measurements to discuss changes among various demographics (e.g., age and ethnicity). Similarly, urban development—in particular, access to fast food outlets and recreational facilities—affects obesity. This has been demonstrated by an investigation of socio-geography in Canada (Pouliou & Elliott 2010; Valera et al. 2014) and a historical review of the anthropometry of the Turkish people (Neyzi, Saka & Kurtoğlu 2013). Likewise, Ma et al. (2011) discuss childhood obesity in China, Doak et al. (2012) explore the European region, and other studies explore the Pacific region, which has extreme prevalence towards obesity (Asia Pacific Cohort Studies 2007; Monlux & Nigg 2011).

Table 2-3 Obesity prevalence of nine regions around the world (NCD Risk Factor Collaboration 2016a)

Region Name	Region Number	Obesity Prevalence (Mean % ± SD)
Sub-Saharan Africa	1	28.21 ± 8.4
Central Asia, Middle East and North Africa	2	57.63 ± 11.6
South Asia	3	24.62 ± 3.5
East and South East Asia	4	57.82 ± 12.1
Oceania	5	71.81 ± 10.1
High Income Asia Pacific	6	61.31 ± 5.6
Latin America and Caribbean	7	57.00 ± 5.7
High Income Western Countries	8	59.67 ± 3.6
Central and Eastern Europe	9	53.92 ± 9.3

As shown in Figure 2-6, between 1975 and 2014, the average BMI differed between regions. Five of the nine regions had populations with an average BMI greater than 25 kg•m^2. The figure also shows that BMI has been increasing. Regions encompassing Asia, the Middle East and Africa have lower mean BMI compared with Europe and the Americas.

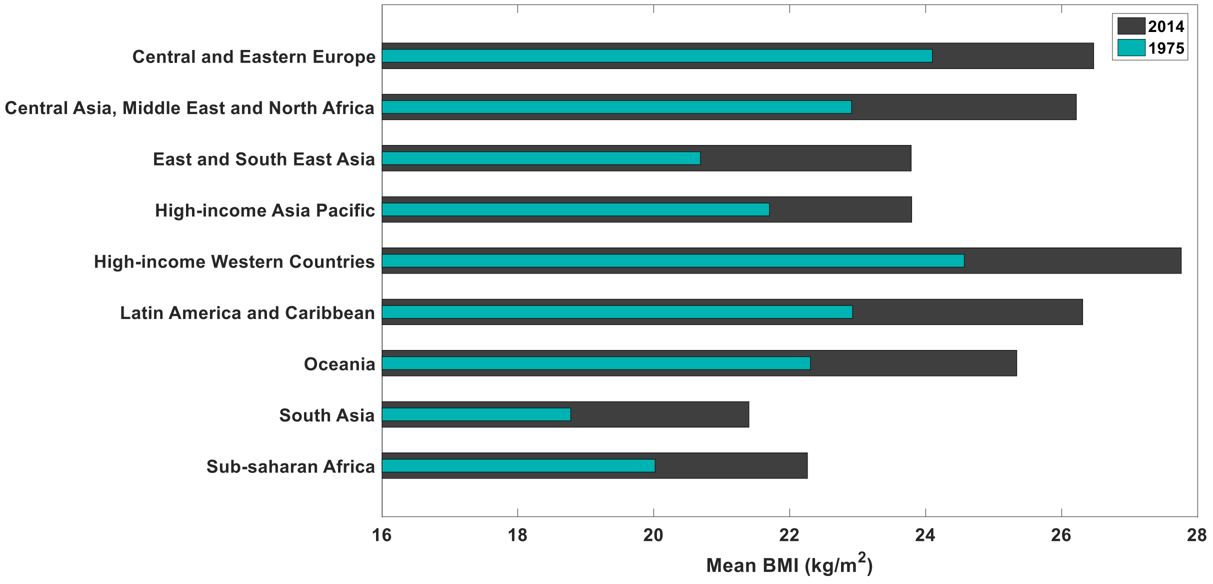


Figure 2-6 Regional average BMI (NCD Risk Factor Collaboration 2016a)

2.4.2.1 High-Income Western Countries

As shown in Table 2-4, for countries in the region categorised as high-income Western countries, the prevalence of BMI greater than 25 kg•m^{-2} is 71% for males and 59% for females. The mean BMI increased by 0.08 kg•m^{-2} per year from 24.7 kg•m^{-2} in 1975 to 27.8 kg•m^{-2} in 2016.

Table 2-4 Countries in the high-income Western region (NCD Risk Factor Collaboration)

High-income Western Countries			
Andorra	Finland	Israel	Portugal
Australia	France	Italy	Spain
Austria	Germany	Luxembourg	Sweden
Belgium	Greece	Malta	Switzerland
Canada	Greenland	Netherlands	United Kingdom
Cyprus	Iceland	New Zealand	US
Denmark	Ireland	Norway	

2.4.2.2 Latin America and Caribbean

As shown in Table 2-5, for countries in Latin America and the Caribbean, the prevalence of BMI greater than 25 kg•m^{-2} is 61% for males and 62% for females. The mean BMI increased by 0.09 kg•m^{-2} per year from 23.1 kg•m^{-2} in 1975 to 26.8 kg•m^{-2} in 2016.

Table 2-5 Countries in the Latin America and Caribbean region (NCD Risk Factor Collaboration)

Latin America and Caribbean				
Antigua and Barbuda	Brazil	Ecuador	Jamaica	Saint Kitts and Nevis
Argentina	Chile	El Salvador	Mexico	Saint Lucia
Bahamas	Colombia	Grenada	Nicaragua	Saint Vincent and the Grenadines
Barbados	Costa Rica	Guatemala	Panama	Suriname
Belize	Cuba	Guyana	Paraguay	Trinidad and Tobago
Bermuda	Dominica	Haiti	Peru	Uruguay
Bolivia	Dominican Republic	Honduras	Puerto Rico	Venezuela

2.4.2.3 Central and Eastern Europe

As shown in Table 2-6, for countries in the Central and Eastern European region, the prevalence of BMI greater than 25 kg•m^{-2} is 64% for males and 56% for females. The mean BMI increased by 0.06 kg•m^{-2} per year from 24.3 kg•m^{-2} in 1975 to 26.8 kg•m^{-2} in 2016.

Table 2-6 Countries in the Central and Eastern Europe region (NCD Risk Factor Collaboration)

Central and Eastern Europe			
Albania	Czech Republic	North Macedonia	Russian
Belarus	Estonia	Moldova	Serbia
Bosnia and Herzegovina	Hungary	Montenegro	Slovakia
Bulgaria	Latvia	Poland	Slovenia
Croatia	Lithuania	Romania	Ukraine

2.4.2.4 Central Asia, Middle East and North Africa

As shown in Table 2-7, for countries in the Central Asia, Middle East and North Africa region, the prevalence of BMI greater than 25 kg•m^{-2} is 60% for males and 67% for females. The mean BMI increased by 0.09 kg•m^{-2} per year from 22.9 kg•m^{-2} in 1975 to 26.7 kg•m^{-2} in 2016.

Table 2-7 Countries in Central Asia, Middle East and North Africa region (NCD Risk Factor Collaboration)

Central Asia, Middle East and North Africa			
Algeria	Iraq	Mongolia	Tajikistan
Armenia	Jordan	Morocco	Tunisia
Azerbaijan	Kazakhstan	Palestinian Territory	Turkey
Bahrain	Kuwait	Oman	Turkmenistan
Egypt	Kyrgyzstan	Qatar	United Arab Emirates
Georgia	Lebanon	Saudi Arabia	Uzbekistan
Iran	Libya	Syria	Yemen

2.4.2.5 East and South-East Asian

As shown in Table 2-8, for countries in the East and South-East Asia region, the prevalence of BMI greater than 25 kg•m^{-2} is 33% for males and 31% for females. The mean BMI increased by 0.08 kg•m^{-2} per year from 20.6 kg•m^{-2} in 1975 to 23.9 kg•m^{-2} in 2016.

Table 2-8 Countries in the East and Southeast Asia region (NCD Risk Factor Collaboration)

East and South-East Asia			
Brunei Darussalam	Indonesia	Myanmar	Taiwan
Cambodia	Lao	North Korea	Thailand
China	Malaysia	Philippines	Timor-Leste
Hong Kong (China)	Maldives	Sri Lanka	Viet Nam

2.4.2.6 High-Income Asia–Pacific Countries

Only three countries—Japan, South Korea and Singapore—are classified as high-income by the NDC Risk Factor Collaboration. Among these nations, the prevalence of BMI greater than 25 kg•m^{-2} is 34% for males and 24% for females. The mean BMI increased by 0.05 kg•m^{-2} per year from 21.8 kg•m^{-2} in 1975 to 23.9 kg•m^{-2} in 2016.

2.4.2.7 South Asia

The prevalence of BMI greater than 25 kg•m^{-2} in South Asia is 19% for males and 24% for females. The mean BMI increased by 0.08 kg•m^{-2} per year from 18.6 kg•m^{-2} in 1975 to 21.9 kg•m^{-2} in 2016. Six nations make up this region: Afghanistan, India, Bangladesh, Nepal, Bhutan and Pakistan.

2.4.2.8 Oceania

The Oceania region consists of a variety of Polynesian, Micronesian and Melanesian countries (see Table 2-9). In this region, the prevalence of BMI greater than 25 kg•m^{-2} is 53% for males and 63% for females. The mean BMI increased by 0.1 kg•m^{-2} per year from 21.9 kg•m^{-2} in 1975 to 25.9 kg•m^{-2} in 2016.

Table 2-9 Countries in the Oceania region (NCD Risk Factor Collaboration)

	Oceania	
American Samoa	Micronesia	Solomon Islands
Cook Islands	Nauru	Tokelau
Fiji	Niue	Tonga
French Polynesia	Palau	Tuvalu
Kiribati	Papua New Guinea	Vanuatu
Marshall Islands	Samoa	

2.4.2.9 Sub-Saharan Africa

The region of Sub-Saharan Africa consists of several impoverished countries and developing nations (see Table 2-10). The prevalence of BMI greater than 25 kg•m^{-2} is 21% for males and 38% for females. The mean BMI increased by 0.08 kg•m^{-2} per year from 19.2 kg•m^{-2} in 1975 to 22.4 kg•m^{-2} in 2016.

Table 2-10 Countries in the sub-Saharan Africa region (NCD Risk Factor Collaboration)

		Sub-Saharan Africa		
Angola	Congo	Guinea	Mozambique	South Africa
Benin	Cote d'Ivoire	Guinea Bissau	Namibia	Sudan
Botswana	Djibouti	Kenya	Niger	Swaziland
Burkina Faso	DR Congo	Lesotho	Nigeria	Tanzania
Burundi	Equatorial Guinea	Liberia	Rwanda	Togo
Cabo Verde	Eritrea	Madagascar	Sao Tome and Principe	Uganda
Cameroon	Ethiopia	Malawi	Senegal	Zambia
Central African Republic	Gabon	Mali	Seychelles	Zimbabwe
Chad	The Gambia	Mauritania	Sierra Leone	
Comoros	Ghana	Mauritius	Somalia	

2.4.3 Increasing Body Mass Index and its Effects on Society

Within the anthropometrical literature, there is a growing concern for the rapid change in size facing humanity—particularly regarding weight—with much of the literature reflecting this issue (Ewing et al. 2014; Kitahara et al. 2014; Padwal 2014; Thomas et al. 2014; Via & Mechanick 2014; Wang, Y & Lim 2014). Others discuss the economic burden to society of obesity in particular (Brownell 2005; Wang et al. 2011; Ananthapavan et al. 2014; Siahpush et al. 2014; Lobstein 2015). Other applications include ergonomic design issues (Gordon & Bradtmiller 2012; Nadadur & Parkinson 2012). However, few studies have examined the effect of evolving anthropometry features on the transport industry—particularly the aviation domain. Two anthropometrical traits are primarily used to govern both the design and operation of aircraft: weight and height. Other secondary characteristics, such as waist size, leg length and BMI, may also be referenced in technical literature in relation to some ergonomic design aspects of aircraft components (e.g., seats), although their use is less common because they can be implicit to weight and height.

Weight is by far the most important anthropometric factor that can affect health. Many illnesses and disorders can be attributed to improper weight—that is, whether a person is under or overweight. The WHO (1995) discussed anthropometry as an indicator of nutritional and health status and collected anthropometrical data for selected countries. One of the main findings revealed by this study was the high prevalence of obesity among persons of Polynesian origin. Other aspects of health, such as diabetes and problems with anatomical systems like cardiovascular, have also been assessed. For example, Tanamas et al. (2014) explore waist circumference, weight and the prevalence of diabetes in Australia, while Allman-Farinelli (2011) discusses obesity and causal links to vein thromboembolism. The literature also provides insights into respiratory systems and the mechanism affected by obesity. Steier et al. (2014) investigate the lung capacity of obese persons and determines that added pressure from adipose tissues on the respiratory system make breathing increasingly difficult. Other studies conclude that obese people are more susceptible to hypoxia (Ri-Li et al. 2003; Mohr 2008; Sherpa et al. 2010; Ali et al. 2012; Hodson et al. 2013; Ichiki & Sunagawa 2014; Netzer et al. 2013; Trayhurn 2014; Goossens & Blaak 2015), which is an important safety issue in flight operations at altitudes above 12,500 feet (i.e., where commercial aeroplanes frequently operate). There is a strong emphasis in society that obesity is unhealthy, but further research is required to provide an improved understanding of the many dimensions of this disease and similar mechanisms of treatment (Atkinson 2014).

Chapter 3: Literature Review

3.1 Introduction

This chapter investigates relevant anthropometric studies and presents a holistic ‘map’ of their potential effect on commercial air travel. This study identifies several unexplored effects on aircraft design, operation and regulation. It is the first of its kind to map these effects, and it will provide a framework for future research that is relevant to aircraft engineers, airline operators and regulators. This chapter focuses on the passengers’ anthropometric relationship with aircraft and covers five areas:

- First, there is a short investigation into other transport sections and flight crews.
- Second, the passenger experience is explored with a focus on passenger anthropometry on comfort.
- Third, literature is examined that explores the effect on airline economics, such as charging airfares by weight and operational cost (fuel) relating to passenger weight.
- Fourth, safety aspects relating to passenger anthropometry aboard aircraft are explored.
- Fifth, regulatory constraints facing anthropometrical aspects within the various technical regulations and standards for design and safety are explored.

This chapter was first published in 2017 in the journal *Transport Reviews* under the title ‘Impact of biometric and anthropometric characteristics of passengers on aircraft safety and performance’, and it was assigned a journal issue in 2018.

Additional elements of this chapter have been presented in a conference paper titled ‘The changing size of the commercial aviation passenger and its potential impact on the aviation industry’ at the *7th Asia–Pacific International Symposium on Aerospace Technology* in 2015.

3.2 Other Transport Sectors—A Brief Highlight

3.2.1 Road and Commuter Rail Transports

The primary goal of any transport system is to provide people with a fast, safe and reliable service to get from point A to B. A study by Zhang et al. (2014b) explores the link between commuting and obesity and determines that there are different links between the two factors across different levels of regional urbanisation. In rail commuting, peak and off-peak travel results in commuters experiencing overcrowding—particularly on suburban commuter trains—which heightens the passengers' anxiety (Cheng 2010). As more people decide to commute into large urban areas, greater pressure is placed on rail networks to match capacity. There are many issues with overcrowded trains; however, the increasing anthropometric characteristics of the population (e.g., obesity and waist size) reduce the ability to find viable solutions to overcome this problem as a result of many constraints in the design of carriages. Further, as weight increases, the braking systems of trains rely on weight data to efficiently stop the moving train. Inversely, it is possible to determine passenger load using the built-in self-weighting system used in most modern trains to control braking (Nielsen et al. 2013).

Other land-based modes of travel can experience similar problems resulting from passengers' anthropometrical changes. For example, there are more cars on roads because people are increasingly driving instead of using public transport. Jacobson et al. (2006) describe a method for estimating passengers' excess weight based on anthropometric characteristics to determine fuel usage caused by additional weight. This represents a 0.7% annual increase in fuel since 1960 and is attributed to increased passenger weight in the US. In a later paper, Jacobson et al. (2009) explore the effect of reducing the weight of obese, overweight and extreme obese individuals on automobile fuel usage. It was determined that reducing weight could save 0.8% of fuel and 0.5% of emissions annually from the transport sector in 2005 in the US.

Further, a 0.5 kg (one pound) increase in average weight per passenger increases fuel consumption by 150.6 million litres (39.8 million gallons). Further applications of anthropometric characteristics can be made in automotive design, particularly in the area of ergonomics (Haslegrave 1980). Comfort relies on the occupant having anthropometric features that approximately align with the car seat. Fazlollahtabar (2010) and Hiamtoe et al. (2012) explore how anthropometry relates to seat comfort and the space surrounding the occupant inside the automobile. Mohamad et al. (2010) use image analysis to gather anthropometric data relating to body angles of drivers in current car seats for applications in design process.

Beyond the visible aspect of automotive travel, fuel usage and design, the literature highlights the crashworthiness of vehicles and occupants' injury levels relating to their anthropometric characteristics—particularly weight. Obese occupants in automotive accidents have a 54–61% increased risk of injury compared with non-obese individuals (Viano et al. 2008), and their body weight increases the risk of mortality from an accident (Mock et al. 2002). The added tissue around the lower torso of an obese occupant results in less chance of a pitch forward motion in an accident. However, the lack of movement may increase the injury caused by the seatbelt loading on the upper torso (Kent et al. 2010; Carter et al. 2014). Obesity in children is becoming as prevalent as it is in adults; as a result, younger children have a high risk of head and thoracic injury, and as the child enters their teenage years, the injury pattern becomes similar to that of obese adults (Haricharan et al. 2009). Studies focus not only on weight, but also highlight height as a factor in car accidents. The literature on car accidents stresses that the effectiveness of seatbelts for obese people might be compromised. Prevention of injury in accidents relies on the occupant wearing their seatbelt, and manufacturers develop seatbelts with a finite length that, in some cases, may not fit an obese car occupant. Obese passengers reduce the effectiveness of a seatbelt because there is an inherent increase in the slack in the belt and greater distance from the skeleton.

Additionally, an increase in BMI by 10 $kg \bullet m^{-2}$ increases lap belt webbing length by 130 mm (Reed et al. 2012). Not only does obesity affect adults, but a study of seatbelt usage among adolescent students determined that obese students were 1.72 times less likely to wear a seatbelt (Price et al. 2011). In addition to automotive studies, research has explored the link between logistics trucking accidents and obese truck drivers (Anderson et al. 2012) and truck driver health with a focus on obesity (Damon & McFarland 1955; Sanders 1977; Kinghorn & Bittner 1993; Sieber et al. 2014). Others have explored logistic vehicle cabs concerning anthropometric characteristics. An early study explored driver workspace in commercial vehicle cabs to highlight the need for designers to incorporate anthropometrical studies into the design process (McFarland et al. 1958). One study examined variations in dimensions between the seat, steering wheel and pedals in British buses imported into Hong Kong (Courtney & Wong 1985), while another surveyed and compared changes in truck driver anthropometry to develop a multivariate model of future cab design (Guan et al. 2012).

3.2.2 Military Flight Crew Research Featuring Anthropometry

Global military (air force) hardware is developed by only a few nations and exported to militaries across the world. The annual account of the arms industry issued by the Stockholm International Peace Research Institute (SIPRI) tabulates data from various sources, including company annual reports and articles in journals and newspapers, to determine the biggest producers of arms and military hardware around the world. According to the SIPRI, the major companies that export military hardware are located within the global superpowers. The top five manufacturers are the US (44%), Russia (9%), United Kingdom (UK) (8%), France (6%) and Japan (5%) (SIPRI 2018). Other countries, such as Germany, South Korea and India, account for 4% each, while the remaining 17% of manufactures can be found in 13 other countries around the world.

The top five nations export their products to nations around the world that have different anthropometric needs to the exporters' own markets. Instead, these manufacturers generally design their hardware for national usage and thus use anthropometric data related to that nation. For example, anthropometric studies focus on ergonomic design of the aircraft cockpit or flight crew clothing (Bolton et al. 1975; Hobbs 1972; Simpson 1974; Simpson & Bolton 1968; Meunier 2008; Lovesey 1980). In these studies, surveys of military personnel are conducted to ascertain details regarding anthropometric features. This places a distinct anthropometric focus on design that is based on the anthropometry of the manufacturing nation's military serves personal for exported military hardware. However, the designed features may not match the recipients' anthropometrical characteristics. Foreign militaries then need to spend additional funds to redevelop or design custom-made components as a result of the different anthropometrics of their military personnel. Studies that explore the differences between military personnel have highlighted the differing anthropometric characteristics among different national militaries (Lovesey 1980; Singh et al. 1995; Tomkinson et al. 2010; Blanchonette & Smith 2015).

3.2.3 Civil Flight Crew Research Featuring Anthropometry

Flight crews come in all shapes and sizes; however, there are only a handful of aircraft manufacturers around the world. These manufacturers rely on standards that might not represent the product destination market. General anthropometric considerations are taken into account when designing equipment features and interfaces in the cockpit. One important feature in the cockpit that appears in the literature and provides pilots with an ergonomic fit based on anthropometric data is the cockpit seat.

Cockpit seats are a complicated part of the cockpit and provide the pilot with support and comfort for long periods. The academic literature is limited in terms of the level and detail of cockpit seat design. However, research conducted into the ergonomic aspects has focused on anthropometric characteristics (Hawkins 1974). For example, a study to evaluate the selected seat for the Qantas fleet in relation to the comfort and anthropometric data of pilots shows that lumbar and thigh support is required, as well as full seat adjustment (Lusted et al. 1994). Similarly, Goossens et al. (2000) compare flight deck seats with biomechanical and anthropometric criteria for seat design and find that the selected seats do not meet the designed criteria. A different study develops a generic algorithm based on estimating the anthropometric data that can help seat manufacturers design seats for 90% of airline pilots (Poirson & Parkinson 2014). Seat design must take into account not only ergonomics, but also crashworthiness and survivability (van der Merwe Meintjes et al. 2004).

In addition to cockpit design, pilot health is discussed in the literature. Qiang et al. (2005) investigate the prevalence of cardiovascular disease and obesity in a cohort of pilots and determine that the prevalence mirrors that of the general population. However, the risk inherent to this pathological condition in flight crews assumes a particular relevance given the safety consequences resulting from an eventual acute episode affecting their performance. Chaturvedi et al. (2012) conduct a toxicological examination of obese pilots and find that the primary medications used are for obesity-related illnesses. Pilots are required to undertake periodic medical examinations to ensure they are fit to fly. A case study examination of the current medical certification of pilots demonstrates inconsistencies in medical specifications and regulatory requirements (Hince 2006). Most of the existing literature on cabin crew anthropometric attributes (e.g., Snow et al. 1975) is scarce and has been developed over the past few decades, so it does not necessarily accurately represent the current anthropometric nominal parameters.

3.3 Passenger Experience

3.3.1 Tourism, Discrimination and Airline Weight Policies

The tourism industry has conducted studies on the discrimination of obesity and disability conditions in relation to air passengers (primarily tourists) (Small & Harris 2012; Harris & Small 2014), concluding that current research does not account for more anthropometrically challenged people. The more the tourists’ anthropometry differs from the preconceived physical norms, the greater the disparity concerning equality and stigma placed upon these passengers. In particular, airline passengers are often exposed to discrimination as a result of their anthropometric attributes (O’Neill 2004). There has been an increase in the number of legal suits lodged by passengers against airlines as a result of weight discrimination, mainly in Canada and the US. The literature discusses the issue of discrimination and airline policy development through anecdotal evidence, legal studies and surveys (Lynch 1996; Higginbotham 2003; O'Neill 2004; Williams 2009; Mylrea 2009; Harris & Small 2009). Consequently, obesity is now considered a form of disability under certain travel regulations. Overweight passengers may experience significant distress when boarding an aircraft or purchasing an extra seat at the airport. In Canada, the 'One Passenger, One Fare' policy (Williams 2009) allows larger passengers to purchase two seats for the price of one.

Airlines and the tourism industry are at the forefront when it comes to dealing with passengers' anthropometrical changes. Despite this, many global airlines still do not have a clearly defined excessive passenger weight (size) policy (Bolton 2004). Nevertheless, stricter policies have been introduced on US airlines. The major airlines (Alaskan, American, Delta, Southwest, United and Spirit) commonly state that if the passenger cannot sit comfortably, encroaches on the adjacent seat or requires a seatbelt extension, they are required to purchase an extra ticket (Hewitt & Schlichter 2017). Airlines will often refund passengers if the flight is not full. Further, larger passengers have the option of purchasing a premium class ticket, where the seats are larger than those in economy (Howe 2012b). The issue has been further aggravated because airlines are slowly reducing seat pitch and width to enable higher capacity in the economy cabin.

3.3.2 Passenger Comfort

Cabin facilities and the environment play a major role in determining passenger comfort. Literature shows that passengers experience comfort through anthropometric, physiological and psychological elements from their past flight experience (Ahmadpour, Lindgaard, Robert & Pownall 2014; Kremser, Guenzkofer, Sedlmeier, Sabbah & Bengler 2012). These elements have been explored by qualitative measures of crew service, in-flight amenities, cabin lighting/temperature, noise levels, odour and vibration (Greghi, Rossi, de Souza & Menegon 2013; Vink & Van Mastrigt 2011; Vink, Bazley, Kamp & Blok 2012; Patel & D'Cruz 2017). A common denominator in the literature highlights how personal space plays a major role in perceived comfort. Legroom and other anthropometrical aspects of seat and cabin design can enhance passengers' comfort or discomfort, particularly in long-haul flights. The literature and media show that seat pitch has decreased from an average of 88.9 cm (35 in) in the 1970s to a current average of 76.2 cm (30 in). Recently, the media drew attention to a bipartisan bill introduced in 2017 by US senators to set minimum seat pitch standards (Vasel 2017). Further, in July 2017, the US Federal Court issued a ruling to the Federal Aviation Administration (FAA) to develop minimum seat pitch standards (Levin 2017; Wattles 2017). To date, only exit rows have a mandated seat pitch, primarily to ensure safe egress in emergency situations. The Human Factor and Ergonomics Society (HFES) introduced a policy statement in 2019 in regards to airline seats. They recommended that the FAA should update the existing standards to account for widespread anthropometrical composition of the average passenger. According with the HFES recommendations, the seat widths and seat belts standards should be revised to accommodate 95 percent of the general population. This requirement is also extended to the minimum seat pitch which should be no less than 38.5 inch to accommodate 95 percent of the general population. Additionally, 3 or 4-point restraints should be provided, as it is done in some aircraft for premium cabin configurations. The FAA guidelines should also specify the inclusion of foot rests and adjustable lumbar supports to reduce neck and back strains and injuries, as well as to improve passenger comfort (HFES 2019).

3.3.3 Passenger Mobility

Free-flowing movement in the aircraft cabin is important for safety and efficient passenger boarding. Research has been conducted into the biomechanics of able-bodied passengers (Jurum-Kipke, Baksa & Kavran 2012) and the effect of age differences of passengers entering and exiting seat rows (Lijmbach, Miehlke & Vink 2014). However, passengers with reduced mobility (PRM)—that is, impaired, disabled and requiring additional aid—are receiving increasing attention in the transport sector (Veldhuis & Holt 2012a). Studies demonstrating differences in passenger requirements for comfort (Chang & Chen 2012; Ancell & Graham 2016) can be used to inform key stakeholders of this need. Wide-bodied aircraft are typically more accessible for PRM and larger-framed passengers because aisles are wider. Conversely, regional and commuter aircraft tend to have narrower aisles and shorter seat pitches, which results in a mobility problem.

Boarding PRM presents challenges for airline ground staff because specialised equipment may be required to uplift/downlift these passengers to the aircraft. Similarly, challenges arise when PRM require the use of the lavatory (Philbrick & Pavol 2008; Grant 2013). Fadul, Brown and Powell-Cope (2014) conduct a comprehensive review and find that no studies have investigated airline policy or standardised methods in relation to this issue. In an emergency, PRM have been found to understand and perform safety instructions differently than the norm, thus presenting higher risks than able-bodied passengers (Chang 2012). Mobility in the cabin is important to passengers' safety and wellbeing throughout the flight. If current trends in anthropometry continue—especially obesity trends—airlines will be dealing with PRM more frequently, which will place increasing pressure on operations and safety for all stakeholders.

3.3.4 Air Travel and Health

Medical issues associated with commercial air travel (DeHart 2003; Silverman & Gendreau 2009) include deep vein thromboembolism (DVT), hypoxia, circadian dysrhythmia (jet lag) and effects of pre-existing medical conditions at high altitude. However, there is limited literature linking the anthropometry of airline passengers with these health issues, and the closest related literature focuses on the transport of overweight and obese medical patients (Crandall, Gardner & Braude 2009; Polikoff & Giuliano 2013; Ali, Smith, Gulati & Shneerson 2014). Most studies that explore long-haul flights show that passengers have greater susceptibility to DVT compared with passengers on short-haul flights. Further, overweight individuals have a higher risk of developing DVT compared with those within the normal weight range who fly on long-haul flights (Philbrick et al. 2007; Gavish & Brenner 2011; MacCallum et al. 2011; Cannegieter 2012; Schellack et al. 2013). Therefore, larger passengers may be more vulnerable to adverse effects in an aircraft cabin environment. The HFES recommends that when updating seat dimension standards, the FAA should take into consideration possible adverse health effects of airline seats and review whether larger seating spaces should be mandated for long-duration flights (HFES 2019).

3.3.5 Knowledge Gap and Future Challenges

Although research into passenger experience has been explored previously, a broader examination is needed of the influence of biometrics—in particular, anthropometry—on the aviation sector. Figure 3-1 highlights various facets of passenger experience that have a direct link to biometrics.

Recent studies of the cabin environment have not considered some environmental aspects that might be influenced by passengers' anthropometry, notably oxygen levels and passengers' respiratory exhalations. Changes in metabolic rate—particularly thermal and respiratory waste—may differ based on a person's anthropometry (Savastano, Gorbach, Eden, Brady, Reynolds & Yanovski 2009; Alvarez, Singh & Sinha 2013). Respiratory waste introduces added humidity and carbon dioxide in the cabin environment, and these factors could impose an extra loading on the aircraft's environmental systems, which could then underperform and lead to an uncomfortable experience for all passengers. Tall or small passengers may find difficulties with the interface between the passenger and the ventilation console located above their seat in the overhead bin compartment. A tall passenger may have to crouch or bend over to egress, while a smaller passenger may need to strain their arms to reach the console.

Similarly, the design of cabin amenities may influence overall aircraft passenger comfort. These amenities include apparel provided in premium classes, seat vanity console, lavatories and other features in the cabin. Cabin amenities that rely on anthropometrical parameters are typically presented as a side note in research and discussions relating to passenger experience and comfort. Further research is needed to explore the options available to enhance the comfort of passengers regardless of their physical attributes, as well as the associated costs for airlines. Despite the significant gap in this area, some recent initiatives have contributed to improving the experience of obese passengers. For example, in 2015, seat manufacturer SII Deutschland developed the SANTO seat (Special Accommodation Needs for Toddlers and Overweight Passengers), which won an award at the Crystal Cabin Awards in Hamburg, Germany (Pemberton 2015).

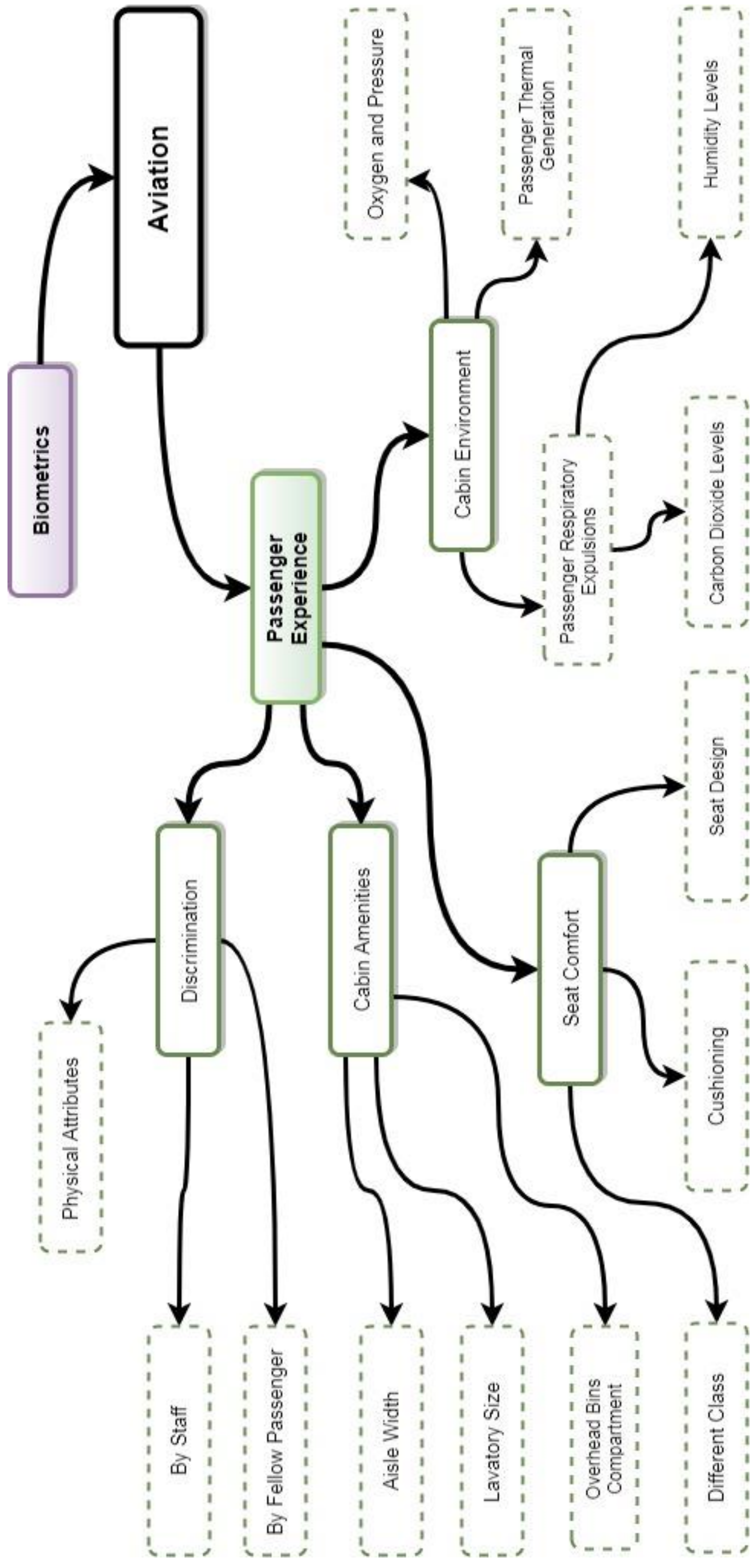


Figure 3-1 Different aspects of passengers' experience affected by biometrics and anthropometry

3.4 Airline Economics

3.4.1 Weight-based Airfares

Airlines charge passengers for excess baggage, but recently, charging passengers by weight has received interest from some operators, such as Samoa Air (Reese 2013). Bresler (2012) highlights the potential disparity of airfares for a person of average weight who pays extra for excess baggage compared with an overweight/obese passenger who has the correct baggage weight allowance and pays the same airfare. This difference may result in a perceived inequality of weight for airfare price. The Pay-As-You-Weigh (PAYW) airfare proposed by Bhatta is based on the combined weight of the passenger and their luggage (Bhatta 2012, 2013). Bhatta proposes three airfare structures and discusses the strengths and weaknesses of each one:

- fares calculated by total weight (including baggage)
- base fare with additional charges determined according to passenger’s weight
- group fares—that is, fare based on a weight range with limits.

These proposed airfare types must be fair and economically sustainable for the benefit of both passengers and airlines. Additionally, the main concern identified by Bhatta with the PAYW model is potential discrimination towards heavier passengers by fellow passengers, which may result in those individuals electing not to fly (Bhatta et al. 2014). Concepts like PAYW that involve sensitive issues such as obesity have generated significant discussions in the media. A follow-up survey of the PAYW model finds neither agreement nor disagreement with the concept among the surveyed media reports. The media has placed PAYW into a negative position based on the argument that passengers should not be discriminated against based on their weight (Bhatta et al. 2014). Conversely, the study notes that the concept would have societal benefits as both an incentive for air travellers to lose weight and for airlines to improve aircraft safety and performance (e.g., shorter egress times and less fuel consumption) through weight-based policies.

3.4.2 Cost of Fuel and Passenger Weight

The relationship between fuel and passenger weight is one factor considered in aircraft performance. Dannenberg et al. (2004) and Howe (2012a, 2012c) briefly highlight the relationship between excess airline passenger weight and fuel, while Tom et al. (2014) analyse the same relationship (1970–2010) as part of a broader examination of the US domestic transport system. Their study estimates that 95.2 billion litres of extra fuel is required as a result of excess passenger weight, which consequently adds 238 million metric tonnes of additional carbon dioxide (CO_2) equivalent emissions. Melis et al. (2017) estimate that the Australian domestic commercial aviation sector used 561 kilotonnes of fuel between 1990 and 2014 to transport 15.8 tonnes of excess weight of passengers at a cost of A$411.7 million. Further, 1.7 million tonnes of equivalent CO_2 was released into the atmosphere. Yin et al. (2015) compare fuel burnt and CO_2 emissions using an estimated passenger weight of 85 kg for their calculations. The preceding literature review highlights that only some areas, such as fuel usage, emissions and airfares, are directly affected by passenger anthropometries.

3.4.3 Knowledge Gap and Future Challenges

The airline business is particularly volatile and requires careful balancing of expenditure and revenue. However, other economic factors may eventuate as the ancillary cause as a result of changes in passengers' anthropometry (see Figure 3-2). Specifically, the sub-dimensions whereby biometrics may affect airline economics are environment, efficiency, performance and revenue/expenditure. This is not an exhaustive list; other aspects of aircraft and airline performance may be affected by changes in passenger anthropometry and therefore affect airline economics.

Economic aspects that affect revenue and expenditure have not been explored in the literature, and other indirect costs have been overlooked, such as gate delays and seat wear and tear resulting from overweight passengers. Components that are directly exposed to the overloading imposed by heavier passengers (e.g., flooring panels and seat frames, aircraft systems such as the air-conditioning, and lavatory/waste systems) may require more frequent maintenance.

Efficient performance and operational procedures have obvious financial benefits for airlines, but having aircraft on the ground or at the gate costs significant money. Studies have explored the various methods that airlines can use to board and disembark passengers in an attempt to optimise these processes and minimise gate times. However, none of these studies have incorporated biometric parameters that can potentially affect the flow and speed of boarding and disembarking an aircraft, such as a passenger's waistline and weight. As the prevalence of obesity increases and airlines squeeze cabin space for increased capacity, a question is raised about the effect on the ideal boarding/disembarking time of 15–30 minutes (Nyquist et al. 2008).

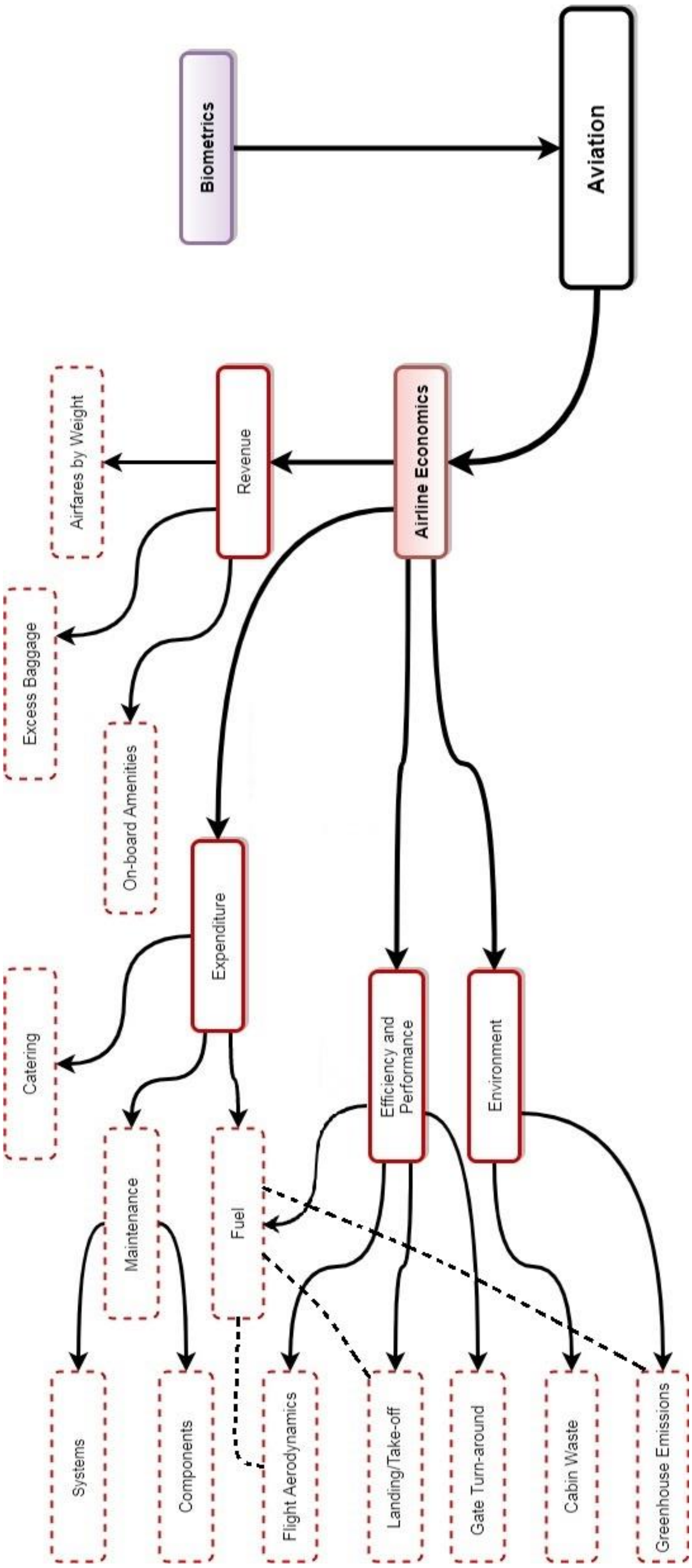


Figure 3-2 Airline economics, biometrics and anthropometry characteristics of passengers

Anthropometric changes may significantly affect the weight-dependent efficiency and performance characteristics of smaller commuter aircraft (e.g., centre of gravity shifts, take-off/landing field lengths, induced drag and fuel consumption). In particular, additional weight imposed by passengers may lead to more frequent maintenance of certain components as well as extra fuel consumption, thereby resulting in increased costs to airlines.

3.5 Safety Aspects

3.5.1 Component Design

The Human Factors and Ergonomics Society (HFES) have highlighted concerns that current trends in passenger anthropometry have not been reflected in current seat design standards. The HFES notes that 97.6% of males and 50% of females in the US have a shoulder width that surpasses the suggested 17.7 in for seat width (HFES 2019). The HFES recommendation is to update the seat standards to account for widespread physical changes of the average passenger. This should reflect requiring seat widths and seat belts that accommodate 95 percent of the general population. Broader shoulders and wider waists lead to encroachment on adjacent seats and create discomfort and possible injury to neighbouring passengers. Quigley et al. (2001) explore the anthropometrical aspects of seat design to develop minimum safety design criteria. They use a survey to elicit the passenger comfort and design importance of seat features in relation to participants' particular body shapes. For seat design, the study recommends using the 1st and 99th percentiles of a population instead of the existing 5th percentile of Asian females and 95th percentile of European males. Nadadur and Parkinson (2009) introduce a method that uses anthropometrical parameters for optimal safety and comfort with cabin seating design. A later paper highlights the potential role of anthropometry in design for sustainability (Nadadur & Parkinson 2012). Newer sleek seat design concepts may require further examination for anthropometrical-based safety and design requirements. Various concepts mentioned by Collins (2015) have not been examined in the literature.

Bhonge et al. (2012) address the structural integrity of an aircraft seat using larger passengers in the 95th percentile body frame of 102 kg (225 lb) compared with the standard weight used for certification purposes—that is, passengers in the 50th percentile of body frames of 77 kg (170 lbs). By using experimental testing and finite element analysis, the authors concluded that seat loads for the 95th percentile body frame have increased between 20% and 30% over standard 50th percentile crashworthiness validation methods. The study notes that further research is needed to explore the effects of larger passengers and seat crashworthiness. Singh and Wereley (2014) examine the effect of exposure of helicopter occupants using a bio-dynamical model based on the 50th percentile of male anthropometry, but they do not extend to other scenarios considering larger passengers. The study of cabin safety features such as size and location of emergency exits has also been explored without considering passengers' anthropometric characteristics (Muir & Thomas 2004; Hsu & Liu 2012). Overweight human manikins that represent passengers' anthropometry more realistically have been incorporated in some computational design studies (Berthelot & Bastien 2009; Park, Park & Kim 2014). Walton (2016) highlights the importance of adopting new and improved test dummies for certification tests of aircraft seats to reflect a wider range of real-life body shapes and sizes of passengers, thereby allowing better correspondence to real operational scenarios.

Other studies have addressed ramifications for the design of other aircraft components, namely lavatories. These facilities are designed to be compact for installation in aircraft, with a typical floor area of approximately 1 m^2. For this reason, anthropometrically challenged passengers may experience difficulty entering and exiting the cubical, and they may require assistance. Grant (2013) addresses this problem by suggesting the adoption of an inclusive design approach to account for PRM by implementing small changes in the layout of components to improve mobility. This benefits the passengers and acts to differentiate airlines from their competitors.

3.5.2 Emergency Equipment, Ingress and Egress

Transport aircraft include emergency systems that might be affected by passengers' anthropometrical parameters, such as slide rafts and life vests for ditching, and masks and oxygen canisters used during emergency decompression. Literature that investigates aircraft emergency system equipment is limited to aviation regulators' studies based on their own certification requirements.

Aircraft boarding, disembarking and emergency egress are key components of cabin safety. Thus, it is important to accommodate passengers' different anthropometric characteristics when designing aisles and cabin layouts. The average weight of passengers has been trending upwards over the last half century, and it should be explored whether the current 90-second limit for passenger evacuation of commercial aircraft is still realistic (FAA n.d.). 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. However, changing passenger anthropometrics and the effect of passenger mobility during egress appears to be of little concern in the regulations. Further, research is mainly conducted on ingress/egress flow, boarding methods and passenger behaviour, and it does not explore or highlight passenger anthropometry (Muir et al. 1996; Martínez-Val & Hedo 2000; Nyquist & McFadden 2008; Steffen 2008; Chang & Yang 2011; Steffen & Hotchkiss 2012; Du, Zhang & Yang 2014; Shi & Mou 2014). Additionally, egress studies that examine 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, Filippidis, Wang & Ewer 2010).

Liu, Wang, Huang, Li and Yang (2014) develop a simulation model that incorporates anthropometrical and behavioural characteristics of airline passengers such as waist size, age, gender, disability, amount of legroom and group motivations. Liu et al. (2014) note that variations in physical characteristics—particularly waist size and age of passengers—could have a considerable effect on the variance of evacuation times produced by simulations.

Different studies recommend variations of the brace position in an aircraft crash landing, such as having the feet in front of the knees (Sperber et al. 2010) or behind the knees (Brownson, Wallace & Anton 1998). The brace position and seatbelt work collectively to protect passengers from impact risks. An automotive study finds that overweight passengers need longer seatbelts and that obese passengers have a greater risk of injury (Reed, Ebert-Hamilton & Rupp 2012). The study highlights that the added belt length effectively introduces slack because the belt is routed further away from the skeleton and the lap belt is fitted high and away from the pelvis. This risk is further elevated in an aircraft because airline seatbelts do not have an upper torso component to restrict movement.

3.5.3 Passengers’ Anthropometry and Accidents and Incidents

There is limited research on the correlation between a passenger’s anthropometry and their survivability in an accident. Investigative reports and recommendations made by aviation accident investigation authorities are often concentrated on operational and structural design features. A key development in cabin safety that addresses the design of aisles, seats and cabin dividers was the accident involving British Airtours Flight 28M (AAIB 1988), which caught fire during take-off and resulted in 55 fatalities because of smoke and the inability of passengers to egress the aircraft. As a result of the accident, regulations governing the aisle, emergency exits and cabin materials were changed to allow greater access for passenger waist and hips to move down the aisle with ease.

Although cabin design will help in emergency situations and save lives, occasionally there are occurrences affected directly by the payload. Van Es (2007) surveys occurrences relating to weight and balance issues of aircraft and notes that 1.9% of passenger flights had incorrect payload information. For example, between 2000 and 2015, there were 25 occurrences in Australia involving unaccounted or additional passengers not added to load manifests or notified to the crew (ATSB 2000–2015). A recent study by Boyd (2016) explores accidents in the US general aviation sector caused by exceeding the centre of gravity limits in which the prevalence of obesity was stated as a probable cause. The study does not substantiate this relationship unequivocally but notes that there is potential for passengers to underestimate their true weight when reporting to the pilot for aircraft with fewer than five seats in the US (FAA 2005) or seven seats in Australia (CASA 1990).

When aircraft weight and balance are close to acceptable limits, any errors introduced by underestimating passengers' weight may result in increased operational risks and potential incidents or accidents. Shifts in centre of gravity can be affected by significant changes in passenger weight, particularly for smaller commuter aircraft. For example, passenger weight accounts for approximately 22% of the total weight of a 10-seat commuter aircraft compared with only 9% for a Boeing 747 (Berdowski et al. 2009). Although commercial airlines can manage aircraft balance by moving correctly weighed freight and fuel inside the aircraft, the difficulties of weighing each passenger before each flight constitute a potential source of inaccuracy for balance distribution. Incorrect standardised weight calculations contributed to the loss of pitch control that resulted in the crash of Air Midwest Flight 5481 in the US (National Transport Safety Board [NTSB] 2004). Although the main cause of this accident was a poorly maintained elevator cable, the accident highlighted the issues around the weight and balance of aircraft and passenger weight standards. The FAA standard passenger weight of 84 kg was used in this case, and the analysis showed that this was well below the actual weight of the passenger payload. Similarly, operation failures resulting in undocumented aircraft loading of passengers and baggage led to the crash of UTAG Flight 141 in Benin (BEA 2003), which encountered a nose-heavy situation while rotating. As a result, more stringent loading procedures were adopted by the airline and the aviation sector in Benin. These studies demonstrate how anthropometry can play an indirect role in the survival of passengers during air accidents in relation to the cabin design. Similarly, passenger weight change can be a contributing factor to accidents and should be regarded as a key parameter in the safe operation of aircraft, particularly in relation to aircraft weight and balance.

3.5.4 Knowledge Gap and Future Challenges

Safety has always been the highest priority of all stakeholders in the aviation industry. However, as demonstrated in the previous sections, limited research has sought to establish the relationship between biometrical changes (primarily anthropometry) in airline passengers and safety. Figure 3-3 illustrates the safety dimensions that might be influenced by passengers' biometrical changes such as crashworthiness, cabin safety, emergency equipment, and weight and balance.

To date, little emphasis has been placed on those components that have a direct interaction with passengers and the cabin environment; for example, the effects of cabin motion on passengers' standing (i.e., walking down the aisle) during aircraft motion, such as a steep bank or sudden turbulence that might result in significant structural loading on certain cabin components due to passengers being overweight. Further, the effectiveness of the brace position on passengers that cannot reach the front seat because of the size of their body requires further study.

The escalating prevalence of obesity may increase in-flight medical emergencies, thereby placing a strain on the medical kits on board and requiring crew training in first aid as well as the lifting and moving of larger passengers. Recent literature does not explore the effects of changes to anthropometry on emergency equipment such as slides, rafts, life vests, passenger oxygen masks and the consumption rates of emergency oxygen canisters. Current airline practice is to provide an extension seatbelt for larger passengers, but no studies have explored the safety implications of such procedures—in particular, whether belt extensions are effective in restraining overweight passengers under high acceleration conditions resulting from impacts or severe turbulence.

Crashworthiness of the components highlighted in Figure 3-3 has not been thoroughly explored in the literature in relation to changes in anthropometry. For the improvement of future designs, it is important to understand the effects of components that fail (i.e., floor structure and seats) during an accident or incident as a result of extra weight. Newer seat design concepts, such as those highlighted by Veldhuis and Holt (2012b) and Collins (2015), involve different seating arrangments. Vertical seating, in which passengers are nearly standing, has been suggested by some low-cost airlines (e.g., Ryanair and Vivacolombia) as a way to increase capacity. Staggered seating arrangements proposed by Molon Labe Designs and Thompson Aero Seating can increase passenger privacy and perceived cabin space, as well as improve access to windows. Although these alternative seating configurations offer obvious financial advantages to airlines in terms of increased passenger capacity, special attention should be given to ergonomic and safety implications—in particular, whether these configurations can accommodate larger passengers.

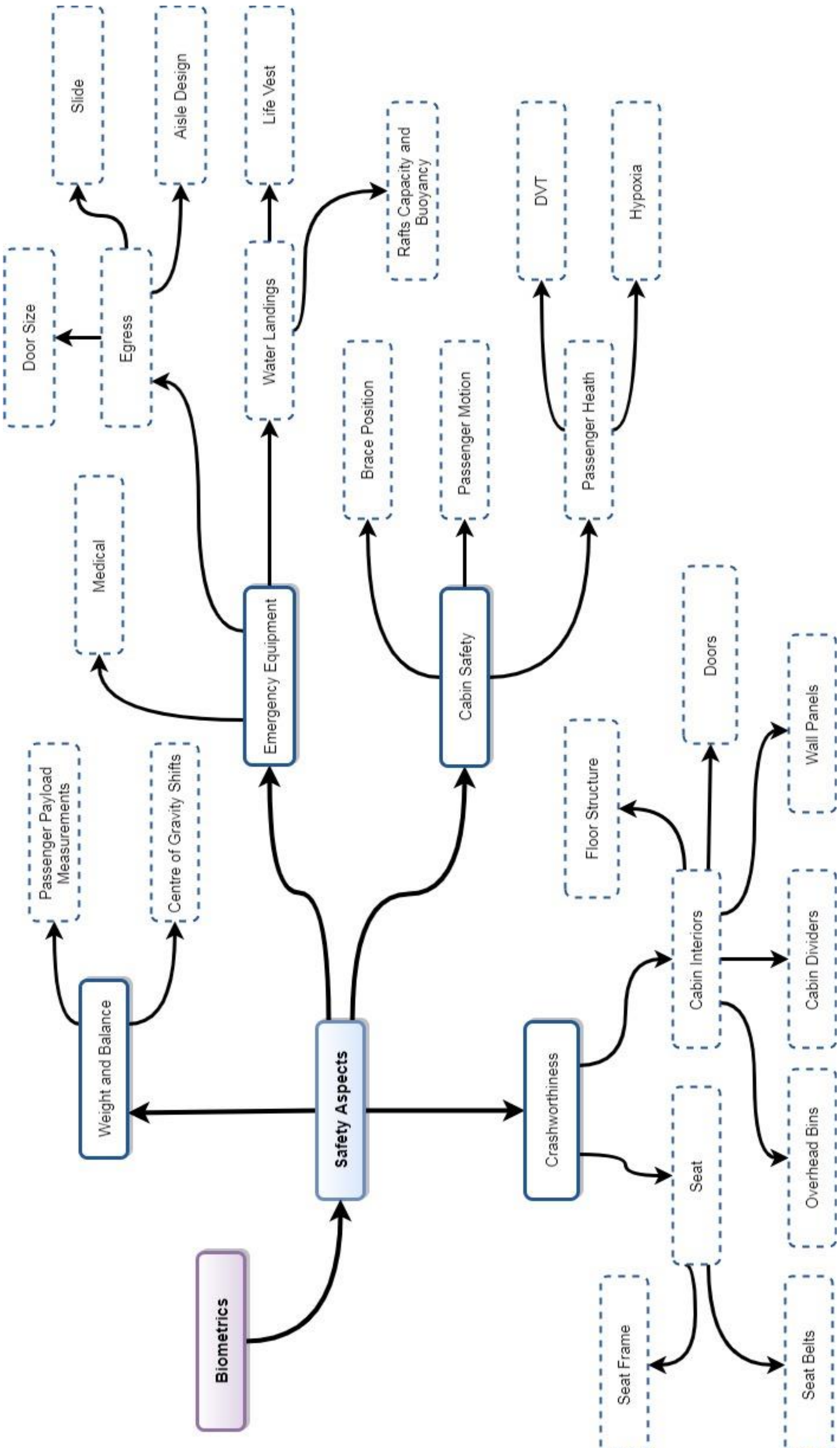


Figure 3-3 Safety aspects affected by biometrics and anthropometry of passengers

The literature on modelling emergency evacuations has not taken into account passengers' anthropometrical features. Conducting real-life simulated aircraft evacuations is costly and presents a risk of injury to participants. Thus, there is a growing trend towards the use of computer modelling and simulation of passenger evacuation. A simulation approach has the benefit of being able to explore the effect of various physical characteristics and behaviours, as well as cabin environments, on egress (Read 2016).

3.6 Regulatory Requirements

Typically, aviation regulations seek to ensure that safety is embedded within all aspects of the aviation industry. Regulatory requirements around the world generally use the FAA's CFR14 Part 25-Airworthiness Standards: Transport Category Airplanes. Regulations issued by the European Aviation Safety Authority (EASA) and the Civil Aviation Authority United Kingdom (CAA UK) follow the same framework but often deviate from the FAA's statutes to better adapt to local needs. These regulatory requirements are often updated based on studies and research conducted by, or on behalf of, the regulator. For example, the NTSB (2000) conducted a study on the certification, equipment, airline training and communication of emergency evacuations by surveying accidents that required evacuations, resulting in a recommendation to increase the dimensions of overwing emergency exits and exit rows for better mobility of passengers.

3.6.1 Cabin Layout and Environment

The minimum dynamic conditions that passengers may experience during an emergency landing are outlined by FAA CFR14 §25.562(b), whereas §25.787(f) discusses the inertial loads placed on passenger seats. In both certification requirements, seat tests must be conducted with an occupant simulated by a 77.1 kg (170 lb) anthropomorphic test dummy.

Regulation §25.817 states that an aeroplane that has one aisle must have a maximum of three seats on either side of the aisle. Thus, a six-abreast seating arrangement is the maximum for a single-aisle aircraft (FAA n.d.). Most commuter aircraft, such as the Embraer and Bombardier fleet, have four abreast, while some aircraft have five abreast (e.g., Sukoi Super-Jet 100) or three abreast (e.g., Embraer ERJ-145). Cabin aisle widths are outlined by §25.818. The passenger aisle width at any point between the seats must equal or exceed the values in Table 3-1. Further, an aircraft may have a narrower width not less than 22.86 cm (9 in) that must be approved when substantiated by tests found necessary by the regulator (FAA n.d.). There are two widths of measure: a narrower width measured either above or below 63.5 cm (25 in) from the floor level. The waist of most people would be approximately situated at that height off the floor level. At that height, a person needs to traverse the aisle with a minimum width of 38.1 cm (15 in).

Table 3-1 Minimum aisle width for an aircraft with various passenger capacities (FAA n.d.)

Passenger seating capacity	Minimum passenger aisle width (inches)	
	Less than 25 inches from floor	25 inch and more from floor
10 or less	12	15
11–19	12	20
20 or more	15	20

Cabins are environmentally controlled; specifically, ventilation, temperature, humidity and explicitly pressure are controlled to ensure passenger comfort at high altitudes. Regulations §25.831 and §25.841 outline the ventilation and pressurisation requirements (FAA n.d.). An aircraft is required to maintain a carbon dioxide level that does not exceed 0.5% of volume (sea level equivalent) in passenger or crew compartments. Similarly, carbon monoxide concentrations must not exceed 1 in 200,000 parts. Cabin air pressure must be maintained at 8,000 ft equivalent pressure to ensure passengers' comfort. Newer aircraft such as the Airbus A350 and Boeing 787 maintain a higher pressure. Any failure in the pressurisation system will lead to passengers and crew experiencing hypoxic conditions. Regulators offer generalised requirements to ensure that environmental systems can handle passengers' metabolic factors in relation to susceptibility to hypoxia, tolerances to carbon dioxide and monoxide levels and ability to withstand low oxygenated environments. These factors vary among individuals based on their anthropometric characteristics.

3.6.2 Emergency Equipment

Aircraft are required to carry various types of equipment for use in emergencies. These items can be used in aircraft operational performance-related situations or by passenger emergency operations. These provisions can be found in FAA CFR14 Part 25 and the FAA Technical Standard Orders. These regulations and standards might require amendments to reflect current biometric and anthropometric trends. Manufacturers of safety equipment are required to demonstrate that their products meet these standards. For example, life jackets must have a buoyancy rating for an adult person over 40 kg (FAA 1992). Slide-rafts are tested to an evacuation rate of 70 evacuees per minute. When used as a raft, a rated capacity of 3.6 ft^2 (0.334 m^2) per person is used as the minimum area available for evacuees (FAA 1999).

3.6.3 Emergency Evacuations

FAA CFR14, §25.803 for emergency evacuation of transport aircraft (FAA n.d.) states that:

> "(a) Each crew and passenger area must have emergency means to allow rapid evacuation in crash landings, with the landing gear extended as well as with the landing gear retracted, considering the possibility of the airplane being on fire.
>
> (c) For airplanes having a seating capacity of more than 44 passengers, it must be shown that the maximum seating capacity, including the number of crewmembers required by the operating rules for which certification is requested, can be evacuated from the airplane to the ground under simulated emergency conditions within 90 seconds. Compliance with this requirement must be shown by actual demonstration using the test criteria outlined in appendix J of this part unless the Administrator finds that a combination of analysis and testing will provide data equivalent to that which would be obtained by actual demonstration."

Originally, airlines were obliged to conduct crew training for the evacuation of large aircraft by conducting trials with volunteers with a 120 s evacuation time target. The time limitation for the experiment was related to the specific time of the breaking up and propagation of fires and toxic gases. However, aviation authorities realised that the same experiment should be performed by manufacturers each time a new aircraft was designed and that the time target should be shortened because the initial value was too generous and not on the safe side. Successive amendments to the regulations explored evacuation emergency exits, flame retardant materials in seats and cabin furniture, improvements in escape means and a better definition of the evacuation trial.

FAA CFR14, Appendix J of Part 25 describes the requirements for demonstrating emergency egress for certification (FAA n.d.). The following illustrates the demographic make-up of the test subjects:

> (h) A representative passenger load of persons in normal health must be used as follows:
>
> (1) At least 40 percent of the passenger load must be female.

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

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

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

The FAA also requires that the evacuation be carried out in darkness and only use half the exits and that before the start of the demonstration, approximately half of the total average amount of carry-on baggage, blankets, pillows and other similar articles should create minor obstructions. However, age and gender composition are specified in the FAA regulations, and other anthropometric factors are neglected (e.g., waist size). HFES recommends that the FAA policy on emergency evacuations should also include consideration for variation in waist size in addition to age and gender. Approximately 19% of males and 5% of females in the US have a waist circumference greater than 41 inches (HFES 2019).

Table 3-2 Changes to FAA evacuation regulations since 1965 (Hedo et al. 2019)

Effective Date	Regulation Amendment
3/03/1965	Amendment 121-2 required all transport-category aircraft operators to conduct demonstrations, to be completed in less than 120 s, for all previously built and new aircraft.
24/10/1967	Amendment 25-15 required manufacturers to conduct a 90-second demonstration and required that aircraft be equipped with automatically deployed egress assist devices. Amendment 121-30 revised the operators' demonstration time limit from 120 seconds to 90 seconds and required retrofit of automatically deployed egress assist devices.
1/12/1978	Amendments 25-46 and 121-149 revised requirements to permit manufacturers and operators to demonstrate compliance with evacuation certification requirements concurrently.
18/01/1982	Amendment 121-176 required if an aircraft is certified to FAR 25.803 per Amendment 25-46, the airline operator to demonstrate crew proficiency by showing that crew members can open half the exits and achieve usable slides within 15 s.
20/08/1990	Amendment 25-72, placed the demonstration conditions previously listed in §25.803(c) into a new Appendix J to part 25 and amended them for consistency with part 121.
27/09/1993	Amendment 25–79 revised the age/gender mix of passengers for performing an emergency evacuation demonstration and allowed the use of stands/ramps for overwing evacuation. Amendment 121–233, revised §121.291 to allow demonstrations in compliance with §25.803 to satisfy the requirements of §121.291.
9/12/1996	Amendment 25-88 redefined and completed emergency exit types and assist means.
29/07/1997	Amendment 25-91 included: asymmetry, uniformity, and location requirements for exits.
25/03/1998	Amendment 25-94 reintroduced the maximum distance between exits of 60 foot and requirements for flight deck emergency exits.
2/06/2004	Amendment 25-114 included more stringent erection times for escape slides and requirements for passageways acceding type III exits.
12/2004	Amendment 25-117 included the requirement of viewing the exterior of each exit and a means to retain the exit open.

3.6.4 Doors and Emergency Exits

A vital feature of the aircraft egress system is the doors—the number and location of which vary depending on the aircraft type. Table 3-3 shows the various types of doors used on aircraft. According to FAA CFR14 §25.807 and EASA CS-§25.807, there are nine exit types of different sizes and shapes (FAA n.d.; EASA 2013). Additionally, a series of FAA studies examine the relationship between different aircraft door exit types and the egress of passengers (McLean & Corbett 2004; McLean et al. 2002; McLean & Wayda 2001). In particular, McLean and George (1995) explore the effects of individual characteristics on egress time from a Type-III overwing exit. They find that weight and waist size significantly increase egress time. There is a half-second increase for a person who weighs 170 kg compared with a person who weighs 60 kg. Similarly, there is a one-second increase for a person with a waist size of 121 cm compared with a person with a waist size of 73 cm.

Table 3-3 Aircraft door types and their characteristics (FAA n.d.)

Type	Width and Height (in)	Maximum number of seats per door	Note
Type I	24x48	45	Corner radii ≤8 in
Type II	20x44	40	Corner radii ≤7 in; over wing step-up inside ≤10 in, step-down outside ≤17 in
Type III	20x36	35	Corner radii ≤7 in; step-up inside ≤20 in, over wing step-down outside ≤27 in
Type IV	19x26	9	Corner radii ≤6.3; over wing step-up inside ≤29 in, step-down outside ≤36 in
Ventral		Type 3 +12	Location Exit flow rate of Type 1 exit
Tailcone	≥20x60 Type III	+25 +15	Exit through aft pressure shell (e.g. DC-9, MD-80, B717)
Type A	42x72	110	Corner radii ≤7
Type B	32x72	75	Corner radii ≤6
Type C	30x48	55	Corner radii ≤10

3.6.5 Passenger Weight Standards

The payload location relative to the aircraft's centre of gravity is a crucial factor in determining its stability characteristics and other flight parameters. General, aviation aircraft pilots usually use the accurate weights of their passengers for weight and balance purposes. However, for large transport category aircraft, weighing individual passengers is considered impractical. As of 2009, the International Civil Aviation Organisation's (ICAO) standard for calculating the average weight for passengers is 100 kg per passenger, including 20 kg for baggage (ICAO 2009). This standard was derived from 28 global airlines responding to a brief survey conducted by the International Air Transport Association at the request of ICAO.

Aviation regulators tend to differentiate standardised weight for different aircraft capacities segmented by gender and, in some instances, a children’s category. Some regulators have different passenger weight schedules for winter versus summer and chartered versus scheduled flights. It is presumed that passengers weigh more during winter as a result of seasonal weight gain or wearing additional clothing. Charter flight operators assume that their passengers are lighter typically because they are travelling to warmer holiday destinations with lighter clothing. Occasionally, weight standards may indicate whether clothing or hand luggage is included. The standard weight adopted by different regulators worldwide ranges from 70 kg to 88 kg. This range shows that standard weights can be inconsistently applied by different operators, thereby raising uncertainties around their accuracy. Additionally, the regulations do not indicate when the last update was made to incorporate any eventual changes in standard passengers’ weight, thus making it difficult to determine whether they match current anthropometry trends.

The main problem with current weight standards is that passenger anthropometry is changing and standards are becoming outdated. Berdowski et al. (2009) conducted a study commissioned by the EASA to update passenger weight standards in Europe based on a thorough survey of airline passengers at various European airports. The findings resulted in the revised recommended weights of 94 kg for adult males and 74 kg for adult females, or 88 kg for adults at a 70:30 male-to-female ratio. These figures reveal a marked increase in existing standard passenger weights of 88 kg for adult males and 70 kg for adult females for aircraft with more than 20 passenger seats (JAA 2007; CAA UK 2006). An earlier standard weight study by the Civil Aviation Authority of New Zealand demonstrates there was a weight increase of 1.4 kg and 3.1 kg (including carry-on baggage) for males and females respectively between 1999 and 2003 (NFO New Zealand 2003). The study also highlights the significance of ethnicity on standard weight, with a fraction of the sample population being of Maori or Asian descent. The finding notes that Maoris are likely to be heavier than European descendants, whereas Asians are the lightest ethnicity. This highlights that demographic ethnicities can affect standard weight, as demonstrated by similar results obtained by Bil and Hanlon (2016). Similarly, Gritsch, Bil and Hanlon (2017) state that in Australia, the standards became outdated within a decade of their inception. The authors recommend using the statistical health data on weight and obesity as a trigger to update the standards once the variance reaches 2%.

Current FAA regulations state that the average weight of passengers (including carry-on baggage) for use during summer operations is 85 kg for adult males, 74 kg for adult females and 30 kg for children under 13 years of age, or 79 kg for adults in a 50:50 male-to-female ratio (FAA 2005). In addition to the safety considerations, inaccurate weights can add an extra cost to airlines regarding fuel and time, as discussed in Section 3.4.2. It is difficult to accurately estimate fuel spent as a result of extra passenger weight because there is not a coherent approach regarding the application of standards across regulators.

Operational protocols in weight and balance and updated weight standards are crucial elements that need to be explored in future research. Current weight standards are potentially obsolete because they either overestimate or underestimate the weight of passengers. Table 3-4 presents a survey of accessible regulatory weight standards from sampled countries. The table includes the average weights of males and females. In most cases, it is evident that many have overestimated the weight of passengers (e.g., Turkey, Ghana and Costa Rica), whereas other countries (e.g., Australia and the US) have underestimated weights. Many of these standards have not been updated in decades. Only the EASA, in 2009, has updated their weight standards to accurately reflect the flying public in Europe (Berdowski et al. 2009). Weight standards should be updated periodically through surveys to capture actual weight trends of passengers. In most cases, developing nations with limited financial resources to conduct such surveys rely on standards set by the FAA, CAA UK and EASA. This means that these countries have not considered the anthropometric features of their respective population. Moreover, many countries adopt the same weight standards used in different regions around the world, which may not reflect the situation with their flying public. For example, El Salvador uses the standards set by the regulator in the UK, where the demographic make-up is different and average weights for males are 63 kg and 72 kg respectively (NCD Risk Factor Collaboration 2016c).

Table 3-4 Comparison of standard weights and average weights in use by different countries

Country	**Average weight (kg)**		**Standard passenger weight (kg)**		
	Male[1,2]	Female[1,2]	Male	Female	Regulator[3]
Antigua and Barbuda	77.6	***72.6***	74	64	ECCAA
Australia	***84.1***	***70.1***	81.8	66.7	CASA
The Bahamas	***77.9***	***71.9***	74	64	BCAA
Canada	***83.7***	69.5	83	73	TC
Costa Rica	72.8	62.7	88	70	DGAC
Europe[4]	80.6	66.1	94	75	EASA
El Salvador	72.7	62.8	88	70	AAC
Fiji	***77.7***	72.8	77	77	CAAF
Ghana	65.1	61.9	83	73	GCAA
India	56.6	49.0	75	75	DGCA
Jordan	78.2	***72.1***	88	70	CARC
New Zealand	84.7	72.4	86	86	CAA NZ
Norway	84.68	68.37	88	70	CAA Norway
South Africa	69.8	***73.0***	88	70	SACAA
St Kitts and Nevis	***79.1***	***77.4***	74	64	ECCAA
St Lucia	***83.3***	***77.6***	74	64	ECCAA
Swaziland	67.1	***71.4***	88	70	SWACAA
Tanzania	60.9	57.3	88	70	TCAA
Trinidad and Tobago	79.9	***73.3***	88	70	TTCAA
Turkey	76.3	69.2	88	70	SHGM
UAE	76.6	70.0	88	70	GCAA
UK	82.6	69.7	88	70	CAA UK
US	***89.3***	***75.5***	83	73	FAA

[1] NCD Risk Factor Collaboration (2016a)
[2] NCD Risk Factor Collaboration (2016b)
[3] Regulatory references are not included due to publication constraints.
[4] Average weight and obesity prevalence are determined by the average of all individual European countries within the jurisdiction of the EASA.
Italics **indicates that the standards are below the average weight.**

Although the average weights of males and females have been increasing for years, these average values encompass wider socioeconomic communities within nations (NCD Risk Factor Collaboration 2016c). However, this may not fully reflect the demographics of the proportion of air travellers versus those who use other transport modes, particularly in developing countries in Africa, Asia, the Pacific, Latin America and the Caribbean. Further studies are needed to investigate the links between socioeconomics, anthropometry and regulatory weight standards. This is a pertinent point, as Figure 3-4 depicts changes in weight and obesity between 1975 and 2014 for the countries listed in Table 3-4.

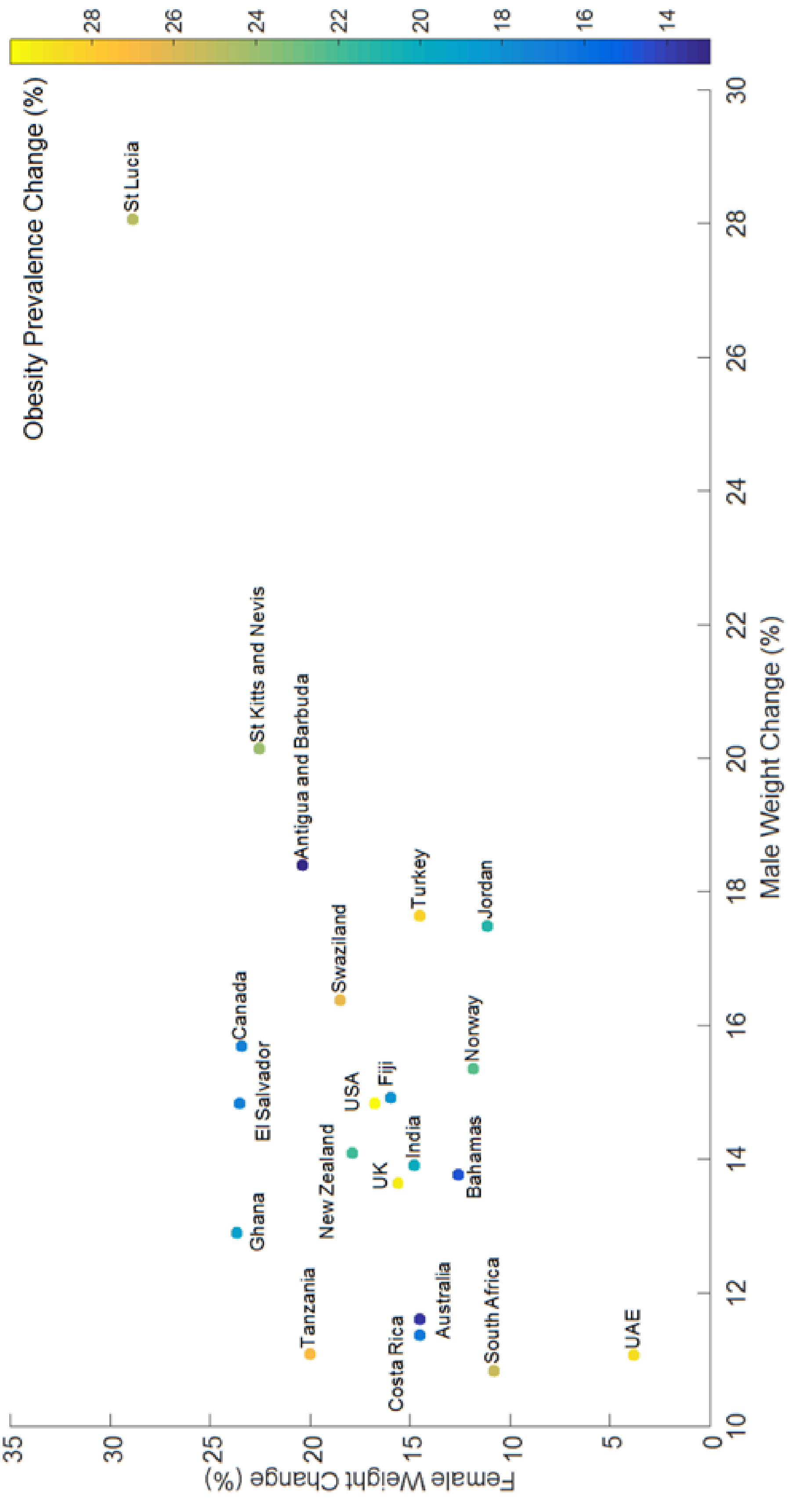


Figure 3-4 Changes in the average weights of male and female individuals of various countries from 1975 to 2014 (NCD Risk Factor Collaboration 2016a, 2016b)

3.7 Knowledge Gap and Future Challenges

Airlines rely on regulations issued by national authorities to set minimum rules and standards for the design, performance and safety of aircraft. In most instances, many of these rules and standards entail the consideration of biometrically based factors of passengers. Therefore, any changes in the passengers' anthropometric characteristics may lead to the need to revise some design aspects of aircraft to maintain concurrency with type certification and aircraft operational limits. Figure 3-5 shows some design and operational requirements that need to be considered to address this issue when operating existing, as well as developing new, aircraft. Many of these facets have been highlighted in previous sections; however, they are noted again herein given their links to defined regulatory standards issued by the FAA and other regulatory bodies around the world.

Components that are particularly exposed to the effects of overweight/sized passengers, such as seats and lavatories, will need to be reviewed and adjusted accordingly to maintain both their functional requirements and safety standards. Typically, changes only occur after aviation regulators promulgate new standards and design requirements for these affected components, which is normally a lengthy process because of the technical challenges associated with new proposed designs and corresponding costs to operators.

FAA CFR14 Part 25 and FAA Technical Standard Orders might require amendments to reflect current biometric and anthropometric trends. Manufacturers of safety equipment are required to demonstrate that their products meet these standards. Questions are then raised regarding whether safety equipment can handle larger passengers: Should the minimum buoyancy rating be increased? Can slide-rafts meet the evacuation rate for larger passengers? Is the capacity of life rafts reduced with increased numbers of larger people? The answers to these questions can only be determined by incorporating larger passengers in the design and certification phases of critical safety equipment, thereby enabling a more accurate understanding of the need to update existing standards.

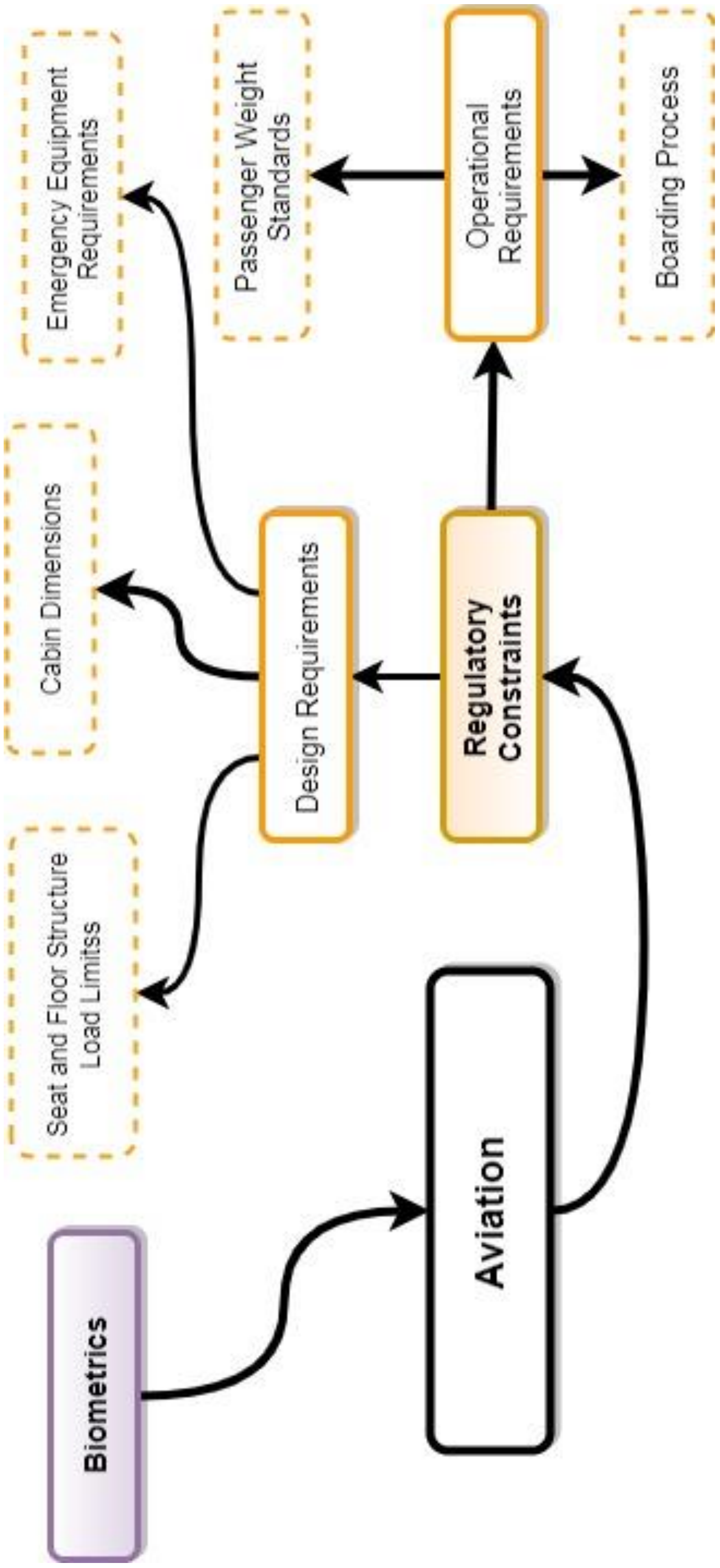


Figure 3-5 Effect of biometrics and anthropometry of airline passengers on aviation regulations

3.8 A Holistic Approach to the Effect of Passengers' Anthropometric and Biometric Parameters

Existing research has primarily investigated the effect of passenger weight within the operational context of commercial aircraft. Areas such as aircraft performance (e.g., fuel usage) and safety design (e.g., seats) have received limited attention regarding the current biometrical and anthropometrical condition of passengers and provide no foundation for understanding how these characteristics can affect other dimensions of flight activity.

Each study in the literature explores individual facets relating anthropometry to performance, design and safety within a certain regulatory environment. There are overlaps between these facets in some cases, but there is no holistic approach that explores all three dimensions concurrently (i.e., the effect of passengers' anthropometric changes in the performance, design and safety of aircraft). The importance of concurrently considering these three elements emerges from the overarching regulations and standards that span across these areas.

Figure 3-6 presents a holistic model that demonstrates the interplay between biometrics, safety, performance and design with regulation and standards. This model has been developed based on the literature conducing to its main elements and inter-relationships. Safety requirements are often the leading drivers during the design phase and have a direct effect on performance. Performance and safety cannot be dissociated because they are intertwined in many aspects. Human biometrics (anthropometry, metabolic rates and biomechanics) should be considered the centrepiece of this triad—a critical factor in what is a multi-criteria design problem.

The advantages of the holistic model presented in Figure 3-6 can be shown using the aircraft seat as an example. The seat's static and dynamic structural limits, as well as crashworthiness characteristics, are associated with safety design requirements, whereas ergonomics, durability and reliability parameters are directly related to design performance. A competing design requirement is to minimise the weight of the seat to maximise the aircraft's performance. Bearing in mind these concurring requirements, an accurate understanding of passenger biometric and anthropometric characteristics should be considered the common denominator for improved design solutions.

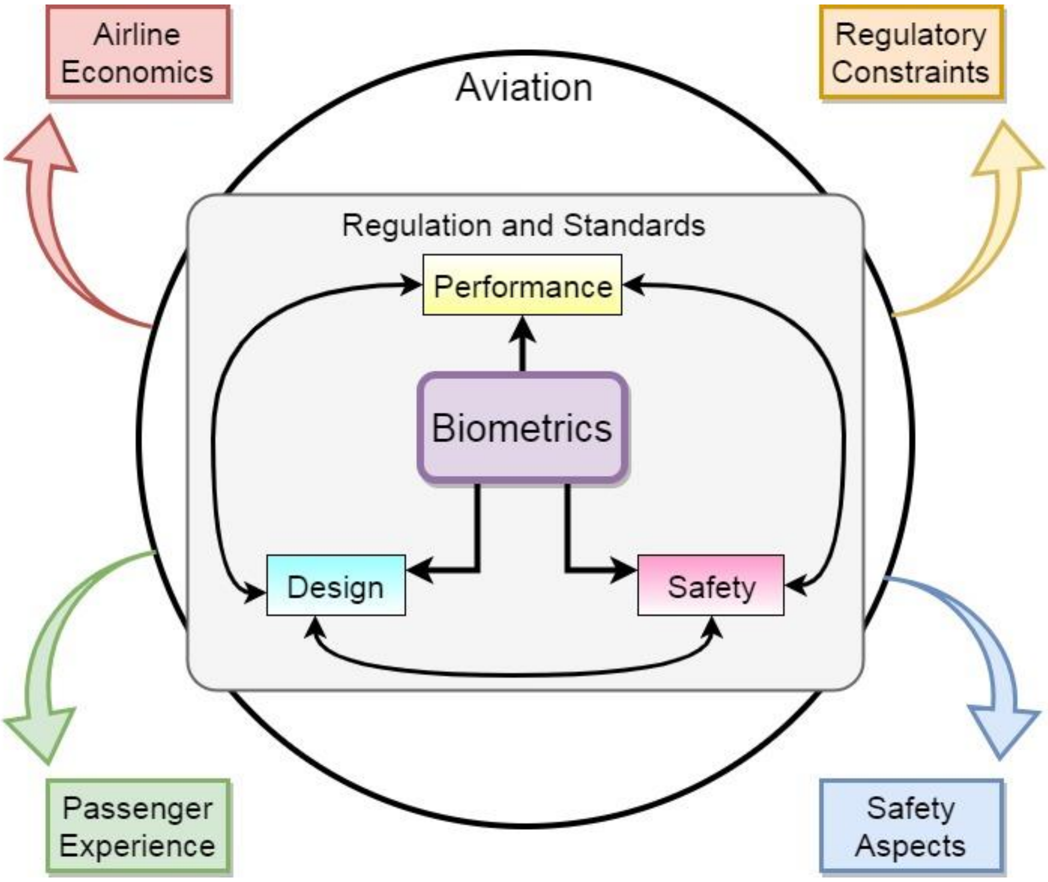


Figure 3-6 Interplay of key elements associated with the design and operation of commercial airline aircraft and the effect of passengers' biometrics

3.9 Summary

Global obesity prevalence and the steady increase in the average weight of humans over the past few decades are among the most pressing issues in modern society. Obesity is a major area of concern to health organisations given not only the negative effects on people's health, but also its overflow effect on society, including the transport sector. Notwithstanding the recognition of key stakeholders regarding the relevance of the changes in the physical size of air travellers, research in this area has been relatively scarce.

The review in this chapter contributes to raising awareness of the importance of the biometrical parameters of airline passengers at different levels, ranging from passenger experience to the safety and operation of aircraft. A holistic model was proposed that aims to consider the concomitant effects of passengers' anthropometric and biometric characteristics on four distinct dimensions: airline economics, passenger experience, safety aspects and regulatory constraints. This model paves the way for future research in areas that are particularly prone to the increasing weight of passengers, such as crashworthiness analysis of aircraft seats, effectiveness of restraining systems in case of emergency, improved performance models to better compute fuel usage as a function of passengers’ weight, design of more ergonomic cabin components adapted to larger passengers (e.g., seats and lavatories) and development of computational models for the simulation of emergency egress that consider passengers with distinct physical attributes and mobility capacity. Perhaps the most important fact brought out by this review is the urgent need to review existing regulations and guidelines that are in use in the aviation sector because most of them are based on anthropometric data collected many years ago; therefore, they fail to correctly represent the current demographics of passengers in different parts of the world. By providing more accurate safety regulations, the passenger experience would significantly improve and airlines would greatly benefit from safer and more cost-effective flights.

Finally, it should be noted that the proposed model has the advantage of being easily adapted to other transport modes that are particularly susceptible to passengers’ weight, such as the road transport and railway sectors. Although a few studies have assessed the effect of larger passengers in cars, buses and trains, these are often limited to specific issues (e.g., design mass limits, crashworthiness characteristics and fuel consumption) and fail to provide a comprehensive approach leading to optimised design solutions.

Chapter 4: Anthropometric Data and Passenger Modelling

4.1 Introduction

This chapter explores three topics relating to the data used in this thesis:

- First, the data from the Centers for Disease Control and Prevention's (CDC) NHANES are introduced, including a brief mention of the reasons why this data set was used.
- Second, details regarding the various demographic profiles used in the performance (see Chapter 5) and emergency egress (see Chapter 7) are discussed.
- Third, a model is presented to manipulate the data from NHANES to create various scenarios of varying BMI prevalence.

Elements of this chapter have been published in the listed publications (p. iii).

4.2 National Health and Nutrition Examination Survey Background

NHANES is a program of studies designed to assess the health and nutritional status of adults and children in the US. The survey is unique because it combines interviews and physical examinations and is overseen by the CDC. The NHANES data are the primary source of body measurement and related health and nutrition data for the civilian US population. Surveys were conducted periodically from 1960 until 1999, when it became a continuous survey. After 1999, the NHANES data were released publicly, with each dataset spanning two years. A combined four-year dataset based on 2003–2004 and 2005–2006 data was used for this report to improve the stability and reliability of the statistical estimates. Additional two-year datasets will be released in the future as more data become available. Each of the continuous NHANES annual survey samples is nationally representative of the US.

Household interviews and health examinations are used to collect the NHANES data. All health examinations are conducted in mobile examination centres. The examination centres are staffed by full-time personnel, including health technicians who obtain body measurements from survey participants. All NHANES health technicians have completed a comprehensive body measurement training program that uses videotape, demonstration and practice exercises with an expert examiner. The performance of health technicians is monitored using direct observation, data review and expert examiner evaluations.

Although the survey is conducted every year, for this research and specifically demographic modelling, an understanding of the specific anthropometrical attributes was the focus rather than the yearly trends. This is because this research focuses on the manipulation of the prevalence of BMI within a sample demographic model used in aircraft safety and performance studies.

4.3 Anthropometrical Profiles and Data Statistics

The NHANES data used during this study were issued in 2015. The data cover the survey period 2013–2014 and provide a large sample of current physical characteristics, such as height, weight, BMI and age. Other anthropometric data, such as leg and arm lengths, upper leg and upper arm circumferences and sagittal abdominal diameter, do not have a full complement of data; therefore, these measures are not considered. The collected data were sorted into age and BMI categories for the sake of a more practical approach.

The NHANES data form the basis of the underlining characteristics assigned to an individual profile. The data are provided in an unsorted, raw format; therefore, categorisation of the raw data is completed before they are implemented into the model. The raw data are organised by gender and age, followed by sorting the data by BMI value in ascending order. Statistical information about the maximum, minimum, average and standard deviation (SD) are then calculated. These statistical quantities are used to create profile attributes for emergency evacuation modelling. Detailed anthropometric statistical quantities relating to each age group and gender are presented in Appendix 4.

The NHANES data contain *n*=5,229 sample individuals with useful data, of which 47.5% and 53.5% are male and female respectively. Figure 4-1 illustrates the statistical attributes of the full NHANES dataset. The age range of the sample is 18–80 years old. The mean age for the population is 47 years, regardless of gender. The mean weight is 70.8 kg (SD 28.2 kg), with a maximum recorded weight of 195.4 kg. Males have a mean weight of 72.7 kg and females have a mean weight of 69.0 kg. The maximum recorded weight for males and females is 184.5 kg and 195.4 kg respectively. The mean height is 159.6 cm (SD 20.5 cm). Males are typically taller than females, with a mean recorded height of 161.9 cm compared with 157.5 cm. The mean waist circumference of the population is 90.6 cm (SD

21.6 cm). The maximum recorded waist circumference is measured at 163.3 cm. The mean BMI of the sample population is 26.5 kg•m^{-2} (SD 7.7 kg•m^{-2}), which classifies the population as overweight.

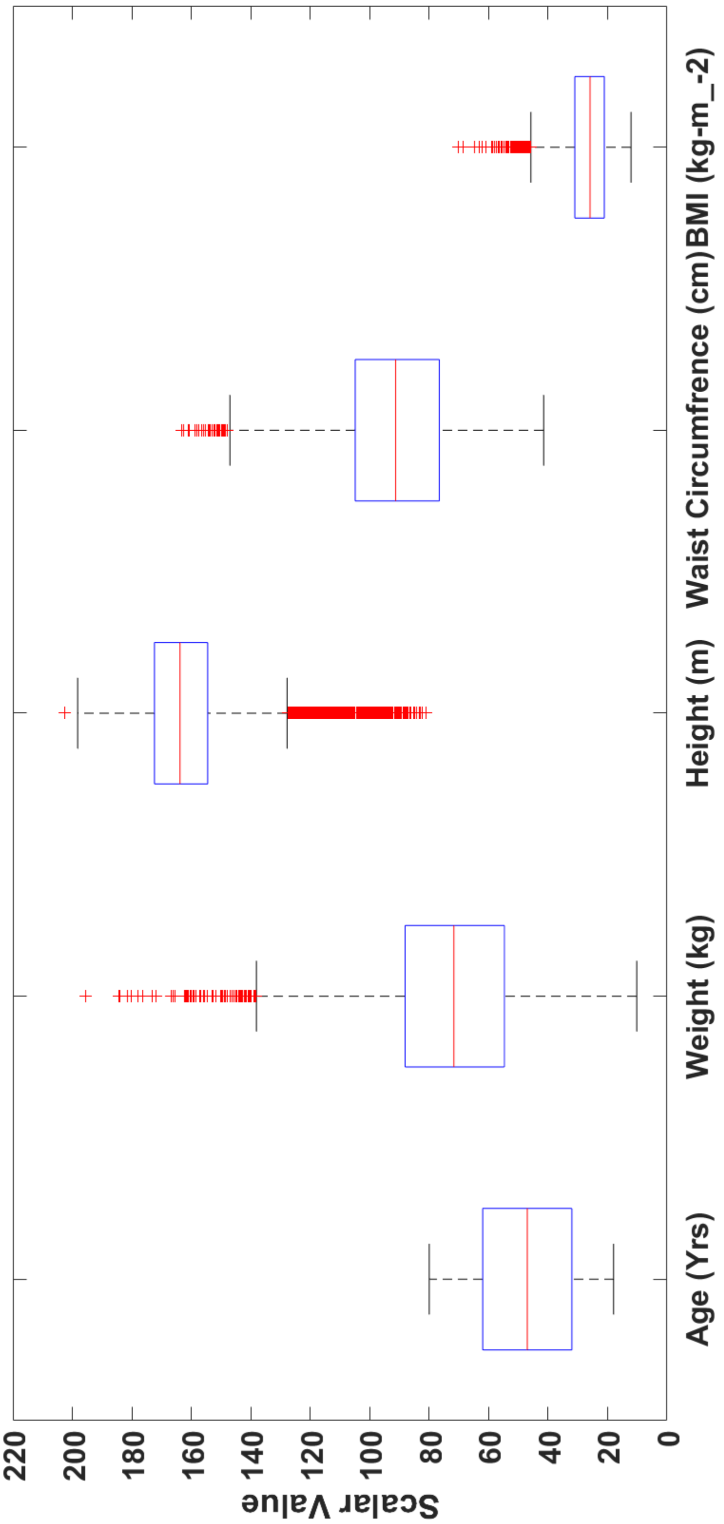


Figure 4-1 Boxplots of age, weight, height, waist circumference and BMI for NHANES data

4.3.1 Age Group 18–24

The age group spanning 18–24 years consists of a sample size of *n(m)*=346 and *n(f)*=379 males and females respectively. Figure 4-2 shows the BMI frequency among this specific cohort, with a medium BMI value of 25 kg•m^{-2} and a mean BMI of 25.9 kg•m^{-2}. A greater proportion of individuals are considered overweight or obese at 50.2%. Other anthropometrical features of this cohort include a weight median and mode of 69.6 kg (SD 27.3 kg), whereby the maximum recorded weight is 184 kg. The tallest individual is 193.1 cm and the shortest is 81.2 cm, with a median height of 163.6 cm (SD 19.6 cm). Further, the median waist circumference is 87.2 cm (SD 20.3 cm) and the maximum is 163.3 cm.

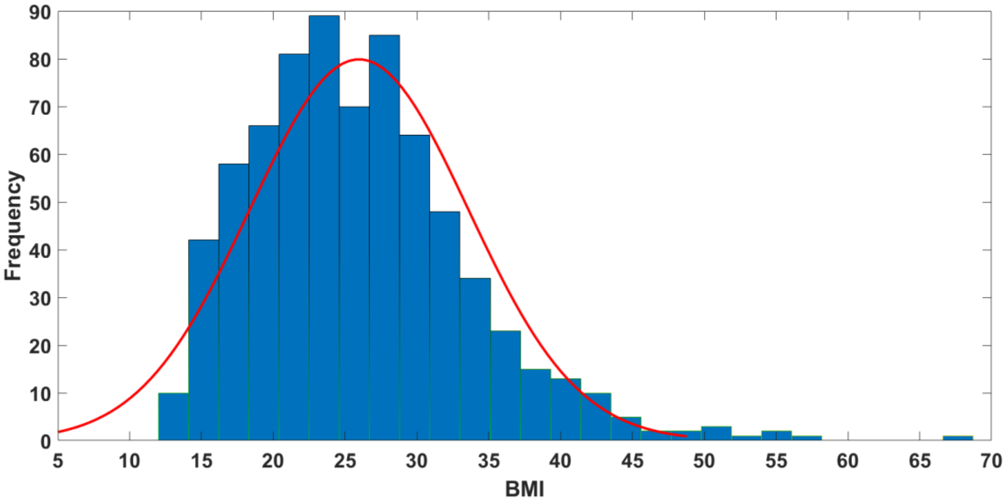


Figure 4-2 Frequency and distribution of BMI among 18–24 year olds

4.3.2 Age Group 25–34

The age group spanning 25–34 years consists of a sample size of *n(m)*=411 and *n(f)*=419 males and females respectively. Figure 4-3 shows the BMI frequency among this specific cohort, with a medium and mode BMI value of 25.6 kg•m^{-2}. A greater proportion of individuals are considered overweight or obese, at 54.6%. Other anthropometrical features of this cohort include a weight median of 78.9 kg and a mode of 66.2 kg (SD 27.3 kg), with a maximum recorded weight of 181.4 kg. The tallest individual is 198.2 cm and the shortest is 86.3 cm, with a median height of 165.2 cm (SD 19.8 cm). Further, the median waist circumference is 90.0 cm (SD 21.3 cm) and the maximum is 162.7 cm.

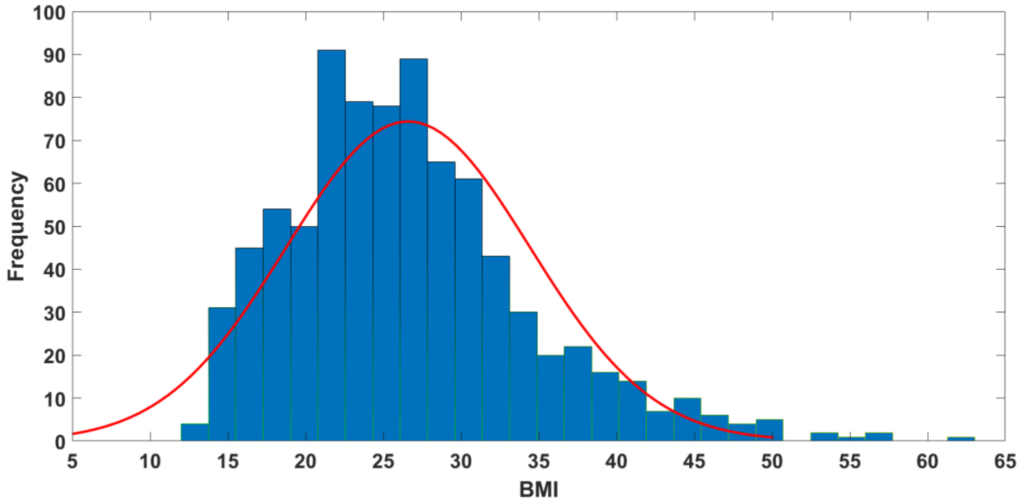


Figure 4-3 Frequency and distribution of BMI among 25–34 year olds

4.3.3 Age Group 35–44

The age group spanning 35–44 years consists of a sample size of *n(m)*=399 and *n(f)*=481 males and females respectively. Figure 4-4 shows the BMI frequency among this specific cohort, with a medium and mode BMI value of 25.8 kg•m^{-2}. A greater proportion of individuals are considered overweight or obese, at 55.5%. Other anthropometrical features of this cohort include a weight median of 71.5 kg and mode of 90.2 kg (SD 27.7 kg), with a maximum recorded weight of 184.5 kg. The tallest individual is 196.1 cm and the shortest is 82.4 cm, with a median height of 164.0 cm (SD 21.5 cm). Further, the median waist circumference is 90.7 cm (SD 20.8 cm) and the maximum is 160.8 cm.

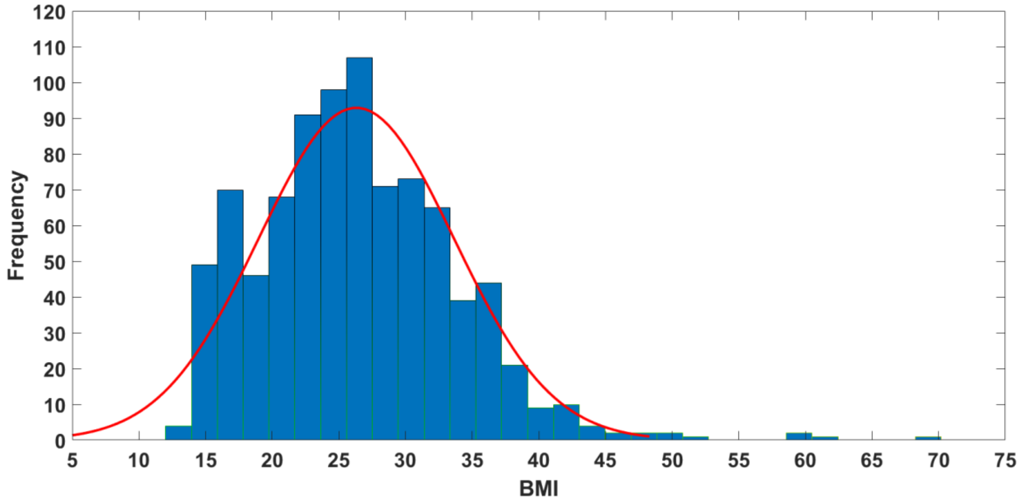


Figure 4-4 Frequency and distribution of BMI among 35–44 year olds

4.3.4 Age Group 45–54

The age group spanning 45–54 years consists of a sample size of *n(m)*=394 and *n(f)*=444 males and females respectively. Figure 4-5 illustrates the BMI frequency among this specific cohort, with a medium and mode BMI value of 26.4 kg•m^{-2} and 27.3 kg•m^{-2} respectively. A greater proportion of individuals are considered overweight or obese, at 57.4%. Other anthropometrical features of this cohort include a weight median of 73.8 kg and mode of 75.5 kg (SD 28.8 kg), with a maximum recorded weight of 162.2 kg. The tallest individual is 196.7 cm and the shortest is 83.3 cm, with a median height of 164.3 cm (SD 21.0 cm). Further, the median waist circumference is 93.2 cm (SD 22.1 cm) and the maximum is 157.4 cm.

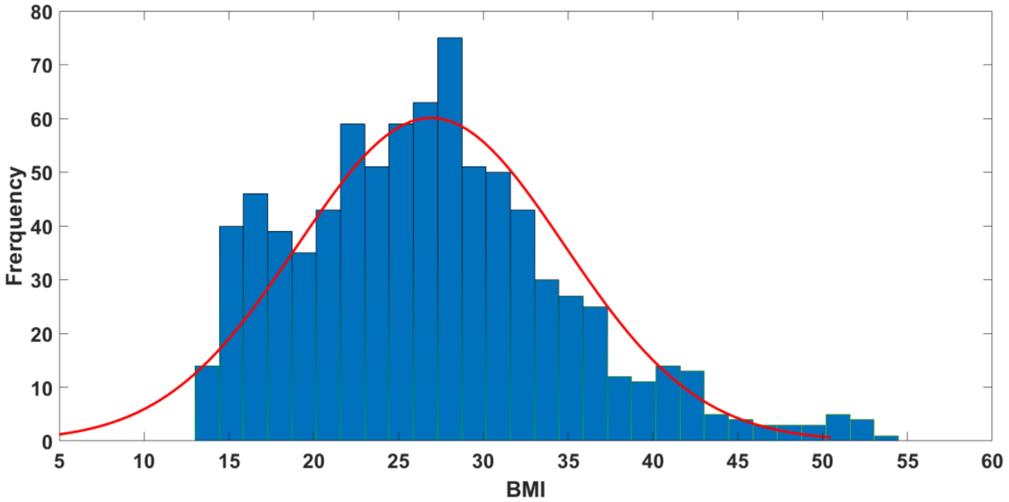


Figure 4-5 Frequency and distribution of BMI among 45–54 year olds

4.3.5 Age Group 55–64

The age group spanning 55–64 years consists of a sample size of *n(m)*=415 and *n(f)*=379 males and females respectively. Figure 4-6 illustrates the BMI frequency among this specific cohort, with a medium and mode BMI value of 26.2 kg•m^{-2} and 25.9 kg•m^{-2} respectively. A greater proportion of individuals are considered overweight or obese, at 56.9%. Other anthropometrical features of this cohort include a weight median of 71.9 kg and mode of 63.9 kg (SD 29.1 kg), with a maximum recorded weight of 180.1 kg. The tallest individual is 194.7 cm and the shortest is 83.1 cm, with a median height of 163.3 cm (SD 20.4 cm). Further, the median waist circumference is 92.7 cm (SD 22.7 cm) and the maximum is 161.0 cm.

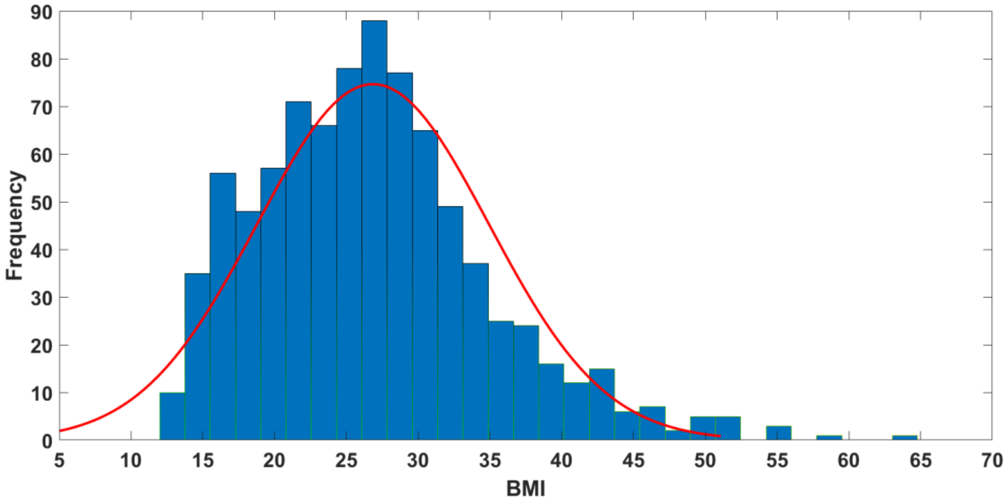


Figure 4-6 Frequency and distribution of BMI among 55–64 year olds

4.3.6 Age Group 65–74

The age group spanning 65–74 years consists of a sample size of *n(m)*=294 and *n(f)*=350 males and females respectively. Figure 4-7 shows the BMI frequency among this specific cohort, with a medium and mode BMI value of 26.5 kg•m^{-2} and 28.2 kg•m^{-2} respectively. A greater proportion of individuals are considered overweight or obese, at 59.0%. Other anthropometrical features of this cohort include a weight median of 72.4 kg and mode of 65.3 kg (SD 27.6 kg), with a maximum recorded weight of 159.9 kg. The tallest individual is 194.2 cm and the shortest is 88.4 cm, with a median height of 163.3 cm (SD 19.1 cm). Further, the median waist circumference is 94.0 cm (SD 21.9 cm) and the maximum is 156.5 cm.

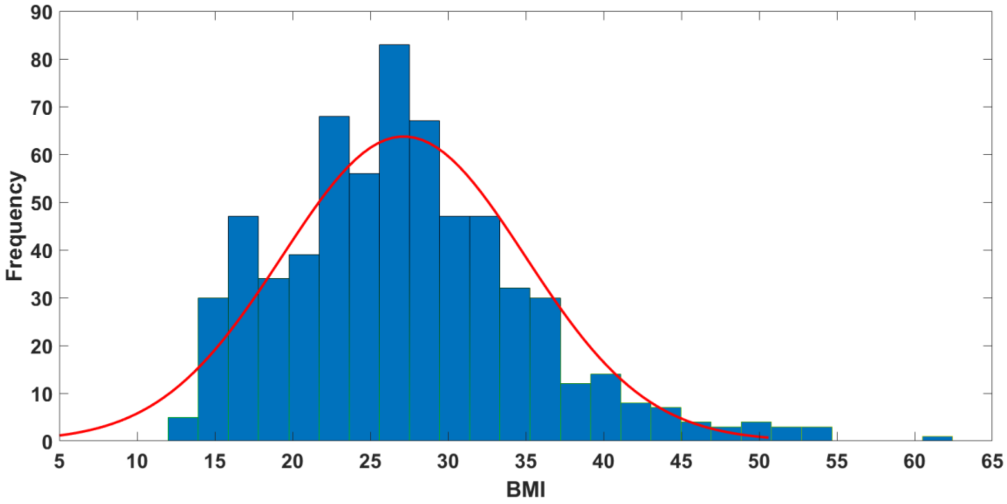


Figure 4-7 Frequency and distribution of BMI among 65–74 year olds

4.3.7 Age Group 75+

The age group spanning 75+ years consists of a sample size of *n(m)*=225 and *n(f)*=238 males and females respectively. Figure 4-8 shows the BMI frequency among this specific cohort, with a medium and mode BMI value of 25.7 kg•m^{-2} and 23.7 kg•m^{-2} respectively. A greater proportion of individuals are considered overweight or obese, at 52.5%. Other anthropometrical features of this cohort include a weight median of 69.4 kg and mode of 76.0 kg (SD 28.7 kg), with a maximum recorded weight of 195.4 kg. The tallest individual is 202.6 cm and the shortest is 84.9 cm, with a median height of 162.2 cm (SD 22.0 cm). Further, the median waist circumference is 92.0 cm (SD 22.4 cm) and the maximum is 155.2 cm.

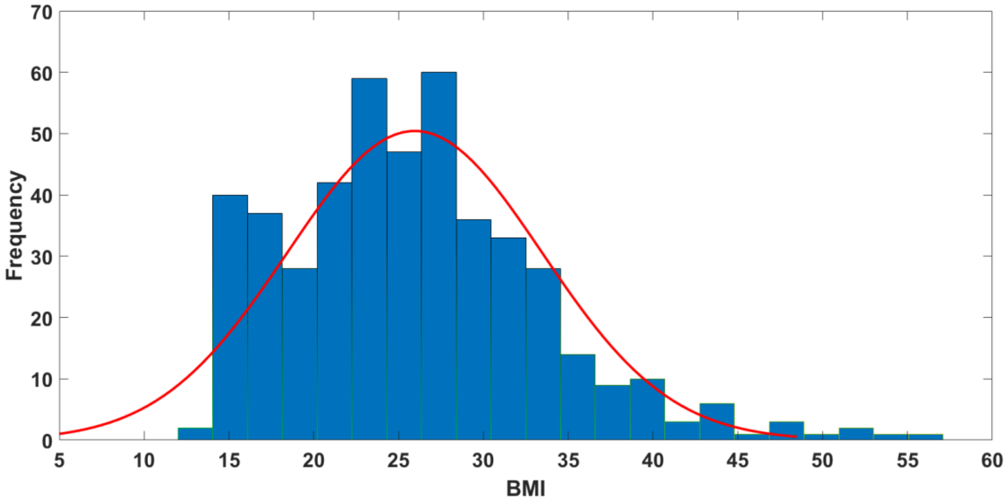


Figure 4-8 Frequency and distribution of BMI among 75+ years

4.4 Modelling BMI Prevalence-based Passenger Demographics

The main goal for establishing this model is to derive a method of determining the demographic composition of an aircraft. The NHANES data provide a base condition for establishing changes in the model. The model is derived from the simple mathematical principle of *ratios*. There are two applications of the passenger demographic model in this research:

- determining passenger payload weight based on changes in BMI prevalence for the performance study;
- establishing BMI prevalence for different profiles for the emergency egress study.

4.4.1 Model Assumptions: Gender and BMI Category Ratios

The scope of this research is to examine the overall BMI prevalence for a given situation. Therefore, understanding changes in gender fluctuations across regions, nations or ethnicity is not considered in this model. It is generally understood that gender ratios fluctuate little over time and generally remain stable. Given that each region is composed of nations with different demographics, modelling based on their respective BMI demographic prevalence would increase the model's complexity. Therefore, the ratios between the BMI categories remain the same for the scenarios explored. The results obtained from these scenarios can then be extrapolated to various regions around the world by adjusting the corresponding BMI ratios. The prevalence of the various BMI categories can change periodically. This passenger characteristic model illustrates the effect of changing obesity scenarios. Figure 4-9 shows passenger BMI category prevalence used for the scenarios BMI>25%, BMI>50% and BMI>85%.

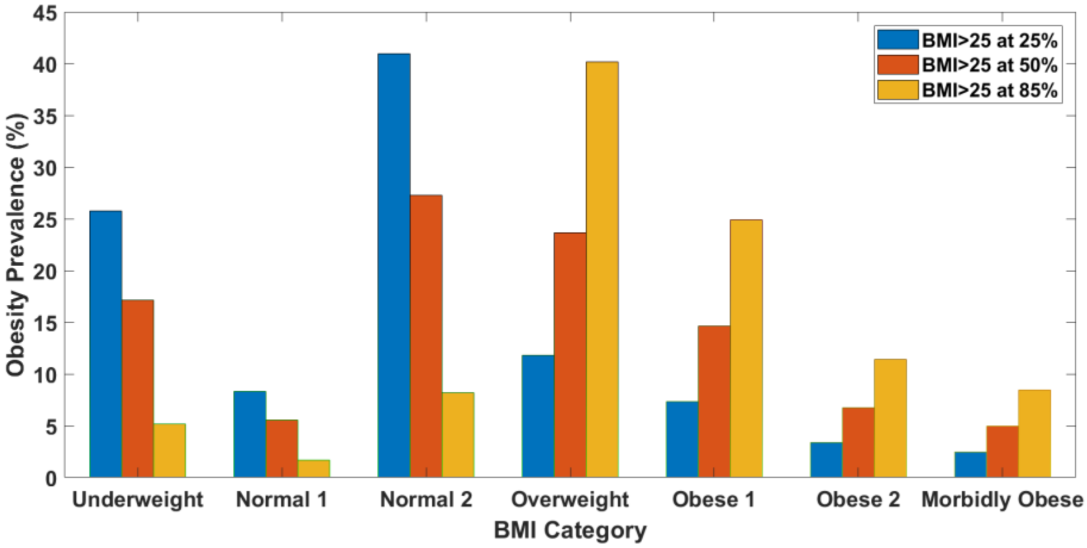


Figure 4-9 Changes in the ratios among the obesity categories at different levels

Thomas et al. (2014) expect obese people in the US (i.e., with BMI>25) to plateau at 69% by 2030 and at 71% by 2033 in the UK. However, the proportions estimated for the obese category were greater than those for the overweight category. Currently, both have a prevalence obesity of 67% and 63% respectively, with the overweight category dominating (NCD Risk Factor Collaboration 2016c). An earlier study reports that people with a BMI greater than 30 is expected to be 42% of the population by 2030 in the US (Finkelstein et al. 2012).

4.4.2 Model for Determining Weight

The NHANES data used to input in the model rely on the population percentages of the various age groups and genders. From the NHANES data, the total number of individuals in the sample population are categorised into *profiles* by age, gender and BMI category. These values are presented in Table 4-1 and Table 4-2 for males and females respectively.

Table 4-1 Number of males by age and BMI category from the NHANES data

BMI	**Under**	**Normal 1**	**Normal 2**	**Over**	**Obese 1**	**Obese 2**	**Morbid**	
Age								Total
18–24	51	21	110	74	54	24	12	346
25–34	59	20	112	111	66	18	25	411
35–44	58	19	86	115	76	32	13	399
45–54	59	17	94	116	64	22	22	394
55–64	62	21	94	117	68	29	24	415
65–74	33	14	68	85	50	29	15	294
75+	33	8	56	60	47	9	12	225
Total	355	120	620	678	425	163	123	2,484

Table 4-2 Number of females by age and BMI category from the NHANES data

BMI	**Under**	**Normal 1**	**Normal 2**	**Over**	**Obese 1**	**Obese 2**	**Morbid**	
Age								Total
18–24	62	25	92	100	55	23	22	379
25–34	56	21	108	107	60	38	29	419
35–44	79	22	128	111	80	47	14	481
45–54	73	17	93	103	76	39	33	434
55–64	67	30	96	118	66	33	34	444
65–74	60	12	77	92	57	27	25	350
75+	50	12	61	59	29	19	8	238
Total	447	139	655	690	423	226	165	2,745

Using only the prevalence percentages of each BMI category, known heights and population percentages for each gender, an average weight for each BMI category is calculated from Eq. 4.1, where $\overline{BMI_i}$ is the average BMI value for given category i, and $h_{(G)}$ is the average height for a given gender:

$$\bar{W}_{i(G)} = \overline{BMI_\iota} h_{(G)}{}^2 \qquad \text{Eq. 4.1}$$

Eq. 4.2 determines the proportion of the population that fits within a particular BMI category, where $P_{(G)}$ is the percentage of the population for a given gender and $P_{(i \cup G)}$ is the proportion of the BMI category within the given gender. The weight of the passenger payload is then determined by Eq. 4.2:

$$P_{i(G)} = P_{(G)}P_{(i\cup G)} \tag*{Eq. 4.2}$$

Once the data were sorted into their respective categories, the next step was to determine the proportion of the given population size (*n*) with a specific BMI category *i*. For an age group and gender (*A*,*G*), the number of elements of that set was divided by the total number of elements in the population, as shown by Eq. 4.3. These values are shown in Table 4-3 and Table 4-4.

$$P_{i(A,G)} = \frac{n_{i(A,G)}}{\sum n_{(A,G)}} \tag*{Eq. 4.3}$$

Table 4-3 Percentage of the male population by age and BMI category from the NHANES data

BMI	**Under**	**Normal 1**	**Normal 2**	**Over**	**Obese 1**	**Obese 2**	**Morbid**	
Age								Total
18–24	0.98%	0.40%	2.10%	1.42%	1.03%	0.46%	0.23%	6.6%
25–34	1.13%	0.38%	2.14%	2.12%	1.26%	0.34%	0.48%	7.9%
35–44	1.11%	0.36%	1.64%	2.20%	1.45%	0.61%	0.25%	7.6%
45–54	1.13%	0.33%	1.80%	2.22%	1.22%	0.42%	0.42%	7.5%
55–64	1.19%	0.40%	1.80%	2.24%	1.30%	0.55%	0.46%	7.9%
65–74	0.63%	0.27%	1.30%	1.63%	0.96%	0.55%	0.29%	5.6%
75+	0.63%	0.15%	1.07%	1.15%	0.90%	0.17%	0.23%	4.3%
Total	6.79%	2.29%	11.86%	12.97%	8.13%	3.12%	2.35%	47.50%

Table 4-4 Percentage of the female population by age and BMI category from the NHANES data

BMI	**Under**	**Normal 1**	**Normal 2**	**Over**	**Obese 1**	**Obese 2**	**Morbid**	
Age								Total
18–24	1.19%	0.48%	1.76%	1.91%	1.05%	0.44%	0.42%	7.2%
25–34	1.07%	0.40%	2.07%	2.05%	1.15%	0.73%	0.55%	8.0%
35–44	1.51%	0.42%	2.45%	2.12%	1.53%	0.90%	0.27%	9.2%
45–54	1.40%	0.33%	1.78%	1.97%	1.45%	0.75%	0.63%	8.3%
55–64	1.28%	0.57%	1.84%	2.26%	1.26%	0.63%	0.65%	8.5%
65–74	1.15%	0.23%	1.47%	1.76%	1.09%	0.52%	0.48%	6.7%
75+	0.96%	0.23%	1.17%	1.13%	0.55%	0.36%	0.15%	4.6%
Total	8.55%	2.66%	12.53%	13.20%	8.09%	4.32%	3.16%	52.50%

Eq. 4.4 describes the sum of the element weights for a given BMI category (*i*) for an age group and gender (*A*,*G*). It is then divided by the number of elements in that group to determine the average weight for that particular age group and gender (*A*,*G*). The results are shown in Table 4-5 and Table 4-6.

$$\overline{W}_{i(A,G)} = \frac{\sum W_{i(A,G)}}{n_{i(A,G)}} \qquad \text{Eq. 4.4}$$

Table 4-5 Average weight of males calculated from NHANES data and categorised by age and BMI category

BMI	Under	Normal 1	Normal 2	Over	Obese 1	Obese 2	Morbid
Age							
18–24	29.4	51.1	63.6	78.0	90.9	109.1	128.7
25–34	26.9	49.1	64.1	80.6	93.0	104.4	130.5
35–44	24.6	45.3	62.7	80.1	93.1	107.7	123.2
45–54	27.9	43.7	63.0	82.1	93.7	108.9	129.8
55–64	26.6	40.0	61.6	78.7	94.2	105.4	132.7
65–74	28.0	46.1	63.1	76.5	93.3	102.4	127.7
75+	25.9	48.9	61.8	77.4	93.8	103.0	127.4

Table 4-6 Average weight of females calculated from NHANES data and categorised by age and BMI category

BMI	Under	Normal 1	Normal 2	Over	Obese 1	Obese 2	Morbid
Age							
18–24	29.06	46.46	59.96	76.59	89.67	101.53	122.56
25–34	28.83	48.24	60.28	75.77	86.79	99.64	126.11
35–44	27.04	44.90	60.88	72.54	89.02	97.86	127.86
45–54	27.53	45.11	60.98	74.64	88.24	99.15	121.31
55–64	26.89	47.40	59.46	75.05	86.78	101.66	121.61
65–74	25.91	49.07	60.83	73.75	85.96	93.91	124.32
75+	24.54	53.03	60.29	73.36	85.47	98.70	136.45

Using only the prevalence percentages of each BMI category, known heights and population percentages for each gender, an average weight for each BMI category is calculated from Eq. 4.5, where $\overline{BMI_i}$ is the average BMI value for a given category *i*, and $h_{(G)}$ is the average height for a given gender:

$$\overline{W}_{i(G)} = \overline{BMI_i} h_{(G)}{}^2 \qquad \text{Eq. 4.5}$$

4.4.3 Model for Determining Demographic Prevalence

The weight of the passenger from the NHANES data is categorised by age and BMI category. Exploring the effects of passenger weight changes for this model is dependent on the prevalence of obesity being modelled. The total percentage of $\left(P^{j}_{BMI>25}\right)_{(G)}$ is determined by Eq. 4.6, where *REF* is the reference value calculated from NHANES and *j* is obesity prevalence as a percentage. The same equation is used to evaluate the percentage of BMI of less than 25 kg•m^{-2}:

$$\left(P^{j}_{BMI>25}\right)_{(G)} = (P^{REF}_{BMI>25})_{(G)}\left(\frac{P^{j}_{BMI>25}}{P^{REF}_{BMI>25}}\right)_{Total} \qquad \text{Eq. 4.6}$$

Using the same process as Eq. 4.5, the proportion of a newly estimated sample size *j* was determined with Eq. 4.7, where *REF* denotes the reference value calculated from NHANES:

$$P^{j}_{i(A,G)} = \left(P^{j}_{BMI>25}\right)_{(G)}\left(\frac{P_{i(A,G)}}{(P_{BMI>25})_{(G)}}\right)_{REF} \qquad \text{Eq. 4.7}$$

Chapter 5: Aircraft Performance and Passenger Anthropometry

5.1 Introduction

This chapter explores the effect of passenger anthropometry on aircraft performance, with a focus on passenger weight. The passenger demographic model developed in Section 4.4 is used to develop passenger payload. Aircraft performance characteristics are determined from traditional analytical methods to examine three aircraft types. This chapter is composed of three main parts:

- First, background information is discussed, with a focus on key literature not covered in depth in Chapter 3.
- Second, analytical methods employed in the performance model are introduced and discussed, including passenger weight payload models and aircraft performance models.
- Third, results from the model with scenarios reflecting various degrees of obesity prevalence are presented through comparisons between standard passenger weights from key aviation regulators around the world. These scenarios are further compared with global variations across different regions around the world.

This chapter was published in 2019 in the *Journal of Transport and Health* with the title, ‘The effects of changing passenger weight on aircraft flight performance’.

5.2 Background

It is widely known that the average person’s weight is increasing and that obesity has become a global problem, especially in developed regions (NCD Risk Factor Collaboration 2016c; Wang & Lim 2014; Finucane et al. 2011). The WHO (2016) notes that worldwide obesity prevalence tripled between 1975 and 2016. Increasing body weight has many social implications, especially in health. People with a higher body mass are more susceptible to diseases such as diabetes, vascular disorders and muscular-skeletal problems. Managing and preventing direct health effects can be costly to society. Further, there are other secondary and tertiary indirect costs to the economy resulting from obesity (Ananthapavan et al. 2014; Hammond & Levine 2010). For example, Lobstein (2015) highlights that medical costs relating to associated obesity health issues cost US$150 billion to the US economy and £5 billion to the UK economy.

Pertinent issues encompassing changes in airline passenger anthropometry primarily focus on passenger comfort and experience (Vink & van Mastrigt 2011; Ahmadpour et al. 2014; Patel & D’Cruz 2017). Passengers of all sizes feel discomfort during flight, especially long-haul flights. Aircraft seat pitches (distance between two rows) have generally decreased in size, with most airlines offering a seat pitch between 30 and 32 in (Vasel 2017). As a result, larger-framed passengers experience greater discomfort, which then places a stigma on them by both cabin crew and fellow passengers (Small & Harris 2012; Mylrea 2009; Bolton 2004).

Commercial aviation continues to grow, resulting in falling airfares and increasing demand, particularly in emerging economies. Airlines continue to balance customer expectations for high levels of service while striving to maintain profitability and market share. This situation is further complicated by the demand for continual safety improvements and efficiency increases. These drivers have led to substantial research into technologies that predominantly strive to make aircraft operations more efficient, including biofuels, light-weight materials, more aerodynamic designs and advancements in air traffic management. Despite the advances made in all of these areas, Melis et al. (2018) demonstrate that a limited amount of research has explored the issues associated with anthropometrical changes in commercial aviation passengers, which is a key factor affecting the performance of commercial aircraft.

Fuel expenditure is a significant cost for airlines. Global fuel demand is expected to rise by 1.9% annually between 2008 and 2025 (Chèze et al. 2011). Conjunctly, as fuel usage increases, so does the greenhouse emissions produced by aircraft. The International Civil Aviation Organisation (ICAO) estimates that for every kilogram of aviation fuel burnt, 3.157 kg of carbon dioxide emissions are produced (ICAO 2014). Surprisingly, only a few studies have explored the effects of the relationship between aircraft fuel burnt and passenger weight.

Dannenberg et al. (2004) estimate that 1.3 billion litres of extra fuel was burnt as a result of excess weight in the decade between 1994-2004 in the US. A comprehensive study by Tom et al. (2014) of the US domestic transport systems during 1970–2010 shows that 95.2 billion litres of extra fuel was required by the domestic aviation sector as a result of excess passenger weight. This resulted in a net output of 238 billion metric tonnes of additional greenhouse emissions from US$37 billion (adjusted to 2012) of extra fuel. Yin et al. (2015)

explore the greenhouse emissions produced by international flights for selected Australian routes using actual passenger and cargo data from airlines. Their study compares aircraft and airline frequency and determines that greenhouse emissions rely not only on aircraft type and passengers, but also on cargo payload.

A short study was conducted using the methods by Tom et al. (2014) to explore the Australian domestic commercial aviation sector (the full conference paper is presented in Appendix 12). Ultimately, the study concludes that an estimated 561 kilotonnes of fuel was consumed between 1990 and 2014. Over this period, a total of 15.8 tonnes of excess passenger weight was transported at a cost of A$411.7 million dollars and produced 1.7 million tonnes of equivalent CO_2.

Various studies have explored fuel-saving measures for the different phases of a flight. Fuel savings during the ground phase can vary greatly between various airport layouts through improved ground operating procedures (Khadilkar & Balakrishnan 2012); for example, taxi scenarios consisting of multiple stops and starts can experience 18% higher fuel requirements (Nikoleris et al. 2011). Aircraft can be held on the ground for a considerable time, and pilots often request a single-engine taxi to save fuel. Fuel savings have also been explored during the climb and descent phases (Soler et al. 2012; Slater 2002). However, these savings are explored from an operational point of view. Ultimately, the cruise portion of the flight consumes most of the fuel depending on the range. Dalmau and Prats (2015) highlight that for a continuous cruise climb profile phase, fuel savings range from 0.5% to 2% for a narrow-body aircraft, while for a wider-body aircraft, potential savings are between 1% and 2%. In the same way, Turgut et al. (2014) demonstrate that a reduction of one tonne of aircraft mass can result in 15–21 kg less of hourly fuel consumption.

Kaivanto and Zhang (2018) develop a new metric for idealised optimal flight segmentation based on the Breguet range equations and the weight model presented by Küchemann (1978). Their approach verifies the conventional representation of the payload-fuel-efficiency metric and complements the model with new findings. The payload-fuel-efficiency metric proposed by these authors gives direction on comparing the efficiency levels of multiple aircraft with different design ranges, including aircraft that can be grouped to serve a flight route containing multiple segments. Similarly, Hileman et al. (2008) incorporate the specific energy of aviation fuel into the payload-range efficiency metric to highlight the energy costs for a given range and payload. They highlight that, as a result of the advent of new technologies, there was a 51% increase in payload-fuel-energy efficiency between 1991 and 2007.

Understanding the demographic composition of the passenger payload can play an important role in understanding the performance characteristics of an aircraft. For example, some airlines operate fly-in, fly-out (FIFO) operations. In this context, FIFO operations primarily consist of charter flight operations that transport workers to remote locations such as mines and off-shore oil platforms. Generally, FIFO workers are predominantly male and are characterised as being more overweight than the public and other industry sectors (Barclay et al. 2013). In a study by Joyce et al. (2013), 79.3% of the FIFO workers surveyed were either overweight or obese. This proportion is higher than the average of 56% in the NHANES 2013–2014 data. Aircraft operated for FIFO missions are generally narrow-bodied 90–150 seat aircraft such as Boeing 717, Embraer 170/190 and Fokker 100. In an emergency, these aircraft carry large FIFO workers who may have the added difficulty of exiting the aircraft through the emergency overwing exits, which are often smaller than those on larger narrow-bodied aircraft.

Similar to FIFO operations, airlines that provide contracts for transporting military personnel have to consider the difference in additional carry-on weight of individual military equipment. In most cases, this additional carry-on weight may not match the civilian standards being used by the charter airline. One such instance was that of Arrow Air in 1988 in Gander, Canada. Part of the cause of the fatal crash was that the pilots estimated the military personnel weight using standard passenger weight issued for civilian flights. The consequence was that the pilots underestimated the weight and thus failed to calculate the correct thrust required for take-off and take-off distance (CASB 1988).

The opposite can also be true; pilots may overestimate the passenger payload, causing incorrect trim conditions and resulting in increased fuel burn as a result of drag from incorrect attitude settings. One such incident occurred on a Qantas flight in 2014 that was carrying a large number of school children. In this event, the pilots were not aware that the children were aboard and subsequently calculated the passenger weight using adults. It was only during lift-off that the pilots noticed that the aircraft was nose heavy, as the children were seated at the rear of the cabin. As a result, the pilots exceeded the lift-off speed calculated by 25 kt and potentially used more runway distance (ATSB 2014). A study by Van Es (2007) surveyed occurrences relating to weight and balance issues of aircraft and noted from the collated data that 1.9% of passenger flights had incorrect payload information. A notable incident was that of Midwest Airlines Flight 5481 in 2003, which experienced a tail-heavy attitude during take-off and subsequently stalled and crashed as a result of improper weight and balance. The investigation noted, in part, that a contributing factor was the inaccurate weight estimation of the passengers (NTSB 2004). As part of the recommendations, the NTSB recommended that passenger weight standards should be updated. Weight and balance is a key factor in determining the stability and performance of the aircraft. Knowledge of the centre of gravity position relative to the mean aerodynamic centre enables the pilots to elevate the moment created by setting the correct trim condition. It has been noted that pilots rely heavily on standard passenger weight estimators for weight and balance and that an in-flight centre of gravity position estimator could be used to improve cruise flight trim and fuel savings (Chaves et al. 2018).

The literature has not explored the detailed effects of aircraft flight and ground performance characteristics concerning passenger weight changes. Aircraft experience different conditions for each consecutive flight, particularly for characteristic change, depending on the weight of the aircraft. Manufacturers provide airlines with detailed performance charts and data in aircraft manuals, technical documents and onboard software packages to calculate flight performance. These software packages calculate everything from arrival to departure, including ground characteristics such as take-off distance, lift-off and landing speeds and distances, as well as flight characteristics such as climb thrust, cruising speed and distances, and fuel consumed.

Although aircraft experience different passenger payloads for consecutive missions, the long-term implications of increasing passenger weight changes have not been analysed. This model uses established analytical methods to explore the effects of passenger weight change on selected aircraft mission performance attributes. Three types of aircraft will be explored: narrow-body Airbus A320, wide-body Airbus A330-200 and turboprop aircraft Avions de Transport Regional (ATR) ATR-72. This study aims to answer two questions related to passenger weight and obesity: How does the current obesity environment affect selected flight parameters regarding the current standard weights recommended by leading national aviation regulatory authorities? How do different scenarios of varying obesity prevalence affect the same selected flight parameters?

5.3 Anthropometric and Aircraft Data

5.3.1 Data Sources

The model presented is based on data collected from various sources, such as aircraft handling documents for aircraft weights, the ICAO (2017) engine emissions databank for engine information (e.g., maximum thrust and fuel flow at particular phases of flight at certain thrust levels) and reference literature on aircraft performance, including Sadraey (2017), Filippone (2012), Niţă (2008), Howe (2000), Eshelby (2000) and McCormick (1995).

These texts provide examples and case studies of particular aspects of flight that can be compared to verify the analysis developed in this study. Additionally, the literature cited in Section 5.2 contributes with some examples for comparison purposes. A flight plan for an A320 flight between Singapore and Male (SIN-MLE) was obtained from an undisclosed airline source and used to validate the analytical aircraft model. This flight flew 3,060 km, used 11.6 tonnes of fuel and carried 13.9 tonnes of payload. Additional comparisons are made using the Airbus-issued Aircraft Characteristics—Airport And Maintenance Planning document for the A320 and A330 aircraft (Airbus, 2014, 2015).

The characteristics of the population weight and obesity profiles were obtained from the NHANES 2013–2014 report issued by the CDC (2015) in the US. Additional global data were sourced from the Global Health Observatory Data from the WHO (2016) and the NCD Risk Factor Collaboration (2016a), in which individual country data are divided into several categories based on regions (see Table 2-3).

5.3.2 Passenger Demographic Characteristics

The passenger demographic characteristics models presented in Section 4.4 are applied to determine the passenger payload (Section 4.4). These models describe the current situation of obesity prevalence at current levels and incorporate changes in overall obesity prevalence using a sample population from NCD Risk Factor Collaboration (2016a) with constant BMI category ratios.

5.3.3 Aircraft Characteristics

Three types of aircraft are examined in this study: narrow-body Airbus A320, wide-body Airbus A330-200 (A330-200) and turboprop aircraft ATR-72. The aircraft characteristics are presented in Table 5-1. These aircraft are frequently used aircraft platforms that are in service by many airlines around the world. The model presented herein explores the flight characteristics from a single take-off to landing cycle, excluding loiter and taxi. The following assumptions are not considered, additional cargo, headwinds and tailwinds, additional fuel for holding patterns and alternative airports. Similarly, regulatory mandated fuel reserves and International Standard Atmospheric conditions are observed. The characteristics calculated in Table 5-2 are derived from methods outlined by Howe (2000), such as TSFC and lift-to-drag ratio, which are then compared with the values given by Babiklin (2002) and Roskam (1985).

Table 5-3 Key aerodynamic and propulsive characteristics of the three aircraft types considered in this study

Characteristic	Narrow-body	Wide-body	Turboprop
Aircraft	A320[1]	A330-200[2]	ATR 75[3]
Capacity	180	267	70
Maximum Take-off Weight (MTOW) (tonnes)	73.5	238	23
OEW (tonnes)	41.3	120.2	13.5
Wing Span (m)	35.8	60.3	27.05
Wing Area (S) (m^2)[8]	122.0	361.6	61.0
Aspect Ratio	10.51	10.06	12.00
Zero-Lift Drag Coefficient (C_{Do})[6]	0.01296	0.0123	0.0274[7]
Induced Drag Coefficient (k)[6]	0.0422	0.0447	0.0342[7]
Cruise Mach Speed (M)	0.79	0.82	0.42
Engine Model	CFM56-5b	Trent 700	P&W PW127[5]
Maximum Thrust per engine (T_0)[4] (kN)	117.9	299.1	
Shaft Horse Power per engine (P)[5] (HP)			2,132
Bypass Ratio (β)[4]	5.9	5.07	
Propeller Efficiency (η)[7]			0.859
Thrust Specific Fuel Consumption[6] (c_{TF}) ($NN^{-1}s^{-1}$)	15.9×10^{-5}	16.2×10^{-5}	
Power Specific Fuel Consumption[5] (c_{TP}) ($NW^{-1}s^{-1}$)			85.0×10^{-7}
Idle Fuel Flow (kg s^{-1})[4] per engine	0.107	0.243	0.051[5]
Take-off Fuel Flow (kg s^{-1})[4] per engine	1.166	2.886	0.165[5]
Climb Fuel Flow (kg s^{-1})[4] per engine	0.961	2.353	0.139[5]
Descent Fuel Flow (kg s^{-1})[4] per engine	0.326	0.783	0.085[5]

[1] Airbus (2015)
[2] Airbus (2014)
[3] ATR DC/E (2014)
[4] ICAO (2017)
[5] Avions de Transport Regional (2001)
[6] Calculated values using methods from Howe (2000), pg.147
[7] Niţă (2008)
[8] Heinemann (2001)

5.4 Method for Passenger Payload and Fuel Fraction Relation

5.4.1 Passenger Payload

It is assumed that the model explores the effect of obesity of an adult population; therefore, aircraft are assumed to carry no passengers under the age of 18 years. The second assumption is that the demographic distribution of adults of the NHANES population mirrors the aircraft passenger payload population. The final assumption is that the aircraft has a 100% load factor. However, airline statistics show that load factors on domestic markets normally range from 75% to 85% (Arul 2014; Mazarrati et al. 2009).

The total weight of the passenger payload (W_{pax}) is limited by the capacity of a given aircraft. Knowing the proportion of the particular BMI group and the average weight of that group, the total weight for that BMI group aboard the aircraft can be determined using Eq. 5.1, where *N* is the aircraft passenger capacity. It is important to note that the value of $NP_{i(A,G)}$; where *A* is age, *G* is gender and *i* represents a BMI category, will be an integer, because there cannot be a fraction person on an aircraft. If the value is rounded to the nearest smaller whole number, the value representing the number of passengers is underestimated for lower-capacity aircraft and towards the outer extremes of the BMI range:

$$W_{pax_{i(A,G)}} = NP_{i(A,G)}\bar{W}_{i(A,G)} \qquad \text{Eq. 5.1}$$

Once the weight for the individual category is calculated, the total sum of the passenger payload can be determined using Eq. 5.2:

$$W_{pax} = W_{(BMI>25)} + W_{(BMI<25)} \qquad \text{Eq. 5.2}$$

Where,

$$W_{(BMI>25)} = \sum\nolimits_{i=4,5,6,7} W_{pax_{i(A,G)}} \qquad W_{(BMI<25)} = \sum\nolimits_{i=1,2,3} W_{pax_{i(A,G)}}$$

This study explores one set of conditions relating to BMI demographics. In each case, the underlining ratio between the higher BMI categories remained constant (i.e., the ratio of Under, Normal 1, Normal 2, Over, Obese 1, Obese 2 and Morbid remains the same). The model is capable of determining the payload (passenger) weight based on any given aircraft capacity and total obesity prevalence. Therefore, conducting the study in this manner does not take into account the periodic changes of the various BMI categories, because the scope of this study is to compare the implications of current obesity prevalence trends using current passenger weight standards.

Additional passenger payload scenarios using standard weights based on the ICAO, FAA, EASA and CAA UK are used to establish a baseline comparison. ICAO uses a standard 80 kg per passenger regardless of passenger gender or ratio. FAA uses a 60:40 male-to-female ratio at 83 kg and 73 kg respectively. EASA establishes weights of 95 kg and 75 kg for males and females respectively, while CAA UK has male and female weights of 88 kg and 70 kg respectively. An additional estimation of passenger baggage (W_{BAG}) is added to the overall payload, assuming that each item of luggage is 25 kg and that 70% of passengers take one bag and 30% take two bags. The model assumes that no additional air freight or cargo is carried for simplicity purposes. The payload weight is added to the operational empty weight (OEW) of the aircraft to determine the zero-fuel weight (ZFW) (Eq. 5.3). In an optimal situation, at the end of a flight, the aircraft will ultimately have the exact weight consisting of the reserve fuel (if any) plus payload and the OEW. Figure 5-1 shows the passenger payloads calculated for each aircraft at the different obesity prevalence levels.

$$ZFW = OEW + W_p + W_{BAG} \qquad \text{Eq. 5.3}$$

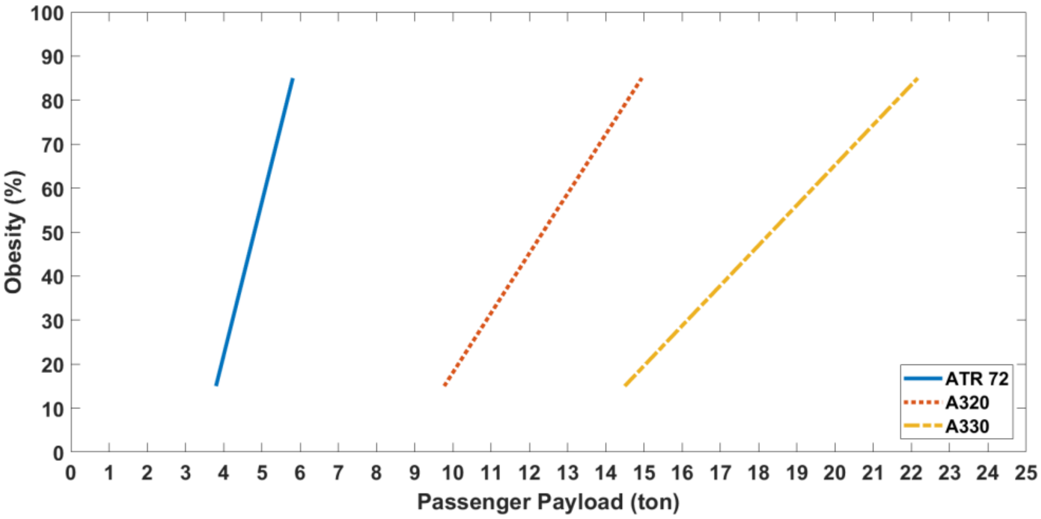


Figure 5-1 Aircraft passenger payload for the three aircraft at various obesity levels

5.4.2 Fuel Fraction, Cost and Emissions

An aircraft's range performance is often determined by the non-dimensional factor known as the fuel fraction or zeta value (ξ). Knowing that the fuel fraction must be the same as the change in weight, ξ can be determined from Eq. 5.4. Thus, the fuel fraction value can be used to illustrate the effects of payload weight variations on the range of an aircraft:

$$\frac{W_j}{W_i} = 1 - \frac{\Delta W}{W_i} = 1 - \xi \qquad \text{Eq. 5.4}$$

Substituting the assumed final weight of the aircraft as the ZFW from Eq. 5.3 into Eq. 5.4, the initial aircraft weight can be determined from Eq. 5.5:

$$W_i = \frac{ZFW}{1-\xi} \qquad \text{Eq. 5.5}$$

The fuel used by the aircraft (W_f) can be calculated either from fuel flow (Q), time (t) or directly from the fuel fraction (Eq. 5.6):

$$W_f = Q_i t = W_i \xi \qquad \text{Eq. 5.6}$$

The fuel price is updated regularly and can be found on numerous online sources. An October 2018 listed fuel price of US$751.12 per metric tonnes was used in this study (IATA 2018). Fuel cost is calculated using Eq. 5.7, where i represents a different flight phase. Similarly, the pollutants can be calculated using Eq. 5.8 using the emissions index (EI_i) listed in the ICAO engine emissions databank, which is presented as a unit of a pollutant for a unit of fuel burnt, where *i* represents the different pollutants.

The ICAO databank provides engine performance and emissions data acquired from full-scale engine tests at sea level for the idle, climb, descent and take-off segments of flight. For most jet and turbofan commercial engines, it provides values of fuel flow (kgs^{-1}) and emission indices (grams of pollutant emitted per kilogram of fuel burnt) taken at 7%, 30%, 85% and 100% rated thrust outputs. The pollutants included in the databank are hydrocarbons, carbon monoxide and nitric oxides. Further, it was considered that 3.157 kg of CO_2 is emitted for each kilogram of aviation fuel burnt to estimate the total emissions associated with the cruise flight segment (ICAO 2014):

$$Fuel\ Cost = \sum_i W_{f_i} f_{price} \qquad \text{Eq. 5.7}$$

$$Emissions = \sum_i W_f EI_i \qquad \text{Eq. 5.8}$$

5.5 Method for Aircraft Performance Calculations

A performance model was developed to investigate the effects of passenger weight change on mission performance. The effects of passenger obesity were predicted on the aircraft for cruise range, climb and descent, and take-off and landing performance (see Figure 5-2).

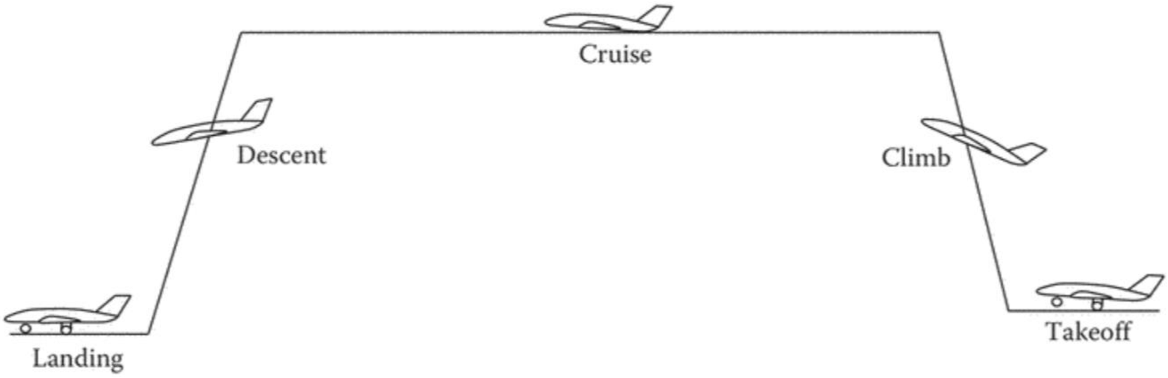


Figure 5-2 Main phases of an aircraft's flight trajectory (Sadreay 2017)

5.5.1 Aircraft Range during Cruise

There are three types of cruise regimes; constant lift coefficient and velocity; constant lift coefficient and altitude; and constant velocity and altitude. For this study, only the cruise regime of constant velocity and constant altitude will be explored. The developed model aims to explore changes in flight conditions whereby the only variable is aircraft payload variations resulting from obesity. Thus, certain parameters—particularly Mach speed and altitude—are kept constant.

5.5.1.1 Aerodynamic Forces

In straight-level flight, the aircraft is said to be in a state of equilibrium considering the four main forces depicted in Figure 5-3. This means that the lift force is equal to the weight force and the drag force is equal to the thrust force. The lift coefficient is calculated using an estimated take-off weight (in this case, maximum weight take-off [MTOW]) and the velocity at altitude (Eq. 5.9). The drag coefficient and lift-to-drag ratio is then calculated using Eq. 5.10 and Eq. 5.11, respectively:

$$C_L = \frac{2W}{\rho S(V^2)} \text{, Eq. 5.9} \quad C_D = C_{Do} + kC_L^2 \text{, Eq. 5.10} \quad E = \left(\frac{C_L}{C_D}\right) \qquad \text{Eq. 5.11}$$

Since drag is equal to thrust during the cruise, the available thrust can be obtained by Eq. 5.12:

$$D \approx T = \Delta T_o \left(\frac{\rho}{\rho_o}\right)^i \left(\frac{M}{M_o}\right)^{M_{exp}} \qquad \text{Eq. 5.12}$$

Where T is the available thrust, T_o is the maximum thrust produced by the engine at sea level, i is a factor determined by altitude (below 11,000 m i=1, above 11,000 m i=1.2), Δ is the throttle setting, ρ is the air density at a given altitude and ρ_o is the corresponding sea level value. M_o is a reference Mach number until which T can be kept in the maximum value for that altitude. M_{exp} is the thrust versus speed dependence factor that describes the aircrafts performance; a value of M_{exp}=1 represents a turboprop engine while a value of M_{exp}=0 represent a turbojet. A turbofan engine may sit somewhere in between these values, this model assumes a M_{exp}=0.75. This value is selected to highlight improved engine technologies that engine performance for advanced modern high-bypass turbofan engines may experience in the past decades. A value of M_{exp}=1 means that the bypass ratio is very high to such an extent that the operation of the engine can be compared with that of a propeller-driven engine. The model presented assumes a known ZFW calculated from the OEW plus the calculated payload weight based on BMI prevalence.

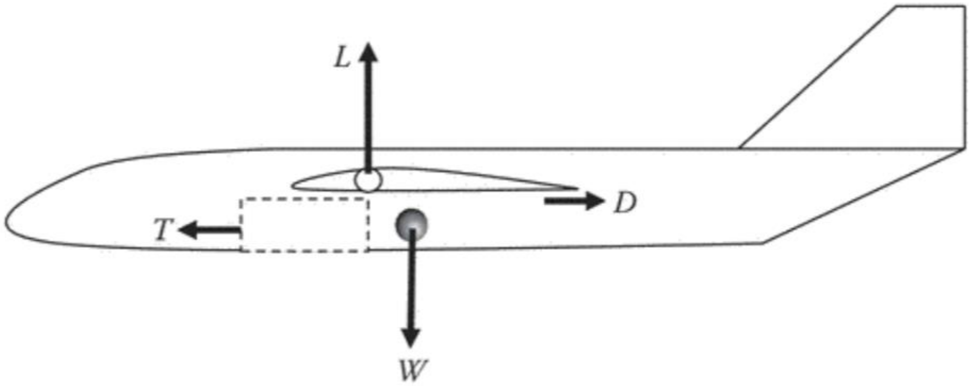


Figure 5-3 Forces on an aircraft in level flight (Sadreay 2017)

5.5.1.2 Range equation

The range models described stem from the Specific Range (SR), Eq. 5.13a and Eq. 5.13b for turbofan and turboprop aircraft respectively. SR is the distance flown divided by the amount of fuel consumed. Then, by integrating the SR over the weight of the aircraft and multiplying both the numerator and denominator by the lift force, the resultant formula is the Breguet range equation (Eq. 5.13c):

$$SR_{TF} = \frac{dx}{dW} = \frac{Vdt}{cTdt} = \frac{V}{cD} \qquad \text{Eq. 5.13a}$$

$$SR_{TP} = \frac{dx}{dW} = \frac{Vdt}{cPdt} = \frac{\eta Vdt}{cTVdt} = \frac{\eta}{cD} \qquad \text{Eq. 5.13b}$$

$$X = \left(\frac{E}{c}\right) \int_{W_1}^{W_2} V \frac{dW}{W} \qquad \text{Eq. 5.13c}$$

Thus, integrating the Breguet range equation yields Eq. 5.14 for a turbofan aircraft, whereas Eq. 5.15 is used for a turboprop aircraft:

$$X_{\mathrm{TF}} = \left[\left(\frac{2VE_{max}}{c_{TF}}\right)\right] \tan^{-1}\left(\frac{E\xi}{2E_{max}(1-kC_L E\xi)}\right) \qquad \text{Eq. 5.14}$$

$$X_{\mathrm{TP}} = \left[\left(\frac{2\eta E_{max}}{c_{TP}}\right)\right]\left[\tan^{-1}\left(\frac{2\frac{ZFW}{(1-\xi)}}{\rho V^2 S\sqrt{C_{Do}/k}}\right) - \tan^{-1}\left(\frac{2ZFW}{\rho V^2 S\sqrt{C_{Do}/k}}\right)\right] \qquad \text{Eq. 5.15}$$

Where V is velocity, E is lift-to-drag ratio, c_{TF} is thrust-specific fuel consumption (TSFC) and c_{TP} is power-specific fuel consumption (PSFC), ξ is fuel fraction, k is induced drag factor, ZFW is zero-fuel weight and η is propeller efficiency. The maximum lift-to-drag coefficient (E_{max}) is given by Eq. 5.16:

$$E_{max} = \frac{1}{\sqrt{4kC_{Do}}} \qquad \text{Eq. 5.16}$$

5.5.1.3 Specific Fuel Consumption—Thrust and Power

The reported fuel flows in the ICAO databank are presented for each phase of the landing/take-off cycle and do not provide cruise fuel flow data. Thus, TSFC needs to be calculated for the cruise segment. TSFC is dependent on Mach, altitude and engine bypass ratio. Howe (2000) presents a method for calculating TSFC for a turbofan based on Mach, altitude and engine bypass ratio (Eq. 5.17). The values of TSFC in Figure 5-1 are calculated from Eq. 5.17 for an altitude of 36,000 ft and a Mach listed in Figure 5-2 for each turbofan aircraft for the respective scenario. The PSFC for the turboprop aircraft is given by ATR (2001) and is shown in Figure 5-1:

$$c = c'(1 - 0.15\beta^{0.65})(1 + 0.28(1 + 0.063\beta^2)M)\left(\frac{\rho}{\rho o}\right)^{0.06} \qquad \text{Eq. 5.17}$$

Where c' is approximate to 20 mg $N^{-1}s^{-1}$ (Howe 2000), β is the bypass ratio and M is the Mach number.

5.5.2 Climb and Descent

The typical profiles of aircraft require the pilot to make step speed and altitude changes during the climb and descent manoeuvres. However, for this study, a continuous climb and descent profile is analysed. Figure 5-4 illustrates the forces of both phases of flight. During the climb, there is a component of the weight forces that must be overcome by the thrust force. During the descent phase, the weight forces provide additional support to the thrust force.

The ability to climb or descend relies on the excess power available, which is the difference of the power available (thrust component) and the power required (drag component). The rate of climb (ROC) for the turbofan and turboprop are determined using Eq. 5.18a and Eq. 5.18b, respectively. The rate of descent (ROD) is present when ROC has negative values:

$$ROC_{TF} = \frac{(TV - DV)}{W} \qquad \text{Eq. 5.18a}$$

$$ROC_{TP} = \frac{(P\eta - DV)}{W} \qquad \text{Eq. 5.18b}$$

The total fuel used is then determined by multiplying the fuel flow by the time taken to climb, considering the fuel flow data for a particular engine type issued in the ICAO database. The time to climb (t_{clb}) is determined by Eq. 5.19, where *h* is the desired altitude, *x* represents the rate of either climb or descent and *i* represents the ROC or ROD at an increment of altitude:

$$t \;= \sum_{i=0}^{n} \left(\frac{\Delta h}{x_i}\right) \qquad \text{Eq. 5.19}$$

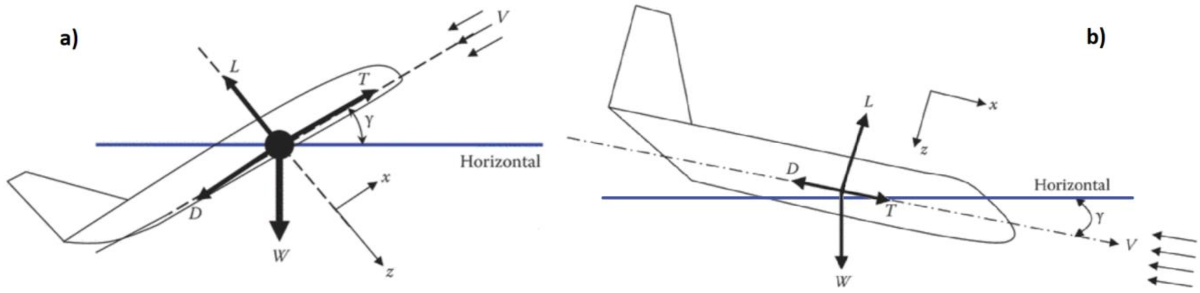


Figure 5-4 Force diagrams for a) climb flight and b) descent flight with thrust (Sadreay 2017)

5.5.2.1 Climb Calculations

The ROC characteristics are established by determining the take-off weight from a calculated fuel fraction value for a cruise situation. The calculated velocity for the climb phase with its associated Mach number for a given altitude is used to determine the thrust (Eq. 5.20 and Eq. 5.12). The Mach number associated with V_{ROC} for a given altitude is used in Eq. 19 to determine the thrust:

$$V_{ROC} = \left[\left(\frac{T}{3\rho C_{Do} S}\right)\left(1 + \sqrt{1 + \left(\frac{3}{\left[\frac{1}{\sqrt{4kC_{Do}}}\left(\frac{T}{W}\right)\right]^{2}}\right)}\right)\right]^{\frac{1}{2}} \qquad \text{Eq. 5.20}$$

The climb angle is determined by Eq. 5.21 (Sadraey 2017), where T is the thrust, k is the induced drag coefficient and W is the aircraft weight. Both the velocity and climb angle need to follow the procedure in Sadraey (2017).

$$\gamma_{ROC} = \sin^{-1}\left[\frac{T-D}{W}\right] = \sin^{-1}\left[\frac{T}{W} - \frac{\rho V_{ROC}^2 S C_{Do}}{2W} - \frac{2kW}{\rho S V_{ROC}^2}\right] \qquad \text{Eq. 5.21}$$

The descent model determines the ROD for a given landing weight and considering a given payload of obesity prevalence among passengers. A typical descent for transport aircraft involves some level of thrust to maintain airspeed. Thus, the model presented also assumes that thrust is being produced during the descent phase. The descent profile for this model is assumed to be a continuous descent flight path with constant deceleration from cruise speed to landing speed and a constant descent angle.

5.5.2.2 Descent Calculations

For this particular scenario, the known quantities of the initial condition are; V_i is equal to cruise velocity and a cruise altitude is assigned from the previous cruise calculations. The final condition consists of V_f being equal to the approach velocity for landing with a final altitude equivalent to the clearance height mentioned in Section 5.5.3. For the results presented, a 2° flight path angle was considered. The air distance was determined using Eq. 5.22, where h_i is the initial altitude and h_{i-1} is a lower altitude. Deceleration is obtained from Eq. 5.23, which applies to a particular phase of descent ranging from an initial altitude and corresponding speed (V_i) to a final altitude and speed (V_j), where a_x is the acceleration along the flight path and X is the distance along the flight path:

$$X = \sqrt{{h_i}^2 + \left(\frac{h_{i-1}}{\tan\gamma_{desc}}\right)^2} \qquad \text{Eq. 5.22}$$

$$a_x = \frac{V_j^2 - V_i^2}{2(X)} \qquad \text{Eq. 5.23}$$

Then, using Eq. 5.24, the speed at a given stage of altitude is determined. The lift component is calculated from Eq. 5.25 followed by the drag (Eq. 5.26) for descent by considering the lift coefficient obtained from Eq. 5.25:

$$V_{h_f} = \sqrt{{V_i}^2 + 2a\Delta h} \qquad \text{Eq. 5.24}$$

$$L_{desc} = W cos(\gamma_{desc}) \qquad \text{Eq. 5.25}$$

$$D_{desc} = \frac{1}{2}\rho V^2 S(C_{Do} + kC_L^2) \quad \text{Eq. 5.26}$$

The required thrust to maintain airspeed during descent is calculated from Eq. 5.27. Then, using Eq. 5.18a and Eq. 5.18b, the rate of descent is calculated for each aircraft type.

$$T_{R_{desc}} = D_{desc} - W sin(\gamma_{desc}) + m_{ac}a_x \quad \text{Eq. 5.27}$$

5.5.3 Take-off and Landing

Take-off and landing consist of three parts: an airborne phase, a rotation phase and a ground phase. Key velocities are based on the stall speed *(V_s)* (Eq. 5.28). V_1 or V_R =1.1V$_s$, V_{LO} and V_{TD} =1.2V$_s$, V_2=1.3V$_s$; these values are taken from Sadraey (2017), and similar approximations are expressed in Filippone (2012) and Eshelby (2000). They are based on FAR regulation Part 25, which also specifies that a transport aircraft must clear a 50 ft obstacle for the take-off and landing manoeuvres:

$$V_s = \sqrt{\frac{2W}{\rho S C_{l_{max}}}} \quad \text{Eq. 5.28}$$

A take-off/landing field distance (D$_Z$) is calculated in Eq. 5.29 as the sum of the distance travelled during the three phases; ground roll (X_{grd}), rotation (X_{rot}) and airborne phase until the clearance height (X_{air}):

$$D_z = \left(X_{grd} + X_{rot} + X_{air}\right)_z \quad \text{Eq. 5.29}$$

where *Z* is take-off or landing.

5.5.3.1 Take-off Run Distance Calculations (Xgrd)

Figure 5-5 illustrates the phase and speed of take-off. The primary parameter required to determine the aircraft's take-off speed relies on knowing the take-off weight and ambient condition (assumed to be the International Standard Atmosphere for this study). The weight can only be known once the flight range is determined. In the model presented, a take-off weight is chosen by selecting the appropriate zeta-range combination. Rearranging Eqs 5.14–5.15 from Section 5.5.1.2 for the fuel fraction yields Eq. 5.30:

$$\xi_i = \frac{B}{BkC_L E + E} \quad \text{Eq. 5.30}$$

where,

$$B = 2E_{max} \tan\left(\frac{X}{A_i}\right), i\ is\ TF\ or\ TP\ ;\ A_{TF} = \frac{2VE_{max}}{c} \text{ or } A_{TP} = \frac{2\xi E_{max}}{c}$$

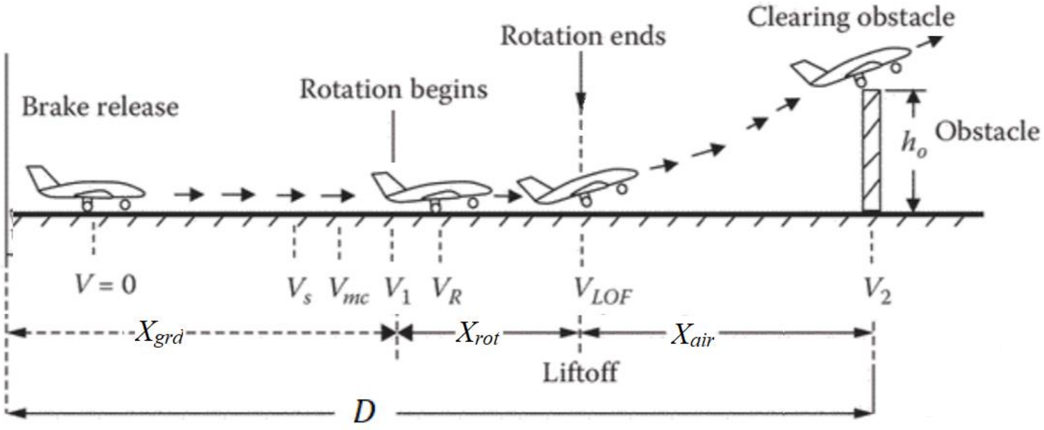


Figure 5-5 Segments and speed characteristics of the take-off phase (Sadreay 2017)

The resultant take-off weight is then calculated using the zeta value and a selected ZFW associated with the obesity passenger payload using Eq. 5.5 in Section 5.4.2. The manoeuvre speeds are determined using the take-off weight and stall speed (Eq. 5.28). The coefficients of drag (C_{DLO}) and lift (C_{LLO}) at lift-off are determined using the related speeds. The ground roll distance is then determined from Eq. 5.31:

$$X_{grd} = \left(\frac{1}{2B}\right) \ln\left(\frac{B}{B+AV_1^2}\right) \qquad \text{Eq. 5.31}$$

where,

$$A = \left(\frac{T_o}{\left(\frac{W_{to}}{g}\right)}\right) - \mu g \; ; B = \frac{-\rho S}{2\left(\frac{C_{LLO}}{g}\right)(1 - C_{DLO} - \mu C_{LLO})}$$

Where V_1 is the speed at the end of the ground roll, T_o is the net thrust, W_{to} is the take-off weight, g is gravity, ρ is air density, S is wing area, μ is the strip surface rolling friction coefficient and C_{iLO} is the lift-off coefficient.

5.5.3.2 Take-off and Landing Rotation Distance

Sadraey (2017) comments that the calculation to determine the distance travelled during the rotation phase is complex and suggests that using the V_{LO} multiplied by the time taken to rotate (Eq. 5.32) is a reasonable approximation. For transport aircraft, a timeframe of 3–6 s is recommended; hence, for this study, a rotation time of 3 s was considered:

$$\mathrm{X_{rot}} = \mathrm{t_{rot} V_{LO}} \qquad \text{Eq. 5.32}$$

5.5.3.3 Take-off and Landing Airborne Distance

The airborne distance covered is determined using Eq. 5.33 and Eq. 5.34, where T_{ab} is approximately 90% of T_o (Sadraey 2017), X_{ab} is the distance travelled on the ground, X'_{ab} is the distance travelled along the flight path, h_o (50 ft=15.24 m) is the clearance height and D_{ab} is the drag during the airborne phase:

$$X'_{air} = \left(\frac{W}{T_{ab}-D_{ab}}\right)\left[\frac{\left({V_2}^2-V_{LO}^2\right)}{2g} + h_o\right] \qquad \text{Eq. 5.33}$$

$$X_{air} = \sqrt{{X'_{ab}}^2 - h_o^2} \qquad \text{Eq. 5.34}$$

5.5.3.4 Landing Distance Calculations

The landing calculations in this model determine the field length for a given landing weight assumed to be ZFW for a given payload of obesity prevalence. The process of calculating the field length for landing is the reverse process of the take-off calculations. There are three phases to the landing: approach, flare and ground roll (see Figure 5-6). The same method is used to determine the specific landing speed as in the take-off procedure. The manoeuvre speeds are determined from Eq. 5.28. The coefficients of drag (C_{DLgrd}) and lift (C_{LLgrd}) at the point of landing are determined using the related velocities.

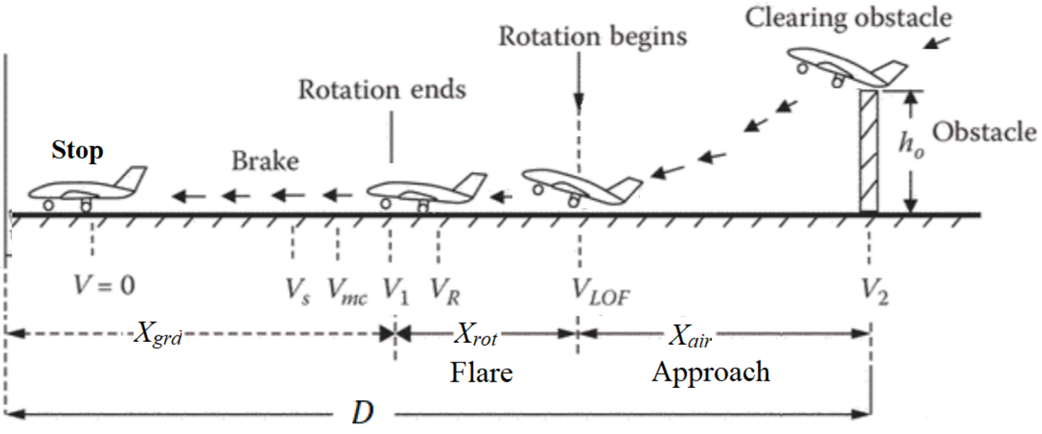


Figure 5-6 Segments and speed characteristics of the landing phase (Sadreay 2017)

The airborne distance covered is determined using Eq. 5.33 and Eq. 5.34; however, in this case, T_{ab} is zero because there is no thrust being produced. The touchdown follows the same method as the rotation phase (Eq. 5.34). The ground roll is determined by Eq. 5.35:

$$X_{L_{grd}} = \left(-\frac{W}{\rho S g\left(C_{D_{Lgrd}}-\mu C_{L_{Lgrd}}\right)}\right) \ln\left[\frac{\left(\left(\frac{1}{w}\right)(T_{rev}+F_B)+\mu\right)}{\left(\frac{1}{W}\right)(T_{rev}+F_B)+\mu\left(\frac{K_L^2}{C_{Lmax}}\right)\left(C_{D_{Lgrd}}-\mu C_{L_{Lgrd}}\right)}\right] \qquad \text{Eq. 5.35}$$

Where T_{rev} is the thrust produced from the thrust reverser (assumed 50% of T_o), K_L is the landing speed factor and F_B is the force resulting from braking.

The time spent during each take-off phase is calculated in Eq. 5.36, where ΔX_z is the change in distance, ΔV_z is the change in speed and Z is the ground, rotation or airborne phase. Then, using the fuel flow data for a particular engine type, the total fuel used is determined:

$$t = \sum_z \frac{2\Delta X_z}{\Delta V_z} \qquad \text{Eq. 5.36}$$

5.6 Results and Discussion

The results discussed in this chapter focus on a simplified particular mission for each type of aircraft: 1) the narrow-body aircraft mission profile consists of a range of 3,000 km flying at a cruise Mach of 0.79 at an altitude of 36,000 ft (FL360); 2) the wide-body aircraft mission profile with a range of 7,500 km flying at a cruise Mach of 0.82 at an altitude of 36,000 ft; and 3) the turboprop aircraft mission profile consisting of a range of 900 km flying at a cruise Mach of 0.42 at an altitude of 25,000 ft. Table 5-4 presents the results corresponding to the three aircraft for the performance factors using passengers' weights defined by the ICAO for the purposes of comparison with standardised weights issued by regulators in the US (FAA), Europe (EASA) and UK (CAA UK). In the absence of self-developed standards, many nations may opt to follow either of these regulators. Of the four regulators, the EASA updated its passenger weight standards in 2009 (Berdowski et al. 2009). Consequently, the results for aircraft using current passenger standards from the EASA are higher than those of the other regulators, which use lower standard weights.

Table 5-4 Calculated performance characteristics for three aircraft with specified flight parameters based on standard passenger weights from key aviation regulatory bodies

	Fuel Used (kg)	Fuel Cost (US$)	Emissions Produced (tonne)	Time to Climb (min)	Fuel to Climb (kg)	Take-off Distance (m)	Landing Distance (m)
A320: Range 3,000 km, Cruise altitude 36,000 ft, M=0.79							
ICAO	9,213.7	6,955.3	19.42	18.02	2,077.6	1,744.1	1,352.7
FAA	9,167.7	6,920.5	19.32	17.81	2,053.5	1,734.4	1,341.9
EASA	9,453.0	7,135.9	19.82	18.91	2,181.2	1,980.9	1,397.8
CAA UK	9,191.5	6,938.5	19.37	17.91	2,065.5	1,884.2	1,347.3
A330-200: Range 7,500 km, Cruise altitude 36,000 ft, M=0.82							
ICAO	46,704.7	30,873.7	129.24	15.05	4,249.4	1,850.7	1,338.2
FAA	46,647.1	30,830.6	129.06	15.01	4,236.7	1,856.7	1,334.8
EASA	47,187.0	31,234.7	130.75	15.43	4,356.6	1,906.4	1,366.3
CAA UK	46,647.1	30,830.6	129.06	15.01	4,236.7	1,850.7	1,334.8
ATR 72: Range 700 km, Cruise altitude 25,000 ft, M=0.42							
ICAO	1,441.1	1,087.9	2.88	23.62	2,724.3	1,408.7	997.9
FAA	1,434.2	1,082.6	2.86	23.16	2,671.0	1,384.8	1,008.6
EASA	1,471.9	1,111.1	2.94	25.70	2,963.5	1,689.0	1,052.7
CAA UK	1,437.6	1,085.2	2.87	23.39	2,697.5	1,396.7	1,003.3

5.6.1 Aircraft Capacity and Payload

Airlines tread a fine line between payload, range and fuel expenditure, and pilots have to estimate passengers' weight based on standard weights issued by the regulators, which do not necessarily accurately reflect operational circumstances. Further, many countries rely on either the regulations from the FAA, EASA or CAA UK. These countries generally lack the infrastructure or budget to carry out widescale passenger weight surveys such as those conducted in countries such as Australia and Canada, which have adequate resources to perform regular surveys. Table 3-4 presents a comparison of the average weights and regulatory standards for selected countries along with their obesity prevalence. Of the selected countries, St Lucia has the highest difference between average passenger weights and their standards, with a difference in mass of 9.3 kg for males and 13.6 kg for females.

As previously mentioned, obesity is on the rise; consequently, weight per passenger follows an identical increasing trend at a global scale. Currently, the highest prevalence of BMI centres around the overweight and obese categories; however, it is expected that this BMI prevalence will become more skewed towards the higher categories of obese and morbidly obese in the future. Gritsch et al. (2017) discuss that the Australian regulator standards became outdated within a decade of their inception. They also suggest using statistical health data on weight and obesity as a trigger to update the standards once the variance reaches 2%.

Regions 7, 8 and 9 (see Table 2-3) have less spread regarding obesity prevalence, which can be attributed to the fact that these regions encompass countries in Europe and the Americas. In these regions, there are diverse factors for different demographic ethnicities, leading to a change in the overall dynamic of the demography of the people, and therefore on the average weight (Bil & Hanlon 2016). As shown in Figure 5-7, the average weights from many countries in the listed regions (see Table 2-3) lie below the current weight standards from the key regulators.

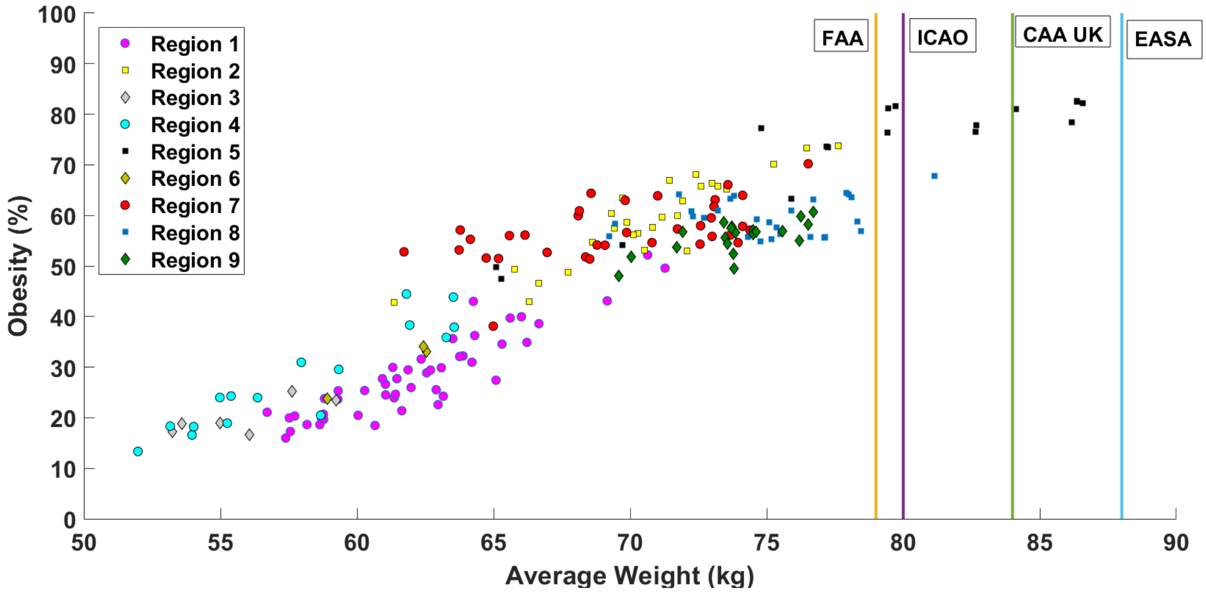


Figure 5-7 Global weight averages for countries separated into regions by obesity prevalence with regulator standard weights

Taking into account the different BMI categories, Figure 5-7 illustrates how the weight per change in obesity prevalence changes with aircraft capacity. The average weight of a passenger is based on the NCD Risk Factor Collaboration (2016a) data. By estimating the average weight in this manner, it is assumed that the typical aircraft demography is a sample representation of the wider population. A key factor that has not been considered is the relationship between obesity and disposable income. The aviation industry's measure for capacity growth is the gross domestic product of a nation. The passenger model developed in this study has not accounted for the effect of the type of people travelling on a given flight. For instance, low-cost carriers attract financially savvy passengers because they have lower airfares.

The data presented for NHANES represent the demographic situation of the US for 2013–2014, with the consensus that the US is a leading nation in the obesity epidemic. Other countries have distinct demographics depending on their social-economic contexts; some nations have a lower relevancies of obesity, like sub-Saharan Africa [28.21% ± 8.4], whereas other nations, such as those in Oceania [71.81% ± 10.1], have a higher relevancies at the more extreme end of the BMI spectrum (NCD Risk Factor Collaboration 2016c). Thus, the performance characteristics of specific aircraft types in those regions may vary greatly as a result of differences in passenger payloads. Figure 5-8 illustrates the number of additional weight changes resulting from a 1% increase in obesity for various aircraft capacities. It is evident that when aircraft capacity increases, more weight is added with a rise in obesity. Therefore, an aircraft with a capacity of 200 passengers will carry an extra 80 kg of passenger weight for every 1% rise in obesity prevalence.

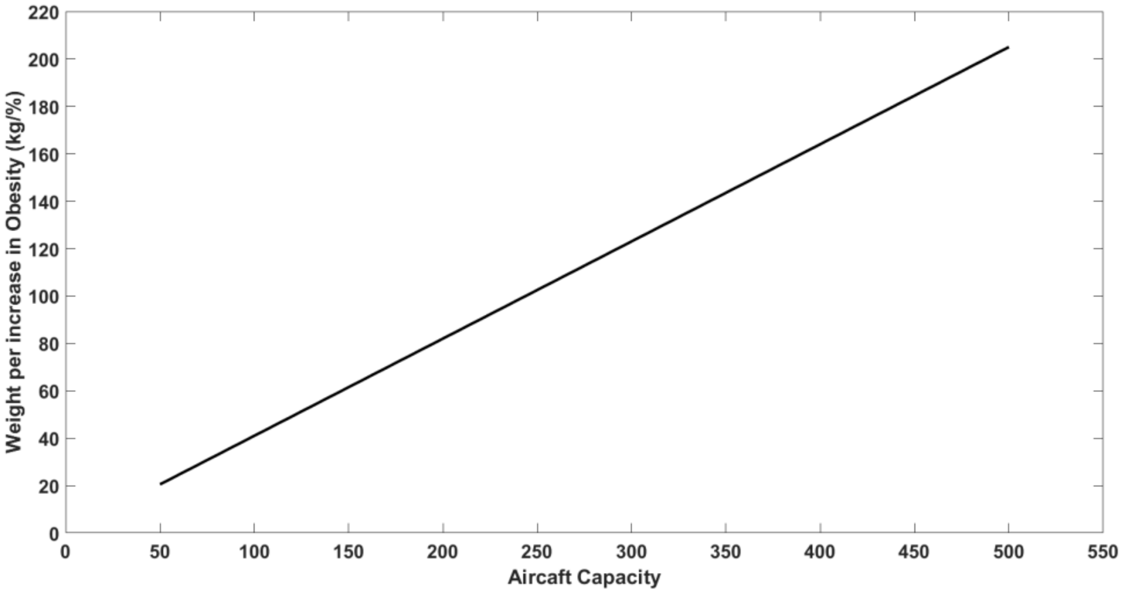


Figure 5-8 Passenger payload weight per BMI increment for the number of seats in an aircraft

5.6.2 Range

Determining the range of a flight relies on knowing exact weights to establish the required fuel. Unlike freight carriers, which can obtain accurate payload weight data, airline operations rely on estimating the passenger payload from standard weights from regulators, or they establish their estimations from surveys of airlines passengers. As a result of the average person becoming heavier and obesity prevalence varying between regions, the use of standard weights can lead to over or underestimations of the fuel necessary for a particular range requirement.

Figure 5-9, Figure 5-10 and Figure 5-11 present the range of the aircraft for various altitudes (flight levels, FLs) concerning different obesity scenarios, as well as additional information relating to passenger payload (W_p) and fuel weight (W_f). These ranges correspond to the maximum possible distance travelled for the payload and fuel combination for MTOW in each scenario. A common trend is that, as obesity prevalence increases, payload also increases, resulting in less available weight for fuel and consequently reducing the possible range. For the three aircraft, the difference between a higher and lower altitude is greater with lower obesity percentages compared with higher scenarios. This indicates that if a pilot has a flight plan for an assigned altitude range combination and decides to fly at a lower altitude, there will be less range as a result; nevertheless, it is common practice to request higher altitudes. It is interesting to note that at an obesity level of approximately 60%, the passenger payload weight equals the fuel weight (see Figure 5-9). The same point occurs at the 20% obesity level for the ATR 72 (see Figure 5-11). There is no point at which this crossover occurs on the A330-200 aircraft (see Figure 5-10). The A330-200 caters for long-range distances and therefore requires greater capacity for fuel (per weight) compared with the payload for the maximum possible range. In comparison, Table 5-5 shows the possible range for each aircraft with the standard passenger weight related to the three regulators from Table 3-4 and ICAO standard weight of 80 kg per passenger. As shown in Figure 5-7, the regulatory standard weights are higher than the average weights of many countries. When comparing the aircraft ranges from Table 5-5 to the corresponding figures in Figure 5-9, Figure 5-10 and Figure 5-11, the range capabilities of the aircraft are conservative. Under regulatory standards, the aircraft show a lower range potential equivalent to a payload with an obesity prevalence of greater than 80% for the turbofan and greater than 70% for the turboprop.

Table 5-5 Comparison of the range possible for the three types of aircraft between key aviation regulators at MTOW with a passenger fuel combination

Regulator	Passenger Payload (kg)	Fuel Weight (kg)	Maximum Range (km)
A320, FL360, Mach=0.79			
ICAO	14,400	11,865	5,684
FAA	14,040	12,225	5,502
EASA	15,894	10,371	4,756
CAA UK	14,220	12,045	5,593
A330-200, FL360, Mach=0.82			
ICAO	21,360	87,570	14,437
FAA	21,093	87,837	14,491
EASA	23,576	85,354	13,993
CAA UK	21,093	87,837	14,491
ATR-72, FL250, Mach=0.42			
ICAO	5,600	2,477	1,852
FAA	5,460	2,617	1,962
EASA	6,181	1,896	1,402
CAA UK	5,530	2,547	1,907

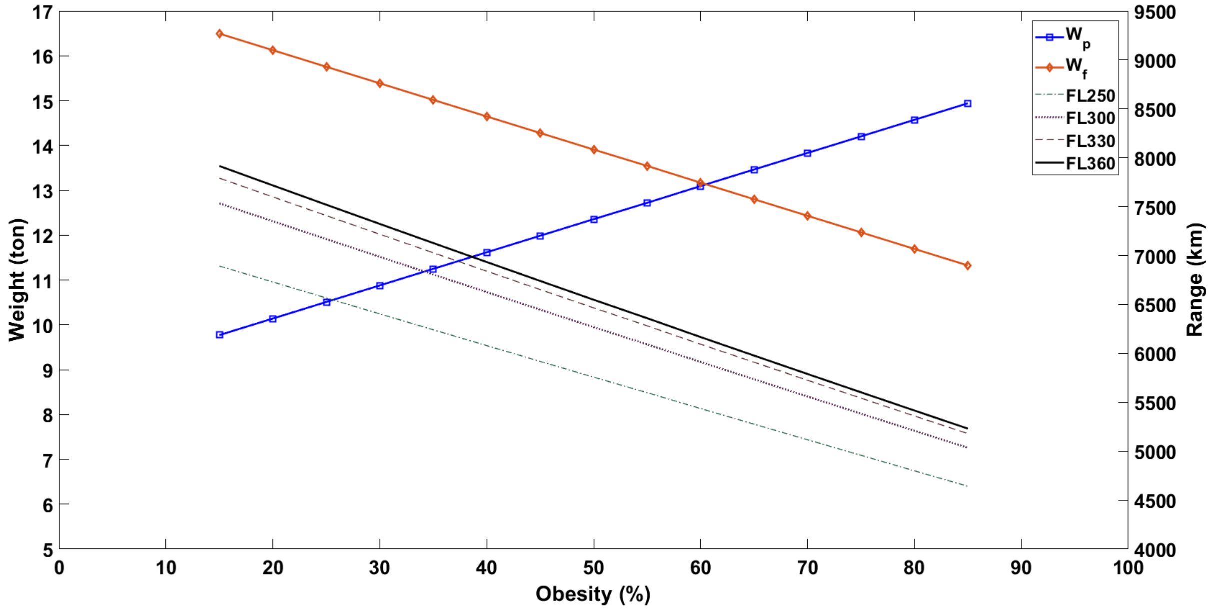


Figure 5-9 Maximum possible range at various altitudes for an A320, with MTOW for specified passenger payload and fuel weight combinations, over different obesity prevalence

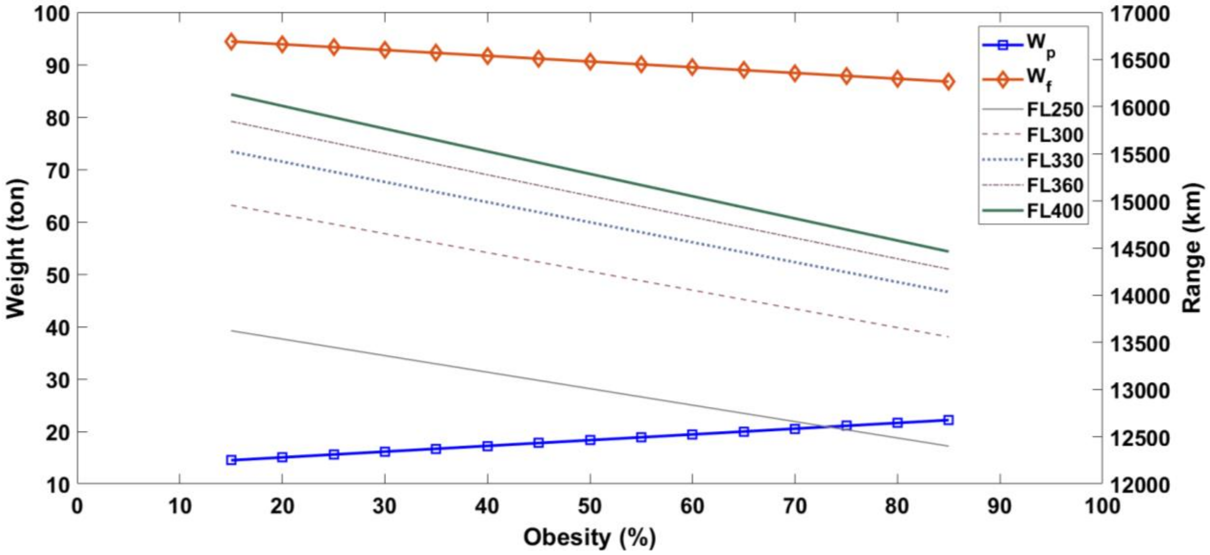


Figure 5-10 Maximum possible range at various altitudes for an A330-200, with MTOW for specified passenger payload and fuel weight combinations over, different obesity prevalence

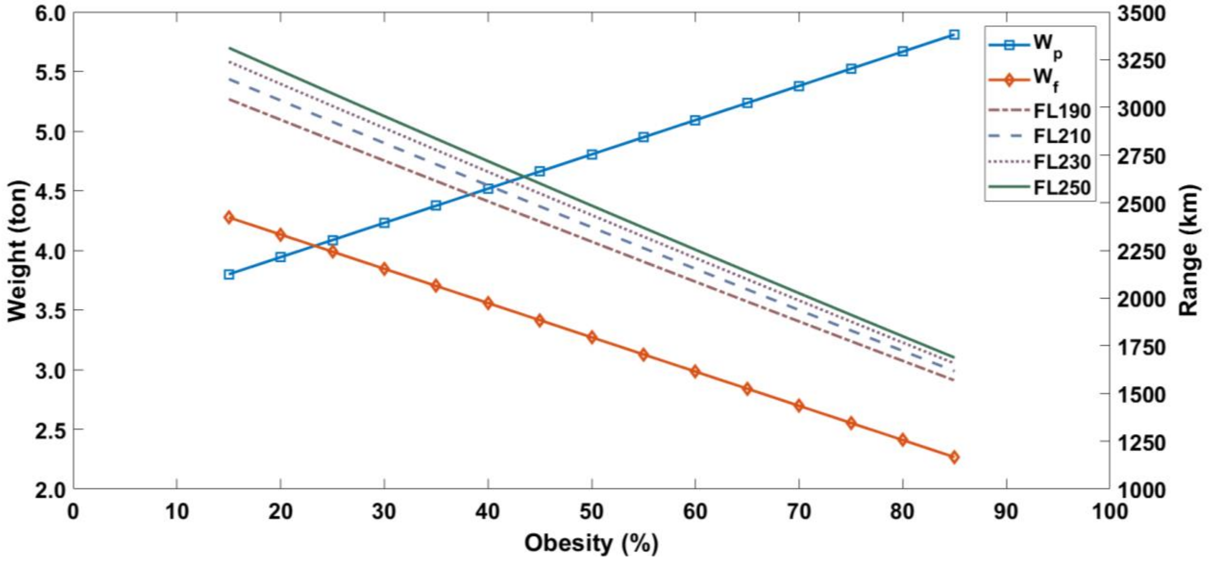


Figure 5-11 Maximum possible range at various altitudes for an ATR-72, with MTOW for specified passenger payload and fuel weight combinations over, different obesity prevalence

5.6.3 Climb

In most flights, the aircraft follows a step-climb procedure. In this situation, the aircraft will fly to an assigned altitude where it may level off. Then, after some time, the air traffic controllers will indicate to the pilot to change altitude and speed, resulting in many potential flight paths from that point onward. This model adopts a simplified approach by considering that the aircraft follows a continuous climb path between take-off and cruise.

Figure 5-12, Figure 5-13 and Figure 5-14 present the time to climb and rate of climb for two obesity scenarios (15% and 85%) for the three aircraft types considered herein. Only the two extreme scenarios are presented, because the variation of the rate of climb and time to climb is small for any other cases. As expected, the general trend illustrates that as obesity increases, the aircraft will take longer to climb to any altitude. Similarly, the lighter the aircraft, the higher the rate of the climb the aircraft can achieve. For example, an A320 will take 16 min to climb to an altitude of 36,000 ft for an 15% obesity case, whereas this time increases to 19 min for an 85% obesity scenario.

Similarly, the A330-200 will take 25 min for an aircraft with 15% obesity and 29 min with 85% obesity. Compared with the turbofan aircraft, the ATR-72 generally flies at lower altitudes. Assuming a climb up to 25,000 ft, the ATR-72 will take 23 min and 32 min for the 15% and 85% obesity cases respectively. Passengers’ weight change has a greater effect on the climb performance of the turboprop aircraft. That is, the results show that the effect of payload weight on the rate of climb and time to climb become less pronounced with the size and gross weight of an aircraft.

Data from the SIN-MLE flight showed a time of 33 min to climb to FL360, corresponding to 2.7 tonnes of fuel. The developed model calculated that it would take 25 min and 2.8 tonnes of fuel to achieve the same FL. The discrepancy in the time may be caused by the model considering a continuous climb profile, while it is highly likely that the flight above experienced a step-climb. Further, the difference in the higher fuel for the model can be attributed to the fact the ICAO engine databank fuel flow data are tested under a thrust condition of 85% maximum thrust. The SIN-MLE flight may have had a different power setting or other unknown aircraft characteristics (e.g., different engine model) that would likely lead to lower fuel consumption. Nevertheless, the calculated performance parameters are within expected values, which demonstrates the robustness of the model developed in this study.

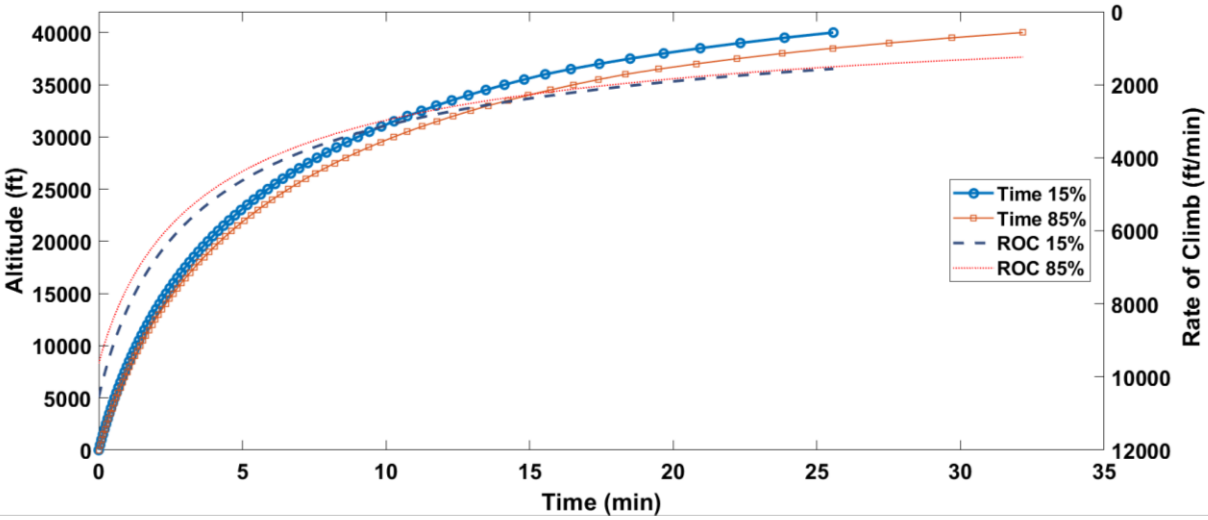


Figure 5-12 A320 time to climb and rate of climb for 15% and 85% obesity considering a fuel weight for 3,000 km range

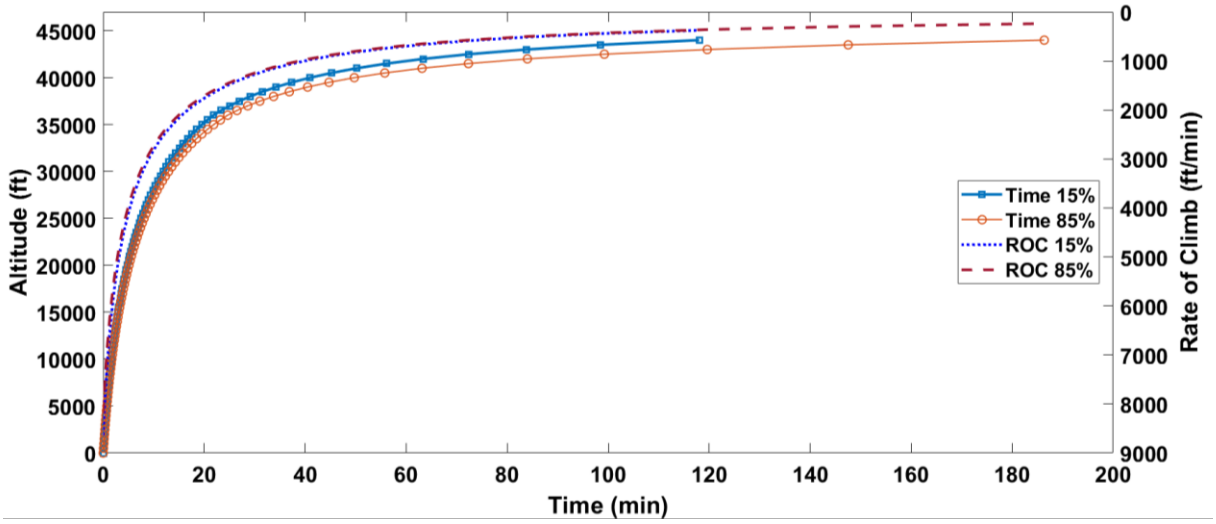


Figure 5-13 A330-200 time to climb and rate of climb for 15% and 85% obesity considering a fuel weight for 7,500 km range

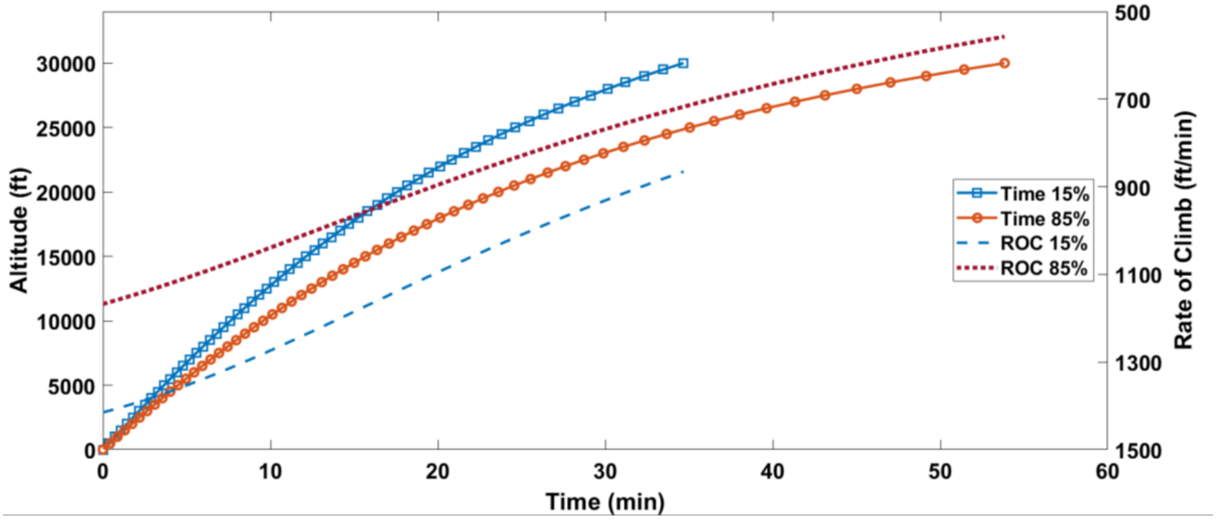


Figure 5-14 ATR 72 time to climb and rate of climb for 15% and 85% obesity considering a fuel weight for 700 km range

5.6.4 Take-off

The take-off phase is the most sensitive to the uncertainty around passengers' weight because any deviation from the calculations made by pilots can lead to exceeding the required take-off distance. Therefore, it is crucial that pilots have the accurate aircraft weight to determine the correct take-off performance characteristics of their aircraft for a particular flight condition. The upper limit of MTOW should not be exceeded to ensure a safe departure. At the MTOW, the model estimates that the A320, A330-200 and ATR-72 use 2,146 m, 2,793 m and 1,689 m of runway respectively. Using the same take-off weight for the A320 operating the SIN-MLE flight (i.e., 73,616 kg), the model predicts a take-off distance of 1,730 m, which is not far from the value obtained from the Airbus A320 handbook (i.e., 1,800 m). For the ATR-72 aircraft, both the example provided in Filippone (2012) and the results obtained from this model led to identical take-off distances (1,600 m) considering a take-off weight of 22,616 kg. These results demonstrate the accuracy of the model used in this study.

Figure 5-15, Figure 5-16 and Figure 5-17 illustrate the take-off distance required for different obesity prevalence situations and selected ranges. Both the A320 and ATR-72 aircraft have relatively close take-off distances for a different range of scenarios, whereas the A330-200 has a relatively wider variation of take-off distances across the considered range of scenarios. Another point is that comparing the different range of scenarios for the smaller aircraft shows that obesity prevalence has a greater effect when comparing the take-off distance for the two extreme obesity cases (i.e., 15% and 85% of obesity prevalence). The increase in the take-off distance can be as high as 300 m for the ATR-72, considering a target range of 1,000 km. For the A330-200 operating in high-income Western countries [59.67% ± 3.6], and considering a range of 12,500 m, the calculated take-off distance is 2,400 m. Comparing a region consisting of lower obesity, such as sub-Saharan Africa [28.21 ± 8.4], for a similar range, the same aircraft would only use 2,300 m of tarmac. This difference is approximately 100 m for close to 30% change in payload as a result of obesity. On high-capacity, short-haul routes (e.g., 2,500 km) in high population–density centres in East and Southeast Asia [57.82% ± 12.1] and high-income Asia–Pacific [61.31% ± 5.6], the same aircraft use only 1,370 m of tarmac. However, using standard passenger weights, the aircraft will use 1,400 m of runway for the same range.

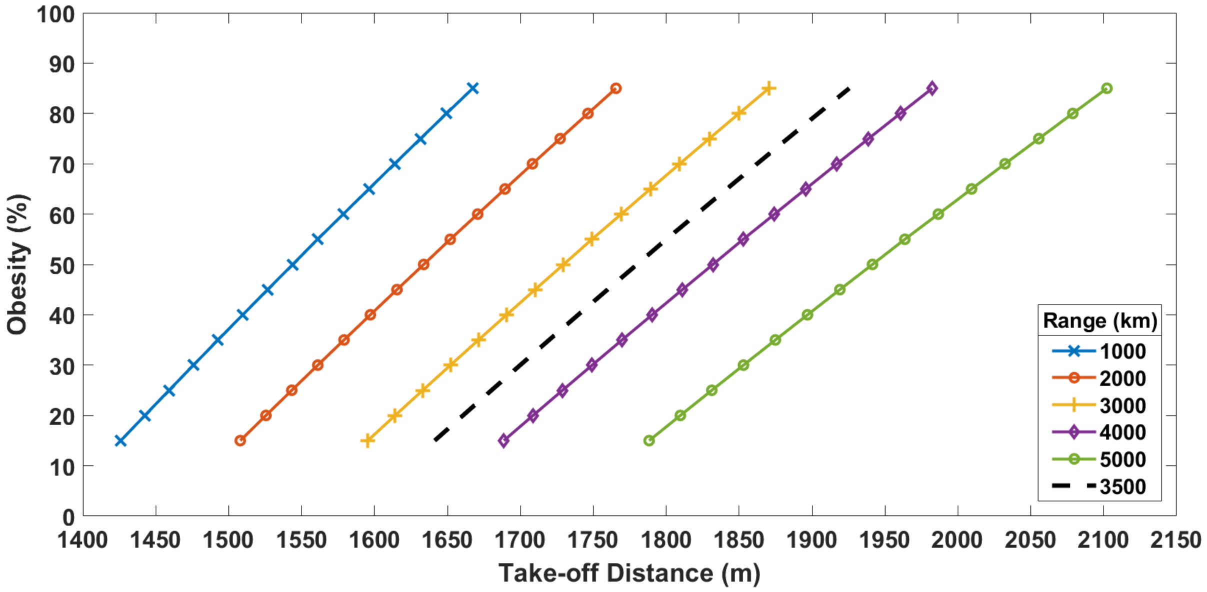


Figure 5-15 A320 take-off distance v. obesity prevalence for various ranges at FL360

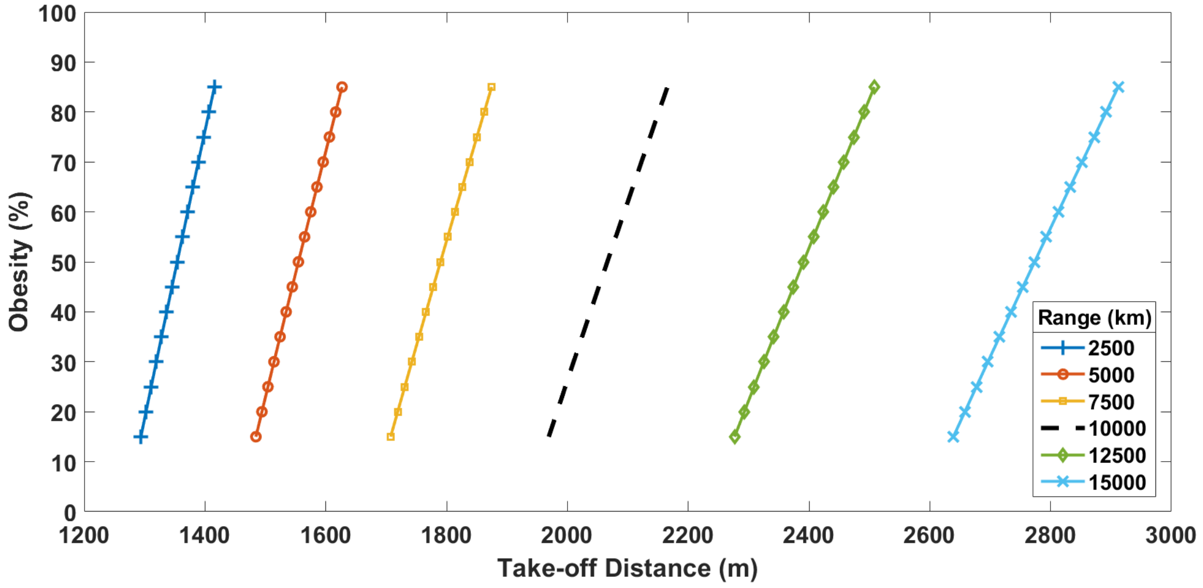


Figure 5-16 A330-200 take-off distance v. obesity prevalence for various ranges at FL360

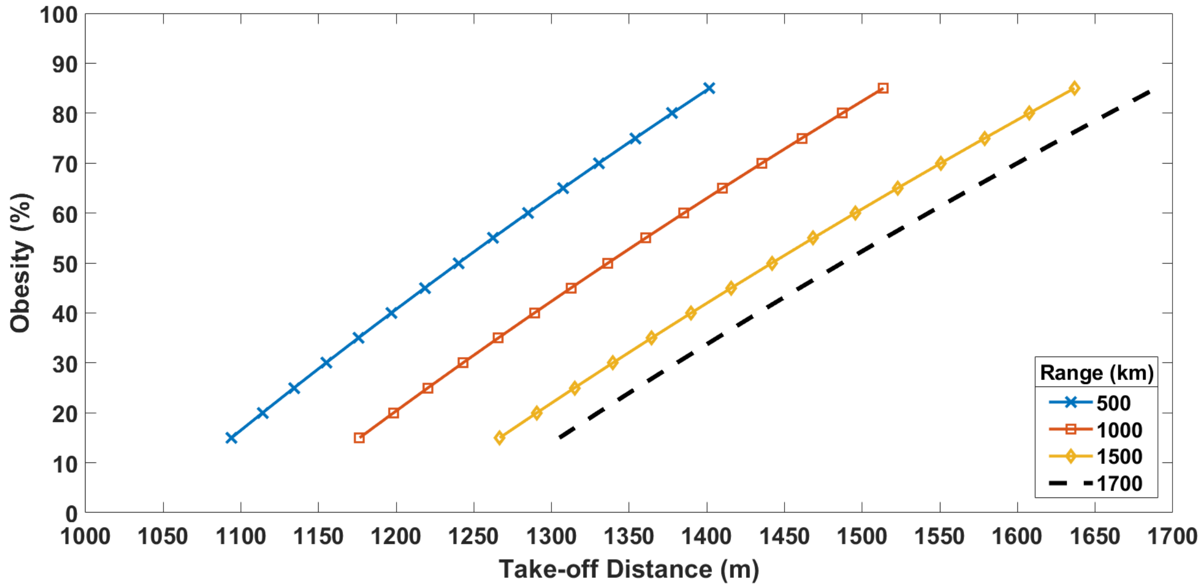


Figure 5-17 ATR-72 take-off distance v. obesity prevalence for various ranges at FL250

5.6.5 Landing

From a performance perspective, ideal aircraft operations would have an aircraft consume the exact amount of fuel predicted for the flight, leaving residual fuel for taxiing purposes. The model considered assumes that the aircraft will arrive at the destination with zero fuel onboard, allowing for the only variable to be passenger payload weight when determining the landing distance. Figure 5-18, Figure 5-19 and Figure 5-20 illustrate the landing distances for the A320, A330-200 and ATR-72 aircraft as a function of obesity prevalence. In each figure, the landing distances determined based on the requirements set by four regulators (i.e., FAA, ICAO, CAA UK and EASA) are shown as vertical lines. All of these distances are shown for the ZFW condition of the aircraft. The standard weights issued by regulators provide a conservative landing distance, as all four regulators' landing distances lie above an obesity equivalent level of 70%. Current global average obesity is close to 53% and is likely to reach 70% in the near future according to recent forecasts (NCD Risk Factor Collaboration 2017); thus narrowing the safety margin for the calculation of landing distances.

Landing distance is heavily influenced by the weight of the aircraft. Manufacturers provide a maximum landing weight of aircraft to prevent structural damage on touch down, including to the landing gear. This weight incorporates the maximum difference of fuel weight not spent during a flight for any ZFW. In an emergency during the early phases of flight, the aircraft would dump fuel to reach this weight. At maximum landing weight, the model predicts that the A320, A330-200 and ATR-72 use 1,439 m, 1,744 m and 1,148 m of runway respectively. Comparatively, the Airbus reference handbooks for the A320 and A330-200 show an approximate landing distance value of 1,400 m and 1,700 m respectively. These distances are computed based on standard passenger weights. However, as discussed earlier, different geographical regions may significantly deviate from the standard weight, thus resulting in deviations in calculated landing distances. This limitation may pose a serious operational risk for airports with relatively short runways and when other external factors may also have a concomitant detrimental effect on aircraft performance, such as environmental temperature, condition of the runway pavement (e.g., wet v. dry) and airport altitude. For example, an A320 operated by an airline in South Asia [24.62% ± 3.5] uses 1,230 m of the runway compared with 1,310 m necessary for the same aircraft and total number of passengers in a high-income Western country [59.67% ± 3.6].

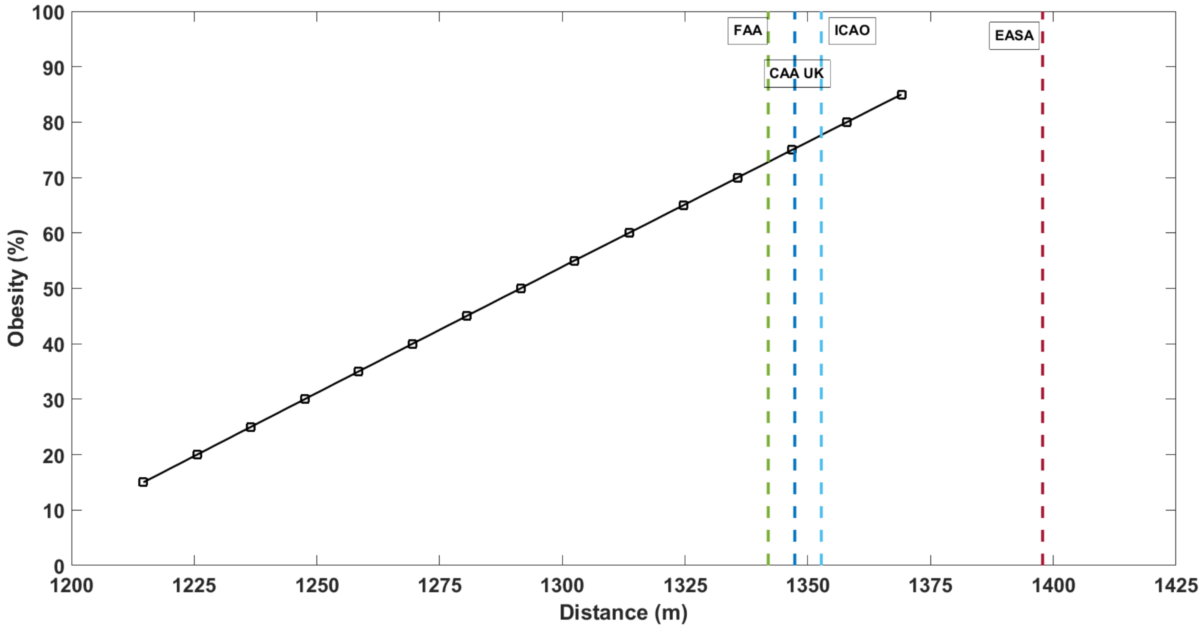


Figure 5-18 Effect of different obesity levels on A320 landing distance; vertical lines represent landing distances as per the requirements set by corresponding regulators

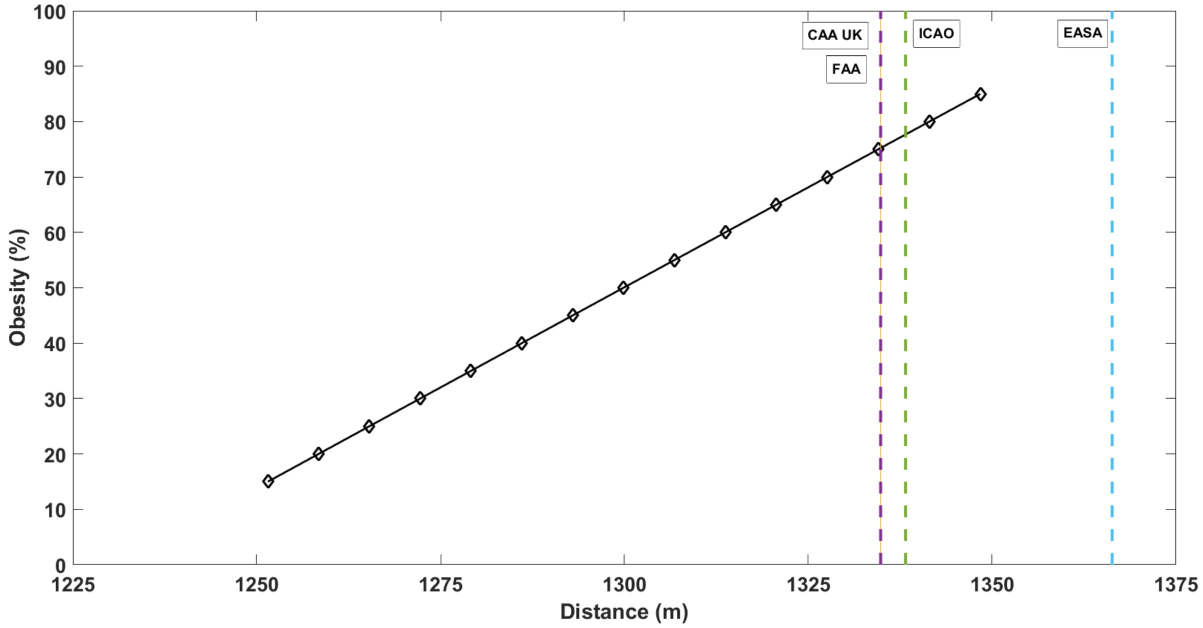


Figure 5-19 Effect different obesity levels on A330-200 landing distance; vertical lines represent landing distances as per the requirements set by corresponding regulators

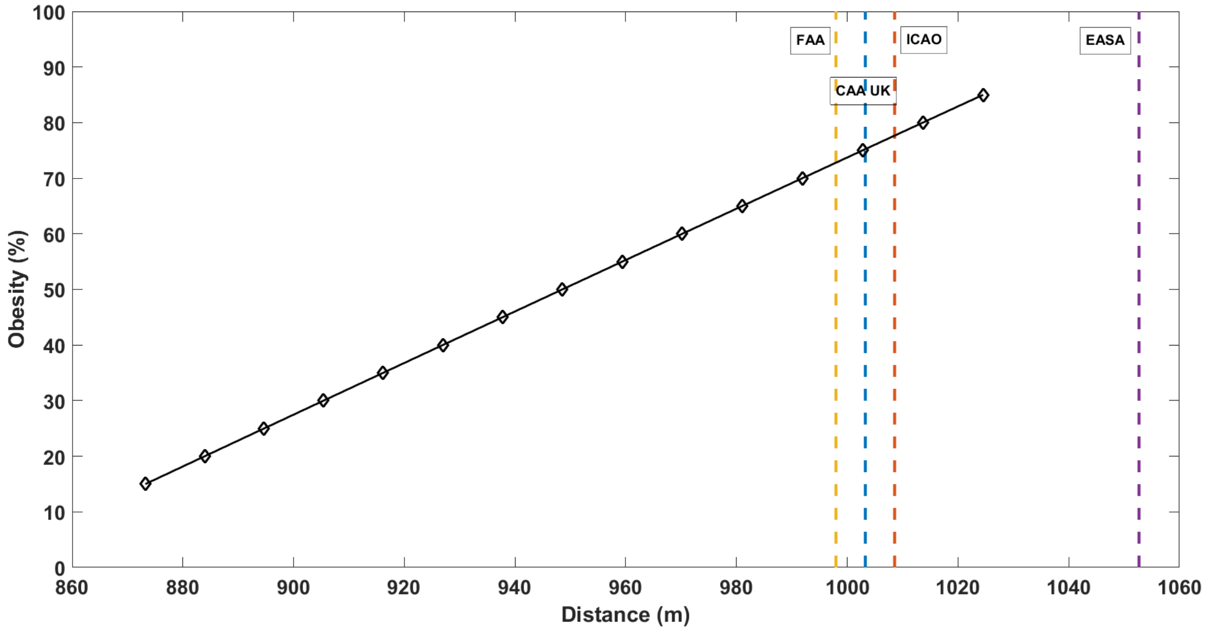


Figure 5-20 Effect of different obesity levels on ATR 72 landing distance; vertical lines represent landing distances as per the requirements set by corresponding regulators

5.6.6 Fuel and Emissions

Knowing the correct amount of fuel needed for a flight is critical because fuel cost is a significant expenditure for airlines. However, the exact amount of fuel can only be calculated once the weights for both passengers and cargo are known for a given flight. The paradox is that only the cargo is weighed before boarding, whereas passenger weight is estimated from the standards adopted by the operator. Not knowing the exact weight of passengers can lead to excess fuel weight being carried during a flight or, worse, not enough fuel.

Figure 5-21, Figure 5-22 and Figure 5-23 present the cost and emissions associated with the fuel used for the three aircraft flight scenarios presented in Table 5-4. In all aircraft cases, the cost of fuel and emissions rises with the prevalence of obesity because of the extra fuel required to transport the increased passenger weight. For example, considering the A330-200 with a range of 7,500 km, for every 5% increment of obesity added to the passenger payload, an additional 122.2 kg of fuel is required, which emits 362.5 kg of extra emissions at a cost of US$92.25. Further, an A320 travelling 3,000 km will need 54.8 kg of fuel and emit 95.4 kg of emissions at an additional cost of US$41.37, while the ATR-72 travelling 700 km will carry 6.77 kg of fuel, which will emit 15.3 kg of emissions and cost US$5.11. However, for the extreme 85% obesity prevalence case, the change in the fuel cost compared with an aircraft carrying a passenger payload based on ICAO standard weights is 1.6% for the A320 and 0.5% for both the A330-200 and ATR-72. Although these percentages are small in absolute terms, it should be noted that the financial effect in the long run is considerable, particularly for long-range operations. This stresses the need for airlines to use actual passenger weights instead of estimations based on standards as a means to save on fuel. Figure 5-21 shows that if an A320 were to operate for an airline in sub-Saharan Africa [28.21% ± 8.4], the airline would spend close to US$6,600, while other nations, such as those in Oceania [71.81% ± 10.1], may spend up to US$6,900 for a similar distance. These values represent significant savings when compared with the fuel cost corresponding to the standard weights based on the ICAO and EASA regulations (US$6,955 and US$7,135 respectively).

Park et al. (2014) determine that an A330-200 uses 43 tonnes of fuel to fly an average distance of 6,315 km, which contrasts with 33 tonnes obtained from the model used in this study. Similarly, Yin et al. (2015) show that a 9,260 km flight carried out by an A330-200 uses 64 tonnes of fuel compared with 51 tonnes derived from the model in this study. Their methods involve aggregating yearly fuel consumption and flight distances to provide flight characteristic estimates. It is noted that there is a difference between the results of Park et al. (2014) and Yin et al. (2015) to those calculated using the model in this study. These differences can be attributed to unstated aircraft weights, the engine model and other parameters that can produce conservative results.

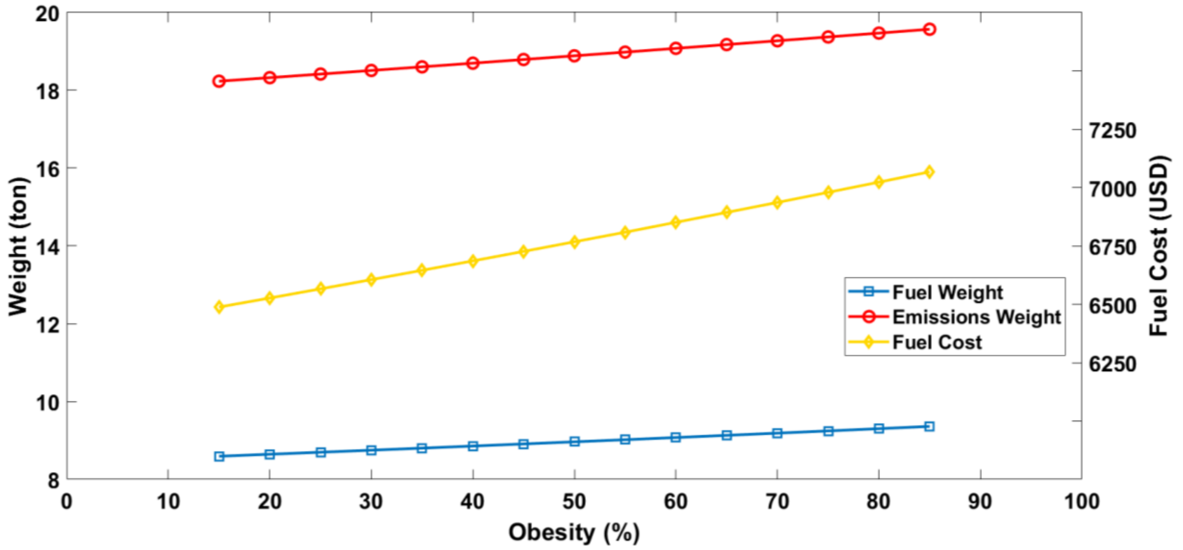


Figure 5-21 A320 fuel cost and emissions with fuel weight as a function of obesity prevalence (considering a range of 3,000 km)

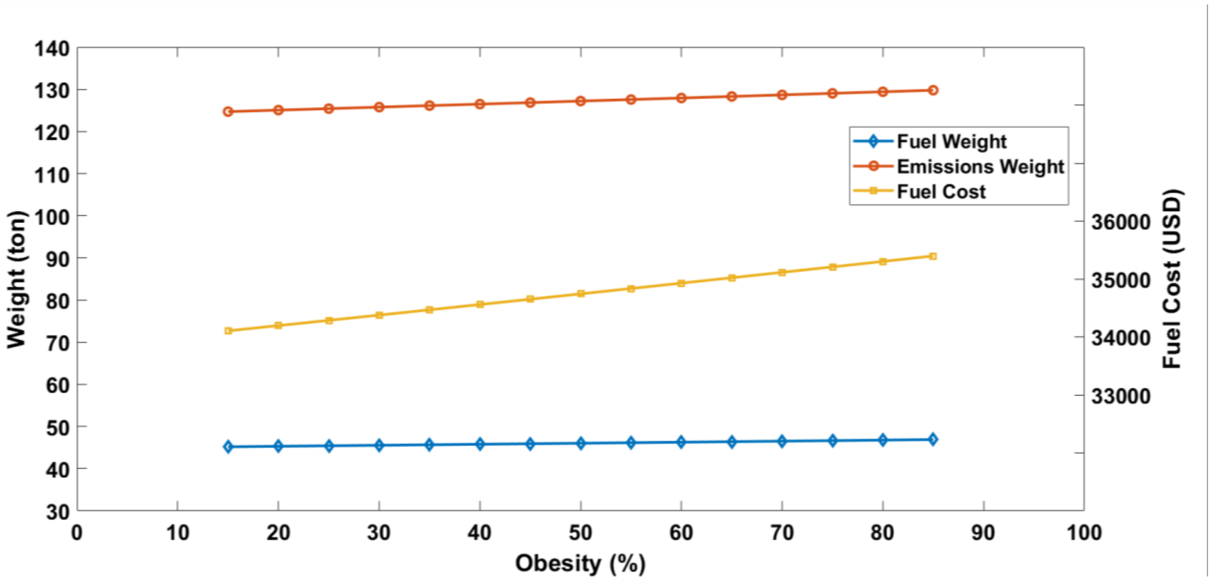


Figure 5-22 A330-200 fuel cost and emissions with fuel weight as a function of obesity prevalence (considering a range of 7,500 km)

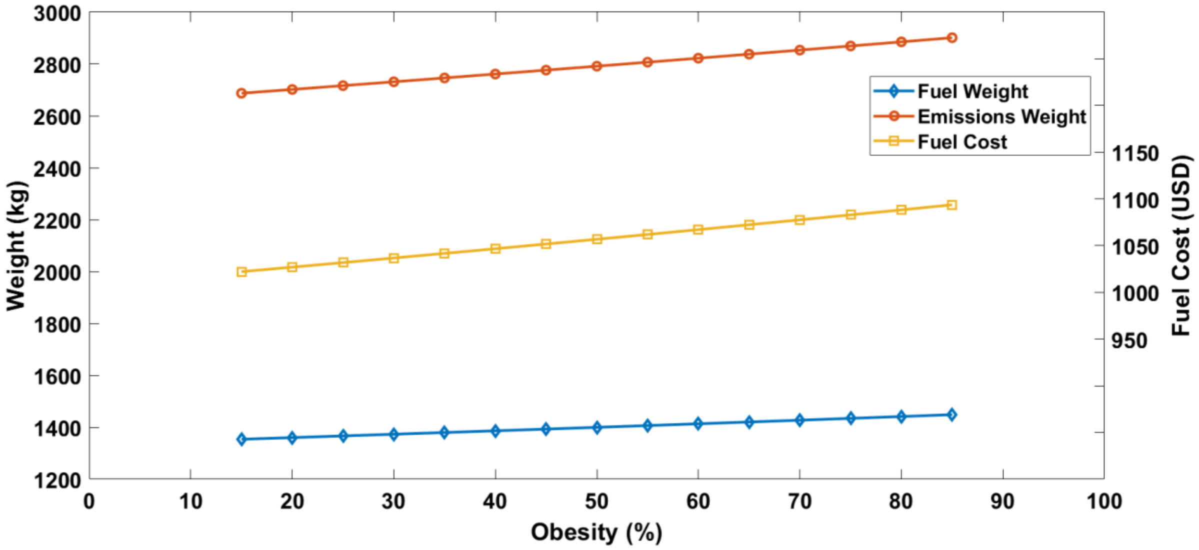


Figure 5-23 ATR72 fuel cost and emissions with fuel weight as a function of obesity prevalence (considering a range of 700 km)

5.7 Summary

Overweight and obesity are placing a strain on society as well as the industry on a global scale. The effects of passenger weight in the transport sector suffer from a lack of interest from key stakeholders—particularly in relation to the associated safety, operational and financial implications. This study addresses this knowledge gap by analysing changes in aircraft performance characteristics as a result of increasing passenger weight. The findings show how obesity affects the main aircraft performance parameters. From a safety and operational perspective, the results show that deviations from average passenger weight (as stipulated by regulators) resulting from different obesity prevalence rates can significantly compromise safety margins. This limitation is particularly evident for higher obesity prevalence rates, which are in line with forecasts of obesity prevalence in the near future. Geographical factors may also play a role in the accuracy of the calculated performance characteristics of different types of aircraft, because distinct regions around the world have significantly different obesity rates. From an economics perspective, the results illustrate that most countries around the world underestimate the standard weights of passengers, which represents unnecessary fuel costs to airlines as well as increased pollutant emissions. Overall, this study has demonstrated the need for regulators to issue standards with updated passenger weights in line with current demographic trends, thereby resulting in more accurate flight performance calculations regardless of the operators' geographical context. Alternatively, measuring passengers' weight prior to boarding would be an effective measure to reduce uncertainty around this parameter, although this procedure would require public acceptance due to privacy issues.

Chapter 6: Emergency Evacuations and Passenger Anthropometry

6.1 Introduction

This chapter explores the effect of passenger anthropometry on aircraft emergency evacuations (also referred to as emergency egress), with a focus on passenger obesity demographics. The passenger demographic model created in Section 4.4 is used to develop the passenger profiles discussed in this chapter. This chapter is composed of four main parts:

- First, background information specific to aircraft emergency evacuations is discussed with specific reference to other software packages and studies that focus on passenger anthropometry.
- Second, details of the simulation modelling process are introduced to highlight the methods relating to simulation inputs.
- Third, aircraft evacuation simulations are conducted for two types of aircraft (single- and double-aisle) considering various passenger demographic compositions.
- Fourth, the methods used to simulate the research in this thesis are validated. This process includes two methods of validation:
    - experimental bus evacuation trials replication
    - A380 evacuation certification trial replication.

At the time of submitting this thesis, this paper has been reviewed but not yet published in the journal *Safety Science* under the title, ‘The effect of airline passenger anthropometry on aircraft emergency evacuations’.

6.2 Background

Little is known about how anthropometric trends will affect aircraft evacuation. In this section, current passenger obesity is recapitulated with a focus on emergency evacuations. This is followed by highlights of the current aircraft evacuation simulation software and literature review.

6.2.1 Current Passenger Demographic Situation Recapitulation

As airlines continue to squeeze an increasing number of passengers into their aircraft, the evacuation of passengers from an aircraft in an emergency is a pressing issue because of the risks associated with this procedure. Airlines around the world are pushed by fierce competition and business pressures to find new ways to increase their passenger load with their fixed aircraft cabin capacity. They have to balance the customer’s expectation of a high level 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 biofuels, light-weight materials, better aerodynamic designs and advancements in air traffic management. Despite this, Melis et al. (2017) demonstrate that limited research has been conducted to explore the issues associated with anthropometrical changes in commercial aviation passengers. The main thrust of research in this domain is limited to passenger’s perceptions of comfort.

The average person’s weight has been increasing, making obesity a global problem, especially in developed regions (NCD Risk Factor Collaboration 2016b; Wang & Lim 2014; Finucane et al. 2011). The WHO (2016) notes that worldwide obesity prevalence tripled between 1975 and 2016. In the majority of Westernised nations concern in the prevalence in obesity has been increasing. Notably, in the US and the UK, the prevalence of BMI greater than 25 $kg \bullet m^{-2}$ is 70% and 66% respectively. Further, the prevalence of BMI greater than 25 $kg \bullet m^{-2}$ is 61% in Latin America and the Caribbean, and 57% and 59% in the Pacific and Central and East European regions respectively. In Central Asia, the Middle East and North Africa, the average prevalence is 63%, while the rest of Africa and Southeast Asia have a prevalence of BMI greater than 25 $kg \bullet m^{-2}$ of less than 35% (NCD Risk Factor Collaboration 2017).

Evacuations from an aircraft are comparatively rare events in today’s aviation industry, but from a safety perspective, it is an important process in an emergency. All manufacturers are required to demonstrate that they meet the evacuation requirements set by the respective aviation authorities. Current regulation §25.803(c) requires that aircraft be evacuated in less than 90 s (FAA 1990b). The limitations of real-life aircraft evacuations is highlighted by Hedo et al. (2019). Full-scale evacuations are generally only performed once for certification purposes due to the number of resources required and the risk of injury to participants. They also highlight demographics of evacuation demonstration that are unrepresentative of actual flights. A cost-effective solution is to perform computer simulations to understand evacuation dynamics. A recent article published by the Royal Aeronautical Society highlights the changes that are 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).

6.2.2 Aircraft Evacuation Simulation Programs and Literature

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. 2014a), passenger emotions and behaviour (Du & Yang 2014; Miyoshi et al. 2012) and different cabin/aircraft configurations (Galea et al. 2010). There are some evacuation software packages available with different analysis capabilities, as shown in Table 6-1. However, minimal information is available on egress simulations considering the effects of passengers' anthropometry. Liu et al. (2014) and Wang et al. (2012) highlight simulations involving physical characteristics of passengers and note that waist size and passenger age can have a considerable effect on the variance of evacuation times produced by simulations.

Table 6-1 Emergency evacuation simulation model summary (Hedo & Martinez-Val 2011)

Model Name	Year	Institution	Purpose
GPSS	1978–1980	CAMI-FAA	Certification
FIREVAC	1984	NASA/Simulation Tech, Inc.	Fire accident reconstruction
GA	1987–1992	FAA/Gourary Associates	Accident reconstruction
AIREVAC **AIRCEVAC**	1991–1994	ATA/South West Research Institute	Certification
airEXODUS	1993–	Greenwich University	Certification, design and accident reconstruction
RAM	1994–1996	Cranfield University	Certification and accident reconstruction
OOO	1996–1997	CAMI-FAA/Oklahoma University	Theoretical model
DEM	2001–	Strathclyde University	Certification (psychological aspects)
VacateAir	2008–	State University of New York at Buffalo	Certification and design
ETSIA	2009–	Universidad Politecnica de Madrid	Certification and accident reconstruction

Table 6-2 shows six prominent simulation model products that have been tailored to aircraft evacuations studies. The GPSS (General Purpose Simulation System) and AvatarSim models have been developed to validate the 90 s rule. However, airEXODUS, MACEY, VacateAir and DEM (Discrete Element Method) models can simulate both the 90 s rule scenario and the accident scenario to a degree of realism. Accident scenarios may refer to the 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 the 1980s, which do not reflect current demographics (Thompson et al. 2015).

Table 6-2 Evacuation time of various aircraft for the 90 s test and simulation verification (Chen, Qian & Xue 2014)

Model	Aeroplane Type		No. 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 Simulator	Straight aisle	51	40.87	37.73
		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
ETSIA	A320		179	81.4	77.8

The behaviour among passengers during an evacuation is not consistent. Passengers may feel overwhelmed by emotions and disorientated during an evacuation. Few studies have explored the influence of psychological behaviour on evacuation time. Panic-stricken passengers behave inconsistently during egress, and it has been demonstrated that panic could lead to increased evacuation time (Miyoshi et al. 2012). Hong-bing et al. (2018) explore the effects of gender and panic-stricken evacuees during the evacuation of a narrow-body aircraft followed by simulation. However, they do not explore the effects on changes to passenger attributes. Unlike simulations, real evacuations are more complex and involve behaviour variations. Greater urgency is exhibited in passenger behaviour during an emergency. It has been shown that introducing competitive behaviour during evacuation experiments results in decreased evacuation time compared with evacuation times in which a non-competitive emphasis is employed (Muir et al.1996). Participants of evacuation trials can be manipulated by financial enticements, verbal commands or other motivation incentives to mimic these behaviours (McLean & George 1995; Muir et al. 1992). A survey by Chang and Yang (2011) of passengers after experiencing a real-life aircraft evacuation reveals that passengers rely heavily on cabin crew directions and have concerns over specific aspects of cabin design, such as the width of aisles.

Existing aviation regulations emphasise 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 & Hedo 2000). However, the regulations have a minimum focus on changes in passenger anthropometrics and the effect of passenger mobility during egress. Studies focusing on aircraft cabin layout predominantly explore the overwing exits and cabin aisles. A critical development in cabin safety addressing the design of aisles, seats and cabin dividers occurred after an accident involving British Airtours Flight 28M (AAIB 1988), which 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 resulted in changes to the regulations governing the aisle, emergency exits and cabin materials.

Aircraft exit size is an essential feature in emergency evacuations. A larger opening allows a higher number of passengers to exit quickly (Daoliang, Lizhong & Jian 2006). These doors are often located along the fuselage in large aircraft. Martínez-Val et al. (2017) explore the effects of uncommon exit arrangements on evacuation time. Their parameters explore door location, various combinations of door types and different capacities for a narrow-body aircraft. Small commuter-sized aircraft through to large narrow-body aircraft often incorporate a Type-III door over the wing. Unlike larger exit types, Type-III exits require the passenger to manually remove the exit hatch and deposit the hatch away from the exit opening. Experiments and studies of accidents have shown that a panicked passenger might dispose of the hatch in an inappropriate location, thereby obstructing the exit (Wilson & Muir 2010; McLean & Corbett 2004; McLean et al. 2002). Similarly, obstructions in the cabin aisle (e.g., baggage) can hinder passenger evacuation flow. Narrower aisle dimensions lead to increased congestion, decreased flow rates and therefore longer egress times (Huang, Lu et al.

2018; Huang, Zhang et al. 2014a). Further obstructions can occur as a result of the behaviour of passengers, who may block aisles while retrieving carry-on luggage during the evacuation (Read 2016).

Muir and Thomas (2004) highlight passenger safety in very large aircraft. Factors that explore the behaviours of passenger and crew are central to ensure an orderly evacuation, and cabin design, including the location and size of exits, aisles and cross aisles for many wide-body aircraft, is important to evacuation flow. With most wide-body commercial aircraft cabins situated approximately 5 m off the ground, a second full-length deck requires innovative changes to evacuation procedures and equipment (e.g., longer slides). Zhang et al. (2014a) 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 (which is also used in this thesis) on aircraft evacuation applications. Additionally, egress studies that examine 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).

6.3 Simulation Method—Occupant Modelling

In Pathfinder, occupants are defined in two ways: profiles and behaviours. The profile defines fixed characteristics of the occupants, such as gait speed, radius, occupant avatar and colour. Behaviour defines a sequence of actions the occupant will undertake throughout the simulation, such as waiting and exiting.

6.3.1 Occupant Anthropometry

6.3.1.1 Anthropometric Data

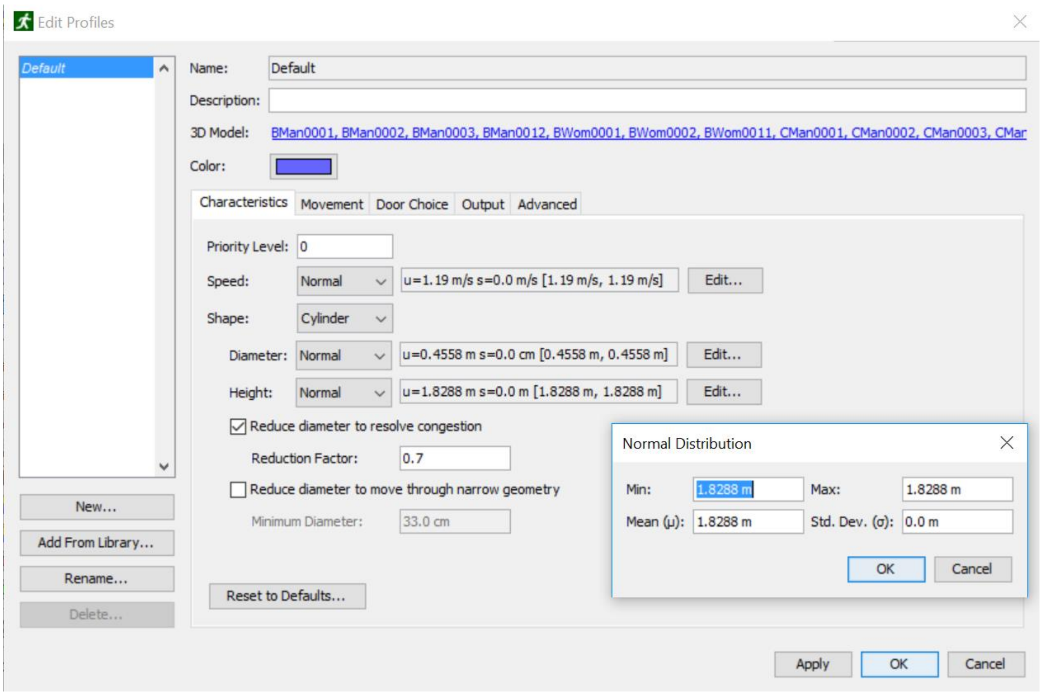
Each passenger dataset created in Pathfinder relied on anthropometrical attributes generated from statistical distributions. Key characteristics such as height, speed and waist diameter were considered to demonstrate their relative effect on evacuation time. These data were subsequently used to create demographic profiles based on age, gender and BMI category (see Table 6-3). 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’. This study used the 2013–2014 NHANES data (see Chapter 4).

Table 6-3 Age and BMI categories with associated input variable value for regression model

Age Group (Years)	Regression Model Variable Value	Pathfinder Identifier	BMI Category	BMI Range (kg•m^{-2})	Regression Model Variable Value (*k*)	Pathfinder Identifier
18–24	21	*A*	Underweight	Under 18.5	1	*U*
25–34	30	*B*	Normal Weight Cat. 1	18.5–19.99	2	*N1*
35–44	40	*C*	Normal Weight Cat. 2	20–24.99	3	*N2*
45–54	50	*D*	Overweight Cat. 1	25–29.99	4	*OW*
55–64	60	*E*	Obese Cat. 1	30–34.99	5	*O1*
65–74	70	*F*	Obese Cat. 2	35–39.99	6	*O1*
75+	80	*G*	Morbidly Obese	40+	7	*MO*

6.3.1.2 Profile Creation

Pathfinder uses an occupant profile method to manage distributions of parameters across groups of occupants. This system helps to control the occupant speed, size and visual distributions. The profile dialogue box (see Figure 6-1) shows multiple tabs, but only the characteristic and advance tabs are discussed here. All other parameters are left in the default setting.



Default

Name: Default

Description:

3D Model: BMan0001, BMan0002, BMan0003, BMan0012, BWom0001, BWom0002, BWom0011, CMan0001, CMan0002, CMan0003, CMar

Color: 🟦

Priority Level: 0

Speed: Normal u=1.19 m/s s=0.0 m/s [1.19 m/s, 1.19 m/s]

Shape: Cylinder

Diameter: Normal u=0.4558 m s=0.0 cm [0.4558 m, 0.4558 m]

Height: Normal u=1.8288 m s=0.0 m [1.8288 m, 1.8288 m]

☑ Reduce diameter to resolve congestion

Reduction Factor: 0.7

☐ Reduce diameter to move through narrow geometry

Minimum Diameter: 33.0 cm

Normal Distribution

Min: 1.8288 m

Max: 1.8288 m

Mean (μ): 1.8288 m

Std. Dev. (σ): 0.0 m

Figure 6-1 Pathfinder profile editing box showing the characteristics tab, including the sub-dialogue box for inputting data as a normal distribution

Each profile that is created is labelled with a profile designation in the *name* input box. The example describing a passenger profile of a 'Female', 'Age 45 to 50 years old' with a 'Normal Weight Cat. 1' will be *FDN1* according to the identifier nomenclature in Table 6-3.

In the *Characteristics* tab, several options are available to tailor a specific group of occupants to a specific profile:

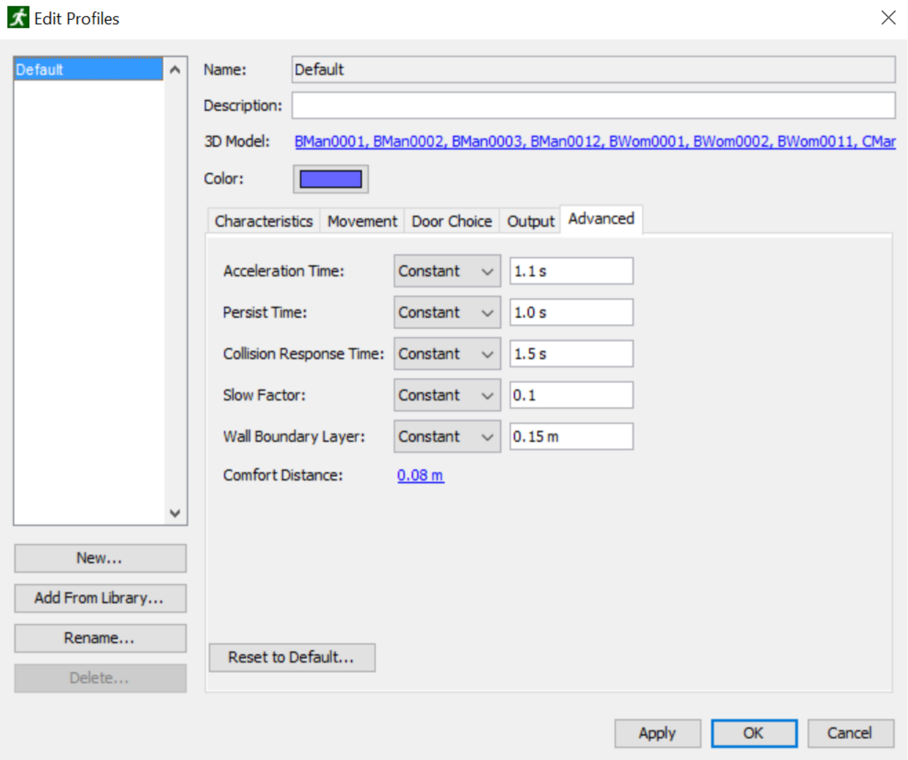
- An occupant priority setting is featured in Pathfinder; this function is not used in this study. All occupants are assigned a priority value of '0'. Higher values indicate higher priority, causing lower-priority occupants to move out of the way. Uniform priority is assigned to replicate the behaviour associated with self-preservation, allowing for pushing and shoving in the model.
- The 3D model allows for the visual representation of the individual occupants. Pathfinder provides multiple options for occupant representation in the output; these models include disks, cylinders, polygons (for use as wheelchair occupants), human dummies and 3D human models. In this study, the cylindrical model is used because it

allows for the visual representation of height and waist/shoulder diameter. The 3D human models do not provide this visual representation of anthropometric features.

- A colour is designated to each profile to distinguish each profile from the others. These colours are random and have no specific bearing on the overall simulation other than to provide a visual representation of the different profiles scenarios.
- Pathfinder provides a reduction factor parameter that specifies how well an occupant may squeeze past others in tight corridors (see Figure 6-1). This factor should be specified as greater than 0 and less than or equal to 1. The factor is directly multiplied by the diameter value during calculations, so a reduction factor of 0.5 will lead to the occupant being able to squeeze to one-half their shoulder width. In the model discussed in this study, the reduction factor is set uniformly at a value of 0.7.

In the *Characteristics* tab, several options are available to tailor a specific group of occupants to a specific profile. All of these factors are left as the default values in Pathfinder unless specified:

- *Acceleration time* indicates the amount of time taken by the occupant to reach the maximum speed indicated. This value is set to the default value of 1.1 s.
- *Persist time* is the amount of time an occupant spends at a higher priority level when resolving movement conflicts. This value is set to the default value of 1.0 s.
- *Collision response time* controls the distance at which the occupant will start recording a cost for colliding with other occupants when steering. This value is set to the default value of 1.5 s.
- The *slow factor* is the fraction of the occupant’s maximum speed that would be considered slow for the occupant. A slow occupant will consider backward directions to separate with others, while a fast-moving occupant has a tighter, more focused direction. This value is set to the default value of 0.1.
- *Wall boundary layer* and *comfort distance* specify the distance that occupants try to maintain with walls and other static obstructions or others in a queue. In the case of this study, the wall boundary layer is set to 0.15 m and comfort distance value is set to 0.08 m to mimic behaviour during an emergency. Passengers are less concerned about their comfort when pressed up against the wall. People from behind will push them closer into seats and bulkheads as they evacuate.



Name: Default
Description:
3D Model: BMan0001, BMan0002, BMan0003, BMan0012, BWom0001, BWom0002, BWom0011, CMar
Color: 🟦

Acceleration Time: Constant 1.1 s
Persist Time: Constant 1.0 s
Collision Response Time: Constant 1.5 s
Slow Factor: Constant 0.1
Wall Boundary Layer: Constant 0.15 m
Comfort Distance: 0.08 m

Figure 6-2 Pathfinder profile editing box showing the *Advanced Setting* tab

6.3.1.3 Height and Diameter

The NHANES data show that a person’s height and waist/shoulder diameters vary within the prescribed profiles. The heights and diameters of occupants are entered into the profile dialogue box (Figure 6-1) following a normal distribution; data relating to the maximum, minimum, standard deviation and mean are determined from the NHANES data and can be found in Appendix 4.

6.3.1.4 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 & Gormley 2013). However, their height plays a pivotal role in determining gait stride and speed, because taller people generally have longer legs, which allow for greater stride length and lower cadence.

Gait speed was introduced into the Pathfinder profile models. Figure 6-1 shows the dialogue box for inputting gait speed and provides different option to provide a constant, uniform, standard normal or logarithmic distribution and an advanced setting. For all studies using the NHANES anthropometric models, the normal distribution input is used. From the

NHANES data, the maximum, minimum, standard deviation and mean values are calculated. The normal distribution details for each profile can be found in Appendix 4.

The method presented in Samson et al. (2001) provides regression equations (Eq. 6.1, Eq. 6.2) correlating an individual's age (A), height (h) and weight (W) with their gait speed (V). The data regarding these variables were obtained from NHANES. Thus, the estimated gait speed is indicative of the individual within the NHANES dataset:

$$V_{female} = -0.001(A) + 0.879(h) - 0.003(W) + 0.316 \qquad \text{Eq. 6.1}$$

$$V_{male} = -0.001(A) + 0.486(h) - 0.001(W) + 0.72 \qquad \text{Eq. 6.2}$$

In an emergency egress scenario, a passenger will endeavour to move at a faster pace. These calculated speeds from Eq. 6.1, Eq. 6.2 represent a normal gait. However, increasing gait speed will cause an increase in stride length and frequency (Browning & Kram 2007). A gait speed factor is applied to the calculated normal speed of a person to obtain a faster gait speed for a specific age group. For example, a male with an age of 25, a weight of 70 kg and height of 1.657 m would have a normal gait speed of 1.43 m•s^{-1}. This value is then multiplied by the gait factor 1.75 for the age group 25-35 from Table 6-5 to give a faster gait speed of 2.5 m•s^{-1}. This factor is derived from the percentage increase of normal to fast gait speed from data found in Bohannon (1997).

Table 6-4 Factor used to increase normal gait speed to a fast gait speed

Age Group	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

6.3.2 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 mode developed by the Society of Fire Protection Engineers 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 by Amor, Murray and Obst (2006). Pathfinder's steering mode allows 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. The following sections outline the behaviour parameters manipulated or introduced into the model. Any other behavioural aspects that are capable of manipulation have been left to the default setting established by Pathfinder.

6.3.2.1 Occupant Behaviour

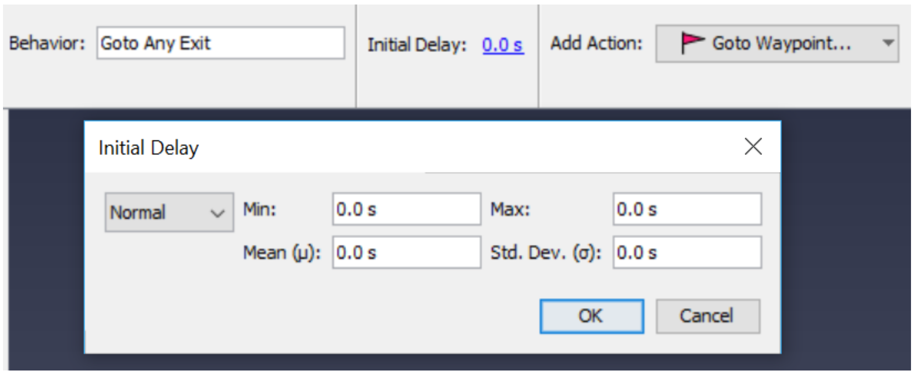
Passenger behaviour is difficult to simulate. Behaviours vary with the situation, and passengers will experience higher levels of anxiety and a sense of urgency in a real evacuation (McLean & Corbett 2004). Further, one individual’s behavioural response will be different from that of the next person. In this respect, this study’s model simplifies the passengers’ behaviour by assuming that all passengers have similar behavioural tendencies and priority levels. These psychological behaviours use the default settings 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). For idle goals, the occupant must wait at a location until an event occurs. In this study, this equates to time delays mimicking the time it takes for passengers to stand up from their seat. Seek goals are those for which an occupant moves towards a destination, such as a waypoint or an exit.

6.3.2.2 Behaviour Creation

Behaviours are created using the behaviour profile panel (see Figure 6-3) and are assigned a label based on the emergency door number. For example, the foremost forward door on the left side of the aircraft would be labelled ‘L1’, whereas the opposite door on the right would be labelled ‘R1’. An initial delay can be added using either constant, uniform normal or logarithmic distribution or discrete options; for this study, the normal distribution is used (see Figure 6-3). Details regarding the initial delay parameters are discussed in Section 6.3.2.3.

Waypoints involve adding an action from the dropdown box and selecting ‘Go to Waypoint’. These waypoints are placed at specific locations throughout the aircraft model, predominantly at the intersections between the aisles and exits. In this way, waypoints are used to move occupants to the nearest available door. This action prevents occupants from travelling against the flow towards an irrelevant door, and it prevents a cross flow between duel-aisle wide-body aircraft. Other parameters provided in the ‘Add Action’ dropdown box are not considered in this study. Some of these functions relate to waiting behaviours, waiting for assistance and moving to elevators or other rooms.


Behavior: Goto Any Exit
Initial Delay: 0.0 s
Add Action: Goto Waypoint...

Initial Delay
Normal
Min: 0.0 s
Max: 0.0 s
Mean (μ): 0.0 s
Std. Dev. (σ): 0.0 s

Figure 6-3 Behaviour profile panel and initial delay box

6.3.2.3 Sit-to-Stand Delay Time

The time taken by each passenger to evacuate during an emergency is influenced by their ability to respond to visual and audio cues from the cabin crew. Once these cues have been activated, the passenger will need a short amount of time to unstrap themselves from their seatbelt and stand up from their seat to prepare for egress.

The time required for each passenger to stand from a seated position varies depending on gender, age and body size (weight). In particular, the weight factor has a direct effect on the time taken to stand. A higher weight will increase the time needed. Pataky et al. (2014) noted in five sit-to-stand tasks that people with a normal weight (BMI<25) took 8.28 ± 1.42 s, while people in the obesity category took 11.29 ± 3.14 s. Further, it was determined that the timing did not change significantly between people in higher BMI categories. Similarly, when exiting from their seat, elderly passengers will support themselves by holding on to the seat frames, while youthful passengers can stand up without any additional support (Lijmbach, Miehlke & Vink 2014).

Therefore, it is necessary to include a time delay in Pathfinder to simulate the sit-to-stand motion of passengers. Pathfinder’s mechanics do not allow for an occupant to begin from a seated position. The time delay imitation was overcome by implemented sit-to-stand times based on the research by Bohannon et al. (2010) to the Pathfinder behaviour mechanics to replicate the sit-to-stand phase. Given that delay times cannot be added to each profile, a mean delay of 1.56 s with a standard deviation of 0.41 s following a normal distribution is implemented (see Figure 6-3) with a range of 1.20 s–2.16 s (Bohannon et al. 2010). This delay time is applied to all passengers, as the sit-to-stand times reflect the age range explored in Bohannon et al.’s (2010) study of passengers aged 18–75+ years.

6.4 Simulation Method—Aircraft Modelling

Pathfinder is built on the idea of creating floor spaces across which occupants can traverse, ranging from floors to doorways to stairs. Obstructions within the floor structure exist as holes in the drawn space.

6.4.1 Creating Aircraft Models

The main egress components include rooms, which are empty floor spaces bounded by walls; doors, which connect rooms on the same level; stairs/ramps, which connect rooms on different levels; and elevators, which connect multiple levels. Rooms can have any polygonal shape and can never overlap. Doors can be thick if they are occupying a doorway (the area between two rooms) or thin if they are connecting two touching rooms. The stairs are not considered for this study.

To create the basic model in which the simulation mesh is applied, Pathfinder allows for imports of images or computer-aided drafting files. In this study, an image detailing the utilised cabin layout was imported. The cabin layout considered for each aircraft is shown in Figure 6-4. The geometry for the models was then built upon a cabin layout image consisting of floor, wall and door elements.

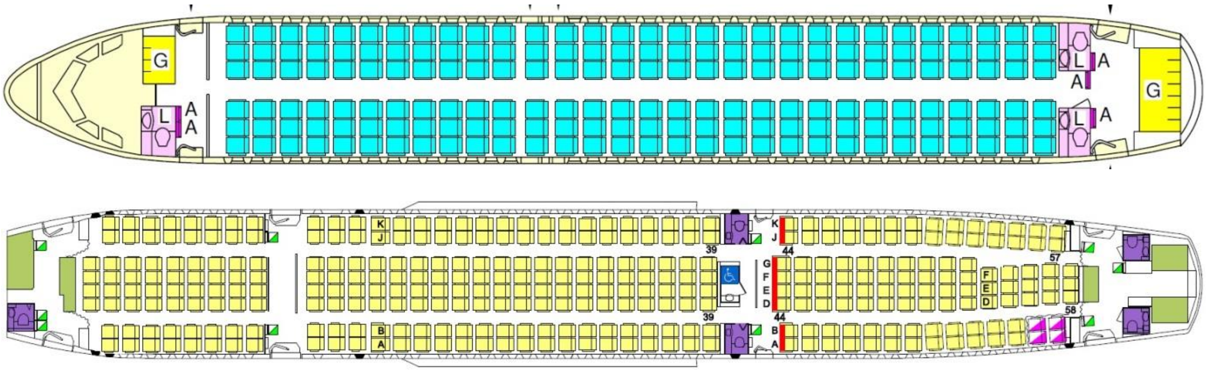
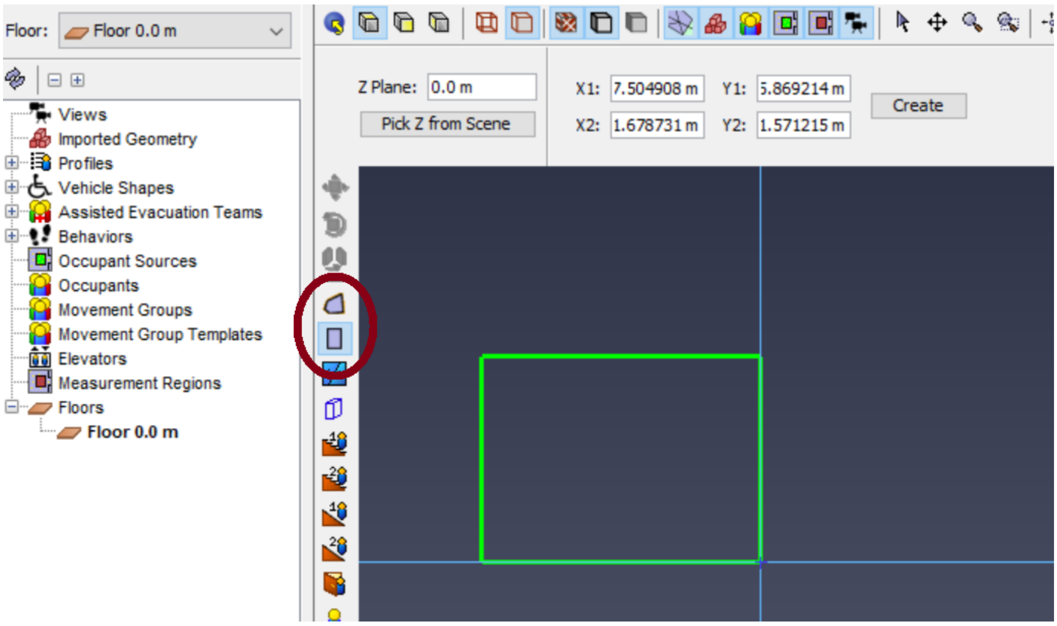


Figure 6-4 Cabin layout used for simulation for the A320 (above) and A330-200 (below) (Airbus, 2014; Airbus 2015)

Floors can be created using two methods: the polygon room tool or rectangular room tool (shown in Figure 6-5 by the red circle). Given the intricacies of the floor surface of the aircraft cabin, the polygon tool was used. However, the rectangular floor tool was used to create the spaces representing the seatbacks. Doors were then added to the floor model as described in Section 6.4.3.



Floor: Floor 0.0 m

Z Plane: 0.0 m

X1: 7.504908 m

Y1: 5.869214 m

X2: 1.678731 m

Y2: 1.571215 m

Figure 6-5 Floor-creating tools (red circle)

6.4.2 Aircraft Model Parameters

Two aircraft types were considered for this research: narrow- and wide-body aircraft with a capacity of 180 (see Figure 6-6) and 339 passengers (see Figure 6-7) respectively, in a single economy-class configuration. Note that these figures are examples of two simulation scenarios; other passenger distributions have been considered for the same aircraft types.

6.4.2.1 Narrow-Body Aircraft Attributes

The narrow-body aircraft has three seats either side of the aisle. It also has two lavatories and a galley located in the rear of the main cabin. In the front, some bulkheads separate the main cabin from the forward galley and the lavatory. The seat pitch for this aircraft is 73- 78 cm (29- 31 in) and the aisle width is 61 cm. The aircraft features four overwing exits with seat pitches of 68.5 cm (27 in).

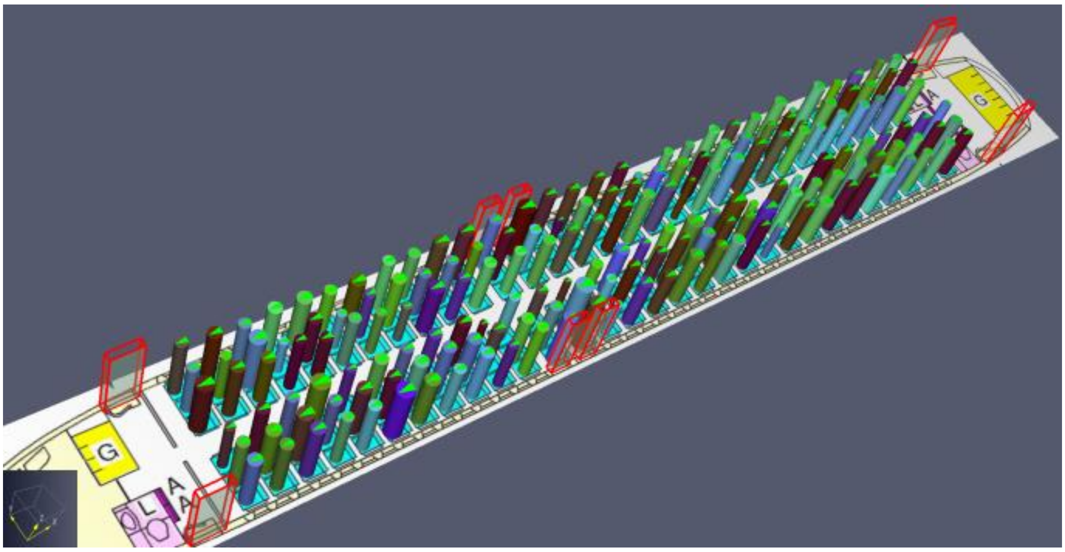


Figure 6-6 Narrow-body aircraft Pathfinder model featuring 180 passengers in a single class layout

6.4.2.2 Wide-Body Aircraft Attributes

The wide-body aircraft has a cabin layout of three-four-three sets per row. The wide-body aircraft has a seat pitch of 76- 81 cm (30- 32 in) and an aisle width of 51 cm. The cabin is split into three main sections. The forward section accommodates 68 passengers and contains the forward galley and the lavatory. The middle section accommodates 160 passengers and has three lavatories in the rear. The aft section accommodates 111 passengers and contains the rear galley and lavatories.

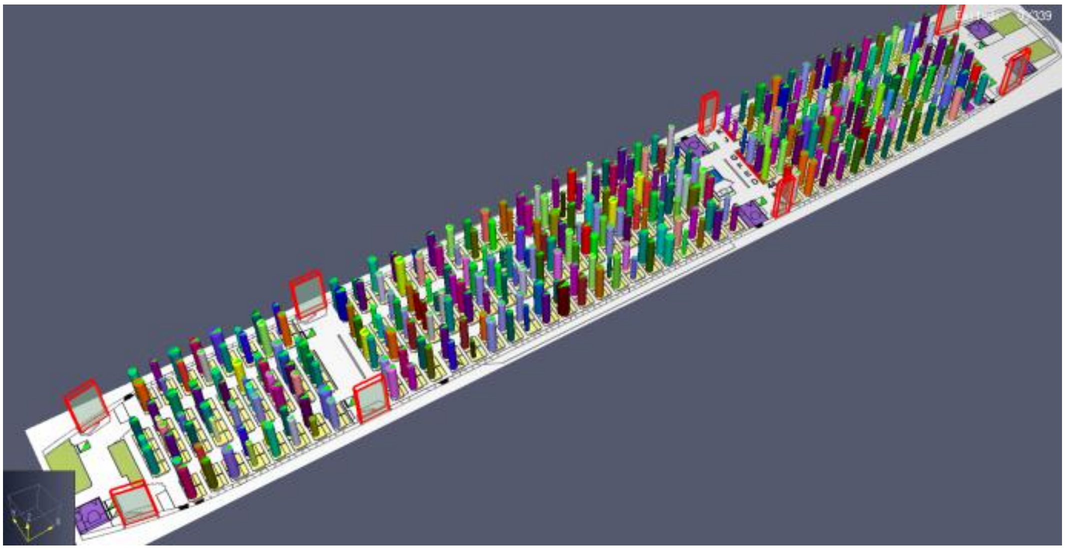


Figure 6-7 Wide-body aircraft Pathfinder model featuring 339 passengers in a single class layout

6.4.3 Exit Types

Aircraft exit (door) type depends on the aircraft's 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 aircraft evacuation. A smaller exit increases the time required to traverse the exit. A wider exit door allows for increased flow rates because the opening may accommodate two passengers simultaneously to negotiate egress.

6.4.3.1 Exit Modelling Process

In Pathfinder, occupants cannot pass between rooms unless the rooms are joined by a door. Further, they are required to have a path to at least one exit door. Doors are added using the 'Add a New Door' tool, which is circled in red in Figure 6-8. Exits are added to the model and characterised by the width, flow rate and opening delay. Under the *state*, property details about when the doors are open or closed are added to the model. The *wait time* parameter is left at 0 s because the doors implemented in the model contain a specified flow rate, which will moderate the flow through the door. These parameters are discussed for the specific doors in each aircraft model in Section 6.4.3.2.


Door02
☑ Visible
☐ Color:
Opacity: 100.0 %
X Bounds: -27.11 m, -27.11
Y Bounds: 0.34 m, 1.15 m
Z Bounds: 0.00 m, 0.00 m
Width: 81.28 cm
☐ Flow Rate: <unlimited>
State: Always Open
Wait Time: 0.0 s

Figure 6-8 Door property panel and tool (red circle)

6.4.3.2 Aircraft Model Exit Characteristics

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. These characteristics are implemented as shown in Table 6-5 (McLean & Corbett 2004; McLean et al. 2002). In an emergency, all doors might not be used for various reasons. For example, a door may not be used if it is damaged or faulty, if the emergency slides improperly deploy or if there are hazards and obstructions directly in front of the exit (e.g., fire, debris or water). Therefore, the certification requirements necessitate that only half of the total number of doors on an aircraft are used for certification purposes.

Table 6-5 Aircraft door types and characteristics used for these simulations (McLean & Corbett 2004; McLean et al. 2002)

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

6.4.4 Occupant Creation

Occupants are placed individually in the 3D or 2D view, distributed in a rectangular region of a particular room or distributed through the entire area of a room or multiple rooms. For this study, occupants had to be placed individually into a position that represented a seat in the aircraft.

6.4.4.1 Occupant Seeding

Occupants are created using the single occupant tool highlighted in red in Figure 6-9. Occupants can only be placed in pre-existing rooms and cannot overlap other occupants or room boundaries. The seeded occupants are then grouped by creating groups in the Occupants tab in the left panel. Once occupants have been grouped, the distribution of profiles and behaviours can be reshuffled among them. The relevant demographic profile distributions derived in Section 4.4 are introduced using the group property interface.

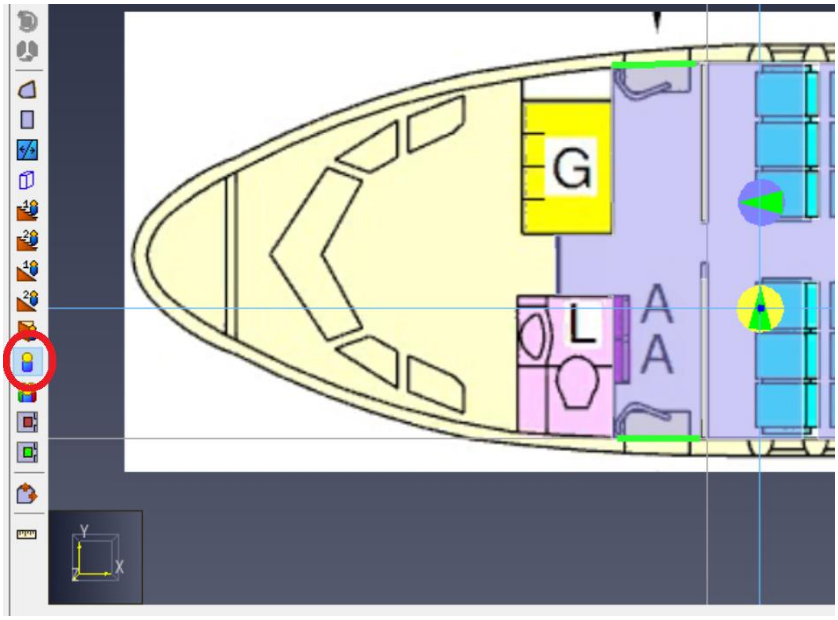
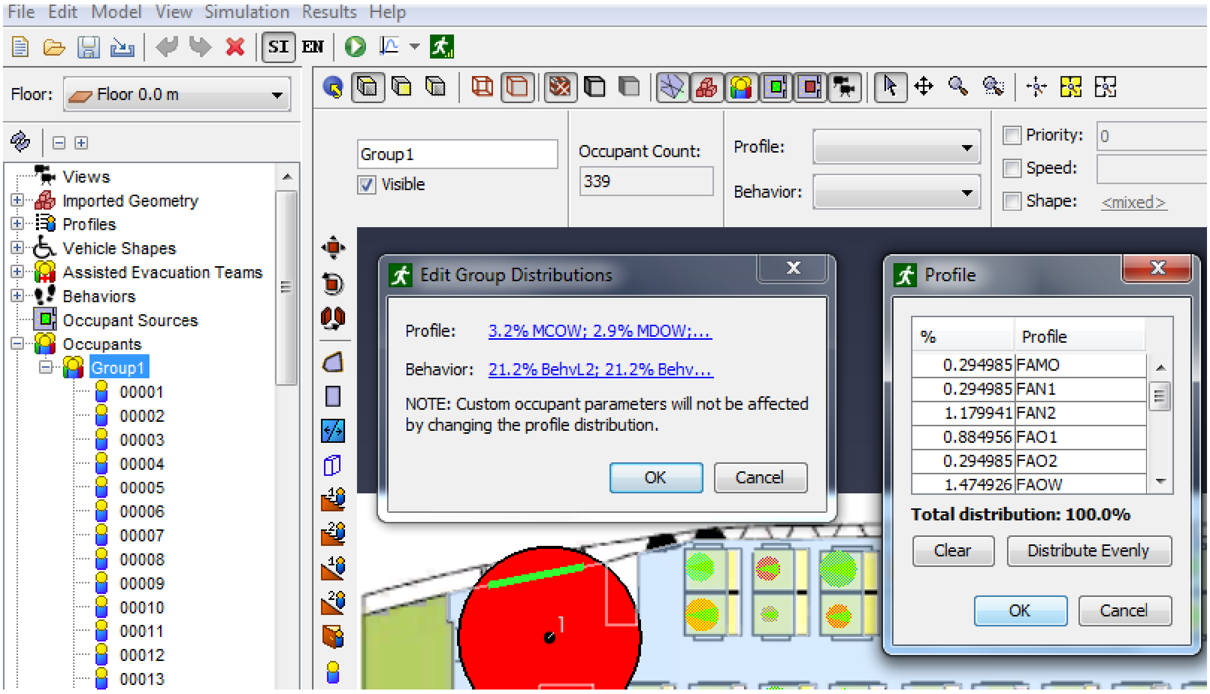


Figure 6-9 Occupant seeding tool (red circle)

6.4.4.2 Grouped Occupant Profiles Distribution

Once the occupants have been seeded, they are grouped into a single group to allow for profile distribution. The distribution of profiles is accomplished by opening the 'Edit Group Distribution' window (see Figure 6-10) by double-clicking the newly created group. Two options can be edited: "Profile" and "Behaviour". In the case of this study, the "Profile" is manipulated and the "Behaviour" has already been set based on door proximity; this is not manipulated. The second window in Figure 6-10 is used to edit the occupant profiles.

Using the methods outlined in Section 4.4, the simulated profile distributions are added. Pathfinder will self-adjust the calculated distributions to ensure that integer values of occupants are present in the simulation—for example, a calculated distribution of 0.2% may yield a 0% presence in the simulations. A larger occupancy capacity increases the chance that all profiles may be accounted for in the simulation. Appendix 5 and Appendix 6 present tables for the A320 and A330-200 profile distributions, respectively. Note that the calculated values are entered into Pathfinder. Simulated values are those that are adjusted by the software to accommodate non-fractional representations of occupants.



Floor: Floor 0.0 m

Group1

☑ Visible

Occupant Count: 339

Profile:

Behavior:

☐ Priority: 0

☐ Speed:

☐ Shape: <mixed>

Profile: 3.2% MCOW; 2.9% MDOW;...

Behavior: 21.2% BehvL2; 21.2% Behv...

NOTE: Custom occupant parameters will not be affected by changing the profile distribution.

%	Profile
0.294985	FAMO
0.294985	FAN1
1.179941	FAN2
0.884956	FAO1
0.294985	FAO2
1.474926	FAOW

Total distribution: 100.0%

Figure 6-10 Profile distribution editing windows

The profile distribution for the control scenario is presented in Table 6-6 for the A320 and A330-200 aircraft. The control scenario uses the methods outlined in Section 4.4; however, the distributions are further manipulated to meet the FAA aircraft certification requirements for passenger demographics.

Table 6-6 Profile distributions for the control scenario for the A320 and A330-200

Control Profile Distribution															
Profile	Calculated	Simulated A320	Simulated A330	**Profile**	Calculated	Simulated A320	Simulated A330	**Profile**	Calculated	Simulated A320	Simulated A330	**Profile**	Calculated	Simulated A320	Simulated A330
FAMO	0.30	0.56	0.29	**FDO2**	0.50	0.56	0.59	**MAMO**	0.20	0.00	0.29	**MDO2**	0.50	0.56	0.59
FAN1	0.30	0.00	0.29	**FDOW**	1.50	1.67	1.47	**MAN1**	0.50	0.56	0.59	**MDOW**	2.90	2.78	2.95
FAN2	1.30	1.11	1.18	**FDU**	1.50	1.67	1.47	**MAN2**	2.80	2.78	2.65	**MDU**	1.40	1.67	1.47
FAO1	0.80	0.56	0.88	**FEMO**	0.50	0.56	0.59	**MAO1**	1.30	1.11	1.18	**MEMO**	0.60	0.56	0.59
FAO2	0.30	0.00	0.29	**FEN1**	0.40	0.56	0.29	**MAO2**	0.60	0.56	0.59	**MEN1**	0.40	0.56	0.29
FAOW	1.40	1.67	1.47	**FEN2**	1.40	1.67	1.47	**MAOW**	1.90	1.67	1.77	**MEN2**	2.10	2.22	2.06
FAU	0.90	1.11	0.88	**FEO1**	1.20	1.11	1.18	**MAU**	1.30	1.11	1.18	**MEO1**	1.50	1.67	1.47
FBMO	0.40	0.56	0.29	**FEO2**	0.40	0.56	0.29	**MBMO**	0.60	0.56	0.59	**MEO2**	0.70	0.56	0.59
FBN1	0.30	0.56	0.29	**FEOW**	1.80	1.67	1.77	**MBN1**	0.50	0.56	0.59	**MEOW**	2.60	2.78	2.65
FBN2	1.60	1.67	1.47	**FEU**	1.50	1.67	1.47	**MBN2**	2.80	2.78	2.65	**MEU**	1.40	1.67	1.47
FBO1	0.80	0.56	0.88	**FFMO**	0.40	0.56	0.29	**MBO1**	1.70	1.67	1.77	**MFMO**	0.30	0.56	0.29
FBO2	0.50	0.56	0.59	**FFN1**	0.10	0.00	0.29	**MBO2**	0.40	0.56	0.29	**MFN1**	0.30	0.56	0.29
FBOW	1.50	1.67	1.47	**FFN2**	1.20	1.11	1.18	**MBOW**	2.80	2.78	2.65	**MFN2**	1.50	1.67	1.47
FBU	0.80	0.56	0.88	**FFO1**	0.80	0.56	0.88	**MBU**	1.40	1.67	1.47	**MFO1**	1.20	1.11	1.18
FCMO	0.20	0.00	0.29	**FFO2**	0.40	0.56	0.29	**MCMO**	0.20	0.00	0.29	**MFO2**	0.70	0.56	0.59
FCN1	0.30	0.56	0.29	**FFOW**	1.40	1.67	1.47	**MCN1**	0.50	0.56	0.59	**MFOW**	1.90	1.67	1.77
FCN2	1.80	1.67	1.77	**FFU**	0.80	0.56	0.88	**MCN2**	2.10	2.22	2.06	**MFU**	0.70	0.56	0.59
FCO1	1.60	1.67	1.47	**FGMO**	0.10	0.00	0.29	**MCO1**	2.50	2.78	2.36	**MGMO**	0.20	0.00	0.29
FCO2	1.10	1.11	1.18	**FGN1**	0.10	0.00	0.29	**MCO2**	0.80	0.56	0.88	**MGN1**	0.20	0.00	0.29
FCOW	0.60	0.56	0.59	**FGN2**	0.90	1.11	0.88	**MCOW**	2.90	2.78	3.24	**MGN2**	1.30	1.11	1.18
FCU	1.10	1.11	1.18	**FGO1**	0.40	0.56	0.29	**MCU**	1.40	1.67	1.47	**MGO1**	1.20	1.11	1.18
FDMO	0.40	0.56	0.29	**FGO2**	0.30	0.56	0.29	**MDMO**	0.50	0.56	0.59	**MGO2**	0.20	0.00	0.29
FDN1	0.20	0.00	0.29	**FGOW**	0.80	0.56	0.88	**MDN1**	0.40	0.56	0.29	**MGOW**	1.30	1.11	1.18
FDN2	1.30	1.11	1.18	**FGU**	0.80	0.56	0.88	**MDN2**	2.40	2.22	2.36	**MGU**	0.70	0.56	0.59
FDO1	1.10	1.11	1.18					**MDO1**	1.60	1.67	1.47				

6.5 Egress Simulations Process

The egress simulations were conducted with different scenarios of BMI prevalence. A control scenario has been used for comparisons with scenarios consisting of BMI greater than 25 kg•m^{-2}. The control scenario comprises NHANES data (with 55% obesity) adjusted to meet the FAA evacuation requirements (FAA 1990a). Although all aircraft are expected to meet the FAA requirements, obesity prevalence varies in different countries. Hence, this study explores various situations in which the obesity prevalence scenario changes. A total of 40 iterations were made for each scenario to ensure that the results were statistically significant. Simulations were considered for obesity scenarios beginning at 65% and incrementing by 5% until the final scenario of 90%. Three overarching situations scenarios are considered: a higher prevalence of overweight (25<BMI<30), obese (30<BMI<40) constituting prevalence rates of 65%, 70% and 80%; the morbidly obese (BMI>40) situation only considered the scenario of 65%.

Table 6-7 presents a list of input factors based on the information that governs each simulation, as discussed in the previous section. All 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 because they cannot be modelled in Pathfinder. Furthermore, to simplify the simulation, carry-on baggage, blankets, pillows and other similar articles that create minor obstructions are not modelled. 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 for each of the variable parameters. Each simulation run was made with the following randomised attributes, except for the occupant location: occupant gait speed, height, waist diameter and delay time.

Table 6-7 List of input factors used in Pathfinder that are variable or fixed

Variable	**Fixed**	
Passenger	***Passenger***	***Aircraft***
Height	Priority Level	Door Width
Waist Diameter	Reduction Factor	Door Flow Rate
Gait Speed	Acceleration	Door Height
Delay Time	Persist Time	Door Open Delay
	Collision Response Time	Cabin Aisle Width
	Slow Factor	Seat Pitch
	Wall Boundary	Seat Width
	Comfort Factor	

The simulation process was manually completed for each of the 40 iterations following the flow chart in Figure 6-11. Once all the input data were entered into Pathfinder, the simulation was started by pressing the simulation start button (green circle with a white arrow in Figure 6-10). After each iteration, the output files were catalogued and the relevant data about the *Profile* exit times were extracted into a spreadsheet. When the 40 iterations were completed, the next scenario was considered. Once all the obesity scenarios were completed, the next set of situation scenarios began, repeating the simulation process. An example of the Pathfinder Summary Output files can be found in Appendix 7.

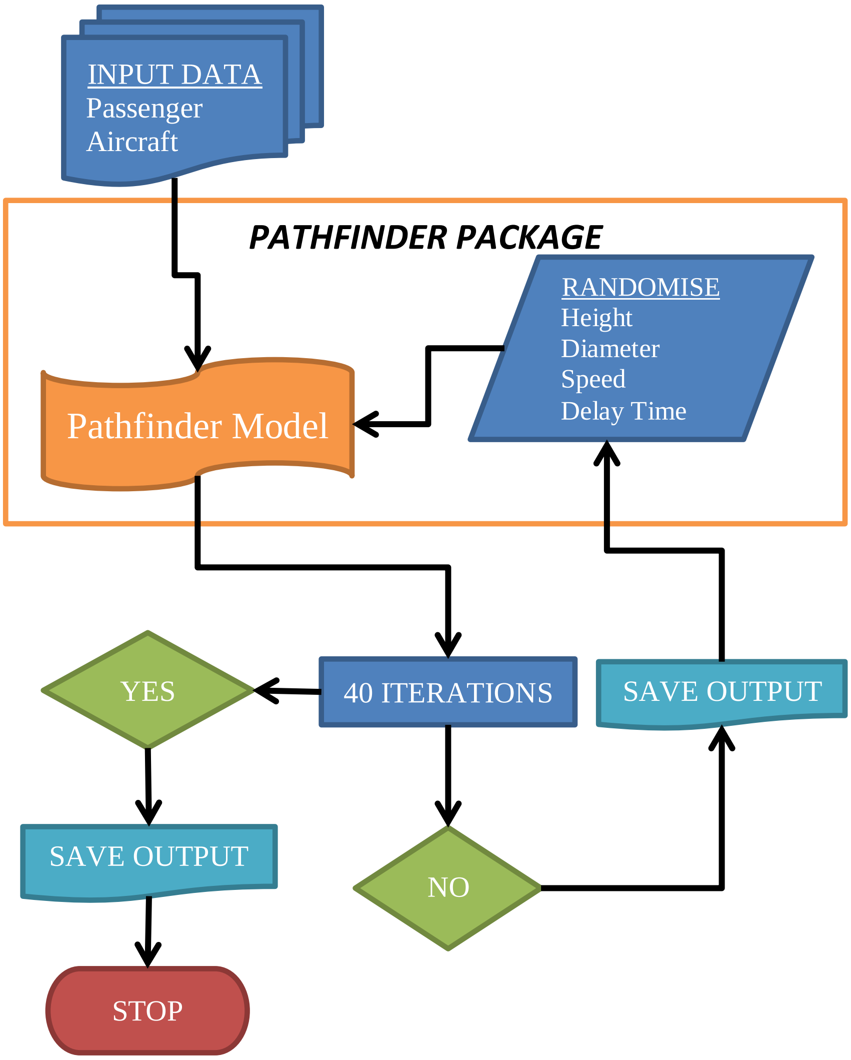


Figure 6-11 Simulation process flowchart

6.6 Simulations Results

6.6.1 Simulation Scenario Statistics

Increasing the prevalence of overweight and obese passengers has shown to increase evacuation times in specific scenarios for both aircraft types. The total evacuation time for each of the 40 iterations can be seen in Appendix 8 and Appendix 9 for the A320 and A330-200 respectively. The statistical descriptions of the data for the narrow-body and wide-body aircraft are shown in Table 6-8 and Table 6-9 respectively. The scenarios consist of the control group, with BMI greater than 25 kg•m^{-2} at 55% prevalence, followed by three sets of scenarios beginning at 65% and increasing at increments of 5% until reaching BMI greater than 25 kg•m^{-2} at 90% prevalence. For each set of scenarios, the results show an increase in evacuation time. The control scenario shows a baseline evacuation mean time of 76.61 s (SD 1.13 s) for the narrow-body aircraft and 87.13 s (SD 1.53 s) for the wide-body aircraft. Both aircraft types experienced greater mean evacuation time over the 90 s certification requirement when considering a scenario in which a population with BMI greater than 40 kg•m^{-2} predominates. The 90 s threshold is also surpassed when considering a population consisting of BMI 30–40 for the wide-body aircraft.

Table 6-8 Narrow-body aircraft descriptive statistics 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	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 6-9 Wide-body aircraft descriptive statistics 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	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

6.6.2 Obesity Prevalence and the 90 s Requirement

Simulations conducted in this study explored the effects of various BMI above 25 kg•m^{-2} 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 s regulatory requirement. Table 6-10 and Table 6-11 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 highest mean difference, with this difference decreasing as BMI prevalence increased over both predominant BMI category scenarios.

Similarly, the wide-body aircraft had 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) also increases, however the prevalence becomes less significant as the egress time approaches the test value of 90 s. The reason why BMI greater than 25 kg•m^{-2} is not significant at 70% and 80% is because the t-test value was set at 90 s; this indicates that the evacuation time in these scenarios is approaching the regulatory threshold. In scenarios where greater obesity (BMI 30–40) is prevalent for the wide-body aircraft, the mean difference is positive because the evacuation times surpass the 90 s rule.

Table 6-10 One sample t-test results for various obesity scenarios for the narrow-body aircraft against the 90 s rule

Scenario predominance BMI Category	**BMI>25 Prevalence**	**One-Sample Statistics**			**One-Sample Test**				
					Test Value = 90			95% Confidence Interval of the Difference	
		Mean	*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

Table 6-11 One sample t-test results for various obesity scenarios for the wide-body aircraft against the 90 s rule

Scenario predominance BMI Category	**BMI>25 Prevalence**	**One-Sample Statistics**			**One-Sample Test**				
					Test Value = 90			95% Confidence Interval of the Difference	
		Mean	*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

6.6.3 Regression Model

Regression modelling is conducted to establish evacuation times for each aircraft simulated in this study. This study presents two models to determine the evacuation time of an individual based on a combination of the following attributes: gender (G), age group (A) and BMI category ($\mathrm{BMI_k}$), where k is the Regression Model Variable Value in Table 6-3 and the distance to the closest exit (X). Eq. 6.3 corresponds to a model encompassing all variables, whereas Eq. 6.4 presents a second model 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 6-3. The input values for gender in *M1* are 1 and 0 for male and female respectively.

$$t_{M1} = \alpha(G_i) + \beta(A_j) + \gamma(BMI_k) + \delta(X) + C_{M1} \qquad \text{Eq. 6.3}$$

$$t_{M2} = \beta(A_j) + \gamma(BMI_k) + \delta(X) + C_{M2} \qquad \text{Eq. 6.4}$$

The third model (Eq. 6.5) 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 demographic and the BMI categories of overweight (25<BMI<30), obese (30<BMI<40) and morbidly obese (BMI>40), 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 the overweight, obese and morbidly obese BMI categories respectively:

$$t_{M3} = \theta(BMI_{percentge}) + \xi(BMI_{category}) + C_{M3} \qquad \text{Eq. 6.5}$$

6.6.3.1 Regression Analysis for Determining Individual Evacuation Time

Regression analyses for selected scenarios are presented in Table 6-12 and Table 6-13 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 ($0.7<r2<0.85$, $p<0.001$). 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.

Table 6-12 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: (^) $p<0.001$; (*) $p<0.05$

The regression analysis shows that an individual’s distance to an exit is significant for all models ($p<0.001$), whereas individual BMI is significant in most models ($p<0.05$). Passengers’ gender and age are less significant for egress time on a narrow-body aircraft compared with a 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.

Table 6-13 Model 2 regression analysis for 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: (^) $p<0.001$; (*) $p<0.05$

6.6.3.2 Evacuation Time and Body Mass Index Prevalence Regression

Regression Model 3 shows that the percentage of BMI greater than 25 kg•m^{-2} ($p<0.01$) and the predominant BMI category ($p<0.01$) in an aircraft is a significant factor in evacuation time (see Table 6-14). 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 kg•m^{-2}.

The model indicates that as BMI above 25 kg•m^{-2} 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 changes for a scenario from predominantly overweight (BMI 25–30) to a scenario of obese (BMI 30–40) passengers, evacuation time will only differ by 0.87 s and 0.56 s for the narrow- and wide-body aircraft respectively.

Table 6-14 Model 3 regression analysis for 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		

6.6.4 Delay Time Sensitivity Analysis

As discussed in Section 6.3.2.3, delay times (representing the sit-to-stand movement) highlight that the individuals assume a different delay time taken from a normal distributed time delay that is applied to the entire passenger population. 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.

6.6.4.1 Method

Exploring the differences in the time delay of the evacuation time is considered using five alternative scenarios: two scenarios below and three scenarios 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 because it shifted the delay distribution along with the standard deviation of the control scenario. Figure 6-12 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 6-15. The analysis considered the repeats of the 40 iterations conducted for the control group (55% obesity prevalence). Each of the 40 iterations of the control scenario has a corresponding simulation among the five alternative delay scenarios. This ensures that all control simulation attributes and parameters are retained for each alternative scenario and guarantees that the delay time is the only variable being changed.

Table 6-15 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

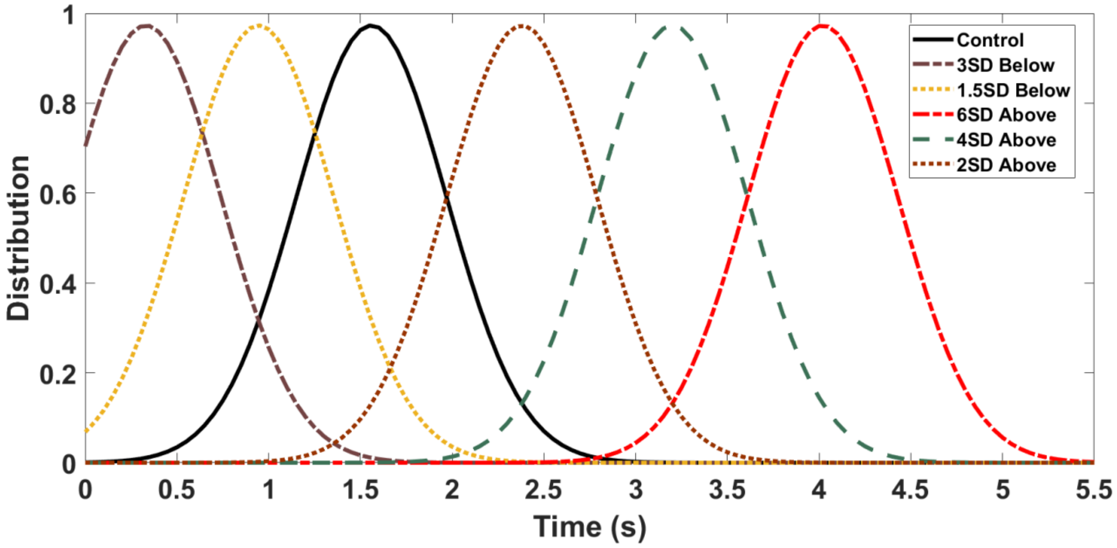


Figure 6-12 Distribution of delay time against the control scenario

6.6.4.2 Summary of Results

The results of the delay sensitivity analysis showed that the effect of the sit-to-stand time delay was not significant at times less than six standard deviations above the control delay time. Figure 6-13 illustrates the spread of the different scenarios considered. The scenarios of 1.5 Below and 2 Above share similar spread properties to that of the control and indicated a narrower spread of evacuation times. The scenarios of 4 Above, 6 Above and 3 Below have a wider spread of evacuation times.

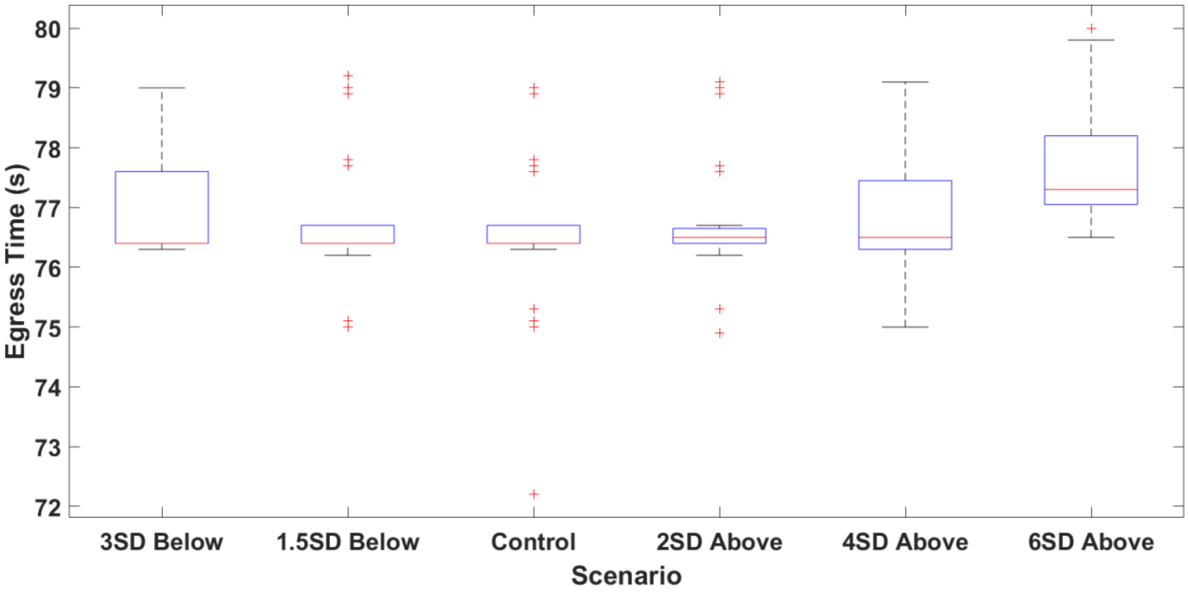


Figure 6-13 Boxplot of the evacuation times for the control and alternative delay time scenarios

A t-test was used to determine whether changes in the delay time affect evacuation time when compared with the control scenario. The results are shown in Table 6-16. 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 supressed by other factors; such as congestion in the aisle and at the exits. Notwithstanding, an additional 2.5 s delay (represented 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 taken to rise from a chair. Elderly (70+) persons take 55% longer to stand from their seat when compared with people aged in their 20s (Bohannon 2010). Similarly, a person's weight can increase the time it takes to stand. An obese person with a BMI of more than 35 takes 31% longer to stand than someone with a BMI of less than 30 kg•m^{-2} (Schmid et al. 2013). These sit-to-stand values are for the physically capable obese or overweight individual; as such, these values reflect the 2SD Above scenario. However, health consequences from obesity that lead to limited movement may increase the time it takes to stand.

Table 6-16 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	df	t-stat	p-value	t-value
Control	76.61	1.13	1.28			(2-tailed)	
3 SD Below	76.88	0.81	0.65	70	−1.23	0.22	1.99
1.5 SD Below	76.74	0.89	0.78	74	−0.60	0.55	1.99
2 SD Above	76.74	0.87	0.75	73	−0.59	0.56	1.99
4 SD Above	76.73	0.87	0.75	73	−0.54	0.59	1.99
6 SD Above	77.67	0.89	0.80	74	−4.67	$p<0.001$	1.99

6.7 Verification of Model for Narrow Aisle-based Evacuations

Verification of the simulation model resorting to a scenario involving narrow aisles and confined space was conducted using two methods. The first method involved conducting a real-life evacuation simulation trial using a 57-seat 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).

6.7.1 Bus Evacuation Exercise

An evacuation exercise using a bus with a similar interior to a narrow-aisle aircraft, with seats facing forward on either side of an aisle, was used to validate the numerical results. Past studies that have used bus evacuations include Purswell and Dorris (1978) and Matolcsy (2009), who explore the design of both emergency doors and windows. Similar 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 conduct partial or full evacuation experiments to explore their goals (e.g., exit accessibility, bus interior layout, passenger behaviour and use of specific exits). Liang, Zhang and Huang (2018) successfully demonstrate the evacuation time of a commuter bus using evacuation software to replicate experimental evacuations.

6.7.1.1 Experimental Background

The decision to conduct an evacuation exercise using a bus came down to two key factors: time constraints and access to aircraft and cabin training facilities. The main goal of the bus exercises was to demonstrate how anthropometric characteristics affect evacuation time in narrow-aisle situations. Ultimately, the bus evacuation was conducted in August 2018, with ethics approval granted on 20 June 2018 (see Appendix 1).

In the initial concept, the experimental design for the verification aimed to conduct the emergency evacuation trials using a full-size aircraft. Multiple contacts were made within airlines regarding aircraft acquisition on the basis that, at some point in time, an aircraft may become available. However, it became apparent that such a request would not be feasible for the level of research being conducted for this thesis, primarily because of financial costs and the timeframe involved.

The fall-back solution was to use cabin flight training centres. Several facilities were contacted but only two were interested in collaboration. Negotiations and discussions ensued: one facility was a cabin crew training organisation and the other was a tertiary education institute offering cabin training in hospitality. Both facilities had suitable-sized mock cabin layouts with aircraft-style seating and dimensions. Towards the end of the negotiations to use the facilities, both organisations pulled out, citing teaching conflicts and safety and liability concerns.

The last contingency option was to conduct the evacuation trials using a bus. Contact was made with multiple bus companies but only two expressed interest. A site visit to both bus depot hubs resulted in the selection of a suitable bus and organisation partner. Key selection criteria for the bus included: seat pitch and aisle width of equivalent size to an aircraft; aisle seats with armrests; seat backs high enough to support the head; a low ceiling over the seats to simulate clearance between the overhead bin and the occupant’s head; and fully opening pivot doors so as not to obstruct egress.

6.7.1.2 Exercise Location and Set-up

The bus exercise was conducted at the Bundoora East Campus at RMIT University, Melbourne. The location of the exercise needed to be away from the main thoroughfare of pedestrians and away from any vehicular movement. A secluded location was chosen away from any access by public vehicle. Further, it was within sight of the primary foot traffic between buildings to facilitate participant recruitment.

Appendix 11 presents a diagram of the exercise set-up. Note that it only depicts the general location of the measuring areas and the participant holding zone. There were two separate locations for measuring the genders on either side of the bus to accommodate privacy concerns. The diagram also shows the position of the two cameras. One camera was located inside the bus and oriented to capture the participants leaving the aisle and moving down the stairs. The second camera was located outside and was orientated to the main exit door approximately 3–5 m away to capture a wide field of view. The first three and last two rows of seats were not used during the exercise. Further, a first aid officer was always located in the participant holding area. Three research team members oversaw each exercise: one was located near the bus exit door and the other two were located outside to usher participants to the holding area. Once seated, the participants were asked to take the brace position to simulate the posture before beginning an evacuation from an emergency landing. A member of the research team demonstrated this process before the trial commenced.

The design of the bus evacuation exercise sessions is shown in Figure 6-14. During this exercise, participants were asked to attend one or more of these sessions. Each trial was conducted with a 10–15 minute interval to allow participants to relax in preparation for the next trial. Each set of exercises had an interval of 20–30 minutes to allow for a new set of participants or a longer respite for ongoing participants, and also to enable the research team to assess/reset their equipment. Each exercise set was scheduled to be approximately 1 hour long. Participates were encouraged to attend as many exercise sessions as possible. Three exercise sessions were available at 10.30 am, 12 pm and 1.30 pm.

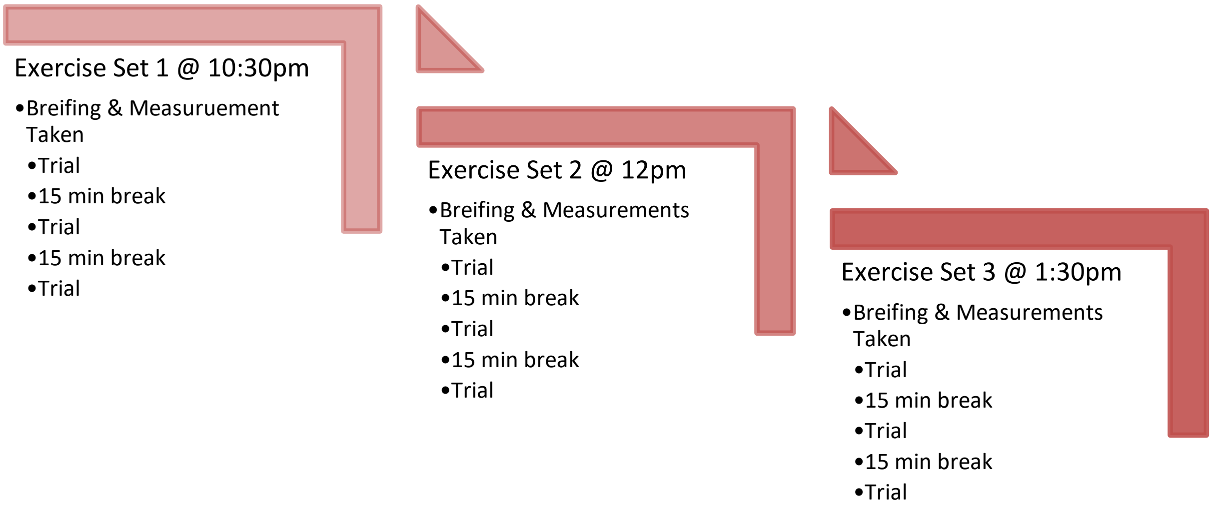


Figure 6-14 Bus evacuation exercise process

6.7.1.3 Bus Evacuation Procedure

The bus evacuation procedure was initially designed with three exercises consisting of three evacuation trials each, as per the outline given in the Participation Information Sheet. However, as a result of a lack of volunteers, only one set of evacuation trials was conducted. A further delay was encountered because the first aid officer arrived late, causing the exercise to be postponed. Upon arrival, participants were asked to have their anthropometric characteristics measured. These characteristics include the following: weight, height, age, waist circumference and shoulder breadth. Before the exercise took place, the measurements were collected using a tape measure, a stadiometer and scales:

- Measurements of the waist were taken around the hips or waist, with the larger being recorded.
- Shoulder span was taken from across the upper back.
- A number for identification purposes was provided at random to each participant.
- The parameters mentioned above were measured by male research assistants for male participants and a female assistant for female participants.

All of the individual anthropometric parameters were collected anonymously to ensure the identity of the participants would not be disclosed at any point. Once all the participants had completed the two tasks, they were asked to board the bus and sit in a seat. The seat number was recorded and the participant was asked to remember the seat number for successive trials.

Each trial was initiated by the phrase ‘EVACUATE, EVACUATE, EVACUATE’. 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. An additional motivation was introduced by repeating some supporting phrases to instil urgency in the behaviour of the participants. Between each trial, a 10–15 minute interval was provided to allow the participants to re-enter the bus and find their allocated seat assignment, and to give the research team time to assess and reset their equipment. It is acknowledged that due to the repetition of the consecutive trials by the participants a learning effect is expected to have occurred. This learning effect would be represented by means of shorter evacuation times with each consecutive trial.

Figure 6-15 Bus evacuation trial interior

Figure 6-16 Bus evacuation trial main exit

6.7.1.4 Bus Configuration

The bus evacuations for this study consisted of three trials that required participants to exit the bus rapidly. The bus used in this study was a road coach with a capacity of 57 passengers. The average seat pitch is 64 cm (25 in) with a seat width of 24 cm (Figure 6-17). The seats on the left side of the bus were staggered by 15 cm behind the right side, and the aisle width was 45 cm. There were 10 rows of seats on either side of the aisle, with four seats per row, and five seats in the back row.

Figure 6-17 Bus interior looking down the aisle towards the rear

The cabin floor was 130 cm above the ground, and there were three 20 cm high steps from the base of the bus door, which was 42 cm above the ground, to the driver's seat landing (see Figure 6-18). There was a small ramp that connected the driver's seat landing to the aisle instead of an additional step. This ramp rose 21 cm and was 182 cm in length, making the first three rows of seats unusable because of Pathfinder's modelling constraints.

Figure 6-18 Bus entrance showing the steps and driver's seat landing

6.7.1.5 Participant Data

A total of 21 random adult participants took part in this exercise, including 12 males and nine females. Participants were measured for their anthropometric attributes. Table 6-17 shows the characteristics of the group of participants. The participants had a mean age of 22.2 years and an average BMI of 22.3. The youngest participant was 18 years old and the oldest was 28 years old. The heaviest participant weighed 98.7 kg and had a BMI of 31 kg•m^{-2}. The lightest participant weighed 53 kg and had a BMI of 18 kg•m^{-2}. The participants' raw data are presented in Appendix 11.

Table 6-17 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

6.7.1.6 Participant Exiting Sequence

An expectation of conducting the bus evacuation exercise was that the sequence in which the participants exited the bus was not the same for each of the three trials. Thus, it was necessary to determine the sequence in which the participants exited the bus from the footage taken during the trials. This sequence information, shown in Table 6-18, was then entered into the Pathfinder's occupant characteristic toolbox under the priority setting (see Figure 6-1).

Table 6-18 Bus evacuation participant exiting order and Pathfinder priority sequence numbering scheme

Participant Number	Trial 1		Trial 2		Trial 3	
	Exit Order	Pathfinder Priority Number	Exit Order	Pathfinder Priority Number	Exit Order	Pathfinder Priority Number
1	13	8	13	8	13	8
2	11	10	10	11	10	11
3	10	11	11	10	11	10
4	9	12	9	12	9	12
5	6	15	7	14	5	16
6	3	18	3	18	3	18
7	21	0	21	0	20	1
8	15	6	15	6	15	6
9	8	13	8	13	8	13
10	20	1	20	1	21	0
11	19	2	19	2	19	2
12	5	16	5	16	6	15
13	14	7	14	7	14	7
14	7	14	6	15	7	14
15	4	17	4	17	4	17
16	2	19	2	19	2	19
17	12	9	12	9	12	9
18	17	4	16	5	16	5
19	18	3	18	3	18	3
20	1	20	1	20	1	20
21	16	5	17	4	17	4

6.7.1.7 Modelling and Simulation Process of Bus Evacuation Trials

Following the bus trials, a model was created in Pathfinder to replicate the same conditions both in terms of cabin layout and participant anthropometric features (see Figure 6-19). Bus dimensions were taken before the exercise. Modelling of the bus interior follows the same process used for Pathfinder described in Section 6.4. The only difference compared with the aircraft modelling is that floors, stairs and ramps were added to the bus model.

Individual egress times and the order in which each participant evacuated was obtained using video footage taken during the trials. Compared with the aircraft study, each occupant seed placed in the corresponding seat was characterised by the matching participant's anthropometric attributes. Shoulder width and waist diameter were used as the limiting model factor for the simulated occupants. For example, if a participant had a shoulder width greater than their waist diameter, then their corresponding occupant model would use their shoulder width as the model factor.

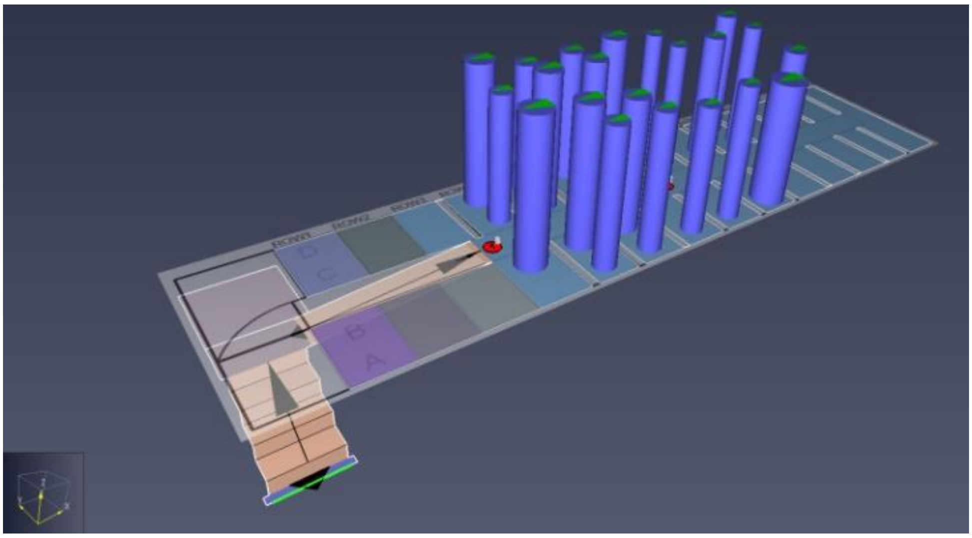


Figure 6-19 Pathfinder bus simulation model

6.7.1.8 Summary of 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. Figure 6-20 shows the evacuation of each of the 21 participants for the trial and simulations, each point represents a participant. Video footage was used to determine the evacuation times for the participant in each trial. Pathfinder provided evacuation times for each occupant (participant) in the summary file. Evacuation time decreased with each consecutive evacuation trial as participants became more aware of and accustomed to the evacuation process. Further, participant location determined the evacuation time because participants towards the rear of the bus had to wait for the participants at the front to move ahead.

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

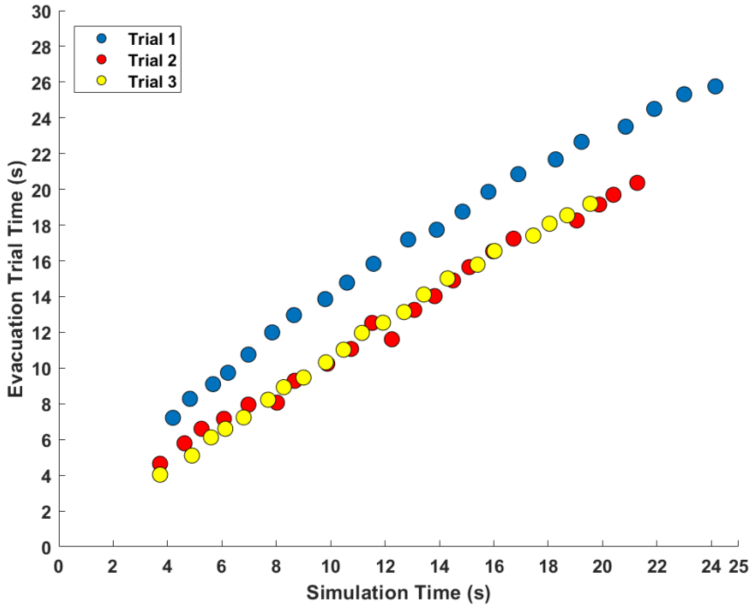


Figure 6-20 Plot showing the evacuation time for each participant with respect to each bus evacuation trial and simulations

Given that the purpose of these trials was to ascertain Pathfinder's validity regarding narrow-aisle evacuation scenarios, the analysis consisted of comparing the results of the bus exercise and the corresponding simulations using a bivariate correlation test in Statistical Package for the Social Sciences (SPSS) software (see Table 6-19). There was a significant correlation between egress time and weight, BMI and distance within the trials and simulations. Further, the results showed that Pathfinder provides a realistically close representation of evacuations when comparing each bus exercise with the Pathfinder simulation counterpart: BusT1-SimT1 (r^2=0.995, p<0.01), BusT2-SimT2 (r^2=0.996, p<0.01) and BusT2-SimT2 (r^2=0.998, p<0.01). The result of this analysis validates the appropriate use of Pathfinder to represent the narrow aisle and confined cabin conditions in transport scenarios.

Table 6-19 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)**				

6.7.2 A380 Aircraft Comparison

The introduction of the A380 aircraft led to a revolution in aviation as a result of the advent of an ultra-high capacity aircraft used for commercial passenger transport. With a capacity of more than 800 in a single-cabin layout configuration, the A380 raised concerns regarding the observance of the 90 s requirement as a result of the large number of passengers. It should be noted that most A380 operators do not operate single-class configurations; 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 its initial certification.

6.7.2.1 Scenario

It has been widely publicised that the A380 evacuation time is 78.04 s (Daly 2006), and a video recording of the evacuation has been uploaded to popular video streaming sites. Details of the anthropometry of the participants involved in the Airbus A380 evacuation certification test are currently publicly unavailable. However, the media reported that more than 1,000 participants were chosen through a vetting process of non-disabled persons after they completed a warm-up exercise. These participants were employees of Airbus and people from local gymnasiums (Daly 2006).

6.7.2.2 A380 Simulation Model

The model presented in the verification study considers an aircraft with 853 occupants seated in a single-class layout (see Figure 6-21). Both the upper and lower decks have a cabin layout consisting of two aisles with a width of 60 cm and a seat pitch of 76- 83 cm (31-33 in). A total of 367 and 486 occupants are seated on the upper and lower decks respectively. The scenario demographics constituted the control scenario passenger's demographic model derived from the NHANES data used for the narrow- and wide-bodied aircraft FAA scenarios. Further, only the doors on the left-hand side were considered in the simulations, and egress time was measured when the last occupant exited the aircraft.

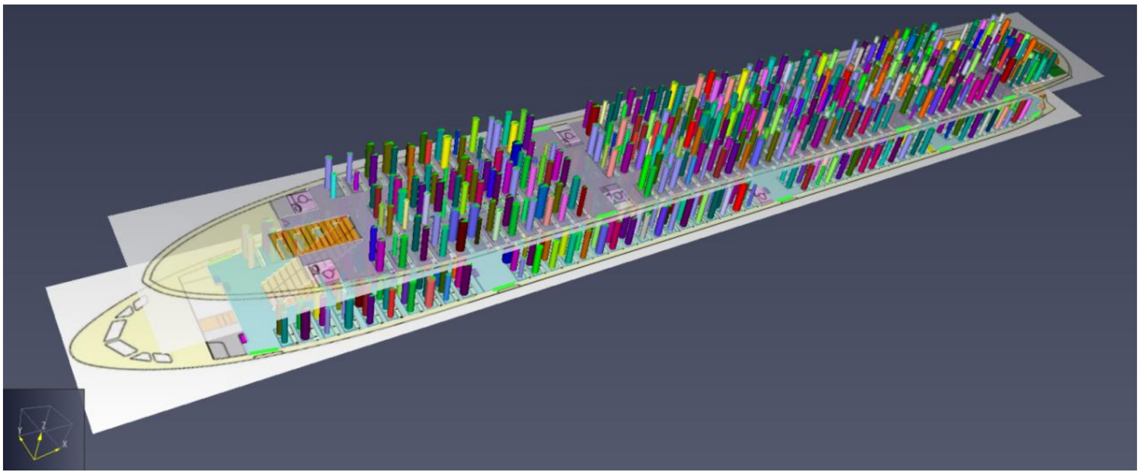


Figure 6-21 A380 aircraft Pathfinder model with 855 passengers in single-class layout

6.7.2.3 Summary of Results

The A380 Pathfinder simulation results show an average 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 with the actual evacuation time of 78.04 s. Many different factors can contribute to the slightly higher evacuation time of the simulation. For instance, the anthropometrical attributes and behaviours of the participants compared with those used in the simulations will be different. The regression models discussed in Section 3.3 have also been applied in this case (see Table 6-20). Both models are statistically significant, although they capture less than 45% of the variance in the data ($r^2_{M1}=0.574$; $r^2_{M2}=0.569$, $p_{M1,M2}<0.001$).

Table 6-20 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		

6.7.3 Verification and Uncertainty

Section 6.7 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. 6.6). 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 and unexpected behaviours that limit the simulation models' potential to precisely reproduce real conditions. The first bus simulation showed a 6.2% faster egress time over the bus trial. In contrast, the second simulation showed a 4.5% slower egress time compared with the second trial; similarly, the third simulation was slower by 1.9%:

$$U_R = \frac{V_s - V_m}{V_m} \qquad \text{Eq. 6.6}$$

For example, the A380 analysis showed that the model in this study produced a 4.4% slower egress time than the actual evacuation time, which is within the margin of uncertainty deduced above. All aircraft evacuation certification trials are conducted as a single egress event and may be 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 because of the large number of resources involved in egress trials. Manufacturers that conduct multiple evacuation trials would show variation 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 bus evacuation trials demonstrate that the level of uncertainty between the trials and the simulation is minimal. Therefore, the models considered in this study can be validated by the fact that the aircraft simulated egress times lie between a slower (4.5%) or faster (6.5%) interval.

6.8 Consequences of Anthropometric and Demographic Change on Evacuation Time

Evacuating an aircraft in less than 90 s is an essential requirement of the safety certification process. If the aircraft does not meet this condition, it will not be certified for commercial use. Manufacturers need to ensure that measures are taken to replicate an emergency that is as close as possible to a real scenario. These might include evacuations in the dark, obstructions within the cabin, not disclosing the exits to be used during the test and, to an extent, simulating smoke in the cabin. Although these certification tests are completed only once, additional analysis can be carried out by resorting to simulations. These simulations tend to explore conditions that cannot be conducted during certification (e.g., smoke hazards and passenger behaviour). Notably, variations in anthropometry have not been investigated thoroughly—particularly BMI prevalence in an airline passenger population.

FAA regulations CFR Title 14 Part 25 on transport aircraft airworthiness standards provide details of critical design and safety requirements for commercial aircraft—particularly rules on the evacuation of aircraft. These rules elaborate on how to conduct evacuations and which door types should be used, among other requirements. However, other than specifying that participants in an evacuation demonstration should be of normal health and particular gender and age requirements, there are no guidelines on the anthropometrical requirements of participants (HFES 2019). Although the demographic data from NHANES are representative of the US, characteristics relating to BMI for those demographics can be inferred to other nations with adequate corrections. It is estimated that, by 2025, the prevalence of global obesity ($30<\text{BMI}<40$) will reach 18% in males and surpass 21% in females, while severe obesity ($\text{BMI}<40$) will surpass 6% in males and 9% in females (NCD Risk Factor Collaboration 2016b). The majority of the concern relates to European countries, the Americas and the Pacific, where obesity has a greater presence than in Africa and Asia.

Further, air travel has higher patronage and frequency in markets where obesity is expected to grow.

This study has shown that for current levels of BMI greater than 25 kg•m^{-2} (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) highlight that for a 180 seat narrow-body aircraft, their study results in an egress time of 79.0 s with a standard deviation of 1.7 s, while Chen, Qian and Xue (2014) use two different egress software packages, MACEY and airEXODUS, to obtain results of 85.0 s for a 179-seat aircraft and 73.0 s for a 188-seat aircraft respectively. Similar results are achieved by Hong-bing et al. (2018), whose simulations using in-development software consider panic-stricken evacuees with evacuation times of 66–72 s. Likewise, the use of GPSS and airEXODUS provide results of 84.9 s for a 356-seat and 71.7 s for a 351-seat wide-body aircraft (Chen et al. 2014). Using ETSIA Martinez-Val et al. (2017) determined an evacuation time of 77.8 s for a 179-seat single aisle aircraft. However, all of these cases are unclear or non-specific on the demographic/anthropometric characteristics considered in the simulations.

The regression analysis in this study has also shown that age and gender have a less significant effect on egress time with most models. Hong-bing et al.’s (2018) results reflect the results in this study, as they found that gender is not a factor in egress time, and the evacuation times are similar. However, the evacuation time was shorter because their model accounted for fewer passengers and focused on panic behaviour. Age led to an increase in egress time by less than 0.1 s, whereas BMI and distance to the nearest exit increased the time by less than 1 s and 5 s respectively. The models also indicate that under certain scenarios, passenger weight significantly contributes to egress time. Therefore, these changes in demographics may reduce the existing occupant flow models. With flow being a product of speed and density, an ageing population constitutes a less mobile population. Likewise, a demographic consisting of high proportions of people with a BMI over 25 have a higher area footprint, leading to a situation in which the speed of the movement is reduced in a narrow aisle or corridor, while the density of a given space is also reduced.

A BMI greater than 25 kg•m^{-2} is not necessarily a predictor of a person’s mobility function. However, maintaining a normal BMI can improve a person’s chance of retaining their mobility function—particularly gait speed. Increasing BMI by 1%/year over 25 years decreases gait speed by 4.5 cm-s^{-1} (Windham et al. 2017). Passengers with a disability that prevents them from standing 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 a disability make up less than 3% of travellers between the ages of 18 and 64. Nevertheless, varying levels of disabled passengers have been shown to increase evacuation times (Liu et al. 2014).

Further, the time it takes a person to stand up from their seat varies between individuals. Age has been shown to increase 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 compared with persons over the age of 80, who take approximately 8 s to complete the same task. This difference of approximately 0.4 s for a single sit-to-stand movement is equivalent to one standard deviation of time delay set in this study. Similarly, it has been shown that people with higher BMI also take longer to stand (Schmid et al. 2013; Kamaruddin, Arif & Salim 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 with the alternative scenarios. The behaviours of passengers moving within the cabin have greater weight on the overall time to exit. Some passengers remain standing in their seat until the path is clear for them to move as they wait for others to pass by, while others block pathways to try to retrieve their hand luggage. Similarly, if a passenger seated in the aisle is slower to stand compared with a passenger in the adjacent window or middle seat, the added time will impede the evacuation of the blocked passenger.

During the safety briefing, passengers are asked to note where their nearest exit is located. Knowledge of how many rows are in front or behind an exit can increase survivability. This study highlights the importance of the passenger’s distance to an exit in evacuation time. In all cases, distance has higher significance when compared with anthropometrical attributes. The further away a passenger is from an exit, the longer it will take that passenger to reach the door. The regression analysis has shown that, regardless of the aircraft type, a higher significance is placed on the passenger’s location within the cabin, as the p-value in all models is less than 0.001.

6.9 Summary

Limited research has explored the relationship between anthropometry and aircraft egress, as much of the literature discusses new simulation methods and passenger behaviour. The innovative research conducted in this study shows that there has been a significant increase in emergency egress time as the prevalence of BMI above 25 increases within the population. The control scenario with 55% obesity, which reflects current trends, was shown to meet the 90 s rule, with an egress time of 76.61 s (95% CI, 76.2–76.9) for the narrow-body aircraft and 87.13 s (95% CI, 86.66–87.60) for the wide-body aircraft. According to the regression analysis, gender is a less significant contributing factor to egress time. The control scenario representing the FAA regulations and incorporating current obesity trends (BMI>25 of 55%) reveals that weight is less of a contributing factor to egress time compared with the passenger's 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 egress time over the other variables considered in the simulations discussed herein. Thus, this study highlights the need for accurate passenger anthropometrical understanding to adapt existing standards and regulations to more realistic conditions for the design of safer commercial aircraft in the future.

Chapter 7: Conclusions and Recommendations

7.1 Introduction

This chapter presents the conclusions and recommendations that have arisen from the research exploring passenger anthropometry. Further, the limitations of this study are highlighted, leading to a discussion of future research. This chapter is composed of three parts:

- First, conclusions are presented for the performance and emergency egress, and summarised answers are provided to the research questions.
- Second, recommendations are presented for the performance and emergency egress.
- Third, limitations are highlighted and potential future research directions are discussed.

7.2 Conclusions

Global demand for air travel is increasing as a result of competitive airfares, and air travel has been made accessible to new markets and passengers from different demographics. Coupled with this, the anthropometric characteristics of these passengers and the world population have changed over time—particularly in relation to obesity. The average weight of the global population has increased over the last few decades, with the proportion of obese and overweight individuals rising from 23% in 1975 to 40% in 2016 (NCD Risk Factor Collaboration 2017), and this trend is set to persist. In particular, regions that cover the Western cultural sphere have been found to have a greater prevalence of obesity. A review of the current literature revealed that manufacturer and regulators do not prioritise changes in anthropometric attributes. This is evident by regulators’ lack of changes in response to these changing anthropometric trends - particularly in terms of weight. This fact has been brought up recently by the HFES by outlining a policy, in 2019, to address the rise in obesity and its effects on seat design. The contribution of the holistic model in Figure 3-6 to the literature provides researchers with a foundation for considering passengers’ anthropometry and the safety, design and performance aspects in aviation and aerospace research. The novel research carried out in this thesis has shown that passengers’ anthropometric attributes affect both the safety and operation of aircraft.

This study addressed the effect of heavier passengers on the operational performance of civil aircraft with a focus on flight performance efficiencies during different phases of flight. Research that explores the effects of passenger weight on aircraft performance has shown that the prevalence of obesity is increasing at a global scale and that as these trends increase, aircraft range will decrease because the higher passenger payload weight reduces the amount of fuel weight carried at MTOW. Chapter 5 has demonstrated, that an increment of 5% in obesity will require an additional 119.1 kg of fuel at a cost of US$89.90 for an A330 flying a prescribed range of 7,500 km. A similar obesity increase will see an A320 travelling 3,000 km consume 51.4 kg of fuel at an additional cost of US$38.80. An ATR-72 travelling 700 km will carry additional 6.4 kg of fuel and cost US$4.83 for every 5% increment in obesity. This study has simulated various obesity situations, explored the effects of the increased number of obese/overweight passengers onboard both short and long-haul aircraft and compared them with current standards and places with equivalent obesity levels around the world. Parts of Africa and Asia that have low obesity prevalence but use standard passenger weights are overestimating aircraft performance characteristics - notably fuel costs. In contrast, regions with higher obesity prevalence, such as those in Westernised nations, may begin to see significantly compromised safety margins if increasing weight trends continue.

Aircraft safety has focused on the emergency evacuations of large aircraft subjected to direct physical interaction with passengers. The simulated results shown in Chapter 6 that for current levels of BMI prevalence, the time taken to evacuate an aircraft is 76.6 s (95% CI, 76.2 - 76.9) for a narrow-body aircraft and 87.1 s (95% CI, 86.7 - 87.7) for a wide-body aircraft. Leaving the current prevalence of BMI categories unchanged but increasing overall obesity by just 5% can lead to an increase of approximately 2 s in egress time for the wide-body aircraft scenario. Egress time significantly increases when greater percentages of obese passengers are considered. The results show that egress time for a population with a demographic distribution similar to that expected in the next 30 years exceeds the current time limit considered by aviation authorities for certification purposes of passenger aircraft. The models used in the emergency egress were validated in a bus evacuation exercise. The results demonstrate that the bus evacuations correlated to the result of the bus simulations with $r^2>0.995$ and $p<0.001$.

In conclusion, the passenger interface between anthropometrical characteristics and the aircraft environment is an area of focus that requires further exploration. The demographics of society are constantly shifting, and airline, aircraft manufacturers and regulators have been slow to adapt. This thesis outlines the effects of these changing anthropometric trends and shows that airlines, aircraft manufacturers and regulators are not exploring these changes.

7.3 Recommendations

This research has built on the current body of knowledge to show the trends in passenger anthropometry juxtaposed with the ramifications of aviation attributes such as aircraft performance and emergency evacuations. These two issues converge to the inevitable problem of dealing with a combination of increasing numbers of passengers on aircraft and their corresponding weight. Most aircraft performance assumptions rely on knowing the weight of the aircraft. However, the precise passenger payload weight is unknown, and pilots rely on estimates that are often out of date and may not reflect the current population demography.

The novelty of this research resides in the collation of the current knowledge of anthropometrical change by applying the concept in the aviation safety and performance context through cross-disciplinary applications. It is vital to undertake this research to emphasise the effect of passengers' anthropometric features on different disciplines of aerospace engineering and aviation. This will provide a foundation for more in-depth studies of all aspects relating to safety where passenger weight is concerned. The results of this research can also be used to inform key stakeholders in the aviation sector of the need to update existing standards for the design of next-generation aircraft and policies and procedures for passenger safety.

Recommendation 1) Regulators and aircraft manufacturers should strive to bolster the significance of anthropometrical change in current regulations and standards underpinning the design of passenger aircraft, including the need to update standard passenger weights with greater frequency to ensure passenger weights reflect current trends so that safety is uncompromised from both a design and operational levels.

Recommendation 2) Leading researchers in the aircraft evacuation field need to ensure that current and in-development egress software better incorporate anthropometrical features.

Recommendation 3) Regulations for emergency evacuation certification should endeavour to reflect the demographics of the travelling public so that the safety of all passengers is uncompromised regardless of their physical attributes.

Recommendation 4) Airlines should change their current check-in procedures to allow for all passengers to be weighed so that this information can be taken into consideration for an accurate calculation of the weight and balance of the aircraft, as well as other operational parameters with an impact in both the safety and operational efficiency of commercial flights.

7.4 Limitations and Future Research

The conclusions drawn from this research contribute to filling the gap concerning the current lack of knowledge regarding whether existing design and operation standards adequately incorporate the anthropometric changes of passengers. Therefore, it provides better insights into adjacent issues with a potential effect on both the safety requirements and performance efficiency of commercial aircraft. Passengers' changing anthropometric characteristics present a significant challenge to the aviation industry, especially in terms of maintaining and improving passenger safety. Thus, identifying the effect of passengers' anthropometric characteristics across different disciplines of aerospace engineering and aviation is important for future research. Each regulator is expected to determine its requirements for updating or revising existing regulations and standards as a result of new research. Any regulatory material that is dependent on anthropometrical data should be regularly updated and reviewed to ensure that the design requirements follow current trends, especially in relation to passenger weight standards.

Further research exploring the areas in Figure 1-2 should be conducted under the holistic framework introduced in Figure 3-6. For example, the design of certain aircraft components which are directly impacted by the weight of passengers (e.g., seat frames, floor panels) should take into consideration crashworthiness requirements to cater for adequate survivability levels for all passengers irrespective of their physical attributes. Biomechanical factors are another important consideration that largely depends on the physical attributes of passengers and is typically associated with the reachability, mobility and flexibility of a person in an aircraft cabin environment. Therefore, these factors play an important role in the design and usability of cabin components such as seats and overhead luggage bins. Although the literature focuses on particular biometrics such as height and weight, a holistic approach based on a broader inter-relationship between anthropometric and biometric characteristics should be employed—for example, how weight affects fitness and therefore mobility.

A limitation of this study that requires consideration is future developments in unconventional aircraft configurations. These unconventional designs predominantly focus on the newer concept of the blended wing-body. In this type of aircraft, the available space for exits is limited, while the internal structure has been projected to accommodate more than 800 passengers. Although this study has not explored unconventional aircraft designs, future research should explore these concept aircraft for evacuation simulations.

An observation noted during the simulations related to the obesity of an occupant, their location and, in particular, the Type-III overwing exits of the narrow-body aircraft. During the simulation phase, an obese passenger was occasionally located near the overwing exit. As they endeavoured to egress the aircraft, the simulation would fail to complete, often trapping smaller-sized occupants and preventing them from exiting. This simulation issue was resolved by relocating the obese passenger closer to either the aft or forward Type-A main cabin doors. It was surmised that the exit orifice of the Type-III exit was too small for the obese occupant to egress. Future studies should explore the ability of larger individuals to egress through Type-III overwing exit in addition to their ability to operate said exit door.

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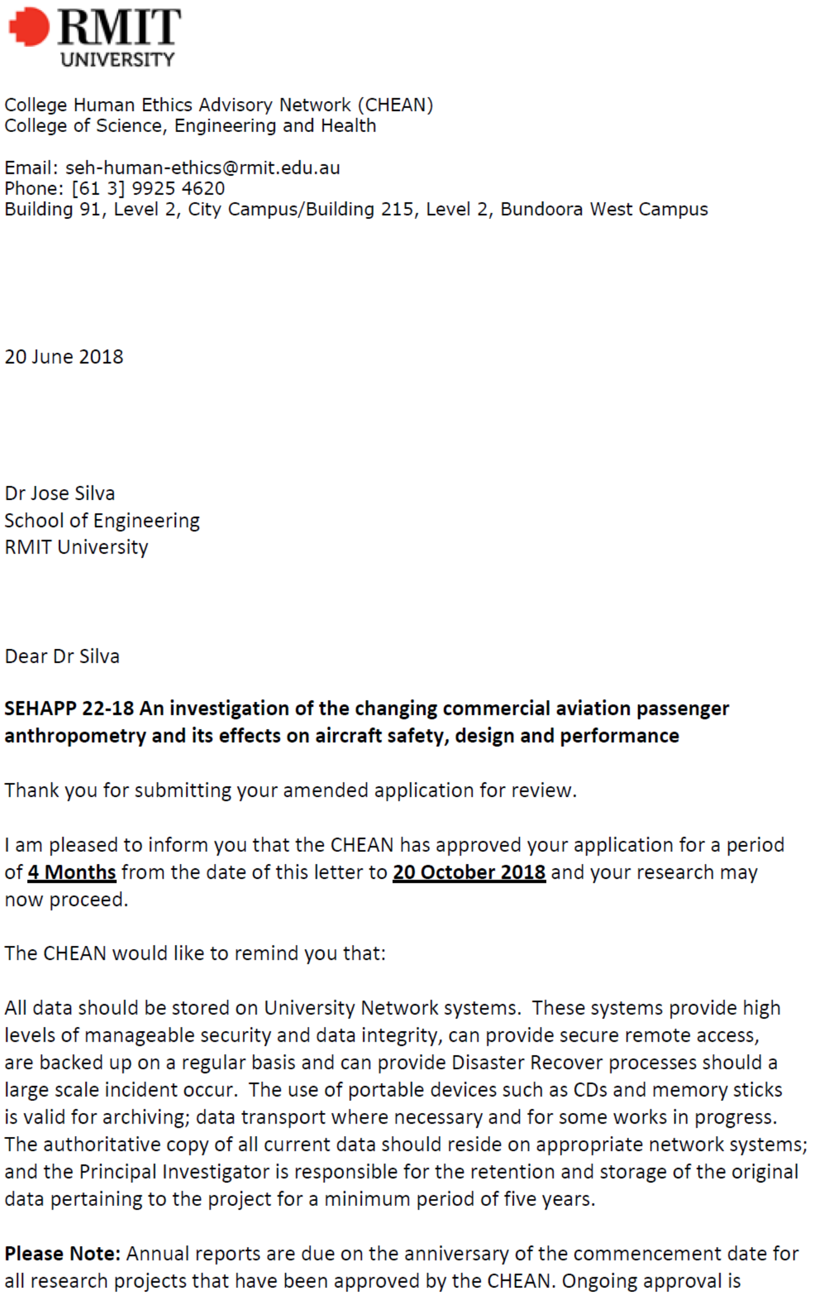
Appendix 1: Ethics Approval Letter



RMIT UNIVERSITY

College Human Ethics Advisory Network (CHEAN)
College of Science, Engineering and Health

Email: seh-human-ethics@rmit.edu.au
Phone: [61 3] 9925 4620
Building 91, Level 2, City Campus/Building 215, Level 2, Bundoora West Campus

20 June 2018

Dr Jose Silva
School of Engineering
RMIT University

Dear Dr Silva

SEHAPP 22-18 An investigation of the changing commercial aviation passenger anthropometry and its effects on aircraft safety, design and performance

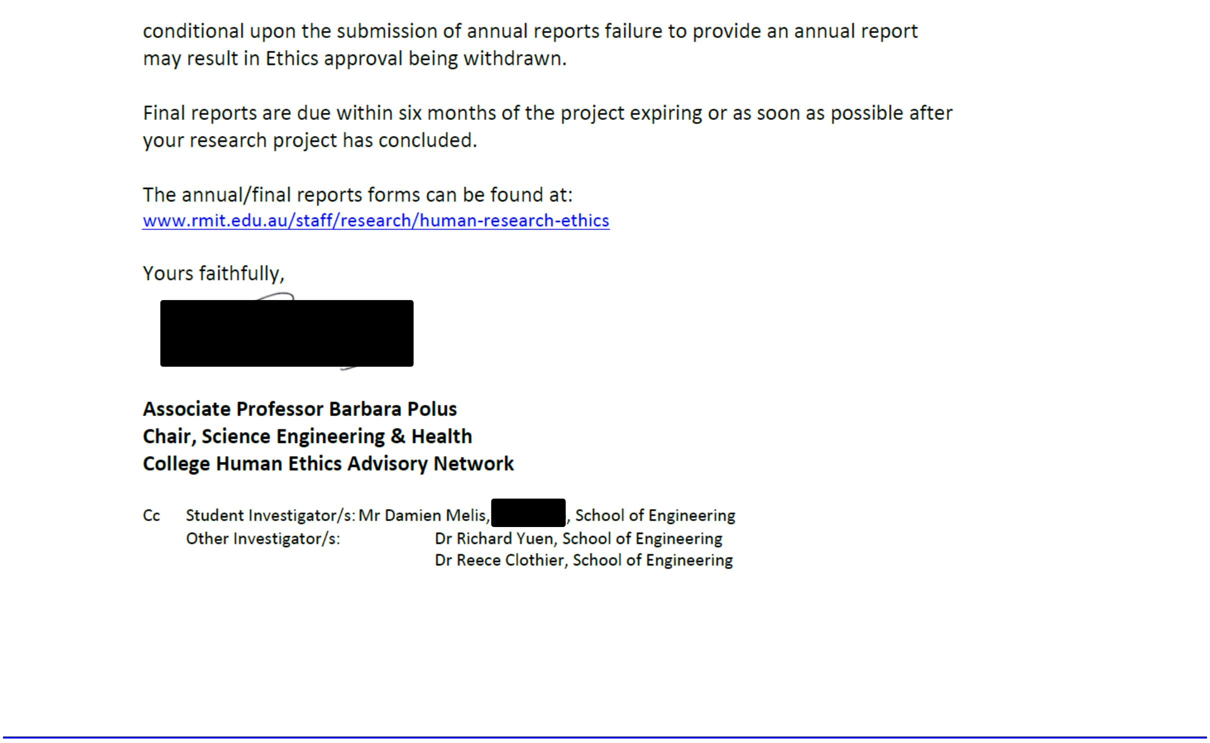
Thank you for submitting your amended application for review.

I am pleased to inform you that the CHEAN has approved your application for a period of **4 Months** from the date of this letter to **20 October 2018** and your research may now proceed.

The CHEAN would like to remind you that:

All data should be stored on University Network systems. These systems provide high levels of manageable security and data integrity, can provide secure remote access, are backed up on a regular basis and can provide Disaster Recover processes should a large scale incident occur. The use of portable devices such as CDs and memory sticks is valid for archiving; data transport where necessary and for some works in progress. The authoritative copy of all current data should reside on appropriate network systems; and the Principal Investigator is responsible for the retention and storage of the original data pertaining to the project for a minimum period of five years.

Please Note: Annual reports are due on the anniversary of the commencement date for all research projects that have been approved by the CHEAN. Ongoing approval is



conditional upon the submission of annual reports failure to provide an annual report may result in Ethics approval being withdrawn.

Final reports are due within six months of the project expiring or as soon as possible after your research project has concluded.

The annual/final reports forms can be found at:
www.rmit.edu.au/staff/research/human-research-ethics

Yours faithfully,

[redacted]

Associate Professor Barbara Polus
Chair, Science Engineering & Health
College Human Ethics Advisory Network

Cc Student Investigator/s: Mr Damien Melis, [redacted], School of Engineering
Other Investigator/s: Dr Richard Yuen, School of Engineering
Dr Reece Clothier, School of Engineering

Appendix 2: BMI Prevalence of Nations around the World—Females in 2016

	Underweight	Normal 1	Normal 2	Overweight	Obese 1	Obese 2	Morbidly Obese
Afghanistan	15.6%	13.6%	43.7%	19.1%	6.1%	1.4%	0.5%
Albania	2.0%	5.5%	39.8%	30.0%	15.5%	5.4%	1.8%
Algeria	3.3%	3.3%	25.4%	31.9%	22.6%	9.3%	4.3%
American Samoa	0.2%	0.5%	9.5%	24.4%	25.7%	20.9%	18.7%
Andorra	1.5%	4.0%	36.1%	32.1%	17.0%	6.7%	2.7%
Angola	10.6%	11.7%	41.6%	23.5%	8.5%	3.0%	1.1%
Antigua and Barbuda	4.0%	5.4%	33.3%	30.4%	15.2%	7.2%	4.5%
Argentina	1.1%	4.0%	33.8%	30.9%	17.7%	9.0%	3.4%
Armenia	3.2%	4.8%	35.9%	32.1%	15.4%	6.0%	2.6%
Australia	1.7%	5.0%	33.5%	30.3%	16.1%	8.4%	5.0%
Austria	2.7%	6.4%	42.7%	29.1%	12.6%	4.4%	2.0%
Azerbaijan	2.9%	4.9%	36.5%	31.2%	15.3%	6.5%	2.8%
Bahamas	2.3%	3.4%	24.4%	30.5%	20.4%	11.5%	7.6%
Bahrain	3.3%	2.9%	23.3%	32.3%	24.1%	9.7%	4.3%
Bangladesh	22.8%	13.7%	40.4%	17.8%	4.3%	0.6%	0.2%
Barbados	2.8%	4.7%	30.8%	29.1%	17.1%	8.9%	6.6%
Belarus	2.0%	4.6%	35.4%	30.7%	17.5%	7.0%	2.8%
Belgium	1.7%	5.6%	39.8%	31.1%	15.0%	4.7%	2.1%
Belize	2.7%	4.4%	29.9%	30.3%	17.3%	9.0%	6.4%
Benin	8.4%	10.6%	42.5%	23.7%	9.3%	3.2%	2.3%
Bermuda	1.9%	2.9%	22.0%	30.1%	21.6%	12.8%	8.7%
Bhutan	10.4%	13.4%	45.6%	21.8%	7.0%	1.4%	0.4%
Bolivia	1.3%	3.4%	34.0%	34.8%	17.6%	6.5%	2.4%
Bosnia and Herzegovina	2.3%	6.4%	42.7%	29.3%	13.4%	4.3%	1.5%
Botswana	6.2%	6.1%	29.5%	27.8%	18.3%	7.3%	4.9%
Brazil	3.1%	5.3%	34.4%	30.7%	16.3%	7.5%	2.6%
Brunei	5.9%	9.1%	42.1%	26.4%	10.9%	4.1%	1.4%
Bulgaria	1.8%	5.0%	37.1%	30.8%	16.9%	6.1%	2.3%
Burkina Faso	12.5%	12.8%	44.4%	21.8%	6.0%	1.5%	1.0%
Burundi	10.9%	12.5%	45.5%	22.1%	6.6%	1.6%	0.8%
Cabo Verde	6.9%	9.6%	40.7%	25.8%	11.3%	3.6%	2.1%
Cambodia	13.8%	13.7%	47.4%	20.0%	4.0%	0.8%	0.2%
Cameroon	6.0%	8.9%	42.1%	25.8%	10.8%	3.9%	2.4%
Canada	1.8%	4.5%	33.5%	29.7%	16.8%	8.3%	5.4%
Central African Republic	12.0%	11.9%	41.7%	23.0%	8.0%	2.6%	0.8%
Chad	13.0%	12.2%	43.9%	21.5%	6.4%	2.0%	0.9%
Chile	0.9%	3.4%	32.7%	30.9%	19.2%	8.8%	4.1%
China	6.1%	10.6%	52.2%	24.3%	5.8%	0.8%	0.2%
Hong Kong	6.7%	8.7%	46.6%	27.2%	9.1%	1.3%	0.3%
Colombia	2.4%	3.9%	30.7%	35.3%	19.1%	6.3%	2.3%

Comoros	8.2%	11.0%	43.9%	24.2%	8.9%	2.5%	1.3%
Congo	11.1%	10.8%	39.4%	24.6%	9.9%	3.1%	1.1%
Cook Islands	0.3%	0.8%	11.4%	26.7%	26.4%	17.9%	16.6%
Costa Rica	2.1%	3.6%	29.3%	33.4%	19.3%	7.7%	4.5%
Cote d'Ivoire	7.3%	10.0%	41.8%	25.0%	10.6%	3.2%	2.0%
Croatia	1.8%	5.2%	38.3%	29.2%	16.0%	6.2%	3.3%
Cuba	4.3%	4.3%	27.1%	32.7%	18.1%	8.7%	4.7%
Cyprus	1.7%	4.6%	39.5%	31.7%	14.9%	5.6%	2.0%
Czech Republic	1.5%	4.8%	36.9%	30.2%	17.0%	6.9%	2.6%
Denmark	2.9%	6.2%	42.1%	31.0%	11.9%	4.2%	1.6%
Djibouti	7.1%	8.8%	38.1%	27.0%	12.8%	4.3%	2.0%
Dominica	2.6%	3.8%	26.1%	30.6%	19.4%	10.8%	6.7%
Dominican Republic	3.1%	3.9%	25.9%	31.8%	19.7%	10.1%	5.6%
DR Congo	12.9%	12.0%	42.0%	23.1%	6.9%	2.3%	0.9%
Ecuador	1.2%	3.4%	34.7%	35.1%	17.7%	5.9%	2.0%
Egypt	1.0%	2.4%	25.3%	28.8%	23.1%	11.9%	7.4%
El Salvador	2.0%	3.7%	30.4%	33.9%	19.5%	7.6%	2.9%
Equatorial Guinea	9.8%	11.5%	42.0%	23.5%	8.7%	3.2%	1.3%
Eritrea	16.6%	11.9%	42.2%	21.4%	6.2%	1.4%	0.4%
Estonia	2.1%	5.3%	38.9%	30.9%	14.9%	5.7%	2.2%
Ethiopia	14.2%	12.7%	44.1%	21.8%	5.7%	1.1%	0.4%
Fiji	1.7%	2.6%	26.3%	32.9%	22.1%	9.6%	4.8%
Finland	1.5%	5.6%	41.3%	30.1%	14.2%	5.1%	2.2%
France	2.8%	5.1%	38.3%	31.8%	14.2%	5.9%	1.9%
French Polynesia	0.8%	1.1%	13.1%	28.1%	25.9%	16.9%	14.1%
Gabon	6.5%	8.8%	36.7%	26.8%	13.2%	6.3%	1.7%
Gambia	9.2%	9.9%	40.6%	24.8%	10.2%	3.3%	2.0%
Georgia	3.3%	5.3%	36.2%	30.5%	15.3%	6.0%	3.4%
Germany	1.7%	5.9%	42.3%	28.8%	14.3%	4.9%	2.1%
Ghana	6.8%	9.6%	41.2%	25.0%	11.0%	3.7%	2.6%
Greece	1.1%	4.0%	37.1%	31.4%	16.9%	6.9%	2.6%
Greenland	2.1%	5.3%	40.0%	29.8%	14.5%	5.8%	2.4%
Grenada	3.2%	4.8%	31.4%	30.4%	16.5%	8.4%	5.4%
Guatemala	1.7%	3.9%	33.0%	34.0%	18.1%	6.7%	2.7%
Guinea	9.8%	11.3%	43.5%	23.4%	8.1%	2.5%	1.4%
Guinea Bissau	8.7%	10.6%	42.2%	24.3%	9.4%	3.1%	1.8%
Guyana	4.2%	5.2%	32.2%	30.2%	15.8%	8.1%	4.3%
Haiti	4.6%	5.0%	30.2%	32.1%	16.6%	8.0%	3.5%
Honduras	2.4%	4.2%	32.2%	33.3%	18.0%	6.9%	3.1%
Hungary	2.5%	5.3%	36.7%	29.9%	16.8%	6.5%	2.4%
Iceland	1.7%	5.5%	40.9%	31.7%	13.7%	4.9%	1.6%
India	23.7%	14.0%	39.9%	17.1%	4.2%	0.9%	0.2%
Indonesia	12.4%	11.4%	43.9%	23.0%	7.4%	1.5%	0.4%
Iran	3.5%	3.6%	25.5%	33.9%	22.9%	7.9%	2.7%
Iraq	2.0%	2.9%	25.1%	31.6%	24.7%	9.0%	4.6%
Ireland	1.2%	4.5%	37.5%	30.2%	16.0%	6.6%	3.9%

Israel	1.3%	4.0%	35.3%	32.2%	18.1%	6.8%	2.4%
Italy	1.6%	4.9%	40.4%	32.7%	14.5%	4.4%	1.5%
Jamaica	3.1%	4.1%	27.8%	30.2%	18.7%	9.4%	6.6%
Japan	9.3%	15.2%	52.9%	18.8%	3.4%	0.5%	0.0%
Jordan	1.2%	2.3%	22.3%	29.6%	25.0%	12.6%	7.1%
Kazakhstan	3.4%	5.3%	36.9%	30.7%	15.0%	6.0%	2.6%
Kenya	9.4%	11.3%	43.9%	23.8%	8.4%	2.1%	1.1%
Kiribati	1.1%	1.1%	14.9%	30.9%	26.0%	15.3%	10.6%
Kuwait	1.1%	1.9%	20.0%	30.0%	25.7%	13.2%	8.2%
Kyrgyzstan	3.7%	5.7%	40.2%	30.9%	12.8%	4.9%	1.8%
Lao PDR	11.1%	12.8%	47.2%	21.9%	5.8%	0.9%	0.3%
Latvia	2.0%	4.8%	36.6%	30.4%	16.7%	6.7%	2.8%
Lebanon	2.2%	2.9%	23.8%	32.7%	23.7%	10.0%	4.7%
Lesotho	4.3%	6.6%	33.8%	27.6%	16.9%	6.5%	4.4%
Liberia	7.6%	10.2%	42.6%	24.8%	9.4%	3.2%	2.2%
Libya	1.7%	2.7%	23.6%	30.9%	24.0%	10.9%	6.2%
Lithuania	1.4%	4.6%	35.8%	29.3%	17.8%	7.7%	3.5%
Luxembourg	1.8%	5.4%	40.7%	30.5%	14.0%	5.4%	2.2%
North Macedonia	2.2%	5.5%	39.4%	29.8%	15.3%	5.5%	2.2%
Madagascar	14.4%	12.1%	42.9%	22.8%	6.1%	1.4%	0.4%
Malawi	8.8%	12.2%	46.5%	23.1%	7.0%	1.8%	0.8%
Malaysia	6.8%	8.6%	40.3%	25.7%	12.6%	4.4%	1.7%
Maldives	8.2%	10.6%	45.8%	23.6%	8.8%	2.3%	0.8%
Mali	9.4%	11.1%	43.1%	23.5%	8.8%	2.6%	1.5%
Malta	1.2%	3.6%	34.0%	31.6%	18.4%	7.9%	3.3%
Marshall Islands	0.6%	0.8%	11.8%	27.7%	27.1%	18.1%	13.8%
Mauritania	7.5%	9.2%	39.5%	24.5%	11.8%	4.4%	3.0%
Mauritius	6.9%	9.9%	42.0%	24.8%	10.9%	3.7%	1.7%
Mexico	1.5%	3.0%	27.9%	33.6%	20.7%	9.0%	4.3%
Micronesia	1.0%	1.3%	15.9%	28.6%	24.2%	15.7%	13.3%
Moldova	2.4%	5.5%	40.4%	29.7%	14.5%	5.3%	2.3%
Mongolia	2.6%	4.7%	35.5%	33.0%	17.0%	5.3%	1.9%
Montenegro	2.2%	5.3%	38.3%	30.1%	16.1%	5.8%	2.2%
Morocco	3.1%	3.5%	27.4%	32.5%	21.5%	7.8%	4.2%
Mozambique	9.7%	11.5%	44.0%	23.8%	8.1%	2.1%	0.8%
Myanmar	14.1%	11.9%	45.2%	21.2%	5.7%	1.4%	0.5%
Namibia	8.1%	7.0%	31.3%	27.1%	15.9%	6.7%	3.9%
Nauru	0.2%	0.5%	9.0%	25.5%	26.3%	18.6%	19.9%
Nepal	17.2%	14.1%	45.0%	18.1%	4.7%	0.7%	0.2%
Netherlands	1.7%	5.7%	40.9%	30.8%	14.1%	4.9%	1.9%
New Zealand	1.5%	4.1%	32.0%	29.8%	17.1%	9.2%	6.3%
Nicaragua	2.1%	3.6%	31.2%	32.9%	18.5%	7.8%	3.8%
Niger	12.3%	12.5%	44.5%	21.6%	6.4%	1.8%	0.9%
Nigeria	9.3%	10.7%	42.6%	23.7%	8.8%	3.0%	1.9%
Niue	0.6%	1.0%	14.0%	27.6%	25.8%	17.6%	13.3%
North Korea	7.6%	10.3%	50.3%	24.1%	6.5%	0.9%	0.2%
Norway	1.7%	5.4%	40.1%	29.4%	15.0%	5.7%	2.7%

Palestinian Territory	1.2%	2.8%	24.5%	31.3%	23.4%	10.9%	5.8%
Oman	4.3%	3.4%	24.6%	32.7%	21.5%	8.1%	5.4%
Pakistan	14.4%	11.9%	41.3%	20.7%	8.1%	2.5%	1.2%
Palau	0.6%	0.8%	11.0%	27.2%	27.4%	18.8%	14.3%
Panama	2.4%	3.8%	30.7%	34.3%	18.1%	7.0%	3.6%
Papua New Guinea	2.8%	4.2%	33.3%	32.9%	17.0%	7.0%	2.8%
Paraguay	2.1%	5.3%	37.8%	30.5%	15.0%	6.5%	2.9%
Peru	1.4%	3.3%	33.8%	36.4%	17.9%	5.7%	1.6%
Philippines	13.4%	12.5%	44.2%	22.0%	6.2%	1.3%	0.4%
Poland	2.3%	6.1%	38.8%	29.6%	15.5%	5.6%	2.0%
Portugal	1.6%	4.8%	40.0%	31.5%	15.6%	4.9%	1.6%
Puerto Rico	2.2%	3.0%	23.0%	30.2%	20.9%	12.9%	7.8%
Qatar	1.7%	2.2%	20.8%	30.7%	24.8%	11.5%	8.3%
Romania	2.1%	5.5%	39.7%	30.2%	15.2%	5.3%	2.0%
Russian	2.1%	4.9%	35.5%	29.4%	17.7%	7.3%	3.0%
Rwanda	7.4%	11.3%	46.6%	24.9%	7.6%	1.6%	0.6%
Saint Kitts and Nevis	2.8%	4.7%	31.4%	29.8%	16.4%	8.6%	6.3%
Saint Lucia	3.5%	5.0%	33.5%	30.0%	15.7%	7.3%	5.0%
Saint Vincent and the Grenadines	3.2%	4.5%	29.4%	30.7%	17.5%	9.0%	5.8%
Samoa	0.4%	0.9%	14.9%	27.2%	24.6%	17.5%	14.5%
Sao Tome and Principe	7.3%	9.3%	40.3%	25.4%	10.9%	3.8%	2.9%
Saudi Arabia	2.1%	2.5%	21.7%	30.0%	24.3%	11.5%	7.9%
Senegal	10.3%	10.8%	41.8%	23.6%	8.9%	2.9%	1.8%
Serbia	2.6%	5.8%	39.5%	29.4%	14.9%	5.7%	2.2%
Seychelles	4.9%	8.8%	39.7%	25.2%	13.0%	5.2%	3.1%
Sierra Leone	9.3%	10.7%	42.7%	23.3%	9.0%	2.8%	2.1%
Singapore	7.9%	12.0%	51.8%	21.7%	5.6%	1.0%	0.1%
Slovakia	2.6%	6.4%	40.6%	29.7%	14.5%	5.0%	1.4%
Slovenia	2.5%	5.8%	40.2%	29.6%	15.1%	5.2%	1.5%
Solomon Islands	1.9%	3.5%	32.6%	33.9%	18.7%	6.8%	2.6%
Somalia	9.1%	10.9%	42.8%	24.4%	9.1%	2.6%	1.1%
South Africa	2.7%	4.4%	25.6%	26.2%	20.0%	11.2%	9.8%
South Korea	5.2%	11.9%	55.7%	22.3%	4.4%	0.6%	0.0%
Spain	1.3%	4.5%	38.4%	32.0%	16.0%	5.4%	2.4%
Sri Lanka	12.5%	12.3%	46.8%	20.8%	6.0%	1.2%	0.4%
Sudan	7.9%	10.9%	43.8%	24.4%	9.3%	2.9%	0.7%
Suriname	2.8%	3.8%	27.3%	31.1%	18.3%	10.0%	6.6%
Swaziland	4.9%	6.7%	34.1%	27.1%	16.3%	6.6%	4.3%
Sweden	1.9%	6.0%	42.2%	31.1%	13.0%	4.2%	1.7%
Switzerland	3.2%	6.7%	42.8%	29.7%	12.1%	3.9%	1.6%
Syrian Arab Republic	2.5%	3.3%	26.9%	31.3%	21.9%	9.2%	5.0%
Taiwan	6.3%	9.8%	49.4%	25.9%	7.5%	1.0%	0.2%
Tajikistan	4.5%	6.0%	41.6%	30.4%	11.8%	4.1%	1.5%

Tanzania	9.6%	10.9%	42.8%	23.5%	9.2%	2.8%	1.2%
Thailand	7.9%	10.5%	44.8%	23.6%	9.2%	3.1%	1.0%
Timor-Leste	17.6%	12.5%	44.7%	20.0%	4.0%	0.8%	0.3%
Togo	8.6%	11.0%	43.4%	23.9%	8.7%	2.8%	1.5%
Tokelau	0.5%	1.3%	17.6%	28.4%	23.3%	16.1%	12.7%
Tonga	0.3%	0.9%	14.8%	27.9%	25.7%	17.9%	12.5%
Trinidad and Tobago	3.3%	5.7%	34.9%	29.1%	14.3%	7.2%	5.6%
Tunisia	3.0%	3.3%	26.0%	32.2%	21.8%	9.4%	4.4%
Turkey	1.5%	2.6%	24.6%	30.7%	23.8%	11.1%	5.8%
Turkmenistan	3.6%	5.3%	37.9%	31.3%	14.0%	5.6%	2.2%
Tuvalu	0.5%	0.9%	12.9%	27.9%	26.8%	17.3%	13.7%
Uganda	9.9%	12.5%	45.6%	22.9%	6.8%	1.6%	0.6%
Ukraine	1.9%	4.7%	36.3%	30.5%	17.2%	6.7%	2.8%
United Arab Emirates	2.1%	2.6%	22.3%	30.6%	24.6%	11.3%	6.6%
UK	1.6%	4.0%	33.9%	30.8%	16.9%	8.1%	4.7%
US	1.7%	4.1%	29.4%	26.6%	17.4%	10.7%	10.1%
Uruguay	1.2%	4.1%	32.2%	30.8%	18.2%	8.9%	4.7%
Uzbekistan	3.8%	5.6%	40.1%	30.6%	12.9%	4.9%	2.1%
Vanuatu	2.2%	3.5%	30.6%	32.5%	19.0%	7.6%	4.6%
Venezuela	1.6%	3.5%	29.4%	35.8%	19.7%	7.6%	2.5%
Viet Nam	17.9%	14.4%	46.4%	18.5%	2.4%	0.3%	0.0%
Yemen	7.6%	5.3%	32.0%	32.1%	16.0%	4.9%	2.0%
Zambia	8.5%	10.9%	43.1%	24.6%	9.2%	2.7%	1.1%
Zimbabwe	4.6%	6.8%	34.1%	28.2%	16.8%	6.1%	3.4%

Appendix 3: BMI Prevalence of Nations around the World—Males in 2016

	Underweight	Normal 1	Normal 2	Overweight	Obese 1	Obese 2	Morbidly Obese
Afghanistan	16.7%	14.3%	48.5%	17.1%	3.0%	0.2%	0.1%
Albania	0.4%	1.6%	31.8%	43.9%	17.9%	3.8%	0.7%
Algeria	3.3%	4.0%	33.0%	39.0%	16.4%	3.2%	1.1%
American Samoa	0.0%	0.2%	11.4%	29.6%	26.5%	18.4%	13.9%
Andorra	0.3%	1.2%	26.4%	45.4%	19.9%	5.3%	1.6%
Angola	15.9%	16.6%	47.2%	16.0%	3.5%	0.6%	0.1%
Antigua and Barbuda	4.6%	7.7%	46.1%	29.4%	9.1%	2.0%	1.0%
Argentina	0.3%	1.8%	29.8%	39.8%	20.6%	6.2%	1.4%
Armenia	1.7%	3.3%	39.1%	38.2%	13.8%	2.8%	1.1%
Australia	0.3%	1.3%	25.5%	42.3%	20.7%	7.3%	2.7%
Austria	0.6%	2.0%	33.8%	40.9%	16.6%	4.6%	1.4%
Azerbaijan	1.3%	3.4%	40.7%	38.1%	13.2%	2.6%	0.7%
Bahamas	2.1%	3.3%	32.5%	36.8%	17.1%	5.5%	2.7%
Bahrain	2.4%	2.7%	28.9%	39.5%	19.5%	5.4%	1.6%
Bangladesh	19.7%	15.1%	46.6%	16.3%	2.2%	0.1%	0.0%
Barbados	3.3%	6.4%	44.0%	31.0%	11.0%	2.9%	1.3%
Belarus	0.7%	1.9%	32.9%	41.5%	17.4%	4.5%	1.0%
Belgium	0.3%	1.1%	29.2%	45.5%	18.8%	4.1%	1.0%
Belize	3.3%	5.8%	41.3%	32.6%	12.1%	3.3%	1.7%
Benin	10.3%	14.5%	53.2%	17.1%	3.9%	0.7%	0.4%
Bermuda	1.6%	2.5%	28.4%	37.7%	19.4%	7.0%	3.5%
Bhutan	10.7%	12.4%	50.7%	21.3%	4.5%	0.3%	0.1%
Bolivia	1.3%	3.7%	41.2%	38.8%	12.8%	1.8%	0.5%
Bosnia and Herzegovina	0.4%	1.9%	36.2%	43.7%	14.9%	2.4%	0.6%
Botswana	11.6%	11.6%	45.9%	22.3%	6.6%	1.2%	0.7%
Brazil	1.8%	3.5%	35.3%	40.2%	14.9%	3.4%	0.9%
Brunei	5.6%	7.7%	44.3%	29.5%	9.8%	2.3%	0.8%
Bulgaria	0.3%	1.3%	27.6%	44.4%	20.4%	4.8%	1.2%
Burkina Faso	10.4%	16.9%	56.0%	14.0%	2.3%	0.2%	0.2%
Burundi	14.0%	18.2%	53.3%	12.3%	1.9%	0.2%	0.1%
Cabo Verde	8.2%	11.6%	51.6%	21.4%	5.7%	1.0%	0.5%
Cambodia	12.6%	16.0%	52.1%	16.5%	2.6%	0.2%	0.1%
Cameroon	7.0%	12.9%	53.9%	19.8%	5.1%	0.8%	0.5%
Canada	0.4%	1.3%	26.6%	41.3%	20.3%	7.2%	3.0%
Central African Republic	17.2%	16.9%	46.8%	15.2%	3.2%	0.5%	0.1%
Chad	12.9%	16.8%	53.7%	13.4%	2.5%	0.3%	0.4%
Chile	0.3%	1.8%	31.4%	40.8%	19.6%	4.9%	1.3%
China	3.8%	8.6%	52.0%	29.5%	5.5%	0.5%	0.2%
Hong Kong	3.4%	5.2%	44.1%	35.8%	9.9%	1.1%	0.3%
Colombia	1.6%	3.4%	36.7%	40.1%	14.4%	3.1%	0.8%

Comoros	11.6%	15.7%	53.8%	15.5%	3.0%	0.3%	0.1%
Congo	14.5%	14.8%	45.5%	19.4%	4.7%	1.0%	0.1%
Cook Islands	0.1%	0.3%	14.0%	31.7%	27.5%	15.6%	10.8%
Costa Rica	1.0%	2.9%	34.4%	39.8%	16.0%	3.8%	2.0%
Cote d'Ivoire	7.9%	12.7%	54.0%	19.4%	4.8%	0.7%	0.6%
Croatia	0.3%	1.3%	30.2%	43.2%	19.3%	4.4%	1.3%
Cuba	3.9%	4.5%	35.3%	36.6%	13.7%	3.9%	2.1%
Cyprus	0.4%	1.6%	31.0%	44.4%	17.1%	4.2%	1.3%
Czech Republic	0.2%	1.1%	27.3%	44.1%	21.1%	4.8%	1.4%
Denmark	0.5%	1.8%	32.2%	42.3%	16.8%	4.8%	1.5%
Djibouti	8.5%	10.2%	47.7%	24.6%	7.3%	1.2%	0.5%
Dominica	2.7%	4.5%	36.3%	35.8%	15.2%	3.8%	1.8%
Dominican Republic	2.6%	3.9%	34.8%	36.9%	15.6%	4.4%	1.7%
DR Congo	18.5%	17.2%	45.6%	15.0%	3.1%	0.5%	0.1%
Ecuador	0.9%	3.4%	41.5%	38.8%	12.8%	2.0%	0.6%
Egypt	1.5%	3.6%	35.9%	35.5%	16.4%	5.1%	1.9%
El Salvador	1.3%	3.0%	36.9%	39.2%	15.1%	3.2%	1.3%
Equatorial Guinea	16.2%	17.1%	47.2%	15.5%	3.3%	0.5%	0.1%
Eritrea	17.5%	16.6%	50.6%	13.2%	1.9%	0.2%	0.1%
Estonia	0.5%	1.9%	36.1%	40.4%	16.4%	3.7%	1.1%
Ethiopia	16.7%	17.9%	51.4%	12.0%	1.8%	0.1%	0.1%
Fiji	1.6%	2.2%	34.6%	35.8%	19.2%	4.7%	2.1%
Finland	0.2%	1.2%	31.1%	42.9%	18.1%	5.1%	1.4%
France	0.4%	1.5%	29.3%	46.0%	17.7%	4.1%	1.0%
French Polynesia	0.1%	0.5%	17.2%	33.3%	26.2%	13.6%	9.1%
Gabon	10.6%	11.0%	43.3%	25.0%	7.9%	1.8%	0.4%
Gambia	10.0%	12.8%	51.8%	19.6%	4.7%	0.8%	0.4%
Georgia	1.3%	3.5%	38.8%	36.5%	14.5%	4.2%	1.2%
Germany	0.3%	1.4%	31.6%	41.8%	18.5%	4.9%	1.6%
Ghana	10.0%	13.8%	53.2%	18.3%	3.8%	0.6%	0.3%
Greece	0.3%	1.2%	28.4%	45.1%	18.6%	4.8%	1.7%
Greenland	0.5%	1.7%	31.0%	42.2%	18.3%	4.9%	1.5%
Grenada	4.0%	6.7%	44.1%	31.3%	10.7%	2.4%	0.8%
Guatemala	1.5%	4.0%	41.5%	37.4%	12.6%	2.5%	0.6%
Guinea	11.2%	15.3%	54.0%	15.6%	3.1%	0.5%	0.3%
Guinea Bissau	9.9%	13.8%	53.2%	17.9%	4.1%	0.6%	0.5%
Guyana	4.8%	7.4%	44.9%	29.8%	9.5%	2.3%	1.4%
Haiti	3.1%	5.0%	39.1%	34.2%	13.3%	3.6%	1.7%
Honduras	2.0%	4.4%	40.1%	37.3%	12.9%	2.6%	0.8%
Hungary	0.4%	1.2%	26.9%	42.3%	21.7%	5.4%	2.0%
Iceland	0.3%	1.3%	29.1%	44.2%	17.7%	5.4%	1.9%
India	22.6%	15.0%	43.9%	15.7%	2.5%	0.2%	0.1%
Indonesia	12.7%	13.5%	47.8%	21.0%	4.4%	0.4%	0.2%
Iran	3.1%	4.5%	32.9%	39.5%	16.1%	3.1%	0.7%
Iraq	2.0%	3.1%	32.0%	38.6%	17.9%	4.9%	1.5%
Ireland	0.4%	1.5%	30.1%	42.1%	19.2%	4.6%	2.2%

Israel	0.3%	1.2%	25.7%	46.0%	20.0%	5.6%	1.2%
Italy	0.3%	1.5%	31.0%	46.3%	17.1%	3.2%	0.7%
Jamaica	4.3%	6.1%	40.6%	33.1%	11.8%	2.9%	1.2%
Japan	3.5%	7.3%	55.7%	28.5%	4.6%	0.3%	0.0%
Jordan	0.8%	2.1%	28.2%	39.8%	21.2%	5.8%	2.2%
Kazakhstan	1.7%	3.4%	38.9%	36.5%	15.3%	3.5%	0.8%
Kenya	13.7%	16.5%	52.9%	13.8%	2.6%	0.3%	0.1%
Kiribati	0.2%	0.6%	20.4%	35.9%	25.5%	11.4%	5.9%
Kuwait	0.7%	1.5%	23.7%	39.9%	22.6%	8.0%	3.7%
Kyrgyzstan	2.0%	4.6%	44.4%	34.4%	11.7%	2.3%	0.6%
Lao PDR	11.0%	13.9%	51.6%	19.5%	3.3%	0.4%	0.1%
Latvia	0.6%	2.2%	34.6%	40.3%	16.8%	4.4%	1.2%
Lebanon	1.1%	2.2%	27.9%	40.4%	20.9%	5.8%	1.7%
Lesotho	11.5%	15.6%	50.9%	17.2%	3.9%	0.7%	0.3%
Liberia	8.2%	13.2%	54.4%	18.4%	4.6%	0.6%	0.5%
Libya	1.8%	2.8%	30.2%	39.5%	18.8%	5.2%	1.8%
Lithuania	0.3%	1.8%	33.4%	39.4%	18.7%	4.8%	1.5%
Luxembourg	0.3%	1.4%	29.7%	43.2%	18.4%	5.4%	1.6%
North Macedonia	0.5%	1.7%	31.1%	43.3%	18.4%	4.0%	1.1%
Madagascar	13.9%	16.0%	51.6%	15.3%	2.7%	0.3%	0.2%
Malawi	12.6%	17.9%	54.0%	13.1%	2.1%	0.2%	0.1%
Malaysia	5.7%	7.9%	43.1%	29.9%	10.1%	2.5%	0.8%
Maldives	9.5%	12.0%	50.5%	21.9%	5.1%	0.7%	0.2%
Mali	10.5%	14.8%	53.5%	16.4%	3.7%	0.6%	0.4%
Malta	0.3%	0.9%	23.9%	44.7%	21.8%	5.9%	2.4%
Marshall Islands	0.1%	0.3%	15.3%	34.3%	27.3%	13.8%	8.7%
Mauritania	9.4%	12.3%	51.4%	20.1%	5.6%	0.7%	0.6%
Mauritius	8.7%	12.9%	53.1%	19.4%	4.9%	0.7%	0.2%
Mexico	0.8%	2.3%	31.4%	40.3%	18.0%	5.4%	1.7%
Micronesia	0.5%	1.2%	24.0%	32.9%	22.9%	10.6%	8.0%
Moldova	1.0%	3.1%	40.7%	38.4%	13.2%	2.9%	0.8%
Mongolia	1.6%	3.2%	37.9%	39.1%	14.4%	3.1%	0.7%
Montenegro	0.4%	1.5%	29.8%	44.1%	19.0%	4.1%	1.1%
Morocco	2.6%	3.9%	35.2%	38.1%	15.6%	3.6%	1.0%
Mozambique	12.2%	16.4%	52.7%	15.3%	3.0%	0.3%	0.1%
Myanmar	14.5%	14.6%	48.8%	17.9%	3.5%	0.6%	0.1%
Namibia	10.8%	13.2%	47.8%	20.4%	6.1%	1.3%	0.5%
Nauru	0.0%	0.1%	9.9%	30.1%	28.3%	17.5%	14.1%
Nepal	15.6%	14.8%	49.7%	17.1%	2.6%	0.1%	0.1%
Netherlands	0.4%	1.5%	30.9%	45.7%	17.3%	3.4%	0.8%
New Zealand	0.3%	1.3%	25.8%	41.5%	20.8%	7.0%	3.3%
Nicaragua	1.8%	3.6%	38.2%	37.8%	14.1%	3.0%	1.5%
Niger	13.3%	17.6%	53.9%	12.6%	2.1%	0.2%	0.3%
Nigeria	10.6%	14.0%	52.8%	17.8%	3.6%	0.7%	0.5%
Niue	0.1%	0.5%	19.6%	33.6%	26.8%	11.8%	7.6%
North Korea	4.8%	8.4%	51.7%	28.7%	5.7%	0.5%	0.2%
Norway	0.4%	1.4%	31.3%	42.4%	17.6%	5.3%	1.6%

Palestinian Territory	1.0%	2.6%	30.5%	38.8%	19.4%	6.1%	1.7%
Oman	3.0%	3.3%	31.2%	38.7%	17.2%	4.4%	2.2%
Pakistan	14.8%	12.1%	46.4%	20.5%	5.4%	0.6%	0.3%
Palau	0.1%	0.3%	13.3%	33.2%	27.9%	15.7%	9.5%
Panama	1.6%	3.5%	36.9%	39.5%	13.9%	3.2%	1.4%
Papua New Guinea	1.3%	3.9%	45.8%	31.7%	13.4%	2.6%	1.2%
Paraguay	1.2%	3.9%	39.5%	37.6%	13.9%	3.0%	0.9%
Peru	0.9%	3.0%	39.7%	40.7%	13.3%	2.0%	0.4%
Philippines	10.4%	12.8%	49.7%	21.6%	4.5%	0.7%	0.2%
Poland	0.6%	1.8%	30.0%	42.9%	19.2%	4.5%	0.9%
Portugal	0.5%	1.6%	32.9%	43.9%	16.8%	3.5%	0.8%
Puerto Rico	1.3%	2.6%	29.7%	37.4%	19.2%	6.3%	3.6%
Qatar	1.0%	1.7%	24.3%	39.4%	21.6%	8.3%	3.5%
Romania	0.8%	1.9%	31.1%	42.0%	18.6%	4.2%	1.4%
Russian	0.9%	2.5%	36.5%	41.3%	15.0%	3.2%	0.6%
Rwanda	11.5%	17.5%	54.8%	14.2%	1.8%	0.1%	0.0%
Saint Kitts and Nevis	3.2%	6.3%	44.0%	30.6%	10.9%	3.1%	1.9%
Saint Lucia	4.8%	7.9%	46.6%	28.2%	9.4%	2.1%	1.1%
Saint Vincent and the Grenadines	3.3%	5.5%	40.6%	33.3%	12.4%	3.2%	1.6%
Samoa	0.1%	0.6%	23.5%	34.5%	23.3%	11.1%	6.8%
Sao Tome and Principe	6.7%	11.4%	52.7%	21.8%	5.7%	1.0%	0.8%
Saudi Arabia	1.5%	2.0%	26.4%	38.4%	20.8%	7.3%	3.7%
Senegal	12.2%	14.9%	52.6%	16.1%	3.4%	0.4%	0.4%
Serbia	0.5%	1.8%	31.9%	43.8%	17.6%	3.6%	0.6%
Seychelles	7.4%	11.7%	51.2%	21.7%	6.6%	1.0%	0.4%
Sierra Leone	10.6%	15.3%	54.1%	15.9%	3.0%	0.5%	0.5%
Singapore	3.7%	6.1%	52.8%	31.4%	5.4%	0.6%	0.1%
Slovakia	0.4%	1.5%	32.6%	43.8%	18.1%	3.0%	0.6%
Slovenia	0.5%	2.0%	33.6%	43.8%	16.8%	2.7%	0.6%
Solomon Islands	0.9%	3.1%	44.7%	32.6%	14.2%	2.8%	1.7%
Somalia	11.7%	14.8%	52.3%	17.0%	3.5%	0.4%	0.2%
South Africa	6.2%	8.9%	42.9%	26.0%	10.4%	3.6%	2.0%
South Korea	2.8%	6.5%	55.7%	30.4%	4.3%	0.3%	0.0%
Spain	0.3%	1.1%	27.7%	45.4%	20.1%	4.4%	1.0%
Sri Lanka	14.8%	15.4%	50.3%	16.4%	2.6%	0.3%	0.1%
Sudan	11.1%	15.2%	53.2%	16.6%	3.4%	0.4%	0.1%
Suriname	3.2%	4.4%	37.3%	35.5%	13.8%	4.0%	1.8%
Swaziland	9.4%	15.1%	52.3%	17.5%	4.4%	0.8%	0.5%
Sweden	0.4%	1.6%	31.9%	42.2%	17.4%	5.1%	1.4%
Switzerland	0.6%	1.9%	33.1%	41.5%	16.8%	4.8%	1.4%
Syrian Arab Republic	2.2%	3.7%	35.0%	37.5%	16.1%	4.1%	1.5%
Taiwan	3.0%	6.7%	49.8%	33.3%	6.6%	0.5%	0.2%
Tajikistan	2.6%	5.0%	46.6%	33.7%	10.0%	1.6%	0.4%

Tanzania	11.9%	15.4%	52.3%	16.2%	3.5%	0.5%	0.1%
Thailand	8.6%	11.7%	49.4%	23.0%	6.1%	1.0%	0.2%
Timor-Leste	14.1%	14.8%	51.6%	16.8%	2.5%	0.2%	0.1%
Togo	10.3%	14.7%	54.6%	16.4%	3.3%	0.4%	0.3%
Tokelau	0.2%	1.0%	26.6%	30.8%	22.7%	10.6%	8.1%
Tonga	0.2%	0.7%	22.3%	34.2%	24.2%	12.0%	6.6%
Trinidad and Tobago	3.8%	8.5%	49.3%	27.2%	8.8%	1.7%	0.7%
Tunisia	2.8%	4.1%	34.1%	39.2%	15.4%	3.4%	1.1%
Turkey	0.9%	2.1%	31.0%	40.7%	19.2%	4.9%	1.2%
Turkmenistan	1.7%	3.6%	41.1%	37.2%	13.3%	2.5%	0.6%
Tuvalu	0.1%	0.4%	17.3%	33.7%	26.2%	13.6%	8.6%
Uganda	11.9%	18.5%	55.3%	12.4%	1.7%	0.1%	0.1%
Ukraine	0.7%	2.1%	34.1%	40.5%	17.2%	4.3%	1.2%
United Arab Emirates	1.4%	2.2%	28.2%	39.7%	20.1%	6.2%	2.2%
UK	0.5%	1.5%	27.4%	42.7%	19.8%	6.0%	2.1%
US	0.5%	1.2%	23.7%	38.1%	21.3%	9.2%	6.0%
Uruguay	0.6%	2.2%	30.5%	41.0%	19.2%	4.8%	1.7%
Uzbekistan	2.0%	4.6%	44.5%	34.5%	11.5%	2.2%	0.6%
Vanuatu	1.2%	3.0%	41.9%	32.9%	15.6%	3.5%	1.8%
Venezuela	0.9%	2.1%	32.3%	41.5%	17.2%	4.6%	1.4%
Viet Nam	16.8%	17.0%	49.7%	14.8%	1.6%	0.1%	0.0%
Yemen	5.0%	6.6%	42.7%	33.2%	10.1%	1.7%	0.6%
Zambia	13.3%	15.6%	51.2%	16.1%	3.3%	0.4%	0.1%
Zimbabwe	10.7%	15.2%	51.0%	18.2%	4.1%	0.5%	0.3%

Appendix 4: Anthropometric Characteristics from NHANES 2013–2014

BMI	**MALE**	**18-24**			**Number**
>18.5	Min	max	Aver	SD	
Weight	11.5	60.1	29.4	11.9	51.0
Height	87.7	187.5	132.0	23.3	
Waist	43.6	76.6	58.8	7.5	
WHdiam	15.42	27.09	20.79	2.65	
Speed	2.022	2.820	2.386	0.186	
18.5<19.99	Min	max	Aver	SD	
Weight	33.9	62.0	51.1	7.9	21.0
Height	87.7	177.3	161.7	13.0	
Waist	66.2	80.9	70.2	3.6	
WHdiam	23.41	28.61	24.81	1.27	
Speed	2.383	2.726	2.612	0.102	
20<24.99	Min	max	Aver	SD	
Weight	33.4	85.7	63.6	9.9	110.0
Height	129.3	192.1	168.1	12.1	
Waist	66.5	98.9	80.1	6.7	
WHdiam	23.52	32.96	28.27	2.27	
Speed	2.353	2.822	2.644	0.091	
25<29.99	Min	max	Aver	SD	
Weight	51.7	96.8	78.0	9.5	74.0
Height	143.3	186.9	168.9	9.4	
Waist	79.5	108.9	93.5	6.6	
WHdiam	28.12	34.66	31.40	1.33	
Speed	2.446	2.758	2.625	0.068	
30<34.99	Min	max	Aver	SD	
Weight	71.3	118.8	90.9	12.3	54.0
Height	149.1	191.6	168.0	10.1	
Waist	92.0	119.0	104.8	6.9	
WHdiam	29.92	37.88	33.49	2.06	
Speed	2.454	2.757	2.594	0.069	
35<39.99	Min	max	Aver	SD	
Weight	86.0	143.0	109.1	11.2	24.0
Height	153.2	193.1	171.0	11.2	
Waist	102.2	129.0	115.4	6.5	
WHdiam	32.53	41.06	36.73	2.08	
Speed	2.469	2.725	2.587	0.074	
40+	Min	max	Aver	SD	
Weight	92.1	184.0	128.7	28.2	12.0
Height	149.2	190.7	167.4	11.1	
Waist	97.3	148.6	125.9	14.4	
WHdiam	30.97	47.30	40.07	4.58	
Speed	2.419	2.626	2.519	0.061	
BMI	FEMALE	18-24			number
>18.5	Min	max	Aver	SD	

Weight	10.2	62.4	29.1	12.4	62.0
Height	81.2	187.7	130.9	25.5	
Waist	42.7	80.9	57.6	8.0	
WHdiam	15.99	27.75	21.48	2.82	
Speed	1.633	2.900	2.259	0.305	
18.5<19.99	Min	max	Aver	SD	
Weight	15.1	64.1	46.5	11.7	25.0
Height	87.8	181.1	154.0	22.3	
Waist	52.0	81.2	70.6	7.1	
WHdiam	19.47	29.92	26.24	2.51	
Speed	1.708	2.804	2.503	0.262	
20<24.99	Min	max	Aver	SD	
Weight	20.2	88.4	60.0	10.0	92.0
Height	97.8	189.3	162.5	12.9	
Waist	55.8	97.2	80.1	6.4	
WHdiam	20.90	30.94	27.71	1.55	
Speed	1.824	2.810	2.554	0.140	
25<29.99	Min	max	Aver	SD	
Weight	30.4	101.3	76.6	11.7	100.0
Height	106.5	191.4	166.2	12.7	
Waist	76.0	127.0	95.0	8.1	
WHdiam	25.75	40.43	30.41	2.35	
Speed	1.903	2.770	2.520	0.127	
30<34.99	Min	max	Aver	SD	
Weight	67.8	119.2	89.7	13.0	55.0
Height	149.1	187.9	166.4	10.1	
Waist	87.5	132.1	105.5	9.5	
WHdiam	27.85	42.05	33.58	3.04	
Speed	2.272	2.610	2.454	0.084	
35<39.99	Min	max	Aver	SD	
Weight	77.9	128.8	101.5	11.8	23.0
Height	146.6	182.2	165.7	9.3	
Waist	94.6	139.2	113.8	8.4	
WHdiam	30.11	44.31	36.24	2.68	
Speed	2.229	2.516	2.382	0.079	
40+	Min	max	Aver	SD	
Weight	97.6	173.3	122.6	18.3	22.0
Height	150.9	176.2	162.6	6.4	
Waist	105.6	163.3	128.8	14.6	
WHdiam	33.61	51.98	40.98	4.65	
Speed	1.910	2.383	2.226	0.099	

BMI	**MALE**	**25-34**			**Number**
>18.5	Min	max	Aver	SD	
Weight	12.6	59.1	26.9	10.7	59.0
Height	87.8	184.8	126.2	23.1	
Waist	43.2	79.0	57.2	7.2	
WHdiam	15.28	27.94	20.21	2.55	
Speed	1.932	2.678	2.235	0.179	
18.5<19.99	Min	max	Aver	SD	
Weight	24.5	65.8	49.1	11.3	20.0
Height	113.7	184.2	158.6	18.8	
Waist	58.7	81.0	71.6	4.8	
WHdiam	20.76	28.65	25.33	1.70	
Speed	2.133	2.667	2.471	0.142	
20<24.99	Min	max	Aver	SD	
Weight	16.6	90.0	64.1	12.2	112.0
Height	88.4	194.4	168.1	15.3	
Waist	56.7	99.9	81.4	7.3	
WHdiam	20.05	32.29	28.62	2.27	
Speed	1.923	2.705	2.526	0.112	
25<29.99	Min	max	Aver	SD	
Weight	56.9	103.9	80.6	10.5	111.0
Height	141.6	195.2	171.9	10.0	
Waist	81.5	117.5	95.4	7.3	
WHdiam	28.82	37.40	31.87	1.43	
Speed	2.317	2.687	2.529	0.069	
30<34.99	Min	max	Aver	SD	
Weight	60.0	124.8	93.0	12.1	66.0
Height	140.9	198.2	170.2	10.0	
Waist	90.3	120.9	106.3	7.3	
WHdiam	29.92	38.48	34.03	2.05	
Speed	2.299	2.685	2.493	0.066	
35<39.99	Min	max	Aver	SD	
Weight	85.2	140.1	104.4	14.6	18.0
Height	152.8	190.8	167.1	11.0	
Waist	106.5	127.8	117.0	6.0	
WHdiam	33.90	40.68	37.25	1.90	
Speed	2.349	2.580	2.446	0.068	
40+	Min	max	Aver	SD	
Weight	96.6	162.0	130.5	21.3	25.0
Height	153.2	187.2	169.3	11.3	
Waist	115.9	158.2	134.7	12.0	
WHdiam	36.89	50.36	42.86	3.83	
Speed	2.287	2.549	2.420	0.075	

BMI	**FEMALE**	**25-34**			**Number**
>18.49	Min	max	Aver	SD	
Weight	11.4	62.6	28.8	13.4	56.0
Height	86.3	189.0	129.6	26.4	
Waist	42.0	76.7	58.2	8.3	
WHdiam	15.73	28.72	21.78	3.10	
Speed	1.639	2.831	2.163	0.305	
18.5<19.99	Min	max	Aver	SD	
Weight	27.6	66.7	48.2	9.9	21.0
Height	121.1	66.7	48.2	9.9	
Waist	61.5	83.0	71.1	5.3	
WHdiam	23.03	29.10	26.40	1.72	
Speed	2.056	2.750	2.464	0.183	
20<24.99	Min	max	Aver	SD	
Weight	29.4	83.9	60.3	9.3	108.0
Height	118.3	186.1	163.9	11.9	
Waist	63.1	98.2	80.7	7.3	
WHdiam	23.63	31.26	27.72	1.53	
Speed	2.006	2.708	2.484	0.124	
25<29.99	Min	max	Aver	SD	
Weight	55.0	103.1	75.8	9.9	107.0
Height	143.9	190.5	166.8	9.5	
Waist	80.0	117.7	94.1	7.5	
WHdiam	25.46	37.47	29.97	2.38	
Speed	2.205	2.660	2.444	0.089	
30<34.99	Min	max	Aver	SD	
Weight	58.1	108.0	86.8	11.1	60.0
Height	138.1	185.1	164.3	9.8	
Waist	92.6	123.1	105.5	6.9	
WHdiam	29.48	39.18	33.59	2.19	
Speed	2.130	2.547	2.354	0.087	
35<39.99	Min	max	Aver	SD	
Weight	77.4	121.0	99.6	10.8	38.0
Height	142.5	177.0	163.1	8.3	
Waist	99.5	132.7	115.6	9.0	
WHdiam	31.67	42.24	36.79	2.87	
Speed	2.102	2.402	2.272	0.067	
40+	Min	max	Aver	SD	
Weight	87.6	181.4	126.1	21.1	29.0
Height	147.8	182.9	165.6	8.4	
Waist	105.5	182.9	165.6	8.4	
WHdiam	34.44	51.79	42.05	4.29	
Speed	2.035	2.335	2.173	0.063	

BMI	**MALE**	**35-44**			**Number**
>18.49	Min	max	Aver	SD	
Weight	11.5	53.2	24.6	10.6	58.0
Height	87.4	172.3	121.5	22.9	
Waist	43.4	75.2	55.5	6.9	
WHdiam	15.35	26.60	19.62	2.44	
Speed	1.834	2.466	2.093	0.169	
18.5<19.99	Min	max	Aver	SD	
Weight	18.6	60.1	45.3	11.6	19.0
Height	100.1	176.5	151.8	21.0	
Waist	56.0	86.1	69.9	6.5	
WHdiam	19.81	30.45	24.72	2.29	
Speed	1.932	2.479	2.307	0.150	
20<24.99	Min	max	Aver	SD	
Weight	29.5	90.2	62.7	10.7	86.0
Height	113.6	192.4	165.7	13.1	
Waist	68.0	97.4	81.3	6.2	
WHdiam	24.05	33.07	28.66	2.07	
Speed	2.024	2.563	2.390	0.091	
25<29.99	Min	max	Aver	SD	
Weight	56.3	103.3	80.1	10.0	115.0
Height	145.2	196.1	170.9	10.7	
Waist	81.8	124.0	96.6	7.2	
WHdiam	28.93	39.47	31.97	1.55	
Speed	2.217	2.578	2.403	0.073	
30<34.99	Min	max	Aver	SD	
Weight	61.0	124.0	93.1	11.7	76.0
Height	141.1	192.8	170.6	10.5	
Waist	87.3	123.1	105.8	7.8	
WHdiam	30.05	39.18	33.80	2.28	
Speed	2.200	2.513	2.380	0.067	
35<39.99	Min	max	Aver	SD	
Weight	76.6	142.0	107.7	16.4	32.0
Height	139.4	189.3	170.1	12.7	
Waist	99.9	130.5	118.2	8.5	
WHdiam	31.80	41.54	37.62	2.71	
Speed	2.154	2.472	2.350	0.078	
40+	Min	max	Aver	SD	
Weight	94.7	184.5	123.2	22.6	13.0
Height	151.7	188.1	165.2	9.0	
Waist	114.5	152.2	129.6	10.0	
WHdiam	36.45	48.45	41.25	3.17	
Speed	2.165	2.427	2.288	0.063	

BMI	**Female**	**35-44**			**Number**
>18.49	Min	max	Aver	SD	
Weight	11.1	61.7	27.0	12.7	79.0
Height	82.4	185.6	125.2	22.8	
Waist	45.6	80.2	57.7	7.2	
WHdiam	17.08	29.58	21.56	3.08	
Speed	1.473	2.591	1.957	0.289	
18.5<19.99	Min	max	Aver	SD	
Weight	16.5	60.5	44.9	10.2	22.0
Height	93.7	174.7	151.8	18.9	
Waist	54.7	79.1	70.1	6.1	
WHdiam	20.48	29.62	26.24	2.29	
Speed	1.591	2.454	2.222	0.202	
20<24.99	Min	max	Aver	SD	
Weight	23.5	83.2	60.9	9.8	128.0
Height	108.0	187.7	163.5	12.0	
Waist	66.5	100.5	82.0	7.2	
WHdiam	24.90	31.99	27.65	1.42	
Speed	1.745	2.523	2.299	0.117	
25<29.99	Min	max	Aver	SD	
Weight	45.2	98.4	72.5	10.2	111.0
Height	132.1	187.3	163.6	10.8	
Waist	76.0	113.9	93.6	7.8	
WHdiam	25.53	36.26	29.91	2.33	
Speed	1.968	2.474	2.245	0.097	
30<34.99	Min	max	Aver	SD	
Weight	66.7	120.2	89.0	10.9	80.0
Height	143.6	189.9	166.2	9.8	
Waist	88.4	122.9	105.4	7.9	
WHdiam	28.14	39.12	33.56	2.52	
Speed	1.997	2.399	2.201	0.082	
35<39.99	Min	max	Aver	SD	
Weight	71.0	129.9	97.9	13.5	47.0
Height	137.2	188.5	163.1	10.5	
Waist	95.2	134.8	113.2	8.7	
WHdiam	30.30	42.91	36.03	2.78	
Speed	1.903	2.319	2.118	0.078	
40+	Min	max	Aver	SD	
Weight	96.9	172.0	127.9	21.3	14.0
Height	149.3	174.1	162.4	6.6	
Waist	119.8	160.8	136.6	11.6	
WHdiam	38.13	51.18	43.49	3.70	
Speed	1.800	2.085	1.965	0.090	

BMI	**MALE**	**45-54**			**Number**
>18.49	Min	max	Aver	SD	
Weight	11.6	69.9	27.9	13.7	59.0
Height	83.3	196.7	127.1	27.6	
Waist	44.5	83.8	57.6	8.9	
WHdiam	15.74	29.64	20.36	3.15	
Speed	1.688	2.465	1.991	0.190	
18.5<19.99	Min	max	Aver	SD	
Weight	13.2	66.4	43.7	15.3	17.0
Height	84.2	184.1	147.8	28.7	
Waist	48.6	82.0	69.2	9.6	
WHdiam	17.19	29.00	24.47	3.40	
Speed	1.683	2.377	2.126	0.196	
20<24.99	Min	max	Aver	SD	
Weight	31.4	81.5	63.0	9.6	94.0
Height	123.6	187.2	166.6	11.4	
Waist	70.0	99.3	82.3	6.4	
WHdiam	24.76	33.03	29.01	2.08	
Speed	1.955	2.383	2.239	0.075	
25<29.99	Min	max	Aver	SD	
Weight	54.1	104.1	82.1	10.5	116.0
Height	143.9	194.0	172.4	11.0	
Waist	77.8	112.1	97.4	7.0	
WHdiam	27.52	35.68	31.93	1.43	
Speed	2.086	2.391	2.254	0.069	
30<34.99	Min	max	Aver	SD	
Weight	71.7	126.4	93.7	12.1	64.0
Height	148.3	193.8	170.4	10.1	
Waist	92.2	134.4	106.9	7.4	
WHdiam	30.24	42.78	34.08	2.30	
Speed	2.080	2.347	2.221	0.061	
35<39.99	Min	max	Aver	SD	
Weight	78.9	135.5	108.9	15.8	22.0
Height	150.2	189.0	170.4	11.3	
Waist	98.5	135.4	120.2	8.7	
WHdiam	31.35	43.10	38.26	2.78	
Speed	2.084	2.291	2.196	0.063	
40+	Min	max	Aver	SD	
Weight	101.1	162.2	129.8	14.8	22.0
Height	154.0	182.8	170.6	8.4	
Waist	111.5	157.4	133.2	12.3	
WHdiam	35.49	50.10	42.40	3.91	
Speed	2.074	2.249	2.164	0.052	

BMI	**FEMALE**	**45-54**			**Number**
>18.5	Min	max	Aver	SD	
Weight	11.9	56.6	27.5	11.6	73.0
Height	88.6	180.2	127.8	23.7	
Waist	43.9	77.2	57.0	7.9	
WHdiam	16.44	28.91	21.35	2.96	
Speed	1.422	2.356	1.836	0.239	
18.5<19.99	Min	max	Aver	SD	
Weight	20.1	60.9	45.1	11.5	17.0
Height	101.9	179.1	151.0	20.9	
Waist	60.3	81.6	70.3	5.3	
WHdiam	22.58	29.47	26.05	1.70	
Speed	1.555	2.309	2.041	0.205	
20<24.99	Min	max	Aver	SD	
Weight	21.4	84.9	61.0	10.5	93.0
Height	103.2	187.0	163.1	13.2	
Waist	57.3	101.9	83.7	7.1	
WHdiam	21.46	32.44	27.81	1.66	
Speed	1.560	2.307	2.120	0.120	
25<29.99	Min	max	Aver	SD	
Weight	46.9	98.8	74.6	9.8	103.0
Height	136.5	186.3	164.6	9.4	
Waist	76.6	115.5	95.1	7.6	
WHdiam	25.72	36.76	30.44	2.20	
Speed	1.861	2.251	2.078	0.077	
30<34.99	Min	max	Aver	SD	
Weight	68.6	114.1	88.2	9.8	76.0
Height	148.6	191.8	165.0	9.1	
Waist	94.8	127.8	106.8	6.8	
WHdiam	30.18	40.68	33.99	2.17	
Speed	1.892	2.233	2.022	0.073	
35<39.99	Min	max	Aver	SD	
Weight	75.8	129.8	99.1	10.9	39.0
Height	143.4	182.8	163.5	8.7	
Waist	99.6	131.7	115.5	8.1	
WHdiam	31.70	41.92	36.78	2.57	
Speed	1.820	2.096	1.955	0.064	
40+	Min	max	Aver	SD	
Weight	94.8	160.5	121.3	14.9	33.0
Height	149.7	189.9	164.2	8.8	
Waist	115.5	189.9	164.2	8.8	
WHdiam	36.76	48.96	41.66	3.43	
Speed	1.728	2.049	1.865	0.080	

BMI	**MALE**	**55-64**			**Number**
>18.49	Min	max	Aver	SD	
Weight	11.1	57.3	26.6	11.9	62.0
Height	92.4	178.1	125.4	23.9	
Waist	43.1	78.4	56.4	8.2	
WHdiam	15.24	27.73	19.95	2.92	
Speed	1.588	2.126	1.802	0.152	
18.5<19.99	Min	max	Aver	SD	
Weight	15.1	59.9	40.0	12.9	21.0
Height	90.1	180.1	142.2	24.9	
Waist	53.1	80.9	67.9	7.4	
WHdiam	20.23	28.61	24.00	2.61	
Speed	1.608	2.055	1.895	0.132	
20<24.99	Min	max	Aver	SD	
Weight	25.9	88.0	61.6	11.3	94.0
Height	109.6	190.3	164.4	13.5	
Waist	61.2	101.1	83.3	9.1	
WHdiam	21.65	33.21	29.07	2.77	
Speed	1.687	2.191	2.026	0.081	
25<29.99	Min	max	Aver	SD	
Weight	49.4	101.9	78.7	10.0	117.0
Height	136.6	191.0	168.6	10.2	
Waist	77.4	120.6	97.8	8.0	
WHdiam	27.37	38.39	32.17	1.69	
Speed	1.852	2.160	2.031	0.057	
30<34.99	Min	max	Aver	SD	
Weight	69.7	116.3	94.2	11.4	68.0
Height	150.0	191.9	170.8	10.1	
Waist	83.3	132.2	108.9	8.6	
WHdiam	29.46	42.08	34.96	2.22	
Speed	1.900	2.148	2.025	0.057	
35<39.99	Min	max	Aver	SD	
Weight	80.8	131.8	100.3	13.4	29.0
Height	148.4	186.6	167.6	9.7	
Waist	93.0	135.0	118.8	10.8	
WHdiam	32.89	42.97	37.92	3.21	
Speed	1.882	2.078	1.985	0.050	
40+	Min	max	Aver	SD	
Weight	99.9	166.2	132.7	17.6	24.0
Height	148.4	189.7	169.0	9.7	
Waist	119.5	161.0	136.0	10.9	
WHdiam	38.04	51.25	43.29	3.48	
Speed	1.823	2.050	1.968	0.054	

BMI	**FEMALE**	**55-64**			**Number**
>18.5	Min	max	Aver	SD	
Weight	10.5	62.2	26.9	11.8	67.0
Height	83.1	183.8	126.5	23.5	
Waist	44.1	76.1	56.8	7.2	
WHdiam	16.51	28.50	21.28	2.71	
Speed	1.283	2.246	1.711	0.225	
18.5<19.99	Min	max	Aver	SD	
Weight	15.4	69.2	47.4	12.5	30.0
Height	89.5	187.7	155.4	21.7	
Waist	54.4	84.0	71.8	7.1	
WHdiam	20.37	29.88	26.28	2.19	
Speed	1.337	2.241	1.960	0.199	
20<24.99	Min	max	Aver	SD	
Weight	36.1	86.9	59.5	8.6	96.0
Height	132.4	187.5	161.8	10.0	
Waist	64.1	98.5	82.4	7.0	
WHdiam	24.00	31.35	27.71	1.53	
Speed	1.736	2.172	1.983	0.086	
25<29.99	Min	max	Aver	SD	
Weight	53.5	102.3	75.1	9.4	118.0
Height	143.7	194.7	165.6	10.2	
Waist	81.4	113.5	95.0	6.8	
WHdiam	25.91	36.13	30.23	2.17	
Speed	1.798	2.205	1.961	0.084	
30<34.99	Min	max	Aver	SD	
Weight	64.9	110.0	86.8	9.7	66.0
Height	145.4	181.0	163.9	8.3	
Waist	89.9	123.6	106.5	6.9	
WHdiam	28.62	39.34	33.91	2.21	
Speed	1.765	2.010	1.892	0.060	
35<39.99	Min	max	Aver	SD	
Weight	78.6	122.9	101.7	10.6	33.0
Height	149.2	180.8	165.2	8.2	
Waist	99.8	132.0	116.0	6.9	
WHdiam	31.77	42.02	36.91	2.19	
Speed	1.763	1.941	1.845	0.054	
40+	Min	max	Aver	SD	
Weight	98.2	180.1	121.6	17.0	34.0
Height	149.1	181.4	162.5	6.8	
Waist	110.7	158.7	133.6	10.5	
WHdiam	35.24	50.52	42.52	3.33	
Speed	1.539	1.896	1.729	0.075	

BMI	**MALE**	**65-74**			**Number**
>18.49	Min	max	Aver	SD	
Weight	13.2	55.1	28.0	9.6	33.0
Height	90.7	174.8	128.4	18.7	
Waist	41.5	81.5	58.0	7.8	
WHdiam	14.68	28.82	20.50	2.75	
Speed	1.603	2.148	1.856	0.121	
18.5<19.99	Min	max	Aver	SD	
Weight	30.6	57.7	46.1	9.4	14.0
Height	125.9	175.9	154.3	16.4	
Waist	64.7	79.5	70.3	4.6	
WHdiam	22.88	28.12	24.86	1.77	
Speed	1.839	2.161	2.019	0.105	
20<24.99	Min	max	Aver	SD	
Weight	27.3	83.7	63.1	10.5	68.0
Height	114.5	189.9	166.0	13.2	
Waist	68.3	105.2	85.3	8.3	
WHdiam	24.16	33.49	29.75	2.40	
Speed	1.757	2.234	2.078	0.081	
25<29.99	Min	max	Aver	SD	
Weight	51.5	99.5	76.5	9.9	85.0
Height	140.1	189.7	167.3	9.4	
Waist	75.5	115.6	97.7	8.4	
WHdiam	26.70	36.80	31.97	1.81	
Speed	1.902	2.206	2.067	0.054	
30<34.99	Min	max	Aver	SD	
Weight	71.6	124.8	93.3	11.6	63.0
Height	150.3	194.2	169.7	9.6	
Waist	87.5	123.3	109.3	7.9	
WHdiam	30.95	39.25	34.99	2.14	
Speed	1.955	2.193	2.060	0.053	
35<39.99	Min	max	Aver	SD	
Weight	77.2	124.7	102.4	12.3	29.0
Height	145.4	184.9	166.3	9.5	
Waist	100.9	142.2	118.5	9.4	
WHdiam	32.12	45.26	37.74	2.99	
Speed	1.905	2.127	2.021	0.052	
40+	Min	max	Aver	SD	
Weight	97.0	155.7	127.7	17.4	22.0
Height	148.9	182.7	168.3	10.9	
Waist	118.0	150.6	133.8	11.0	
WHdiam	37.56	47.94	42.59	3.50	
Speed	1.898	2.083	2.000	0.063	

BMI	**FEMALE**	**65-74**			**Number**
>18.5	Min	max	Aver	SD	
Weight	11.8	54.5	25.9	10.6	60.0
Height	88.4	176.5	123.7	22.6	
Waist	44.8	74.5	56.2	7.5	
WHdiam	16.78	27.90	21.03	2.81	
Speed	1.285	2.115	1.634	0.213	
18.5<19.99	Min	max	Aver	SD	
Weight	26.3	65.4	49.1	10.1	12.0
Height	117.7	185.0	158.5	17.1	
Waist	57.1	80.0	72.0	6.0	
WHdiam	21.38	29.43	26.57	2.07	
Speed	1.562	2.170	1.932	0.153	
20<24.99	Min	max	Aver	SD	
Weight	34.3	85.5	60.8	9.5	92.0
Height	130.1	186.7	163.3	11.0	
Waist	69.2	101.0	84.4	7.2	
WHdiam	25.53	32.15	28.09	1.56	
Speed	1.671	2.136	1.938	0.091	
25<29.99	Min	max	Aver	SD	
Weight	45.9	95.5	73.7	8.5	92.0
Height	132.6	190.6	163.6	9.4	
Waist	78.2	113.0	95.0	7.5	
WHdiam	25.62	35.97	30.33	2.25	
Speed	1.649	2.105	1.888	0.076	
30<34.99	Min	max	Aver	SD	
Weight	64.0	120.1	86.0	12.2	57.0
Height	142.6	189.1	163.3	10.6	
Waist	90.0	128.2	107.6	7.4	
WHdiam	28.65	40.81	34.24	2.35	
Speed	1.661	2.035	1.835	0.074	
35<39.99	Min	max	Aver	SD	
Weight	66.3	130.0	93.9	13.8	27.0
Height	135.4	189.6	159.4	11.4	
Waist	102.6	126.7	115.2	7.3	
WHdiam	32.66	40.33	36.66	2.32	
Speed	1.603	1.951	1.758	0.077	
40+	Min	max	Aver	SD	
Weight	102.1	159.9	124.3	17.9	25.0
Height	148.6	183.7	164.1	7.8	
Waist	109.3	156.5	132.2	12.7	
WHdiam	34.79	49.82	42.09	4.03	
Speed	1.497	1.806	1.686	0.075	

BMI	**MALE**	**71+**			**Number**
>18.49	Min	max	Aver	SD	
Weight	11.5	52.9	25.9	10.6	33.0
Height	87.5	174.4	124.3	22.2	
Waist	42.8	75.0	56.4	7.2	
WHdiam	15.14	26.53	19.94	2.53	
Speed	1.651	2.241	1.903	0.153	
18.5<19.99	Min	max	Aver	SD	
Weight	38.0	60.2	48.9	7.4	8.0
Height	138.9	175.1	158.3	12.1	
Waist	65.8	75.3	69.8	3.0	
WHdiam	23.27	26.63	24.67	1.06	
Speed	2.000	2.232	2.126	0.077	
20<24.99	Min	max	Aver	SD	
Weight	18.4	78.6	61.8	10.9	56.0
Height	91.3	188.6	164.7	15.3	
Waist	57.5	98.2	82.0	8.7	
WHdiam	20.34	33.10	28.59	2.55	
Speed	1.665	2.315	2.153	0.100	
25<29.99	Min	max	Aver	SD	
Weight	54.5	102.6	77.4	9.2	60
Height	143.8	185.7	168.1	8.8	
Waist	77.3	118.3	98.6	7.2	
WHdiam	27.34	37.66	32.07	1.81	
Speed	2.004	2.246	2.154	0.054	
30<34.99	Min	max	Aver	SD	
Weight	60.7	127.6	93.8	12.9	47.0
Height	134.0	202.6	170.7	12.0	
Waist	89.5	127.5	111.7	8.6	
WHdiam	31.64	40.58	35.75	2.32	
Speed	1.920	2.335	2.148	0.072	
35<39.99	Min	max	Aver	SD	
Weight	87.2	115.6	103.0	9.3	9.0
Height	148.6	179.6	165.9	9.2	
Waist	103.0	131.3	117.7	9.0	
WHdiam	32.79	41.79	37.45	2.85	
Speed	1.997	2.180	2.100	0.055	
40+	Min	max	Aver	SD	
Weight	94.9	159.0	127.4	19.5	12.0
Height	151.8	179.1	165.4	9.8	
Waist	108.5	155.2	132.3	13.7	
WHdiam	34.54	49.40	42.10	4.37	
Speed	1.955	2.146	2.056	0.057	

BMI	**FEMALE**	**17+**			**Number**
>18.5	Min	max	Aver	SD	
Weight	11.8	51.0	24.5	10.3	50.0
Height	84.9	169.5	120.3	21.9	
Waist	44.3	76.9	56.3	7.3	
WHdiam	16.59	28.80	21.08	2.72	
Speed	1.246	2.049	1.599	0.209	
18.5<19.99	Min	max	Aver	SD	
Weight	37.2	68.8	53.0	8.5	12.0
Height	138.7	187.5	165.7	12.5	
Waist	66.8	83.0	74.2	4.6	
WHdiam	25.02	29.21	27.03	1.19	
Speed	1.755	2.183	1.998	0.111	
20<24.99	Min	max	Aver	SD	
Weight	39.4	80.0	60.3	9.3	61.0
Height	133.8	192.8	162.7	11.7	
Waist	70.9	98.1	83.3	7.0	
WHdiam	25.46	31.23	27.74	1.33	
Speed	1.692	2.211	1.935	0.100	
25<29.99	Min	max	Aver	SD	
Weight	43.0	94.0	73.4	9.9	59.0
Height	128.5	184.6	164.0	11.3	
Waist	79.1	112.7	95.8	7.6	
WHdiam	25.46	35.87	30.56	2.32	
Speed	1.617	2.051	1.895	0.090	
30<34.99	Min	max	Aver	SD	
Weight	69.0	116.4	85.5	11.2	29.0
Height	149.1	188.9	163.3	9.8	
Waist	95.3	118.0	107.7	6.0	
WHdiam	30.33	37.56	34.28	1.91	
Speed	1.727	2.023	1.836	0.070	
35<39.99	Min	max	Aver	SD	
Weight	78.8	130.7	98.7	13.2	19.0
Height	148.4	183.5	162.2	9.8	
Waist	102.5	133.3	115.8	8.6	
WHdiam	32.63	42.43	36.87	2.74	
Speed	1.690	1.935	1.771	0.064	
40+	Min	max	Aver	SD	
Weight	96.8	195.4	136.5	29.9	8.0
Height	150.6	195.4	172.2	14.1	
Waist	122.9	149.9	136.8	10.1	
WHdiam	39.12	47.71	43.56	3.21	
Speed	1.651	1.822	1.727	0.049	

Appendix 5: A320 Simulation Profile Distributions

Obesity Spread = NHANES (greater 25–30 BMI)

	65%		70%		75%		80%		85%		90%	
	Calculated	Simulated	Calculated	Simulated	Calculated	Simulated	Calculated	Simulated	Calculated	Simulated	Calculated	Simulated
FAMO	0.30	0.56	0.40	0.56	0.40	0.56	0.40	0.56	0.50	0.56	0.50	0.56
FAN1	0.30	0.56	0.20	0.00	0.20	0.00	0.20	0.00	0.10	0.00	0.10	0.00
FAN2	1.00	1.11	0.90	1.11	0.70	0.56	0.60	0.56	0.40	0.56	0.30	0.56
FAO1	1.00	1.11	1.00	1.11	1.10	1.11	1.20	1.11	1.30	1.11	1.30	1.11
FAO2	0.30	0.00	0.40	0.56	0.40	0.56	0.40	0.56	0.50	0.56	0.50	0.56
FAOW	1.70	1.67	1.80	1.67	1.90	1.67	2.00	2.22	2.20	2.22	2.30	2.22
FAU	0.70	0.56	0.60	0.56	0.50	0.56	0.40	0.56	0.30	0.56	0.20	0.56
FBMO	0.50	0.56	0.60	0.56	0.60	0.56	0.60	0.56	0.70	0.56	0.70	0.56
FBN1	0.20	0.00	0.20	0.00	0.20	0.00	0.10	0.00	0.10	0.00	0.10	0.00
FBN2	1.20	1.11	1.10	1.11	0.90	1.11	0.70	0.56	0.50	0.56	0.40	0.56
FBO1	1.00	1.11	1.00	1.11	1.10	1.11	1.20	1.11	1.30	1.11	1.30	1.11
FBO2	0.60	0.56	0.70	0.56	0.70	0.56	0.80	0.56	0.80	0.56	0.80	0.56
FBOW	1.70	1.67	1.90	1.67	2.00	2.22	2.20	2.22	2.30	2.22	2.40	2.22
FBU	0.60	0.56	0.60	0.56	0.50	0.56	0.40	0.56	0.30	0.56	0.20	0.00
FCMO	0.30	0.56	0.30	0.56	0.30	0.56	0.30	0.56	0.30	0.56	0.40	0.56
FCN1	0.20	0.00	0.20	0.00	0.20	0.00	0.10	0.00	0.10	0.00	0.10	0.00
FCN2	1.40	1.67	1.20	1.11	1.00	1.11	0.80	0.56	0.60	0.56	0.40	0.56
FCO1	1.80	1.67	2.00	2.22	2.10	2.22	2.20	2.22	2.40	2.22	2.50	2.22
FCO2	1.30	1.11	1.40	1.67	1.50	1.67	1.60	1.67	1.70	1.67	1.80	1.67
FCOW	0.80	0.56	0.80	0.56	0.90	1.11	1.00	1.11	1.00	1.11	1.10	1.11
FCU	0.90	1.11	0.80	0.56	0.60	0.56	0.50	0.56	0.40	0.56	0.30	0.56
FDMO	0.50	0.56	0.60	0.56	0.60	0.56	0.60	0.56	0.70	0.56	0.70	0.56
FDN1	0.20	0.00	0.20	0.00	0.10	0.00	0.10	0.00	0.10	0.00	0.10	0.00
FDN2	1.10	1.11	0.90	1.11	0.80	0.56	0.60	0.56	0.50	0.56	0.30	0.56
FDO1	1.30	1.11	1.40	1.67	1.50	1.67	1.60	1.67	1.70	1.67	1.80	1.67
FDO2	0.60	0.56	0.70	0.56	0.70	0.56	0.80	0.56	0.80	0.56	0.80	0.56
FDOW	1.70	1.67	1.90	1.67	2.00	2.22	2.20	2.22	2.30	2.22	2.40	2.22
FDU	0.80	0.56	0.70	0.56	0.60	0.56	0.50	0.56	0.40	0.56	0.20	0.00
FEMO	0.60	0.56	0.70	0.56	0.70	0.56	0.80	0.56	0.80	0.56	1.00	1.11
FEN1	0.40	0.56	0.30	0.56	0.30	0.00	0.20	0.00	0.20	0.56	0.10	0.00
FEN2	1.10	1.11	1.00	1.11	0.80	0.56	0.60	0.56	0.50	0.56	0.30	0.56
FEO1	1.20	1.11	1.20	1.11	1.40	1.67	1.50	1.67	1.60	1.67	1.70	1.67
FEO2	0.60	0.56	0.60	0.56	0.60	0.56	0.70	0.56	0.70	0.56	0.80	0.56
FEOW	2.10	2.22	2.30	2.22	2.40	2.22	2.60	2.78	2.80	2.78	2.90	2.78
FEU	0.80	0.56	0.70	0.56	0.60	0.56	0.50	0.56	0.30	0.56	0.20	0.00
FFMO	0.50	0.56	0.50	0.56	0.50	0.56	0.60	0.56	0.60	0.56	0.60	0.56
FFN1	0.10	0.00	0.10	0.00	0.10	0.00	0.10	0.00	0.10	0.00	0.00	0.00
FFN2	0.90	1.11	0.80	0.56	0.70	0.56	0.50	0.56	0.40	0.56	0.30	0.56

FFO1	1.00	1.11	1.10	1.11	1.20	1.11	1.20	1.11	1.30	1.11	1.40	1.67
FFO2	0.50	0.56	0.50	0.56	0.50	0.56	0.60	0.56	0.60	0.56	0.60	0.56
FFOW	1.70	1.67	1.80	1.67	1.90	1.67	2.00	2.22	2.20	2.22	2.30	2.22
FFU	0.70	0.56	0.60	0.56	0.50	0.56	0.40	0.56	0.30	0.56	0.20	0.00
FGMO	0.20	0.00	0.20	0.00	0.20	0.00	0.20	0.56	0.20	0.56	0.30	0.56
FGN1	0.10	0.00	0.10	0.00	0.10	0.00	0.10	0.00	0.10	0.00	0.00	0.00
FGN2	0.70	0.56	0.60	0.56	0.50	0.56	0.40	0.56	0.30	0.56	0.20	0.00
FGO1	0.60	0.56	0.60	0.56	0.60	0.56	0.70	0.56	0.70	0.56	0.80	0.56
FGO2	0.40	0.56	0.40	0.56	0.40	0.56	0.50	0.56	0.50	0.56	0.50	0.56
FGOW	1.00	1.11	1.10	1.11	1.20	1.11	1.10	1.11	1.30	1.11	1.40	1.67
FGU	0.60	0.56	0.50	0.56	0.40	0.56	0.40	0.56	0.30	0.56	0.20	0.00
MAMO	0.30	0.56	0.20	0.00	0.40	0.56	0.40	0.56	0.40	0.56	0.40	0.56
MAN1	0.40	0.56	0.40	0.56	0.30	0.56	0.20	0.00	0.20	0.56	0.10	0.00
MAN2	2.20	2.22	1.90	1.67	1.60	1.67	1.20	1.11	0.90	1.11	0.60	0.56
MAO1	1.60	1.67	1.70	1.67	1.80	1.67	1.90	1.67	2.00	2.22	2.10	2.22
MAO2	0.80	0.56	0.80	0.56	0.90	1.11	1.00	1.11	1.00	1.11	1.10	1.11
MAOW	2.20	2.22	2.30	2.22	2.50	2.78	2.70	2.78	2.80	2.78	3.00	2.78
MAU	1.00	1.11	0.90	1.11	0.70	0.56	0.60	0.56	0.40	0.56	0.30	0.56
MBMO	0.80	0.56	0.80	0.56	0.90	1.11	1.00	1.11	1.00	1.11	1.10	1.11
MBN1	0.40	0.56	0.40	0.56	0.30	0.56	0.20	0.00	0.20	0.00	0.10	0.00
MBN2	2.20	2.22	1.90	1.67	1.60	1.67	1.20	1.11	0.80	0.56	0.60	0.56
MBO1	2.00	2.22	2.20	2.22	2.30	2.22	2.50	2.78	2.60	2.78	2.80	2.78
MBO2	0.50	0.56	0.50	0.56	0.50	0.56	0.60	0.56	0.60	0.56	0.60	0.56
MBOW	3.30	3.33	3.50	3.33	3.80	3.89	4.00	3.89	4.30	4.44	4.50	4.44
MBU	1.10	1.11	1.00	1.11	0.80	0.56	0.70	0.56	0.50	0.56	0.30	0.56
MCMO	0.30	0.56	0.20	0.00	0.40	0.56	0.40	0.56	0.40	0.56	0.40	0.56
MCN1	0.40	0.56	0.40	0.56	0.30	0.56	0.20	0.00	0.20	0.00	0.10	0.00
MCN2	1.70	1.67	1.40	1.67	1.20	1.11	1.00	1.11	0.70	0.56	0.50	0.56
MCO1	2.30	2.22	2.50	2.78	2.70	2.78	2.90	2.78	3.00	2.78	3.20	3.33
MCO2	0.90	1.11	1.00	1.11	1.10	1.11	1.10	1.11	1.20	1.11	1.30	1.11
MCOW	3.40	3.33	3.70	3.89	3.90	3.89	4.20	4.44	4.50	4.44	4.70	4.44
MCU	1.10	1.11	1.00	1.11	0.80	0.56	0.70	0.56	0.50	0.56	0.30	0.56
MDMO	0.60	0.56	0.70	0.56	0.70	0.56	0.80	0.56	0.80	0.56	0.90	1.11
MDN1	0.30	0.56	0.30	0.56	0.20	0.00	0.20	0.00	0.10	0.00	0.10	0.00
MDN2	1.90	1.67	1.50	1.67	1.30	1.11	1.10	1.11	0.80	0.56	0.50	0.56
MDO1	1.90	1.67	2.00	2.22	2.10	2.22	2.30	2.22	2.40	2.22	2.60	2.78
MDO2	0.60	0.56	0.70	0.56	0.70	0.56	0.80	0.56	0.80	0.56	0.90	1.11
MDOW	3.40	3.33	3.70	3.89	3.90	3.89	4.20	4.44	4.50	4.44	4.70	4.44
MDU	1.10	1.11	1.00	1.11	0.80	0.56	0.70	0.56	0.50	0.56	0.30	0.56
MEMO	0.70	0.56	0.70	0.56	0.80	0.56	0.80	0.56	0.90	1.11	1.00	1.11
MEN1	0.40	0.56	0.30	0.56	0.30	0.56	0.20	0.00	0.20	0.00	0.10	0.00
MEN2	1.70	1.67	1.40	1.67	1.20	1.11	0.90	1.11	0.70	0.56	0.50	0.56
MEO1	1.80	1.67	1.90	1.67	2.10	2.22	2.20	2.22	2.30	2.22	2.50	2.78
MEO2	0.80	0.56	0.90	1.11	1.00	1.11	1.00	1.11	1.10	1.11	1.10	1.11
MEOW	3.00	2.78	3.30	3.33	3.50	3.33	3.70	3.89	4.00	3.89	4.20	4.44
MEU	1.10	1.11	0.90	1.11	0.80	0.56	0.60	0.56	0.50	0.56	0.30	0.56
MFMO	0.40	0.56	0.40	0.56	0.50	0.56	0.50	0.56	0.50	0.56	0.60	0.56
MFN1	0.30	0.56	0.20	0.00	0.20	0.00	0.20	0.00	0.10	0.00	0.10	0.00

MFN2	1.20	1.11	1.00	1.11	0.90	1.11	0.70	0.56	0.50	0.56	0.30	0.56
MFO1	1.40	1.67	1.50	1.67	1.60	1.67	1.70	1.67	1.80	1.67	1.90	1.67
MFO2	0.80	0.56	0.80	0.56	1.00	1.11	1.00	1.11	1.10	1.11	1.10	1.11
MFOW	2.20	2.22	2.40	2.22	2.50	2.78	2.70	2.78	2.80	2.78	3.00	2.78
MFU	0.60	0.56	0.50	0.56	0.40	0.56	0.30	0.56	0.20	0.00	0.20	0.00
MGMO	0.30	0.56	0.30	0.56	0.30	0.56	0.30	0.56	0.40	0.56	0.40	0.56
MGN1	0.20	0.00	0.20	0.00	0.10	0.00	0.10	0.00	0.10	0.00	0.10	0.00
MGN2	1.00	1.11	0.90	1.11	0.70	0.56	0.60	0.56	0.40	0.56	0.30	0.56
MGO1	1.20	1.11	1.30	1.11	1.40	1.67	1.50	1.67	1.60	1.67	1.70	1.67
MGO2	0.30	0.56	0.20	0.00	0.30	0.00	0.30	0.56	0.40	0.56	0.40	0.56
MGOW	1.50	1.67	1.60	1.67	1.70	1.67	1.80	1.67	2.00	2.22	2.10	2.22
MGU	0.60	0.56	0.50	0.56	0.50	0.56	0.30	0.56	0.20	0.00	0.20	0.00

Obesity Spread = NHANES (greater 30–40 BMI)

	65%		70%		75%		80%		85%		90%	
	Calculated	Simulated	Calculated	Simulated	Calculated	Simulated	Calculated	Simulated	Calculated	Simulated	Calculated	Simulated
FAMO	0.30	0.56	0.40	0.56	0.40	0.56	0.40	0.56	0.50	0.56	0.50	0.56
FAN1	0.30	0.00	0.20	0.00	0.20	0.00	0.20	0.00	0.10	0.00	0.10	0.00
FAN2	1.00	1.11	0.90	1.11	0.70	0.56	0.60	0.56	0.40	0.56	0.30	0.56
FAO1	1.00	1.11	1.00	1.11	1.10	1.11	1.20	1.11	1.30	1.11	1.30	1.11
FAO2	1.70	1.67	1.80	1.67	1.90	1.67	2.00	2.22	2.20	2.22	2.30	2.22
FAOW	0.30	0.56	0.40	0.56	0.40	0.56	0.40	0.56	0.50	0.56	0.50	0.56
FAU	0.70	0.56	0.60	0.56	0.50	0.56	0.40	0.56	0.30	0.56	0.20	0.56
FBMO	0.60	0.56	0.70	0.56	0.70	0.56	0.80	0.56	0.80	0.56	0.80	0.56
FBN1	0.20	0.00	0.10	0.00	0.20	0.00	0.10	0.00	0.10	0.00	0.10	0.00
FBN2	1.20	1.11	1.10	1.11	0.90	1.11	0.70	0.56	0.50	0.56	0.40	0.56
FBO1	1.00	1.11	1.00	1.11	1.10	1.11	1.20	1.11	1.30	1.11	1.30	1.11
FBO2	1.70	1.67	1.90	1.67	2.00	2.22	2.20	2.22	2.30	2.22	2.40	2.22
FBOW	0.50	0.56	0.60	0.56	0.60	0.56	0.60	0.56	0.70	0.56	0.70	0.56
FBU	0.60	0.56	0.60	0.56	0.50	0.56	0.40	0.56	0.30	0.56	0.20	0.00
FCMO	1.30	1.11	1.40	1.67	1.50	1.67	1.60	1.67	1.70	1.67	1.80	1.67
FCN1	0.20	0.00	0.20	0.00	0.30	0.56	0.10	0.00	0.10	0.00	0.10	0.00
FCN2	1.40	1.67	1.20	1.11	1.00	1.11	0.80	0.56	0.60	0.56	0.40	0.56
FCO1	1.80	1.67	2.00	2.22	2.10	2.22	2.30	2.22	2.40	2.22	2.50	2.22
FCO2	0.80	0.56	0.80	0.56	0.90	1.11	1.00	1.11	1.00	1.11	1.10	1.11
FCOW	0.30	0.56	0.20	0.00	0.30	0.56	0.30	0.56	0.30	0.56	0.40	0.56
FCU	0.90	1.11	0.80	0.56	0.60	0.56	0.50	0.56	0.40	0.56	0.30	0.56
FDMO	0.60	0.56	0.70	0.56	0.70	0.56	0.80	0.56	0.80	0.56	0.80	0.56
FDN1	0.20	0.00	0.20	0.00	0.10	0.00	0.10	0.00	0.10	0.00	0.10	0.00
FDN2	1.10	1.11	0.90	1.11	0.80	0.56	0.60	0.56	0.50	0.56	0.30	0.56
FDO1	1.30	1.11	1.40	1.67	1.50	1.67	1.60	1.67	1.70	1.67	1.80	1.67
FDO2	1.70	1.67	1.90	1.67	2.00	2.22	2.20	2.22	2.30	2.22	2.40	2.22
FDOW	0.50	0.56	0.60	0.56	0.60	0.56	0.60	0.56	0.70	0.56	0.70	0.56

FDU	0.80	0.56	0.70	0.56	0.60	0.56	0.50	0.56	0.40	0.56	0.20	0.00
FEMO	0.60	0.56	0.60	0.56	0.60	0.56	0.70	0.56	0.70	0.56	0.80	0.56
FEN1	0.40	0.56	0.30	0.00	0.30	0.00	0.20	0.00	0.20	0.56	0.10	0.00
FEN2	1.10	1.11	1.00	1.11	0.80	0.56	0.60	0.56	0.50	0.56	0.30	0.56
FEO1	1.20	1.11	1.30	1.11	1.40	1.67	1.50	1.67	1.60	1.67	1.70	1.67
FEO2	2.10	2.22	2.30	2.22	2.40	2.22	2.60	2.78	2.80	2.78	2.90	2.78
FEOW	0.60	0.56	0.70	0.56	0.70	0.56	0.80	0.56	0.80	0.56	0.90	1.11
FEU	0.80	0.56	0.70	0.56	0.60	0.56	0.50	0.56	0.30	0.56	0.20	0.00
FFMO	0.50	0.56	0.50	0.56	0.50	0.56	0.60	0.56	0.60	0.56	0.60	0.56
FFN1	0.10	0.00	0.10	0.00	0.10	0.00	0.10	0.00	0.10	0.00	0.00	0.00
FFN2	0.90	1.11	0.80	0.56	0.70	0.56	0.50	0.56	0.40	0.56	0.30	0.56
FFO1	1.00	1.11	1.10	1.11	1.20	1.11	1.20	1.11	1.30	1.11	1.40	1.67
FFO2	1.70	1.67	1.80	1.67	1.90	1.67	2.00	2.22	2.20	2.22	2.30	2.22
FFOW	0.50	0.56	0.50	0.56	0.50	0.56	0.60	0.56	0.60	0.56	0.60	0.56
FFU	0.70	0.56	0.60	0.56	0.50	0.56	0.40	0.56	0.30	0.56	0.20	0.00
FGMO	0.40	0.56	0.40	0.56	0.40	0.56	0.50	0.56	0.50	0.56	0.50	0.56
FGN1	0.10	0.00	0.10	0.00	0.10	0.00	0.10	0.00	0.10	0.00	0.00	0.00
FGN2	0.70	0.56	0.60	0.56	0.50	0.56	0.40	0.56	0.30	0.56	0.20	0.00
FGO1	0.60	0.56	0.60	0.56	0.60	0.56	0.70	0.56	0.70	0.56	0.80	0.56
FGO2	1.00	1.11	1.10	1.11	1.20	1.11	1.10	1.11	1.30	1.11	1.40	1.67
FGOW	0.20	0.00	0.20	0.00	0.20	0.00	0.20	0.56	0.20	0.56	0.30	0.56
FGU	0.60	0.56	0.50	0.56	0.40	0.56	0.40	0.56	0.30	0.56	0.20	0.00
MAMO	0.80	0.56	0.80	0.56	0.90	1.11	1.00	1.11	1.00	1.11	1.10	1.11
MAN1	0.40	0.56	0.40	0.56	0.30	0.56	0.10	0.00	0.20	0.56	0.10	0.00
MAN2	2.20	2.22	1.90	1.67	1.60	1.67	1.20	1.11	0.90	1.11	0.60	0.56
MAO1	1.60	1.67	1.70	1.67	1.80	1.67	1.90	1.67	2.00	2.22	2.10	2.22
MAO2	2.20	2.22	2.30	2.22	2.50	2.78	2.70	2.78	2.80	2.78	3.00	2.78
MAOW	0.30	0.56	0.30	0.56	0.40	0.56	0.40	0.56	0.40	0.56	0.40	0.56
MAU	1.00	1.11	0.90	1.11	0.70	0.56	0.60	0.56	0.40	0.56	0.30	0.56
MBMO	0.50	0.56	0.50	0.56	0.50	0.56	0.60	0.56	0.60	0.56	0.60	0.56
MBN1	0.40	0.56	0.40	0.56	0.30	0.56	0.20	0.56	0.20	0.00	0.10	0.00
MBN2	2.20	2.22	1.90	1.67	1.60	1.67	1.20	1.11	0.90	1.11	0.60	0.56
MBO1	2.00	2.22	2.20	2.22	2.30	2.22	2.50	2.78	2.60	2.78	2.80	2.78
MBO2	3.30	3.33	3.50	3.33	3.80	3.89	4.00	3.89	4.30	4.44	4.50	4.44
MBOW	0.80	0.56	0.80	0.56	0.90	1.11	1.00	1.11	1.00	1.11	1.10	1.11
MBU	1.10	1.11	1.00	1.11	0.80	0.56	0.70	0.56	0.50	0.56	0.30	0.56
MCMO	0.90	1.11	1.00	1.11	1.10	1.11	1.10	1.11	1.20	1.11	1.30	1.11
MCN1	0.40	0.56	0.40	0.56	0.30	0.56	0.20	0.00	0.20	0.00	0.10	0.00
MCN2	1.70	1.67	1.40	1.67	1.20	1.11	1.00	1.11	0.70	0.56	0.50	0.56
MCO1	2.30	2.22	2.50	2.78	2.70	2.78	2.90	2.78	3.00	2.78	3.20	3.33
MCO2	3.40	3.33	3.70	3.89	3.90	3.89	4.20	4.44	4.50	4.44	4.70	4.44
MCOW	0.30	0.56	0.30	0.56	0.40	0.56	0.40	0.56	0.40	0.56	0.40	0.56
MCU	1.10	1.11	1.00	1.11	0.80	0.56	0.70	0.56	0.50	0.56	0.30	0.56
MDMO	0.60	0.56	0.70	0.56	0.70	0.56	0.80	0.56	0.80	0.56	0.90	1.11
MDN1	0.30	0.56	0.30	0.56	0.20	0.00	0.20	0.00	0.10	0.00	0.10	0.00
MDN2	1.90	1.67	1.60	1.67	1.30	1.11	1.10	1.11	0.80	0.56	0.50	0.56
MDO1	1.90	1.67	2.00	2.22	2.10	2.22	2.30	2.22	2.40	2.22	2.60	2.78
MDO2	3.40	3.33	3.70	3.89	3.90	3.89	4.20	4.44	4.50	4.44	4.70	4.44

MDOW	0.60	0.56	0.70	0.56	0.70	0.56	0.80	0.56	0.80	0.56	0.90	1.11
MDU	1.10	1.11	1.00	1.11	0.80	0.56	0.70	0.56	0.50	0.56	0.30	0.56
MEMO	0.80	0.56	0.90	1.11	1.00	1.11	1.00	1.11	1.00	1.11	1.10	1.11
MEN1	0.40	0.56	0.20	0.00	0.30	0.56	0.20	0.00	0.20	0.00	0.10	0.00
MEN2	1.70	1.67	1.40	1.67	1.20	1.11	0.90	1.11	0.70	0.56	0.50	0.56
MEO1	1.80	1.67	1.90	1.67	2.10	2.22	2.20	2.22	2.30	2.22	2.50	2.78
MEO2	3.00	2.78	3.30	3.33	3.50	3.33	3.70	3.89	4.00	3.89	4.20	4.44
MEOW	0.70	0.56	0.70	0.56	0.80	0.56	0.80	0.56	0.80	0.56	1.00	1.11
MEU	1.10	1.11	0.90	1.11	0.80	0.56	0.60	0.56	0.50	0.56	0.30	0.56
MFMO	0.80	0.56	0.90	1.11	1.00	1.11	1.00	1.11	1.10	1.11	1.10	1.11
MFN1	0.30	0.56	0.10	0.00	0.20	0.00	0.20	0.00	0.10	0.00	0.20	0.00
MFN2	1.20	1.11	1.00	1.11	0.90	1.11	0.70	0.56	0.50	0.56	0.30	0.56
MFO1	1.40	1.67	1.50	1.67	1.60	1.67	1.70	1.67	1.80	1.67	1.90	1.67
MFO2	2.20	2.22	2.40	2.22	2.50	2.78	2.70	2.78	2.90	2.78	3.00	2.78
MFOW	0.40	0.56	0.40	0.56	0.50	0.56	0.50	0.56	0.50	0.56	0.60	0.56
MFU	0.60	0.56	0.50	0.56	0.40	0.56	0.30	0.56	0.20	0.00	0.20	0.00
MGMO	0.30	0.56	0.30	0.56	0.30	0.00	0.20	0.00	0.40	0.56	0.40	0.56
MGN1	0.20	0.00	0.10	0.00	0.10	0.00	0.10	0.00	0.10	0.00	0.10	0.00
MGN2	1.00	1.11	0.90	1.11	0.70	0.56	0.60	0.56	0.40	0.56	0.30	0.56
MGO1	1.20	1.11	1.30	1.11	1.40	1.67	1.50	1.67	1.60	1.67	1.70	1.67
MGO2	1.50	1.67	1.60	1.67	1.70	1.67	1.90	1.67	2.00	2.22	2.10	2.22
MGOW	0.30	0.56	0.20	0.00	0.30	0.00	0.30	0.56	0.40	0.56	0.40	0.56
MGU	0.60	0.56	0.50	0.56	0.40	0.56	0.30	0.56	0.20	0.00	0.20	0.00

Obesity Spread = NHANES (greater 40+ BMI)

	65%		70%		75%		80%		85%		90%	
	Calculated	Simulated	Calculated	Simulated	Calculated	Simulated	Calculated	Simulated	Calculated	Simulated	Calculated	Simulated
FAMO	1.70	1.67	1.80	1.67	1.90	1.67	2.00	2.22	2.20	2.22	2.30	2.22
FAN1	0.30	0.00	0.20	0.00	0.20	0.00	0.20	0.00	0.10	0.00	0.10	0.00
FAN2	1.00	1.11	0.90	1.11	0.70	0.56	0.60	0.56	0.40	0.56	0.30	0.56
FAO1	0.30	0.56	0.40	0.56	0.40	0.56	0.40	0.56	0.50	0.56	0.50	0.56
FAO2	1.00	1.11	1.00	1.11	1.10	1.11	1.20	1.11	1.30	1.11	1.30	1.11
FAOW	0.30	0.56	0.40	0.56	0.40	0.56	0.40	0.56	0.50	0.56	0.50	0.56
FAU	0.70	0.56	0.60	0.56	0.50	0.56	0.40	0.56	0.30	0.56	0.20	0.56
FBMO	1.70	1.67	1.90	1.67	2.00	2.22	2.20	2.22	2.30	2.22	2.40	2.78
FBN1	0.20	0.00	0.20	0.00	0.20	0.00	0.10	0.00	0.10	0.00	0.10	0.00
FBN2	1.20	1.11	1.10	1.11	0.90	1.11	0.70	0.56	0.50	0.56	0.40	0.56
FBO1	0.60	0.56	0.70	0.56	0.70	0.56	0.80	0.56	0.80	0.56	0.80	0.56
FBO2	1.00	1.11	1.00	1.11	1.10	1.11	1.20	1.11	1.30	1.11	1.30	1.11
FBOW	0.50	0.56	0.60	0.56	0.60	0.56	0.60	0.56	0.70	0.56	0.70	0.56
FBU	0.60	0.56	0.60	0.56	0.50	0.56	0.40	0.56	0.30	0.56	0.20	0.00
FCMO	0.80	0.56	0.80	0.56	0.90	1.11	1.00	1.11	1.00	1.11	1.10	1.11
FCN1	0.20	0.00	0.10	0.00	0.20	0.00	0.10	0.00	0.10	0.00	0.10	0.00

FCN2	1.40	1.67	1.20	1.11	1.00	1.11	0.80	0.56	0.60	0.56	0.40	0.56
FCO1	1.30	1.11	1.40	1.67	1.50	1.67	1.60	1.67	1.70	1.67	1.80	1.67
FCO2	1.80	1.67	2.00	2.22	2.10	2.22	2.30	2.22	2.40	2.22	2.50	2.22
FCOW	0.30	0.56	0.30	0.56	0.30	0.56	0.30	0.56	0.30	0.56	0.40	0.56
FCU	0.90	1.11	0.80	0.56	0.60	0.56	0.50	0.56	0.40	0.56	0.30	0.56
FDMO	1.70	1.67	1.90	1.67	2.00	2.22	2.20	2.22	2.30	2.22	2.40	2.22
FDN1	0.20	0.00	0.20	0.00	0.10	0.00	0.10	0.00	0.10	0.00	0.10	0.00
FDN2	1.10	1.11	0.90	1.11	0.80	0.56	0.60	0.56	0.50	0.56	0.30	0.56
FDO1	0.60	0.56	0.70	0.56	0.70	0.56	0.80	0.56	0.80	0.56	0.80	0.56
FDO2	1.30	1.11	1.40	1.67	1.50	1.67	1.50	1.67	1.70	1.67	1.80	1.67
FDOW	0.50	0.56	0.60	0.56	0.60	0.56	0.60	0.56	0.70	0.56	0.70	0.56
FDU	0.80	0.56	0.70	0.56	0.60	0.56	0.50	0.56	0.40	0.56	0.20	0.00
FEMO	2.10	2.22	2.30	2.22	2.40	2.22	2.60	2.78	2.80	2.78	2.90	2.78
FEN1	0.40	0.56	0.20	0.00	0.30	0.56	0.20	0.56	0.20	0.56	0.10	0.00
FEN2	1.10	1.11	1.00	1.11	0.80	0.56	0.60	0.56	0.50	0.56	0.30	0.56
FEO1	0.60	0.56	0.60	0.56	0.60	0.56	0.70	0.56	0.70	0.56	0.80	0.56
FEO2	1.20	1.11	1.30	1.11	1.40	1.67	1.50	1.67	1.60	1.67	1.70	1.67
FEOW	0.60	0.56	0.70	0.56	0.70	0.56	0.80	0.56	0.80	0.56	0.90	1.11
FEU	0.80	0.56	0.70	0.56	0.60	0.56	0.50	0.56	0.30	0.56	0.20	0.00
FFMO	1.70	1.67	1.80	1.67	1.90	1.67	2.00	2.22	2.20	2.22	2.30	2.22
FFN1	0.10	0.00	0.10	0.00	0.10	0.00	0.10	0.00	0.10	0.00	0.00	0.00
FFN2	0.90	1.11	0.80	0.56	0.70	0.56	0.50	0.56	0.40	0.56	0.30	0.56
FFO1	0.50	0.56	0.50	0.56	0.50	0.56	0.60	0.56	0.60	0.56	0.60	0.56
FFO2	1.00	1.11	1.10	1.11	1.20	1.11	1.20	1.11	1.30	1.11	1.40	1.67
FFOW	0.50	0.56	0.50	0.56	0.50	0.56	0.60	0.56	0.60	0.56	0.60	0.56
FFU	0.70	0.56	0.60	0.56	0.50	0.56	0.40	0.56	0.30	0.56	0.20	0.00
FGMO	1.00	1.11	1.10	1.11	1.20	1.11	1.20	1.11	1.30	1.11	1.40	1.67
FGN1	0.10	0.00	0.10	0.00	0.10	0.00	0.10	0.00	0.10	0.00	0.00	0.00
FGN2	0.70	0.56	0.60	0.56	0.50	0.56	0.40	0.56	0.30	0.56	0.20	0.00
FGO1	0.40	0.56	0.40	0.56	0.40	0.56	0.50	0.56	0.50	0.56	0.50	0.56
FGO2	0.60	0.56	0.60	0.56	0.60	0.56	0.70	0.56	0.70	0.56	0.80	0.56
FGOW	0.20	0.00	0.10	0.00	0.20	0.00	0.20	0.56	0.20	0.56	0.30	0.56
FGU	0.60	0.56	0.50	0.56	0.40	0.56	0.40	0.56	0.30	0.56	0.20	0.00
MAMO	2.20	2.22	2.30	2.22	2.50	2.78	2.70	2.78	2.80	2.78	3.00	2.78
MAN1	0.40	0.56	0.40	0.56	0.30	0.56	0.20	0.00	0.20	0.56	0.10	0.00
MAN2	2.20	2.22	1.90	1.67	1.60	1.67	1.20	1.11	0.90	1.11	0.60	0.56
MAO1	0.80	0.56	0.80	0.56	0.90	1.11	1.00	1.11	1.00	1.11	1.10	1.11
MAO2	1.60	1.67	1.70	1.67	1.80	1.67	1.90	1.67	2.00	2.22	2.10	2.22
MAOW	0.30	0.56	0.30	0.56	0.40	0.56	0.40	0.56	0.40	0.56	0.40	0.56
MAU	1.00	1.11	0.90	1.11	0.70	0.56	0.60	0.56	0.40	0.56	0.30	0.00
MBMO	3.30	3.33	3.50	3.33	3.80	3.89	4.00	3.89	4.30	4.44	4.50	4.44
MBN1	0.40	0.56	0.40	0.56	0.30	0.56	0.20	0.00	0.20	0.00	0.20	0.00
MBN2	2.20	2.22	1.90	1.67	1.60	1.67	1.20	1.11	0.90	1.11	0.60	0.56
MBO1	0.50	0.56	0.50	0.56	0.50	0.56	0.60	0.56	0.60	0.56	0.60	0.56
MBO2	2.00	2.22	2.20	2.22	2.30	2.22	2.50	2.78	2.60	2.78	2.80	2.78
MBOW	0.80	0.56	0.80	0.56	0.90	1.11	1.00	1.11	1.00	1.11	1.10	1.11
MBU	1.10	1.11	1.00	1.11	0.80	0.56	0.70	0.56	0.50	0.56	0.30	0.56

MCMO	3.40	3.33	3.70	3.89	3.90	3.89	4.20	4.44	4.50	4.44	4.70	4.44
MCN1	0.40	0.56	0.40	0.56	0.30	0.56	0.20	0.00	0.20	0.00	0.10	0.00
MCN2	1.70	1.67	1.40	1.67	1.20	1.11	1.00	1.11	0.70	0.56	0.50	0.56
MCO1	0.90	1.11	1.00	1.11	1.10	1.11	1.10	1.11	1.20	1.11	1.30	1.11
MCO2	2.30	2.22	2.50	2.78	2.70	2.78	2.90	2.78	3.00	2.78	3.20	3.33
MCOW	0.30	0.56	0.30	0.56	0.40	0.56	0.40	0.56	0.40	0.56	0.40	0.56
MCU	1.10	1.11	1.00	1.11	0.80	0.56	0.70	0.56	0.50	0.56	0.30	0.56
MDMO	3.40	3.33	3.70	3.89	3.90	3.89	4.20	4.44	4.50	4.44	4.70	8.89
MDN1	0.30	0.56	0.20	0.00	0.20	0.00	0.20	0.00	0.10	0.00	0.10	0.00
MDN2	1.90	1.67	1.60	1.67	1.30	1.11	1.10	1.11	0.80	0.56	0.50	0.56
MDO1	0.60	0.56	0.70	0.56	0.70	0.56	0.80	0.56	0.80	0.56	0.90	1.11
MDO2	1.90	1.67	2.00	2.22	2.10	2.22	2.30	2.22	2.40	2.22	2.60	2.78
MDOW	0.60	0.56	0.70	0.56	0.70	0.56	0.80	0.56	0.80	0.56	0.90	1.11
MDU	1.10	1.11	1.00	1.11	0.80	0.56	0.70	0.56	0.50	0.56	0.30	0.56
MEMO	3.00	2.78	3.30	3.33	3.50	3.33	3.70	3.89	4.00	3.89	4.20	0.00
MEN1	0.40	0.56	0.30	0.56	0.30	0.56	0.20	0.00	0.20	0.00	0.10	0.00
MEN2	1.70	1.67	1.40	1.67	1.20	1.11	0.90	1.11	0.70	0.56	0.50	0.56
MEO1	0.80	0.56	0.90	1.11	1.00	1.11	1.00	1.11	1.00	1.11	1.10	1.11
MEO2	1.80	1.67	1.90	1.67	2.10	2.22	2.20	2.22	2.30	2.22	2.50	2.78
MEOW	0.70	0.56	0.70	0.56	0.80	0.56	0.80	0.56	0.80	0.56	1.00	1.11
MEU	1.10	1.11	0.90	1.11	0.80	0.56	0.60	0.56	0.50	0.56	0.30	0.56
MFMO	2.20	2.22	2.40	2.22	2.50	2.78	2.70	2.78	2.90	2.78	3.00	2.78
MFN1	0.30	0.56	0.10	0.00	0.20	0.00	0.20	0.00	0.10	0.00	0.10	0.00
MFN2	1.20	1.11	1.00	1.11	0.90	1.11	0.60	0.56	0.50	0.56	0.30	0.56
MFO1	0.80	0.56	0.90	1.11	1.00	1.11	1.00	1.11	1.10	1.11	1.10	1.11
MFO2	1.40	1.67	1.50	1.67	1.60	1.67	1.70	1.67	1.80	1.67	1.90	1.67
MFOW	0.40	0.56	0.40	0.56	0.60	0.56	0.50	0.56	0.50	0.56	0.60	0.56
MFU	0.60	0.56	0.50	0.56	0.40	0.56	0.30	0.56	0.20	0.00	0.20	0.00
MGMO	1.50	1.67	1.60	1.67	1.70	1.67	1.90	1.67	2.00	2.22	2.10	2.22
MGN1	0.20	0.00	0.20	0.00	0.10	0.00	0.10	0.00	0.10	0.00	0.10	0.00
MGN2	1.00	1.11	0.90	1.11	0.70	0.56	0.60	0.56	0.40	0.56	0.30	0.56
MGO1	0.30	0.56	0.30	0.00	0.30	0.00	0.30	0.56	0.40	0.56	0.40	0.56
MGO2	1.20	1.11	1.30	1.11	1.40	1.67	1.50	1.67	1.60	1.67	1.70	1.67
MGOW	0.30	0.56	0.20	0.00	0.30	0.00	0.30	0.56	0.40	0.56	0.40	0.56
MGU	0.60	0.56	0.50	0.56	0.40	0.56	0.20	0.00	0.20	0.00	0.20	0.00

Appendix 6: A330 Simulation Profile Distributions

Obesity Spread = NHANES (greater 25–30 BMI)												
	65%		70%		75%		80%		85%		90%	
	Calculated	Simulated	Calculated	Simulated	Calculated	Simulated	Calculated	Simulated	Calculated	Simulated	Calculated	Simulated
FAMO	0.30	0.29	0.40	0.29	0.40	0.29	0.40	0.29	0.50	0.59	0.50	0.59
FAN1	0.30	0.29	0.20	0.29	0.20	0.29	0.20	0.29	0.10	0.00	0.10	0.00
FAN2	1.00	0.88	0.90	0.88	0.70	0.59	0.60	0.59	0.40	0.29	0.30	0.29
FAO1	1.00	0.88	1.00	0.88	1.10	1.18	1.20	1.18	1.30	1.18	1.30	1.18
FAO2	0.30	0.29	0.40	0.29	0.40	0.29	0.40	0.29	0.50	0.59	0.50	0.59
FAOW	1.70	1.77	1.80	1.77	1.90	1.77	2.00	2.06	2.20	2.06	2.30	2.36
FAU	0.70	0.59	0.60	0.59	0.50	0.59	0.40	0.29	0.30	0.29	0.20	0.29
FBMO	0.50	0.59	0.60	0.59	0.60	0.59	0.60	0.59	0.70	0.59	0.70	0.59
FBN1	0.20	0.29	0.20	0.29	0.20	0.29	0.10	0.29	0.10	0.29	0.10	0.29
FBN2	1.20	1.18	1.10	1.18	0.90	0.88	0.70	0.59	0.50	0.59	0.40	0.29
FBO1	1.00	0.88	1.00	0.88	1.10	1.18	1.20	1.18	1.30	1.18	1.30	1.18
FBO2	0.60	0.59	0.70	0.59	0.70	0.59	0.80	0.88	0.80	0.88	0.80	0.88
FBOW	1.70	1.77	1.90	1.77	2.00	2.06	2.20	2.06	2.30	2.36	2.40	2.36
FBU	0.60	0.59	0.60	0.59	0.50	0.59	0.40	0.29	0.30	0.29	0.20	0.29
FCMO	0.30	0.29	0.30	0.29	0.30	0.29	0.30	0.29	0.30	0.29	0.40	0.29
FCN1	0.20	0.29	0.20	0.29	0.20	0.29	0.10	0.29	0.10	0.29	0.10	0.29
FCN2	1.40	1.47	1.20	1.18	1.00	0.88	0.80	0.88	0.60	0.59	0.40	0.29
FCO1	1.80	1.77	2.00	2.06	2.10	2.06	*2.20*	2.06	2.40	2.36	2.50	2.36
FCO2	1.30	1.18	1.40	1.47	1.50	1.47	1.60	1.47	1.70	1.77	1.80	1.77
FCOW	0.80	0.88	0.80	0.88	0.90	0.88	1.00	0.88	1.00	0.88	1.10	1.18
FCU	0.90	0.88	0.80	0.88	0.60	0.59	0.50	0.59	0.40	0.29	0.30	0.29
FDMO	0.50	0.59	0.60	0.59	0.60	0.59	0.60	0.59	0.70	0.59	0.70	0.59
FDN1	0.20	0.29	0.20	0.29	0.10	0.29	0.10	0.29	0.10	0.29	0.10	0.29
FDN2	1.10	1.18	0.90	0.88	0.80	0.88	0.60	0.59	0.50	0.59	0.30	0.29
FDO1	1.30	1.18	1.40	1.47	1.50	1.47	1.60	1.47	1.70	1.77	1.80	1.77
FDO2	0.60	0.59	0.70	0.59	0.70	0.59	0.80	0.88	0.80	0.88	0.80	0.88
FDOW	1.70	1.77	1.90	1.77	2.00	2.06	2.20	2.06	2.30	2.36	2.40	2.36
FDU	0.80	0.88	0.70	0.59	0.60	0.59	0.50	0.59	0.40	0.29	0.20	0.29
FEMO	0.60	0.59	0.70	0.59	0.70	0.59	0.80	0.88	0.80	0.88	*1.00*	0.88
FEN1	0.40	0.29	0.30	0.29	0.30	0.29	0.20	0.29	0.20	0.29	0.10	0.29
FEN2	1.10	1.18	1.00	0.88	0.80	0.88	0.60	0.59	0.50	0.59	0.30	0.29
FEO1	1.20	1.18	1.20	1.18	1.40	1.47	1.50	1.47	1.60	1.47	1.70	1.77
FEO2	0.60	0.59	0.60	0.59	0.60	0.59	0.70	0.59	0.70	0.59	0.80	0.88
FEOW	2.10	2.06	2.30	2.36	2.40	2.36	2.60	2.65	2.80	2.65	2.90	2.95
FEU	0.80	0.88	0.70	0.59	0.60	0.59	0.50	0.59	0.30	0.29	0.20	0.29
FFMO	0.50	0.59	0.50	0.59	0.50	0.59	0.60	0.59	0.60	0.59	0.60	0.59
FFN1	0.10	0.29	0.10	0.29	0.10	0.29	0.10	0.29	0.10	0.29	0.00	0.00
FFN2	0.90	0.88	0.80	0.88	0.70	0.59	0.50	0.59	0.40	0.29	0.30	0.29

FFO1	1.00	0.88	1.10	1.18	1.20	1.18	1.20	1.18	1.30	1.18	1.40	1.47
FFO2	0.50	0.59	0.50	0.59	0.50	0.59	0.60	0.59	0.60	0.59	0.60	0.59
FFOW	1.70	1.77	1.80	1.77	1.90	1.77	2.00	2.06	2.20	2.06	2.30	2.36
FFU	0.70	0.59	0.60	0.59	0.50	0.59	0.40	0.29	0.30	0.29	0.20	0.29
FGMO	0.20	0.29	0.20	0.29	0.20	0.29	0.20	0.29	0.20	0.29	0.30	0.29
FGN1	0.10	0.29	0.10	0.29	0.10	0.29	0.10	0.29	0.10	0.29	0.00	0.00
FGN2	0.70	0.59	0.60	0.59	0.50	0.59	0.40	0.29	0.30	0.29	0.20	0.29
FGO1	0.60	0.59	0.60	0.59	0.60	0.59	0.70	0.59	0.70	0.59	0.80	0.88
FGO2	0.40	0.29	0.40	0.29	0.40	0.29	0.50	0.59	0.50	0.59	0.50	0.59
FGOW	1.00	0.88	1.10	1.18	1.20	1.18	*1.10*	1.18	1.30	1.18	1.40	1.47
FGU	0.60	0.59	0.50	0.59	0.40	0.29	0.40	0.29	0.30	0.29	0.20	0.29
MAMO	0.30	0.29	0.20	0.29	0.40	0.29	0.40	0.29	0.40	0.29	0.40	0.29
MAN1	0.40	0.29	0.40	0.29	0.30	0.29	0.20	0.29	0.20	0.29	0.10	0.00
MAN2	2.20	2.06	1.90	1.77	1.60	1.47	1.20	1.18	0.90	0.88	0.60	0.59
MAO1	1.60	1.47	1.70	1.77	1.80	1.77	1.90	1.77	2.00	2.06	2.10	2.06
MAO2	0.80	0.88	0.80	0.88	0.90	0.88	1.00	0.88	1.00	0.88	1.10	1.18
MAOW	2.20	2.06	2.30	2.36	2.50	2.36	2.70	2.65	2.80	2.65	3.00	2.95
MAU	1.00	0.88	0.90	0.88	0.70	0.59	0.60	0.59	0.40	0.29	0.30	0.29
MBMO	0.80	0.88	0.80	0.88	0.90	0.88	1.00	0.88	1.00	0.88	1.10	1.18
MBN1	0.40	0.29	0.40	0.29	0.30	0.29	0.20	0.29	0.20	0.29	0.10	0.00
MBN2	2.20	2.06	1.90	1.77	1.60	1.47	1.20	1.18	0.80	0.88	0.60	0.59
MBO1	2.00	2.06	2.20	2.06	2.30	2.36	2.50	2.36	2.60	2.65	2.80	2.65
MBO2	0.50	0.59	0.50	0.59	0.50	0.59	0.60	0.59	0.60	0.59	0.60	0.59
MBOW	3.30	3.24	3.50	3.54	3.80	3.83	4.00	4.13	4.30	4.42	4.50	4.42
MBU	1.10	1.18	1.00	0.88	0.80	0.88	0.70	0.59	0.50	0.59	0.30	0.29
MCMO	0.30	0.29	0.20	0.29	0.40	0.29	0.40	0.29	0.40	0.29	0.40	0.29
MCN1	0.40	0.29	0.40	0.29	0.30	0.29	0.20	0.29	0.20	0.29	0.10	0.00
MCN2	1.70	1.77	1.40	1.47	1.20	1.18	1.00	0.88	0.70	0.59	0.50	0.59
MCO1	2.30	2.36	2.50	2.36	2.70	2.65	2.90	2.95	3.00	2.95	3.20	3.24
MCO2	0.90	0.88	1.00	0.88	1.10	1.18	1.10	1.18	1.20	1.18	1.30	1.18
MCOW	3.40	3.83	3.70	4.42	3.90	4.13	4.20	4.13	4.50	4.42	4.70	4.72
MCU	1.10	1.18	1.00	0.88	0.80	0.88	0.70	0.59	0.50	0.59	0.30	0.29
MDMO	0.60	0.59	0.70	0.59	0.70	0.59	0.80	0.88	0.80	0.88	0.90	0.88
MDN1	0.30	0.29	0.30	0.29	0.20	0.29	0.20	0.29	0.10	0.00	0.10	0.00
MDN2	1.90	1.77	1.50	1.47	1.30	1.18	1.10	1.18	0.80	0.88	0.50	0.59
MDO1	1.90	1.77	2.00	2.06	2.10	2.06	2.30	2.36	2.40	2.36	2.60	2.65
MDO2	0.60	0.59	0.70	0.59	0.70	0.59	0.80	0.88	0.80	0.88	0.90	0.88
MDOW	3.40	3.54	3.70	3.83	3.90	3.83	4.20	4.13	4.50	4.42	4.70	4.72
MDU	1.10	1.18	1.00	0.88	0.80	0.88	0.70	0.59	0.50	0.59	0.30	0.29
MEMO	0.70	0.59	0.70	0.59	0.80	0.88	0.80	0.88	0.90	0.88	1.00	0.88
MEN1	0.40	0.29	0.30	0.29	0.30	0.29	0.20	0.29	0.20	0.29	0.10	0.00
MEN2	1.70	1.77	1.40	1.47	1.20	1.18	0.90	0.88	0.70	0.59	0.50	0.59
MEO1	1.80	1.77	1.90	1.77	2.10	2.06	2.20	2.06	2.30	2.36	2.50	2.36
MEO2	0.80	0.88	0.90	0.88	1.00	0.88	1.00	0.88	1.10	1.18	1.10	1.18
MEOW	3.00	2.95	3.30	3.24	3.50	3.54	3.70	3.83	4.00	4.13	4.20	4.13
MEU	1.10	1.18	0.90	0.88	0.80	0.88	0.60	0.59	0.50	0.59	0.30	0.29
MFMO	0.40	0.29	0.40	0.29	0.50	0.59	0.50	0.59	0.50	0.59	0.60	0.59
MFN1	0.30	0.29	0.20	0.29	0.20	0.29	0.20	0.29	0.10	0.00	0.10	0.00

MFN2	1.20	1.18	1.00	0.88	0.90	0.88	0.70	0.59	0.50	0.59	0.30	0.29
MFO1	1.40	1.47	1.50	1.47	1.60	1.47	1.70	1.77	1.80	1.77	1.90	1.77
MFO2	0.80	0.88	0.80	0.88	1.00	0.88	1.00	0.88	1.10	1.18	1.10	1.18
MFOW	2.20	2.06	2.40	2.36	2.50	2.36	2.70	2.65	*2.80*	2.65	3.00	2.95
MFU	0.60	0.59	0.50	0.59	0.40	0.29	0.30	0.29	0.20	0.29	0.20	0.29
MGMO	0.30	0.29	0.30	0.29	0.30	0.29	0.30	0.29	0.40	0.29	0.40	0.29
MGN1	0.20	0.29	0.20	0.29	0.10	0.29	0.10	0.29	0.10	0.00	0.10	0.00
MGN2	1.00	0.88	0.90	0.88	0.70	0.59	0.60	0.59	0.40	0.29	0.30	0.29
MGO1	1.20	1.18	1.30	1.18	1.40	1.47	1.50	1.47	1.60	1.47	1.70	1.77
MGO2	0.30	0.29	0.20	0.29	0.30	0.29	0.30	0.29	0.40	0.29	0.40	0.29
MGOW	1.50	1.47	1.60	1.47	1.70	1.77	*1.80*	1.77	2.00	2.06	2.10	2.06
MGU	0.60	0.59	0.50	0.59	*0.50*	0.59	0.30	0.29	0.20	0.29	0.20	0.29

Obesity Spread = NHANES (greater 30–40 BMI)												
	65%		70%		75%		80%		85%		90%	
	Calculated	Simulated	Calculated	Simulated	Calculated	Simulated	Calculated	Simulated	Calculated	Simulated	Calculated	Simulated
FAMO	0.30	0.29	0.40	0.29	0.40	0.29	0.40	0.29	0.50	0.59	0.50	0.59
FAN1	0.30	0.29	0.20	0.29	0.20	0.29	0.20	0.29	0.10	0.00	0.10	0.00
FAN2	1.00	0.88	0.90	0.88	0.70	0.59	0.60	0.59	0.40	0.29	0.30	0.29
FAO1	1.00	0.88	1.00	0.88	1.10	1.18	1.20	1.18	1.30	1.18	1.30	1.18
FAO2	1.70	1.77	1.80	1.77	1.90	1.77	2.00	2.06	2.20	2.06	2.30	2.36
FAOW	0.30	0.29	0.40	0.29	0.40	0.29	0.40	0.29	0.50	0.59	0.50	0.59
FAU	0.70	0.59	0.60	0.59	0.50	0.59	0.40	0.29	0.30	0.29	0.20	0.29
FBMO	0.60	0.59	0.70	0.59	0.70	0.59	0.80	0.88	0.80	0.88	0.80	0.88
FBN1	0.20	0.29	0.10	0.29	0.20	0.29	0.10	0.29	0.10	0.29	0.10	0.29
FBN2	1.20	1.18	1.10	1.18	0.90	0.88	0.70	0.59	0.50	0.59	0.40	0.29
FBO1	1.00	0.88	1.00	0.88	1.10	1.18	1.20	1.18	1.30	1.18	1.30	1.18
FBO2	1.70	1.77	1.90	1.77	2.00	2.06	2.20	2.06	2.30	2.36	2.40	2.36
FBOW	0.50	0.59	0.60	0.59	0.60	0.59	0.60	0.59	0.70	0.59	0.70	0.59
FBU	0.60	0.59	0.60	0.59	0.50	0.59	0.40	0.29	0.30	0.29	0.20	0.29
FCMO	1.30	1.18	1.40	1.47	1.50	1.47	1.60	1.47	1.70	1.77	1.80	1.77
FCN1	0.20	0.29	0.20	0.29	0.30	0.29	0.10	0.29	0.10	0.29	0.10	0.29
FCN2	1.40	1.47	1.20	1.18	1.00	0.88	0.80	0.88	0.60	0.59	0.40	0.29
FCO1	1.80	1.77	2.00	2.06	2.10	2.06	2.30	2.36	2.40	2.36	2.50	2.36
FCO2	0.80	0.88	0.80	0.88	0.90	0.88	1.00	0.88	1.00	0.88	1.10	1.18
FCOW	0.30	0.29	0.20	0.29	0.30	0.29	0.30	0.29	0.30	0.29	0.40	0.29
FCU	0.90	0.88	0.80	0.88	0.60	0.59	0.50	0.59	0.40	0.29	0.30	0.29
FDMO	0.60	0.59	0.70	0.59	0.70	0.59	0.80	0.88	0.80	0.88	0.80	0.88
FDN1	0.20	0.29	0.20	0.29	0.10	0.29	0.10	0.29	0.10	0.29	0.10	0.29
FDN2	1.10	1.18	0.90	0.88	0.80	0.88	0.60	0.59	0.50	0.59	0.30	0.29
FDO1	1.30	1.18	1.40	1.47	1.50	1.47	1.60	1.47	1.70	1.77	1.80	1.77
FDO2	1.70	1.77	1.90	1.77	2.00	2.06	2.20	2.06	2.30	2.36	2.40	2.36
FDOW	0.50	0.59	0.60	0.59	0.60	0.59	0.60	0.59	0.70	0.59	0.70	0.59

FDU	0.80	0.88	0.70	0.59	0.60	0.59	0.50	0.59	0.40	0.29	0.20	0.29
FEMO	0.60	0.59	0.60	0.59	0.60	0.59	0.70	0.59	0.70	0.59	0.80	0.88
FEN1	0.40	0.29	0.30	0.29	0.30	0.29	0.20	0.29	0.20	0.29	0.10	0.00
FEN2	1.10	1.18	1.00	0.88	0.80	0.88	0.60	0.59	0.50	0.59	0.30	0.29
FEO1	1.20	1.18	1.30	1.18	1.40	1.47	1.50	1.47	1.60	1.47	1.70	1.77
FEO2	2.10	2.06	2.30	2.36	2.40	2.36	2.60	2.65	2.80	2.65	2.90	2.95
FEOW	0.60	0.59	0.70	0.59	0.70	0.59	0.80	0.88	0.80	0.88	0.90	0.88
FEU	0.80	0.88	0.70	0.59	0.60	0.59	0.50	0.59	0.30	0.29	0.20	0.29
FFMO	0.50	0.59	0.50	0.59	0.50	0.59	0.60	0.59	0.60	0.59	0.60	0.59
FFN1	0.10	0.29	0.10	0.29	0.10	0.29	0.10	0.29	0.10	0.29	0.00	0.00
FFN2	0.90	0.88	0.80	0.88	0.70	0.59	0.50	0.59	0.40	0.29	0.30	0.29
FFO1	1.00	0.88	1.10	1.18	1.20	1.18	1.20	1.18	1.30	1.18	1.40	1.47
FFO2	1.70	1.77	1.80	1.77	1.90	1.77	2.00	2.06	2.20	2.06	2.30	2.36
FFOW	0.50	0.59	0.50	0.59	0.50	0.59	0.60	0.59	0.60	0.59	0.60	0.59
FFU	0.70	0.59	0.60	0.59	0.50	0.59	0.40	0.29	0.30	0.29	0.20	0.29
FGMO	0.40	0.29	0.40	0.29	0.40	0.29	0.50	0.59	0.50	0.59	0.50	0.59
FGN1	0.10	0.29	0.10	0.29	0.10	0.29	0.10	0.29	0.10	0.29	0.00	0.00
FGN2	0.70	0.59	0.60	0.59	0.50	0.59	0.40	0.29	0.30	0.29	0.20	0.29
FGO1	0.60	0.59	0.60	0.59	0.60	0.59	0.70	0.59	0.70	0.59	0.80	0.88
FGO2	1.00	0.88	1.10	1.18	1.20	1.18	1.10	1.18	1.30	1.18	1.40	1.47
FGOW	0.20	0.29	0.20	0.29	0.20	0.29	0.20	0.29	0.20	0.29	0.30	0.29
FGU	0.60	0.59	0.50	0.59	0.40	0.29	0.40	0.29	0.30	0.29	0.20	0.29
MAMO	0.80	0.88	0.80	0.88	0.90	0.88	1.00	0.88	1.00	0.88	1.10	1.18
MAN1	0.40	0.29	0.40	0.29	0.30	0.29	0.10	0.29	0.20	0.29	0.10	0.00
MAN2	2.20	2.06	1.90	1.77	1.60	1.47	1.20	1.18	0.90	0.88	0.60	0.59
MAO1	1.60	1.47	1.70	1.77	1.80	1.77	1.90	1.77	2.00	2.06	2.10	2.06
MAO2	2.20	2.06	2.30	2.36	2.50	2.36	2.70	2.65	2.80	2.65	3.00	2.95
MAOW	0.30	0.29	0.30	0.29	0.40	0.29	0.40	0.29	0.40	0.29	0.40	0.29
MAU	1.00	0.88	0.90	0.88	0.70	0.59	0.60	0.59	0.40	0.29	0.30	0.29
MBMO	0.50	0.59	0.50	0.59	0.50	0.59	0.60	0.59	0.60	0.59	0.60	0.59
MBN1	0.40	0.29	0.40	0.29	0.30	0.29	0.20	0.29	0.20	0.29	0.10	0.00
MBN2	2.20	2.06	1.90	1.77	1.60	1.47	1.20	1.18	0.90	0.88	0.60	0.59
MBO1	2.00	2.06	2.20	2.06	2.30	2.36	2.50	2.36	2.60	2.65	2.80	2.65
MBO2	3.30	3.24	3.50	3.54	3.80	3.83	4.00	4.13	4.30	4.42	4.50	4.42
MBOW	0.80	0.88	0.80	0.88	0.90	0.88	1.00	0.88	1.00	0.88	1.10	1.18
MBU	1.10	1.18	1.00	0.88	0.80	0.88	0.70	0.59	0.50	0.59	0.30	0.29
MCMO	0.90	0.88	1.00	0.88	1.10	1.18	1.10	1.18	1.20	1.18	1.30	1.18
MCN1	0.40	0.29	0.40	0.29	0.30	0.29	0.20	0.29	0.20	0.29	0.10	0.00
MCN2	1.70	1.77	1.40	1.47	1.20	1.18	1.00	0.88	0.70	0.59	0.50	0.59
MCO1	2.30	2.36	2.50	2.36	2.70	2.65	2.90	2.95	3.00	2.95	3.20	3.24
MCO2	3.40	3.83	3.70	4.42	3.90	4.42	4.20	4.13	4.50	4.42	4.70	4.72
MCOW	0.30	0.29	0.30	0.29	0.40	0.29	0.40	0.29	0.40	0.29	0.40	0.29
MCU	1.10	1.18	1.00	0.88	0.80	0.88	0.70	0.59	0.50	0.59	0.30	0.29
MDMO	0.60	0.59	0.70	0.59	0.70	0.59	0.80	0.88	0.80	0.88	0.90	0.88
MDN1	0.30	0.29	0.30	0.29	0.20	0.29	0.20	0.29	0.10	0.00	0.10	0.00
MDN2	1.90	1.77	1.60	1.47	1.30	1.18	1.10	1.18	0.80	0.88	0.50	0.59
MDO1	1.90	1.77	2.00	2.06	2.10	2.06	2.30	2.36	2.40	2.36	2.60	2.65
MDO2	3.40	3.54	3.70	3.83	3.90	3.83	4.20	4.13	4.50	4.42	4.70	4.72

MDOW	0.60	0.59	0.70	0.59	0.70	0.59	0.80	0.88	0.80	0.88	0.90	0.88
MDU	1.10	1.18	1.00	0.88	0.80	0.88	0.70	0.59	0.50	0.59	0.30	0.29
MEMO	0.80	0.88	0.90	0.88	1.00	0.88	1.00	0.88	1.00	0.88	1.10	1.18
MEN1	0.40	0.29	0.20	0.29	0.30	0.29	0.20	0.29	0.20	0.29	0.10	0.00
MEN2	1.70	1.77	1.40	1.47	1.20	1.18	0.90	0.88	0.70	0.59	0.50	0.59
MEO1	1.80	1.77	1.90	1.77	2.10	2.06	2.20	2.06	2.30	2.36	2.50	2.36
MEO2	3.00	2.95	3.30	3.24	3.50	3.54	3.70	3.83	4.00	4.13	4.20	4.13
MEOW	0.70	0.59	0.70	0.59	0.80	0.88	0.80	0.88	0.80	0.88	1.00	0.88
MEU	1.10	1.18	0.90	0.88	0.80	0.88	0.60	0.59	0.50	0.59	0.30	0.29
MFMO	0.80	0.88	0.90	0.88	1.00	0.88	1.00	0.88	1.10	1.18	1.10	1.18
MFN1	0.30	0.29	0.10	0.29	0.20	0.29	0.20	0.29	0.10	0.00	0.20	0.29
MFN2	1.20	1.18	1.00	0.88	0.90	0.88	0.70	0.59	0.50	0.59	0.30	0.29
MFO1	1.40	1.47	1.50	1.47	1.60	1.47	1.70	1.77	1.80	1.77	1.90	1.77
MFO2	2.20	2.06	2.40	2.36	2.50	2.36	2.70	2.65	2.90	2.95	3.00	2.95
MFOW	0.40	0.29	0.40	0.29	0.50	0.59	0.50	0.59	0.50	0.59	0.60	0.59
MFU	0.60	0.59	0.50	0.59	0.40	0.29	0.30	0.29	0.20	0.29	0.20	0.29
MGMO	0.30	0.29	0.30	0.29	0.30	0.29	0.20	0.29	0.40	0.29	0.40	0.29
MGN1	0.20	0.29	0.10	0.29	0.10	0.29	0.10	0.00	0.10	0.00	0.10	0.00
MGN2	1.00	0.88	0.90	0.88	0.70	0.59	0.60	0.59	0.40	0.29	0.30	0.29
MGO1	1.20	1.18	1.30	1.18	1.40	1.47	1.50	1.47	1.60	1.47	1.70	1.77
MGO2	1.50	1.47	1.60	1.47	1.70	1.77	1.90	1.77	2.00	2.06	2.10	2.06
MGOW	0.30	0.29	0.20	0.29	0.30	0.29	0.30	0.29	0.40	0.29	0.40	0.29
MGU	0.60	0.59	0.50	0.59	0.40	0.29	0.30	0.29	0.20	0.29	0.20	0.29

Obesity spread = NHANES (greater 40+ BMI)

	65%		70%		75%		80%		85%		90%	
	Calculated	Simulated	Calculated	Simulated	Calculated	Simulated	Calculated	Simulated	Calculated	Simulated	Calculated	Simulated
FAMO	1.70	1.77	1.80	1.77	1.90	1.77	2.00	2.06	2.20	2.06	2.30	2.36
FAN1	0.30	0.29	0.20	0.29	0.20	0.29	0.20	0.29	0.10	0.29	0.10	0.29
FAN2	1.00	0.88	0.90	0.88	0.70	0.59	0.60	0.59	0.40	0.29	0.30	0.29
FAO1	0.30	0.29	0.40	0.29	0.40	0.29	0.40	0.29	0.50	0.59	0.50	0.59
FAO2	1.00	0.88	1.00	0.88	1.10	1.18	1.20	1.18	1.30	1.18	1.30	1.18
FAOW	0.30	0.29	0.40	0.29	0.40	0.29	0.40	0.29	0.50	0.59	0.50	0.59
FAU	0.70	0.59	0.60	0.59	0.50	0.59	0.40	0.29	0.30	0.29	0.20	0.29
FBMO	1.70	1.77	1.90	1.77	2.00	2.06	2.20	2.06	2.30	2.36	2.40	2.36
FBN1	0.20	0.29	0.20	0.29	0.20	0.29	0.10	0.29	0.10	0.29	0.10	0.29
FBN2	1.20	1.18	1.10	1.18	0.90	0.88	0.70	0.59	0.50	0.59	0.40	0.29
FBO1	0.60	0.59	0.70	0.59	0.70	0.59	0.80	0.88	0.80	0.88	0.80	0.88
FBO2	1.00	0.88	1.00	0.88	1.10	1.18	1.20	1.18	1.30	1.18	1.30	1.18
FBOW	0.50	0.59	0.60	0.59	0.60	0.59	0.60	0.59	0.70	0.59	0.70	0.59
FBU	0.60	0.59	0.60	0.59	0.50	0.59	0.40	0.29	0.30	0.29	0.20	0.29
FCMO	0.80	0.88	0.80	0.88	0.90	0.88	1.00	0.88	1.00	0.88	1.10	1.18
FCN1	0.20	0.29	0.10	0.29	0.20	0.29	0.10	0.29	0.10	0.29	0.10	0.29

FCN2	1.40	1.47	1.20	1.18	1.00	0.88	0.80	0.88	0.60	0.59	0.40	0.29
FCO1	1.30	1.18	1.40	1.47	1.50	1.47	1.60	1.47	1.70	1.77	1.80	1.77
FCO2	1.80	1.77	2.00	2.06	2.10	2.06	2.30	2.36	2.40	2.36	2.50	2.36
FCOW	0.30	0.29	0.30	0.29	0.30	0.29	0.30	0.29	0.30	0.29	0.40	0.29
FCU	0.90	0.88	0.80	0.88	0.60	0.59	0.50	0.59	0.40	0.29	0.30	0.29
FDMO	1.70	1.77	1.90	1.77	2.00	2.06	2.20	2.06	2.30	2.36	2.40	2.36
FDN1	0.20	0.29	0.20	0.29	0.10	0.29	0.10	0.29	0.10	0.29	0.10	0.00
FDN2	1.10	1.18	0.90	0.88	0.80	0.88	0.60	0.59	0.50	0.59	0.30	0.29
FDO1	0.60	0.59	0.70	0.59	0.70	0.59	0.80	0.88	0.80	0.88	0.80	0.88
FDO2	1.30	1.18	1.40	1.47	1.50	1.47	1.50	1.47	1.70	1.77	1.80	1.77
FDOW	0.50	0.59	0.60	0.59	0.60	0.59	0.60	0.59	0.70	0.59	0.70	0.59
FDU	0.80	0.88	0.70	0.59	0.60	0.59	0.50	0.59	0.40	0.29	0.20	0.29
FEMO	2.10	2.06	2.30	2.36	2.40	2.36	2.60	2.65	2.80	2.65	2.90	2.95
FEN1	0.40	0.29	0.20	0.29	0.30	0.29	0.20	0.29	0.20	0.29	0.10	0.00
FEN2	1.10	1.18	1.00	0.88	0.80	0.88	0.60	0.59	0.50	0.59	0.30	0.29
FEO1	0.60	0.59	0.60	0.59	0.60	0.59	0.70	0.59	0.70	0.59	0.80	0.88
FEO2	1.20	1.18	1.30	1.18	1.40	1.47	1.50	1.47	1.60	1.47	1.70	1.77
FEOW	0.60	0.59	0.70	0.59	0.70	0.59	0.80	0.88	0.80	0.88	0.90	0.88
FEU	0.80	0.88	0.70	0.59	0.60	0.59	0.50	0.59	0.30	0.29	0.20	0.29
FFMO	1.70	1.77	1.80	1.77	1.90	1.77	2.00	2.06	2.20	2.06	2.30	2.36
FFN1	0.10	0.29	0.10	0.29	0.10	0.29	0.10	0.29	0.10	0.29	0.00	0.00
FFN2	0.90	0.88	0.80	0.88	0.70	0.59	0.50	0.59	0.40	0.29	0.30	0.29
FFO1	0.50	0.59	0.50	0.59	0.50	0.59	0.60	0.59	0.60	0.59	0.60	0.59
FFO2	1.00	0.88	1.10	1.18	1.20	1.18	1.20	1.18	1.30	1.18	1.40	1.47
FFOW	0.50	0.59	0.50	0.59	0.50	0.59	0.60	0.59	0.60	0.59	0.60	0.59
FFU	0.70	0.59	0.60	0.59	0.50	0.59	0.40	0.29	0.30	0.29	0.20	0.29
FGMO	1.00	0.88	1.10	1.18	1.20	1.18	1.20	1.18	1.30	1.18	1.40	1.47
FGN1	0.10	0.29	0.10	0.29	0.10	0.29	0.10	0.29	0.10	0.00	0.00	0.00
FGN2	0.70	0.59	0.60	0.59	0.50	0.59	0.40	0.29	0.30	0.29	0.20	0.29
FGO1	0.40	0.29	0.40	0.29	0.40	0.29	0.50	0.59	0.50	0.59	0.50	0.59
FGO2	0.60	0.59	0.60	0.59	0.60	0.59	0.70	0.59	0.70	0.59	0.80	0.88
FGOW	0.20	0.29	0.10	0.29	0.20	0.29	0.20	0.29	0.20	0.29	0.30	0.29
FGU	0.60	0.59	0.50	0.59	0.40	0.29	0.40	0.29	0.30	0.29	0.20	0.29
MAMO	2.20	2.06	2.30	2.36	2.50	2.36	2.70	2.65	2.80	2.65	3.00	2.95
MAN1	0.40	0.29	0.40	0.29	0.30	0.29	0.20	0.29	0.20	0.29	0.10	0.00
MAN2	2.20	2.06	1.90	1.77	1.60	1.47	1.20	1.18	0.90	0.88	0.60	0.59
MAO1	0.80	0.88	0.80	0.88	0.90	0.88	1.00	0.88	1.00	0.88	1.10	1.18
MAO2	1.60	1.47	1.70	1.77	1.80	1.77	1.90	1.77	2.00	2.06	2.10	2.06
MAOW	0.30	0.29	0.30	0.29	0.40	0.29	0.40	0.29	0.40	0.29	0.40	0.29
MAU	1.00	0.88	0.90	0.88	0.70	0.59	0.60	0.59	0.40	0.29	0.30	0.29
MBMO	3.30	3.24	3.50	3.54	3.80	3.83	4.00	4.13	4.30	4.42	4.50	4.42
MBN1	0.40	0.29	0.40	0.29	0.30	0.29	0.20	0.29	0.20	0.29	0.20	0.29
MBN2	2.20	2.06	1.90	1.77	1.60	1.47	1.20	1.18	0.90	0.88	0.60	0.59
MBO1	0.50	0.59	0.50	0.59	0.50	0.59	0.60	0.59	0.60	0.59	0.60	0.59
MBO2	2.00	2.06	2.20	2.06	2.30	2.36	2.50	2.36	2.60	2.65	2.80	2.65
MBOW	0.80	0.88	0.80	0.88	0.90	0.88	1.00	0.88	1.00	0.88	1.10	1.18
MBU	1.10	1.18	1.00	0.88	0.80	0.88	0.70	0.59	0.50	0.59	0.30	0.29

MCMO	3.40	3.83	3.70	4.42	3.90	4.42	4.20	4.13	4.50	4.42	4.70	4.72
MCN1	0.40	0.29	0.40	0.29	0.30	0.29	0.20	0.29	0.20	0.29	0.10	0.00
MCN2	1.70	1.77	1.40	1.47	1.20	1.18	1.00	0.88	0.70	0.59	0.50	0.59
MCO1	0.90	0.88	1.00	0.88	1.10	1.18	1.10	1.18	1.20	1.18	1.30	1.18
MCO2	2.30	2.36	2.50	2.36	2.70	2.65	2.90	2.95	3.00	2.95	3.20	3.24
MCOW	0.30	0.29	0.30	0.29	0.40	0.29	0.40	0.29	0.40	0.29	0.40	0.29
MCU	1.10	1.18	1.00	0.88	0.80	0.88	0.70	0.59	0.50	0.59	0.30	0.29
MDMO	3.40	3.54	3.70	3.83	3.90	3.83	4.20	4.13	4.50	4.42	4.70	4.72
MDN1	0.30	0.29	0.20	0.29	0.20	0.29	0.20	0.29	0.10	0.00	0.10	0.00
MDN2	1.90	1.77	1.60	1.47	1.30	1.18	1.10	1.18	0.80	0.88	0.50	0.59
MDO1	0.60	0.59	0.70	0.59	0.70	0.59	0.80	0.88	0.80	0.88	0.90	0.88
MDO2	1.90	1.77	2.00	2.06	2.10	2.06	2.30	2.36	2.40	2.36	2.60	2.65
MDOW	0.60	0.59	0.70	0.59	0.70	0.59	0.80	0.88	0.80	0.88	0.90	0.88
MDU	1.10	1.18	1.00	0.88	0.80	0.88	0.70	0.59	0.50	0.59	0.30	0.29
MEMO	3.00	2.95	3.30	3.24	3.50	3.54	3.70	3.83	4.00	4.13	4.20	4.13
MEN1	0.40	0.29	0.30	0.29	0.30	0.29	0.20	0.29	0.20	0.29	0.10	0.00
MEN2	1.70	1.77	1.40	1.47	1.20	1.18	0.90	0.88	0.70	0.59	0.50	0.59
MEO1	0.80	0.88	0.90	0.88	1.00	0.88	1.00	0.88	1.00	0.88	1.10	1.18
MEO2	1.80	1.77	1.90	1.77	2.10	2.06	2.20	2.06	2.30	2.36	2.50	2.36
MEOW	0.70	0.59	0.70	0.59	0.80	0.88	0.80	0.88	0.80	0.88	1.00	0.88
MEU	1.10	1.18	0.90	0.88	0.80	0.88	0.60	0.59	0.50	0.59	0.30	0.29
MFMO	2.20	2.06	2.40	2.36	2.50	2.36	2.70	2.65	2.90	2.95	3.00	2.95
MFN1	0.30	0.29	0.10	0.29	0.20	0.29	0.20	0.29	0.10	0.00	0.10	0.00
MFN2	1.20	1.18	1.00	0.88	0.90	0.88	0.60	0.59	0.50	0.59	0.30	0.29
MFO1	0.80	0.88	0.90	0.88	1.00	0.88	1.00	0.88	1.10	1.18	1.10	1.18
MFO2	1.40	1.47	1.50	1.47	1.60	1.47	1.70	1.77	1.80	1.77	1.90	1.77
MFOW	0.40	0.29	0.40	0.29	0.60	0.59	0.50	0.59	0.50	0.59	0.60	0.59
MFU	0.60	0.59	0.50	0.59	0.40	0.29	0.30	0.29	0.20	0.29	0.20	0.29
MGMO	1.50	1.47	1.60	1.47	1.70	1.77	1.90	1.77	2.00	2.06	2.10	2.06
MGN1	0.20	0.29	0.20	0.29	0.10	0.29	0.10	0.00	0.10	0.00	0.10	0.00
MGN2	1.00	0.88	0.90	0.88	0.70	0.59	0.60	0.59	0.40	0.29	0.30	0.29
MGO1	0.30	0.29	0.30	0.29	0.30	0.29	0.30	0.29	0.40	0.29	0.40	0.29
MGO2	1.20	1.18	1.30	1.18	1.40	1.47	1.50	1.47	1.60	1.47	1.70	1.77
MGOW	0.30	0.29	0.20	0.29	0.30	0.29	0.30	0.29	0.40	0.29	0.40	0.29
MGU	0.60	0.59	0.50	0.59	0.40	0.29	0.20	0.29	0.20	0.29	0.20	0.29

Appendix 7: Example of Pathfinder Results Summary Output File

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***SUMMARY***SUMMARY***SUMMARY***SUMMARY***SUMMARY***
Simulation:      A320 FAA1
Version:         2017.2.0301
Mode:            Steering (Flow-limited)
Total Occupants:    180

Completion Times for All Occupants (s):
  Min:          5.9     "00162"
  Max:          76.4    "00134"
  Average:       37.6
  StdDev:       19.1

Completion Times by Behavior (s):
     Behavior         Count      Min        Min_Name            Max       Max_Name           Avg        StdDev
       BehvAF           53       5.9        "00162"    76.4     "00134"   41.6         21.2
       BehvFW           36       6.0        "00125"    54.7     "00096"   28.6         13.7
       BehvMD           63       11.2       "00013"    70.5     "00063"   38.7         16.5
  Goto Any Exit         28       6.5        "00020"    70.5     "00181"   39.4         22.1
*all behaviors*        180       5.9        "00162"    76.4     "00134"   37.6         19.1

Completion Times by Profile (s):
     Profile Count       Min        Min_Name            Max       Max_Name           Avg        StdDev
       FAMO              1       9.8        "00126"    9.8      "00126"    9.8         0.0
       FAN2   2        6.5       "00022"    54.9      "00049"   30.7         24.2
       FAO1   1        59.7      "00142"    59.7      "00142"   59.7          0.0
       FAOW              3       14.9       "00166"    35.4     "00094"   26.4         8.6
        FAU   2        17.4      "00028"    52.1      "00177"   34.7         17.3
       FBMO              1       64.3       "00074"    64.3     "00074"   64.3         0.0
       FBN1   1        19.0      "00079"    19.0      "00079"   19.0          0.0
       FBN2   3        31.5      "00042"    50.2      "00048"   38.2          8.5
       FBO1   1        36.7      "00073"    36.7      "00073"   36.7          0.0
       FBO2   1        57.2      "00148"    57.2      "00148"   57.2          0.0
       FBOW              3       26.8       "00012"    53.3     "00056"   36.7         11.8
        FBU   1        39.3      "00009"    39.3      "00009"   39.3          0.0
       FCN1   1        58.5      "00146"    58.5      "00146"   58.5          0.0
       FCN2   3        23.9      "00115"    28.3      "00038"   25.8          1.9
       FCO1   3        15.8      "00027"    54.9      "00083"   39.8         17.1
       FCO2   2        13.6      "00165"    28.3      "00071"   21.0          7.4
       FCOW              1       70.5       "00063"    70.5     "00063"   70.5         0.0
        FCU   2        61.1      "00060"    73.8      "00144"   67.5          6.4
       FDMO              1       7.2        "00121"    7.2      "00121"    7.2         0.0
       FDN2   2        36.2      "00080"    59.6      "00084"   47.9         11.7
       FDO1              2       62.7       "00064"    66.2     "00136"   64.4         1.7
       FDO2              1       61.0       "00145"    61.0     "00145"   61.0         0.0
       FDOW              3       9.6        "00019"    26.4     "00127"   19.9         7.4
        FDU   3         9.7      "00160"    65.8      "00069"   36.6         23.0
       FEMO              1       40.8       "00066"    40.8     "00066"   40.8         0.0
       FEN1   1        50.8      "00176"    50.8      "00176"   50.8          0.0
       FEN2   3         6.5      "00020"    62.3      "00133"   31.3         23.2
       FEO1   2        37.7      "00010"    50.8      "00003"   44.3          6.5
       FEO2   1        11.2      "00024"    11.2      "00024"   11.2          0.0
       FEOW              3       17.4       "00018"    40.8     "00045"   32.1         10.4
        FEU   3        41.8      "00173"    67.4      "00065"   52.4         10.9
       FFMO              1       58.0       "00058"    58.0     "00058"   58.0         0.0
       FFN2   2        11.1      "00122"    49.5      "00103"   30.3         19.2
       FFO1   1        48.3      "00093"    48.3      "00093"   48.3          0.0
       FFO2   1        20.1      "00116"    20.1      "00116"   20.1          0.0
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     FFOW          3     20.5     "00017"  22.6     "00157"  21.5      0.8
      FFU   1     7.2      "00163"   7.2      "00163"   7.2       0.0
     FGN2          2     44.4     "00101"  48.6     "00057"  46.5      2.1
     FGO1          1     69.0     "00075"  69.0     "00075"  69.0      0.0
     FGO2          1     27.7     "00098"  27.7     "00098"  27.7      0.0
     FGOW          1     65.8     "00076"  65.8     "00076"  65.8      0.0
      FGU   1     12.7     "00025"   12.7     "00025"   12.7      0.0
     MAN1          1     21.3     "00131"  21.3     "00131"  21.3      0.0
     MAN2          5      8.5     "00161"  41.8     "00107"  27.7     10.8
     MAO1          2     30.3     "00153"  50.2     "00002"  40.2     10.0
     MAO2          1     23.7     "00036"  23.7     "00036"  23.7      0.0
     MAOW          3     25.1     "00156"  68.7     "00128"  46.5     17.8
      MAU          2     32.8     "00172"  53.4     "00089"  43.1     10.3
     MBMO          1     11.0     "00164"  11.0     "00164"  11.0      0.0
     MBN1          1     23.7     "00061"  23.7     "00061"  23.7      0.0
     MBN2          5     12.4     "00118"  71.3     "00180"  51.4     22.7
     MBO1          3     53.3     "00087"  54.7     "00096"  53.8      0.6
     MBO2          1      8.5     "00124"   8.5     "00124"   8.5      0.0
     MBOW          5     12.3     "00169"  45.7     "00104"  32.4     10.9
      MBU          3      5.9     "00162"  46.9     "00138"  23.4     17.3
     MCN1          1     16.2     "00119"  16.2     "00119"  16.2      0.0
     MCN2          4      9.6     "00034"  47.1     "00005"  30.2     14.0
     MCO1          5     33.0     "00040"  76.4     "00134"  46.4     15.5
     MCO2          1      8.0     "00021"   8.0     "00021"   8.0      0.0
     MCOW          5     14.9     "00117"  59.6     "00044"  44.7     15.8
      MCU          3     22.1     "00041"  56.0     "00001"  40.8     14.1
     MDMO          1     22.1     "00014"  22.1     "00014"  22.1      0.0
     MDN1          1     22.6     "00113"  22.6     "00113"  22.6      0.0
     MDN2          4     14.3     "00030"  70.5     "00181"  42.1     21.2
     MDO1          3     13.6     "00123"  72.6     "00130"  51.2     26.7
     MDO2          1     42.4     "00004"  42.4     "00004"  42.4      0.0
     MDOW          5     11.2     "00013"  67.4     "00077"  43.3     23.5
      MDU          3     12.7     "00033"  75.1     "00135"  39.4     26.3
     MEMO          1     43.1     "00099"  43.1     "00099"  43.1      0.0
     MEN1          1     20.5     "00032"  20.5     "00032"  20.5      0.0
     MEN2          4     18.8     "00112"  47.0     "00088"  33.7     10.6
     MEO1          3     15.8     "00029"  25.2     "00110"  20.0      3.9
     MEO2          1     42.4     "00046"  42.4     "00046"  42.4      0.0
     MEOW          5     14.3     "00026"  64.9     "00143"  37.7     20.2
      MEU   3     6.0      "00125"   36.2     "00072"   25.0      13.5
     MFMO          1     55.9     "00151"  55.9     "00151"  55.9      0.0
     MFN1          1     69.0     "00070"  69.0     "00070"  69.0      0.0
     MFN2          3     17.4     "00159"  61.1     "00059"  40.8     18.0
     MFO1          2     16.2     "00158"  43.1     "00175"  29.6     13.5
     MFO2          1     39.2     "00154"  39.2     "00154"  39.2      0.0
     MFOW          3     26.8     "00031"  44.0     "00047"  36.2      7.1
      MFU   1     51.8     "00055"   51.8     "00055"   51.8      0.0
     MGN2          2     40.6     "00100"  49.5     "00179"  45.0      4.5
     MGO1          2     54.6     "00137"  63.6     "00139"  59.1      4.5
     MGOW          2     34.6     "00067"  51.8     "00090"  43.2      8.6
      MGU          1      8.0     "00023"   8.0     "00023"   8.0      0.0
*all profiles*   180      5.9     "00162"  76.4     "00134"  37.6     19.1

Travel Distances for All Occupants (m):
  Min:        1.2    "00020"
  Max:       19.1    "00134"
  Average:     8.0
  StdDev:     3.7

Movement Distance by Behavior (m):
    Behavior        Count    Min       Min_Name          Max      Max_Name          Avg        StdDev
      BehvAF         53      3.4      "00163"  19.1     "00134"  9.7        3.5
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      BehvFW         36      3.2        "00125"   13.5       "00102"   6.8          2.5
      BehvMD         63      2.5        "00030"   15.0       "00065"   6.4          2.7
 Goto Any Exit       28      1.2        "00020"   16.9       "00075"   9.5          4.9
*all behaviors*     180      1.2        "00020"   19.1       "00134"   8.0          3.7

Movement Distance by Profile (m):
    Profile Count   Min      Min_Name             Max        Max_Name              Avg       StdDev
      FAMO            1       4.3       "00126"   4.3        "00126"   4.3          0.0
      FAN2    2     1.3       "00022"   9.2       "00049"    5.3         3.9
      FAO1    1    12.5       "00142"   12.5      "00142"    12.5        0.0
      FAOW            3       5.7       "00166"   9.2        "00114"   7.3          1.4
       FAU    2     3.7       "00028"   10.6      "00177"    7.1         3.5
      FBMO            1      12.2       "00074"   12.2       "00074"   12.2         0.0
      FBN1    1     3.9       "00079"   3.9       "00079"    3.9         0.0
      FBN2    3     5.5       "00042"   7.8       "00048"    6.4         1.0
      FBO1    1    13.1       "00073"   13.1      "00073"    13.1        0.0
      FBO2    1    12.0       "00148"   12.0      "00148"    12.0        0.0
      FBOW            3       3.9       "00012"   7.5        "00056"   5.7          1.5
       FBU    1     6.1       "00009"   6.1       "00009"    6.1         0.0
      FCN1    1    11.8       "00146"   11.8      "00146"    11.8        0.0
      FCN2    3     4.5       "00015"   6.4       "00115"    5.2         0.8
      FCO1    3     3.6       "00027"   6.4       "00086"    5.1         1.2
      FCO2    2     5.1       "00165"   9.4       "00071"    7.2         2.1
      FCOW            1      13.7       "00063"   13.7       "00063"   13.7         0.0
       FCU    2     9.7       "00060"   14.0      "00144"    11.9        2.1
      FDMO            1       3.5       "00121"   3.5        "00121"   3.5          0.0
      FDN2    2     7.4       "00080"   8.0       "00084"    7.7         0.3
      FDO1            2       9.6       "00064"   14.2       "00136"   11.9         2.3
      FDO2            1      12.1       "00145"   12.1       "00145"   12.1         0.0
      FDOW            3       2.3       "00019"   12.2       "00127"   7.3          4.0
       FDU    3     4.9       "00160"   16.3      "00069"    10.0        4.7
      FEMO            1      10.7       "00066"   10.7       "00066"   10.7         0.0
      FEN1    1     8.9       "00176"   8.9       "00176"    8.9         0.0
      FEN2    3     1.2       "00020"   13.0      "00133"    6.1         5.1
      FEO1    2     8.4       "00010"   8.6       "00003"    8.5         0.1
      FEO2    1     2.6       "00024"   2.6       "00024"    2.6         0.0
      FEOW            3       3.2       "00018"   9.1        "00152"   6.3          2.4
       FEU    3     9.4       "00173"   15.0      "00065"    11.4        2.5
      FFMO            1       7.7       "00058"   7.7        "00058"   7.7          0.0
      FFN2    2     3.8       "00122"   8.8       "00103"    6.3         2.5
      FFO1    1    11.4       "00093"   11.4      "00093"    11.4        0.0
      FFO2    1     4.7       "00116"   4.7       "00116"    4.7         0.0
      FFOW            3       3.7       "00017"   6.6        "00157"   5.3          1.2
       FFU    1     3.4       "00163"   3.4       "00163"    3.4         0.0
      FGN2            2       7.4       "00057"   9.3        "00101"   8.3          0.9
      FGO1            1      16.9       "00075"   16.9       "00075"   16.9         0.0
      FGO2            1       5.9       "00098"   5.9        "00098"   5.9          0.0
      FGOW            1      15.5       "00076"   15.5       "00076"   15.5         0.0
       FGU    1     2.6       "00025"   2.6       "00025"    2.6         0.0
      MAN1            1      12.1       "00131"   12.1       "00131"   12.1         0.0
      MAN2            5       4.5       "00161"   13.0       "00078"   8.5          3.0
      MAO1            2       7.0       "00153"   7.8        "00002"   7.4          0.4
      MAO2            1       5.4       "00036"   5.4        "00036"   5.4          0.0
      MAOW            3       5.7       "00156"   14.5       "00128"   10.2         3.6
       MAU            2       8.2       "00172"   10.9       "00089"   9.5          1.4
      MBMO            1       4.5       "00164"   4.5        "00164"   4.5          0.0
      MBN1            1       9.2       "00061"   9.2        "00061"   9.2          0.0
      MBN2            5       4.6       "00118"   18.3       "00180"   10.8         4.5
      MBO1            3       8.6       "00087"   11.2       "00096"   10.1         1.1
      MBO2            1       3.2       "00124"   3.2        "00124"   3.2          0.0
      MBOW            5       5.1       "00082"   12.6       "00068"   7.7          2.6
       MBU            3       3.6       "00162"   10.8       "00138"   6.5          3.1
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     MCN1          1      4.8       "00119"   4.8      "00119"   4.8       0.0
     MCN2          4      2.8       "00034"   6.9      "00051"   5.7       1.6
     MCO1          5      5.5       "00040"   19.1     "00134"   9.8       4.8
     MCO2          1      1.7       "00021"   1.7      "00021"   1.7       0.0
     MCOW          5      4.6       "00117"   9.8      "00044"   7.4       1.8
      MCU          3      3.9       "00041"   13.3     "00001"   9.1       3.9
     MDMO          1      3.7       "00014"   3.7      "00014"   3.7       0.0
     MDN1          1      6.4       "00113"   6.4      "00113"   6.4       0.0
     MDN2          4      2.5       "00030"   14.6     "00181"   9.2       5.0
     MDO1          3      4.4       "00123"   12.6     "00129"   9.7       3.8
     MDO2          1      5.9       "00004"   5.9      "00004"   5.9       0.0
     MDOW          5      2.9       "00013"   13.3     "00077"   9.7       3.6
      MDU          3      2.9       "00033"   14.0     "00135"   8.3       4.5
     MEMO          1      10.2      "00099"   10.2     "00099"   10.2      0.0
     MEN1          1      3.5       "00032"   3.5      "00032"   3.5       0.0
     MEN2          4      4.9       "00112"   9.0      "00088"   6.2       1.6
     MEO1          3      2.9       "00029"   5.6      "00110"   4.1       1.1
     MEO2          1      5.8       "00046"   5.8      "00046"   5.8       0.0
     MEOW          5      3.2       "00026"   12.4     "00143"   8.1       3.3
      MEU   3     3.2       "00125"   10.1      "00072"   6.6       2.8
     MFMO          1      11.6      "00151"   11.6     "00151"   11.6      0.0
     MFN1          1      15.3      "00070"   15.3     "00070"   15.3      0.0
     MFN2          3      5.6       "00159"   9.1      "00059"   7.2       1.4
     MFO1          2      5.3       "00158"   8.9      "00175"   7.1       1.8
     MFO2          1      9.3       "00154"   9.3      "00154"   9.3       0.0
     MFOW          3      5.6       "00031"   7.1      "00095"   6.2       0.6
      MFU   1     10.0      "00055"   10.0      "00055"   10.0      0.0
     MGN2          2      7.7       "00100"   11.2     "00179"   9.4       1.7
     MGO1          2      10.2      "00139"   10.8     "00137"   10.5      0.3
     MGOW          2      9.5       "00067"   9.8      "00090"   9.6       0.2
      MGU          1      1.9       "00023"   1.9      "00023"   1.9       0.0
*all profiles*     180    1.2       "00020"   19.1     "00134"   8.0       3.7

[Components] All:   9
[Components] Doors: 8
Triangles:      343
Startup Time:     2.1s
CPU Time:       12.7s

Door Flow Rates:
Door       First_In    Last_Out   Total_Use   Flow_Avg
              (s)         (s)       (pers)     (pers/s)
 R1          0.0         0.0         0
 L1          6.0         56.0        40         0.80
 R4          0.0         0.0         0
 L4          5.9         76.4        56         0.79
 L2          6.5         70.5        42         0.66
 L3          6.5         70.5        42         0.66
 R2          0.0         0.0         0
 R3          0.0         0.0         0

Room Usage:
 Room      First_In    Last_Out   Total_Use
              (s)         (s)       (pers)
Room00       0.0         76.4        180
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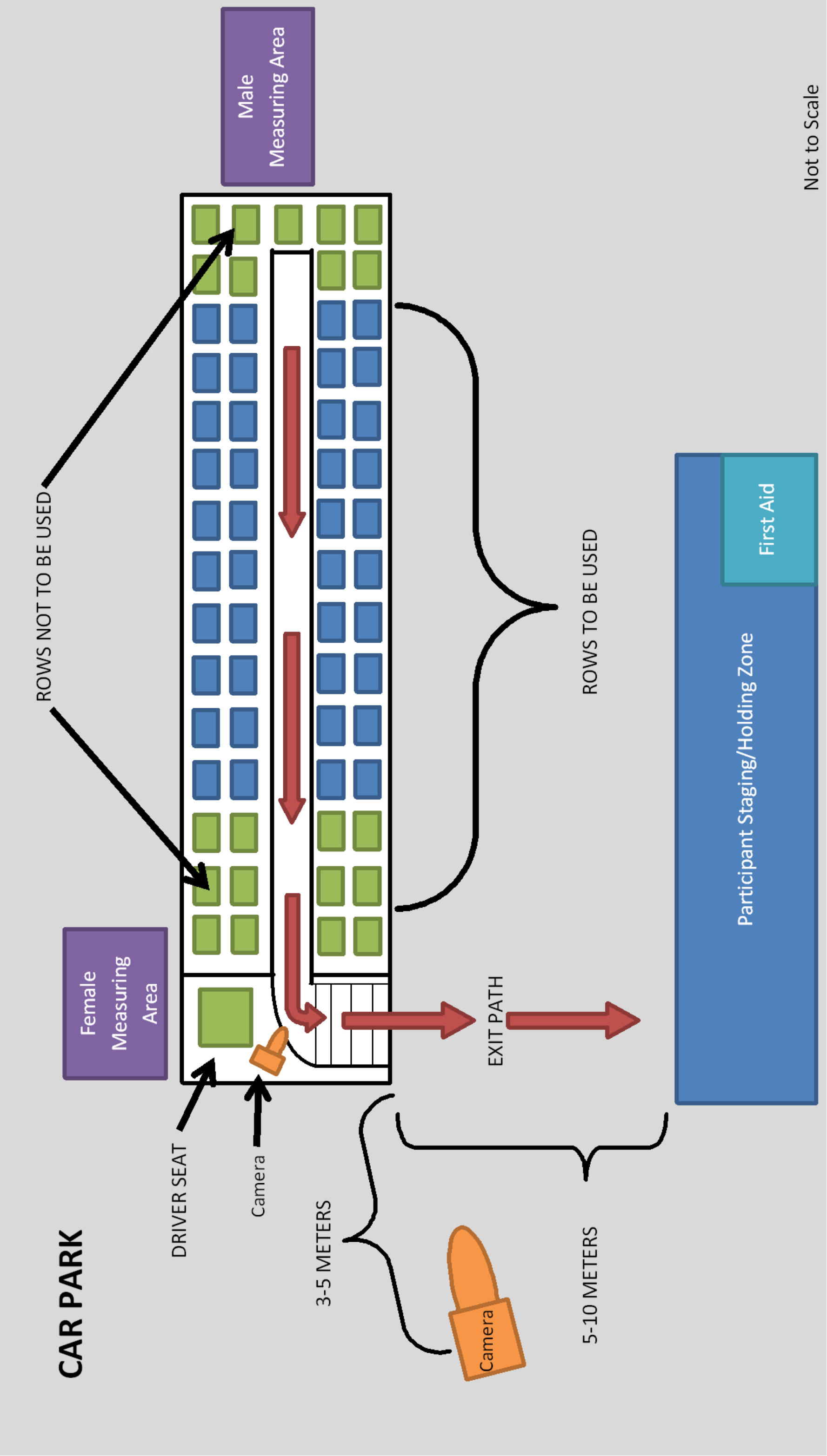
Appendix 8: A320 Simulation Results for Each Scenario

A320		Obesity Spread = NHANES (greater 25–30 BMI)						Obesity Spread = NHANES (greater 30–40 BMI)						Obesity Spread = NHANES (greater 40+ BMI)					
Simulation	Control 55%	FAA+65%	FAA+70%	FAA+75%	FAA+80%	FAA+85%	FAA+90%	FAA+65%	FAA+70%	FAA+75%	FAA+80%	FAA+85%	FAA+90%	FAA+65%	FAA+70%	FAA+75%	FAA+80%	FAA+85%	FAA+90%
1	76.6	78.5	76.3	77.6	77.1	77.6	79.9	80.4	77.3	85.8	89.4	89.3	85.9	90.6	93	90.4	97	97	91.8
2	76.3	77.6	77.6	78.9	77.5	77.8	76.5	77.8	78.9	82.9	89.2	85.4	85.4	90.5	93	94.5	94.4	93.1	95.7
3	78.9	76.8	77.8	76.3	77.7	77.6	76.3	78.2	77.7	85.4	84.1	89.3	86.7	91.6	96.9	93.1	93.1	102.1	91.8
4	79	75.3	77.7	76.4	77.7	79.1	77.8	77.7	80.4	84.1	89.3	86.7	89.8	93.1	94.3	91.7	92.1	99.5	95.7
5	77.7	75.1	77.6	78.9	78.9	77.8	77.8	76.5	77.6	85.5	89.1	89.2	91.9	93	95.9	94.5	91.7	101.1	101.3
6	75.3	75	77.6	77.6	80.1	77.8	77.8	79	77.5	84.2	89.2	88	86.8	91.8	94.4	91.9	101.1	91.9	97
7	76.4	75.1	77.6	78.9	76.4	76.4	80.3	79.1	82.7	86.8	84.1	89.3	90.6	89.3	89.3	91.5	97.3	90.5	93.1
8	77.6	76.2	77.6	77.6	76.5	78.8	79	79.3	79.1	86.7	89.2	85.4	89.3	90.6	93.1	91.7	93	91.9	91.6
9	78.9	77.6	77.6	76.5	77.6	77.6	79.1	77.8	79.1	85.5	89.3	89.1	86.7	97.1	89.3	98.2	96.5	94.5	91.8
10	76.4	73.8	77.6	76.3	76.4	77.6	77.5	78.4	80.2	87.5	84	89.3	88	91.7	94.3	91.9	91.8	93.1	91.8
11	77.8	76.4	77.6	76.5	76.6	77.7	79.1	78.9	79	85.6	89.3	89.3	88	93	95.6	91.7	94.3	91.9	94.7
12	76.4	76.5	77.6	77.7	77.7	77.6	79.1	77.8	79	86.9	89.2	86.7	87.9	94.1	95.7	91.9	91.7	94.5	98.4
13	75	76.5	77.6	78.8	77.7	78.8	77.7	78.9	78.9	85.4	89.2	89.2	88.1	93.2	94.3	93.2	91.8	94.1	99.5
14	72.2	77.8	77.6	77.8	77.7	80.2	76.5	77.6	78.9	84.4	84.1	89.3	90.5	99.4	94.3	93	95.7	93.5	95.7
15	77.7	76.4	77.4	77.7	77.7	80.3	77.8	77.6	78.9	82	89.3	89.4	90.6	94.4	91.8	95.6	93.1	93.2	96.9
16	76.5	76.3	77.6	78	78.9	76.4	79.4	77.8	80.1	83.1	84.3	87.9	91.9	90.6	87.8	93	94.4	100.4	91.8
17	77.6	77.7	77.7	76.6	79	79.1	79	77.8	79.1	85.5	89.3	89.3	94.4	97	93	91.7	90.6	93.1	90.9
18	75.1	76.5	77.6	77.7	77.7	77.7	77.8	76.5	78.9	84.3	89.3	89.1	91.8	91.9	94.3	94.3	90.5	95.7	93.3
19	76.5	76.5	77.6	77.8	77.8	79	79.1	80.1	79.1	85.6	89.2	89.3	90.6	90.6	95.7	91.7	99.5	94.9	99.9
20	77.6	75.1	77.5	77.8	76.4	77.6	77.8	78.7	79	84	89.2	89.6	91.5	89.3	91.7	93.1	93.1	91.9	98.2
21	76.7	76.4	75	76.5	76.6	77.9	76.5	77.6	77.7	83	89.3	86.8	88.9	89.3	88.1	93.2	96.3	100.4	100.6
22	76.4	73.9	76.4	79	76.5	75.3	75.2	77.6	77.6	84.5	84.2	88	97	89.2	87.9	93.2	99.4	98.7	90.6
23	76.3	75.2	76.4	77.6	77.6	76.4	77.7	78.9	81.9	82.9	86.8	86.6	88.1	89.2	88.1	93.2	99.5	90.7	89.3
24	76.3	77.6	76.5	76.4	77.7	76.5	76.4	78.9	78.2	82.9	86.8	86.7	88.1	89.3	87.9	91.9	95.4	98.3	90.6
25	76.4	77.7	76.3	76.3	76.4	76.4	77.8	79.1	80.2	85.3	89.2	86.8	89.1	89.3	87.9	93.1	95.7	90.9	93
26	76.7	75.1	76.4	76.5	76.5	75.2	75.2	79.2	79.1	85.5	89.3	86.5	86.9	89.2	88	91.8	95.8	91.8	92
27	76.3	76.5	76.3	76.4	76.5	75.2	76.5	77.9	80.3	82.9	89.2	85.4	90.4	89.3	94.3	91.9	94.5	91.5	94.5
28	76.4	76.3	76.5	76.5	75.1	75.2	75.2	77.9	79	82.9	86.8	89.3	90.4	89.1	92.9	91.7	97	93.1	95.7
29	76.4	77.7	77.7	75.2	77.3	76.4	76.5	80.4	78.8	84.1	84.2	89.2	86.5	89.2	90.5	91.7	95.7	93.1	95.7
30	76.5	78.9	79	77.2	75.2	75.2	76.5	77.9	80.2	82.8	84.2	89.2	89.3	89.2	95.5	91.8	95.5	91.9	97
31	76.4	77.9	76.3	75	77.8	76.5	77.5	80.4	77.7	84.1	84.1	86.8	90.5	89.2	89.2	94.8	90.5	93.2	93.1
32	76.4	79.2	77.6	79	76.3	77.6	76.5	76.4	80.1	84	84.2	86.6	85.6	89.2	89.2	91.8	91.8	93.1	93.6
33	76.6	76.6	76.4	76.3	77.8	75.4	76.5	77.6	78.6	85.3	84.1	86.8	88.5	91.9	90.4	93	91.7	94.5	94.3
34	76.5	76.6	76.4	76.4	76.3	77.8	75.2	77.9	79	85.3	84.4	86.7	91	91.5	95.5	93.2	90.5	93	93.3
35	76.5	76.5	77.6	77.7	79	76.3	76.5	77.8	78.9	82.8	83.9	89.4	92.5	93	91.8	89.2	93.1	98.3	93.1
36	76.4	76.6	77.8	77.6	75	77.9	75.2	79.1	83.1	82.8	84.1	86.8	86.7	93.2	90.5	93.1	91.9	94.4	103.4
37	76.4	79	79	76.5	75.1	77.8	75.2	77.6	81.2	82.7	84.1	86.8	91.7	91.7	91.7	91.7	93.1	97.1	94.5
38	76.3	75.2	75.1	77.7	76.4	77.8	76.5	80.3	81.5	84.2	84.4	88.1	89.4	90.6	96.9	93.1	91.8	95.7	97
39	76.4	77.6	76.3	75.1	77.7	77.8	76.4	77.7	89.2	85.6	84.2	88.1	86.8	95.3	85.4	93.3	91.8	93.1	98.2
40	76.4	77.8	77.6	75.1	76.5	76.5	76.5	78.9	83.5	85.7	84.2	87.9	86.7	91.8	85.4	91.8	91.9	91.9	94.4

Appendix 9: A330 Simulation Results for Each Scenario

A330-200		Obesity spread = NHANES (greater 25–30 BMI)						Obesity Spread = NHANES (greater 30–40 BMI)						Obesity Spread = NHANES (greater 40+ BMI)					
Simulation	Control 55%	FAA+65%	FAA+70%	FAA+75%	FAA+80%	FAA+85%	FAA+90%	FAA+65%	FAA+70%	FAA+75%	FAA+80%	FAA+85%	FAA+90%	FAA+65%	FAA+70%	FAA+75%	FAA+80%	FAA+85%	FAA+90%
1	89.5	88.1	93.3	91.3	91.7	87.2	93.7	98	98.7	91.8	92.1	92.4	92.4	90.3	98	96.5	101.4	96.4	95.6
2	86.3	85.6	89.8	89.9	90.1	87.1	94.5	85.4	84.9	90.3	93.9	104.8	84.3	92.7	101.4	101.4	99.5	92	105.3
3	88.1	87.3	88.8	87.3	89.6	87.2	91.6	94.7	93.4	89.5	94.5	95.9	98.7	90.9	99.3	96.6	99.1	99.7	105.2
4	85.2	91.7	95.3	90.8	86.3	101.3	87	99.1	102.7	94.4	94.3	92.8	96.1	96.9	98.3	100.7	103.3	105.3	95.2
5	84.1	91	84.9	90.2	89.5	87.5	94.1	95.4	94.2	88.4	94.9	94.2	99.1	104.9	100.2	96.1	98.9	93.6	96.9
6	84.1	89.4	87.2	87.4	86.9	87.4	88.1	93.5	86.1	92.3	95.2	95.7	92.3	108	94.6	97.3	100.8	98.4	99.6
7	86.1	90.6	89	92.9	87.1	92	89.7	84.1	95.5	97.4	95.8	99.2	94.8	101.6	97.2	97	92.3	99.3	95
8	86.8	86.6	88.1	89.7	86.3	86.9	93.1	94.3	92.3	87.8	93.3	94.5	99.2	109.9	98.7	104.8	104.3	104	99.7
9	88.1	88.6	89.5	90.7	94.1	90.7	87.4	92.1	93.3	93.4	98.7	102.7	99.8	97.2	91.7	100.2	92.7	97.1	105
10	87.7	85.4	87.2	86.3	86.5	91.3	86.3	97.2	95.9	96.9	89.2	89.6	86.7	89.6	93.8	92	90.8	95.9	109.8
11	86.6	90.5	88.3	87.7	94.9	86.5	86.6	90.5	91.7	92	91.6	93.3	103.5	102.1	99.2	94.5	92	91.9	94
12	88.7	90.8	93.8	88.1	88.2	90.3	87	98.7	88.5	96.3	94.4	91.1	95.2	93.4	103.3	99.2	101.9	99.7	108.5
13	86.4	87	84.6	91	87.3	94.1	94.8	91.9	88	95.2	91.8	95.4	99	88.3	88.5	100.6	100.7	99.8	99.4
14	89.2	88.9	84.8	87.7	88.9	87.6	83.6	97.8	100.1	96.7	92.7	92.1	88.3	94.1	104.2	99.8	102.3	106.2	103.4
15	88.1	91.2	95	88	85.2	102.1	95.5	93.8	99.7	93.2	101.3	102.4	92.8	98	97.7	97.1	97.9	104	100.3
16	89.2	86.6	89.6	84.7	89.8	88.1	92.3	86.9	88.6	97	91.1	95.1	95.3	101.5	102.9	101.9	91.9	96	104.7
17	86.1	88.8	83.4	89.3	91.5	86.7	91.3	95.6	97.5	103.1	93.4	93.8	96	95.4	98.4	90.2	97.5	107.8	108.5
18	86.4	88.2	89.3	86.2	90.3	89.6	86.8	90.1	82.8	93.7	97.2	94.3	111	96	101.4	95.8	102.7	101.2	103.3
19	87.4	85.9	84.5	87.3	94.8	87	86.2	85.7	93.6	91	97.5	91.4	94.8	95.1	96.7	102.8	100.3	96.4	91.7
20	84.6	86.8	85.7	90.8	84.6	86.9	91.9	94.1	97.4	102.6	96	90.7	102.3	92.7	92.2	100.8	104.9	103	104.9
21	87	91	86.7	88.8	89.6	91.8	89.8	89.9	92.3	87.8	92.5	93.2	104.3	85.5	97.2	95.2	99.6	103.8	106.7
22	88.7	88.7	89	93.3	90.2	88.4	86.4	86	86	98.3	94.6	89.2	95.9	104.2	94.9	102.3	98.1	97.7	101.3
23	87.3	88.8	93.1	87.9	87	87.7	84.5	90.5	98.5	94.1	89.2	97.5	91.7	100.7	101.2	99.9	94.9	98.2	102.6
24	88.4	86.9	89	90	89.9	93.3	88.8	91.7	95.8	100.5	90.2	105.5	90.2	90	93.5	98.8	95.9	100.7	105.1
25	86.9	91.3	93.6	84.6	90.8	90.2	89.3	91.2	91.8	97.5	101.3	95.7	98.9	89.8	104.3	98.9	106.3	102.3	105.3
26	85.8	89.8	88.6	91.1	90.1	87.1	91.4	91.2	91.1	94.1	100.3	98.1	96.6	85.3	96.4	104.7	104.2	105.2	101.2
27	84.9	88.2	90.2	92.6	88.4	86.8	86.4	95.4	98.2	92.1	86.2	94.5	99.1	94.2	104.4	93.5	99.1	97.8	97.8
28	89.2	85.3	86.8	92.3	85.2	87.7	87.9	89	90.3	93	97.4	101.2	103.3	95.2	104.6	95.8	98.7	94.3	103.3
29	87.3	90.8	86	88.2	89.1	87.3	86.7	92.9	99.8	83.9	102.4	100	94.7	84.4	89.9	100.6	99.4	111.6	89.7
30	88.3	89	91.1	93.4	89.5	87.3	85.8	84.5	96	96.6	99.2	91.4	92.8	93.8	86.9	94.7	95.7	109.1	104.7
31	89.3	87.8	89.9	91.7	88.6	92.7	87.6	90.6	93.9	96.5	100.1	97.1	93.9	90.8	88.4	103.3	100.7	101.5	105.5
32	88.8	91.7	90.4	88.4	93.3	85.6	89.3	97.6	95.4	95.1	89.7	92.2	96.5	92.8	103.7	108	99.2	95.8	101.7
33	86	89	89.8	89.3	87.4	91.7	92	86.8	100.2	98.6	89.6	96.9	97.4	104.8	97	94.8	103.1	114.5	107.1
34	87.3	89.1	90.3	87.4	88.5	88.4	85.8	88.4	89.7	100.2	95.9	106.4	90.2	97.4	104.2	103.2	92.3	106.4	105.4
35	86.3	89.7	92.4	85.7	91	85.8	86.6	87.1	93	86.4	100.3	95.1	92.4	96.3	98.9	102	97.7	102.8	107.2
36	85.9	87.4	93.3	89.7	85.4	90.5	88.7	88.5	96.9	83.7	95.5	101.4	96.8	100.6	96.8	87.1	109.4	105	95.4
37	89.4	90.5	90.3	93.3	91	88.3	88	95.7	98.6	96.6	99.3	89.8	97.1	96.5	106.4	102.1	97.6	100.3	103.9
38	88.2	91	86.9	86.7	93.8	90	87.7	83.5	96.9	95.3	89.2	92	93.7	103.2	94.9	107.2	110.5	102.8	108.5
39	86.7	88.4	86.7	91.8	85.9	83.1	87.2	89.7	90.7	103.1	99.1	93	102.7	97.1	101.4	88.2	108.9	91.1	102.9
40	84.9	89.2	88.3	88.5	89.2	91.9	87.3	94	95.8	99	96.4	90.3	93.9	100.3	101.6	94.9	99.6	100.2	103.8

Appendix 10: Bus Evacuation Exercise Set-up Diagram



Appendix 11: Bus Exercise Participant Raw Data

Participant Number	Gender	Age	Shoulder Width (cm)	Waist Cir Size (cm)	Diameter (cm)	Waist Diameter (cm)	Height (cm)	Weight (kg)	BMI	Bus Seat	Distance to Exit (m)
1	M	26	44	100	31.83	35.37	175.2	64.8	21.11	7D	6.85
2	M	36	45	87	27.69	30.77	175	79	25.80	6C	6.29
3	F	38	40	80	25.46	29.96	168	68	24.09	6D	6.53
4	M	21	44	80	25.46	28.29	173.2	65.5	21.83	6A	6.53
5	M	21	41	80	25.46	28.29	174	63.3	20.91	5A	6.21
6	M	21	50	98.3	31.29	34.77	178	98.3	31.03	5B	5.97
7	M	21	48	87	27.69	30.77	174	62.7	20.71	10D	7.81
8	F	21	43	64	20.37	23.97	167	51.6	18.50	8D	7.17
9	M	21	47	92	29.28	32.54	168	76.4	27.07	6B	6.29
10	M	21	47	94	29.92	33.25	174	61.2	20.21	10B	7.57
11	F	21	45	69	21.96	25.84	173	57.2	19.11	10C	7.57
12	M	20	47	97	30.88	34.31	176	73	23.57	5C	5.97
13	F	21	40	65	20.69	24.34	169	53	18.56	8C	6.93
14	M	21	47	80	25.46	28.29	165	57.3	21.05	5D	6.21
15	M	21	47	100	31.83	35.37	180	85	26.23	4D	5.89
16	F	22	45	72	22.92	26.96	162	53	20.20	4C	5.65
17	F	21	47	72	22.92	26.96	162	44.1	16.80	7A	6.85
18	F	20	46	71	22.60	26.59	174	56.5	18.66	8A	7.17
19	F	21	45	162	51.57	60.67	162	56.5	21.53	9A	7.49
20	M	18	48	107	34.06	37.84	184.5	97.7	28.70	4B	5.65
21	F	21	47	81	25.78	30.33	169	63.3	22.16	9C	7.25

Appendix 12: AIAC17 Conference Paper

Characterisation of the anthropometric features of airline passengers and their impact on fuel usage in the Australian domestic aviation sector

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Abstract

This paper discusses the impact of passenger weight changes attributed to obese/overweight passengers on aviation fuel used, greenhouse emissions and fuel cost. The scope of this study is circumscribed to domestic air travel in Australia for the period between 1990 and 2014. It is estimated that the industry has used 561 kilo-tonnes of fuel between 1990 and 2014 to transport 15.8 tonnes of excess weight of passengers across Australia. This is equivalent to 1.2% of all the domestic aviation fuel consumed during this period. The results of this additional fuel usage produced in 1.7 million-tonnes of equivalent CO2 released into the atmosphere. The extra fuel resulted in an expenditure of $411.7 million (Australian dollars at 2015 fuel price) due to the added weight carried over the two decades.

Keywords: aviation passengers' obesity, overweight, fuel usage, commercial aviation.

Introduction

The advent of newer efficient aircraft has led to economical airline models, particularly the low cost carrier, bringing an increased demand in commercial air travel around the world. Lower airfares have increased the accessibility to greater numbers of people from a middle to lower socioeconomic status, who have a higher prevalence for being overweight or obese [1,2]. Currently the prevalence of obesity in Australian society is becoming a major focus for health and social related discussion [3,4].

Over the past two decades the average weight and the proportion of obese/overweight individuals of the Australian population has been increasing. By the year 2000, the prevenance of overweight and obesity in Australia had reached 60% [5]. In 2014, 71% of the adult Australian population or 11.5 million people are overweight or obese. In contrast, 35% or 4.7 million adults where overweight or obese in 1990 [6,7]. Fig. 1a and Fig. 1b show how body mass index (BMI) has changed in both the average male and female populations respectively. It is clear that since 1990 the prevalence of obese persons has increased in approximately 20% in both males and females. Juxtaposed, normal and underweight prevalence has declined. This demonstrates that there is an identifiable change in the skewness in the trend of the Australian population standard weight and BMI [8,9]. This increase in the weight has been overlooked by both decision makers and operators across distinct transport sectors (including aviation), despite the significant consequences on the operational efficiencies resulting thereof.

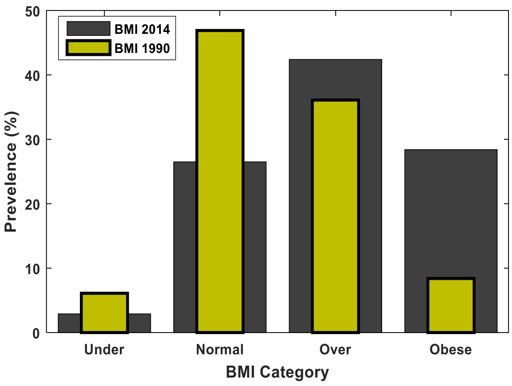

Fig. 1a: Australian male BMI prevalence

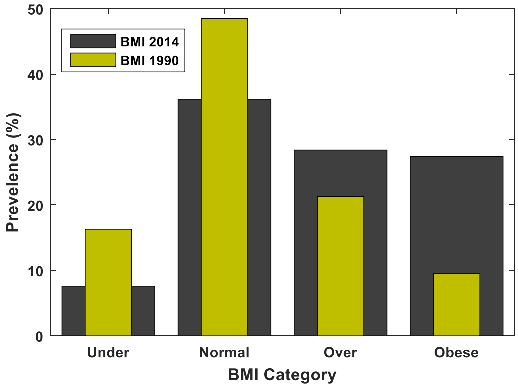

Fig. 1b: Australian female BMI prevalence

Source [6,7]

Regulatory material issued by national aviation authorities provide standard passenger weights for airlines to use for performance calculations. Many of these standard underestimate passengers' standard weight as they have failed to include updated data reflecting the changes in the anthropometric characteristics of population over the last decades. This issue can even be more aggravated for certain populations of passengers who are particularly prone to overweight or obese conditions due to the concomitant effect of different geographical, ethnical and socio-economic factors.

As demand for air travel increases, the rise in passenger weight affects the transportation sector by increasing the fuel usage, greenhouse emissions and overall direct costs to airlines. Global fuel demand is expected to rise 1.9% annually between 2008 and 2025 [10]. Conjunctly, as fuel usage increases so to the greenhouse emissions produced by aircraft. The International Civil Aviation Organisation (ICAO) has estimated that for every kilogram of aviation fuel burnt, 3.157kg of CO2 emissions is produced [11]. Studies exploring the effects of the relationship between fuel and passenger weight are limited to a few studies conducted in the United States of America (USA). An initial estimation of 1.3 billion litres of extra fuel was reported due to excess weight in the decade around 1994 [12]. Furthermore, a more in depth study into the USA domestic transport systems over the period of 1970-2010 has been conducted, showing that 95.2 billion litres of extra fuel was required by the domestic aviation sector due to excess passenger weight. This resulted in a net output of 238 billion metric tonnes of additional greenhouse emissions, from $37 billion USD (adjusted to 2012) of extra fuel [13]. In an Australian context, a recent study has explored the greenhouse emissions produced by international flights for selected Australian routes using actual passenger and cargo data from airlines. The study compared aircraft and airline frequency to determine greenhouse emissions rely not only on aircraft type and passengers but also on cargo payload [15].

The present paper is based on the method presented in Ref [13], adapted to the Australian context. Using data from various sources, the effects of excessive passenger weight on fuel usage and consequently greenhouse emissions and associated cost for the domestic aviation sector are presented. Furthermore, this paper brings to attention the effects that the real passengers' weight has on fuel usage form an aircraft's operation technical point of view.

Method

Data Source

Anthropometric data used throughout this study is retrieved from the National Health Surveys conducted by the Australian Bureau of Statistics (ABS) for the period between 1990-2014 [6,7,16]. The anthropometric data obtained from these sources provide details of the adult populations (18+ years old) sorted by age and gender; height, percentage of adult obesity, average weight and waist size. Additional information regarding the annual populations of Australia by age and gender from 1990 to 2014 is also sourced from the ABS [14]. There is variation on the classification benchmarks for labelling BMI, however for the purposes of this study the classification adopted by the ABS in Table 1 will be used of calculating population-age weights. BMI is calculated by the weight (kg) of a person divided by the square of the persons' height (m).

Table 1: BMI categories and range

Category	BMI Range (kg/m^2)
Underweight	Under 18.5
Normal weight Cat. 1	18.5 to < 20
Normal weight Cat. 2	20 to < 25
Overweight	25 to < 30
Obese	Above 30

Data relating to the Australian aviation sector is sourced from the Bureau for Industry, Transport and Regional Economics (BITRE) within the Department of Infrastructure and Regional Development [17,18]. This data provides annual information on various aviation metrics used in this study; such as the number of passenger movements, number of aircraft departures, aircraft kilometres flown (AKF), annual fuel usage. Additional information regarding the breakdown of aviation fuel is sourced from Department of Industry, Innovation and Science (DIIS) and CO2 equivalent emissions data for the aviation sector is obtained from the Department of Environment and Energy (DEE) [19,20].

The Model

Trends in weight patterns are known to vary with different demographical markers, however for the purpose of this study a general estimate for the country as a whole is used. Identifying the intricate variations based on demographic change is beyond the scope of this paper. This section describes the four models that were developed by Ref [13] to calculate the excess weight of passengers, fuel usage, cost and CO2 equivalent emissions. Note that excess weight of aircraft attributed to passengers is underestimated as calculations do not incorporate children and teenagers under the age of 18 years.

Determining Excess Weight

Using data from the National Health Surveys and population data, the average excess weight (EWG|A) of an individual is separately calculated for the individual age (A) and gender (G). To calculate the EWG|A of an individual, the maximum normal weight (MNWG|A) is calculated first as shown by Eqn 1, where HG|A is the height of a given gender and age and BMI is the body mass index. Maximum normal weight refers to the threshold weight of a person before being classified as overweight or obese; this corresponds to a BMI equal to 25kg/m2.

$$MNW_{G|A} = BMI \times \left(H_{G|A}\right)^2 \tag{1}$$

A variation to the method by Ref [13] is introduced to derive components in Eqn 4. This variation accounts for the weight for a given age-BMI group based on gender. The mean weight (MWi,G) of obese and overweight persons are derived by Eqn 2 using the average height of the age group and median BMI value for categories with a BMI>25kg/m2 in Table 1, where i is the BMI category.

$$MW_{i,G} = BMI_{i,G} \times \left(H_{G|A}\right)^2 \tag{2}$$

Then the collective weight of each population-age group is determined by multiplying MWi,G by the population size of each BMI category. These collective weights are then used to determine the weight of all obese and overweight adults based on age and gender, TWOG|A (Eqn 3).

$$TWO_{(G|A)} = \sum_{(G|A)}^{i}\left(TW_{obese} + TW_{overweight}\right) \tag{3}$$

The average excess weight per overweight and obese person over 18 years is calculated by Eqn 4, where P(OG|A) represents the percentage of adults who are overweight and obese.

$$EW_{G|A} = \frac{TWO_{G|A} - P\left(O_{G|A}\right) \times Population_{G|A} \times MNW_{G|A}}{P\left(O_{G|A}\right) \times Population_{G|A}} \tag{4}$$

Determining Excess Aircraft Weight

The excess weight of an aircraft attributed to overweight and obese passengers per aircraft (EAW) can be determined as follows. The values for the excess weight carried by an individual airline passenger (EWpaxG|A) are calculated in Eqn 5. Where, P(A) is the percentage of the age within the given gender, P(G) is the percentage of a given gender within the age population, P(OG|A) is the percentage of obese and overweight persons for a given age and gender. The assumption is that the demographic distribution of adults of the Australian population mirrors that exhibited on an aircraft operating in the domestic sector in Australia.

$$EW_{paxG|A} = EW_{G|A} \times P(A) \times P(G) \times P\left(O_{G|A}\right) \tag{5}$$

The values from Eqn 5 are then multiplied by an estimated value of passengers per aircraft annually to determine the mean excess aircraft weight, EAW. Due to the fact that different aircraft types have been operated by the many Australian airlines, an estimate for this value is determined by the number of passenger movements per aircraft departure, which will be used as shown in Eqn 6.

$$EAW = \frac{Passenger\ Movements}{Aircraft\ Departures} \times EW_{pax\ G|A} \tag{6}$$

Determining Excess Aircraft Fuel Usage and Cost and Greenhouse Emissions

The data provided by BITRE and DIIS on Australian jet fuel sales account for both domestic and international flights. Eqn. 7 is used to calculate the amount of fuel used based on excess passenger weight.

$$EAF = AKF \times EAW \times R_F \tag{7}$$

Where, AKF is the number of kilometres flown by domestic commercial aircraft in a given year. RF can be determined from Eqn. 8, representing the relationship between the fuel capacity of a given aircraft for its maximum range divided by the aircraft's half range trip weight, i.e., Fcapacity is the fuel capacity of the aircraft, Xmax is the maximum range and MTOW is the maximum take-off weight. Due to the fact that there are many different types of aircraft in service, an average RF value was estimated for the commercial domestic Australian fleet type aircraft.

$$R_F = \frac{\left(\frac{F_{capacity}}{X_{max}}\right)}{MTOW - 0.5F_{capacity}} \tag{8}$$

Determining the cost of the fuel attributed to the excess passenger weight (EAC) is expressed by Eqn 9, where, Fcost is the mean price of fuel for each year. These prices are indexed to 2015 in order to account for inflation.

$$EAC = EAF \times F_{cost} \tag{9}$$

Eqn 10 is used to estimate the amount of greenhouse emissions generated based on the fuel used. Where GHG represents the total CO2 equivalent emissions produced for the aviation sector from DEE in a given year, and TAF is the total fuel used in a given year. For simplicity, it is also assumed that fuel usage is directly proportional to emissions as relationship to fuel used and distance travelled [13].

$$EAGHG = \frac{EAF}{TAF} \times GHG \tag{10}$$

Results

Excess Weight of Passengers

Between 1990-2014 the domestic sector has used 561.04 kilo-tonnes of fuel, transporting 15.8 tonnes of excess weight of passenger across Australia. This is equivalent to 1.2% of all the domestic aviation fuel consumed during this period. Based on the equations in the model described above, in 1990, a total of 3.81 kilo-tonnes of fuel was used from 234.9 kg excess passenger weight carried by a typical commercial aircraft. This was equivalent to an average of 3.3 extra passengers per flight at an average adult weight for 1990. The excess fuel used cost $2.79 million dollar (indexed to 2015) and produced 10.17 kilo-tonnes of CO2 equivalent emissions. Fuel usage has since risen to 54.42 kilo-tonnes as aircraft carry an average of 1,173.9 kg of extra passenger weight in 2014, equivalent to an aircraft carrying 15 extra passengers for the average adult weight in 2014. Costing the sector $38.47 million dollars (indexed to 2015) and producing 148.11 million tonnes of CO2 equivalent emissions. Illustrated in Fig. 2 are the annual weight (EAW) in kilograms, fuel usage (EAF) in kilo-tonnes, cost (EAC) in million dollars and emissions (EAGHG) in kilo-tonnes from excess weight. It is clear that there has been a significant rise in the later years of the first decade of the 21st century.

The RF parameter used in this study is modified from the methods used by Ref [13] and Ref [21], in which a linear rate describes the relationship between the estimated annual fuel economy of the in-service vehicle fleets and the annual average person weight. RF also reflects the technological change and developments of an aircraft. As such, and as the data used to determine this parameter refers to recent aircraft in operation in Australia, the value obtained results in an underestimation of the fuel used due to excess weight. Furthermore there is a level of uncertainty arising from the results due to the accuracy of reported data for the various data sources. The calculation for the uncertainty level is beyond the scope of this paper.

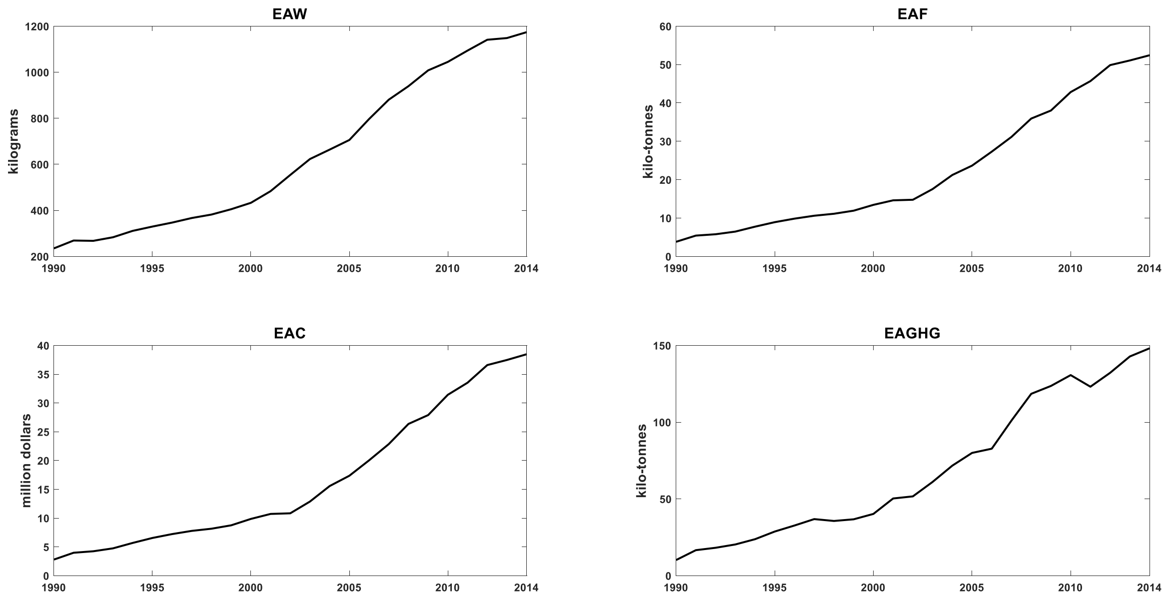

Fig. 2: Domestic aviation excess weight, fuel, cost and emissions

Discussion

The results of this study demonstrate that overweight and obese passengers have exposed the airline industry to consume a greater amount of fuel with associated costs and emissions over the past two decades. The particular vulnerability of the aviation sector to weight sensitivity and fuel price make it highly susceptible to the passengers' obesity problem. Newer aircraft technologies providing improved fuel economy could inevitably counteract the consequence of increased passenger weight. However design standards and operations manuals should be updated to account for recent changes in the standard passenger's weight to ensure nominal specifications translate to real operational conditions, therefore contributing to enhanced operational efficiencies.

Domestic air patronage has been increasing gradually in Australia, with 30.4 million passenger movements in 1990 compared to 114.1 million passenger movements in 2014 [18]. Conjunctly, the Australian mean weight of males has increased from 76.5 kg in 1990 to 85.9 kg in 2014. Females mean weights have also increased from 62.2 kg to 68.4 kg over the same period. Fig. 3a and Fig. 3b shows the change in Australian male and female weights respectively. Each graph shows the mean weight of the adult, the maximum weight threshold before being classified as overweight or obese (BMI≥25 kg/m2) and the Australian standard weight used on aircraft with a capacity of 150-299 passengers (male 81.8kg and female 66.7kg).

Unlike many other national regulators who include standard carry-on baggage as part of the standard passenger weight, the Civil Aviation Safety Authority (CASA) provides passenger standards weight only, these are categorised for varying aircraft capacity and age groupings in addition to gender. As of 1990 the standard adult weight is 83-81.4 kg and 68-66.3 kg for males and females respectively for aircraft capacities ranging between 40-499 passengers [22]. In both figures the fact that the standard weight remained above the maximum weight threshold (as at 1990) shows that that the regulator adopted a conservative approach with their estimates. However, by 2002 the average adult weight had already surpassed the standard weight recommended by CASA. As Australia move towards an aging population, a persons' height naturally decreases in later life, resulting in an increase the obesity prevalence in older aged persons. However, the average weight of the female population has been declining over the last few years juxtaposed to average male weight.

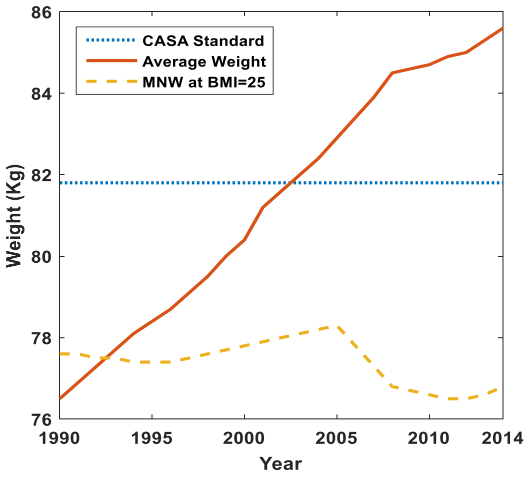

Fig. 3a: Australian male weight comparison

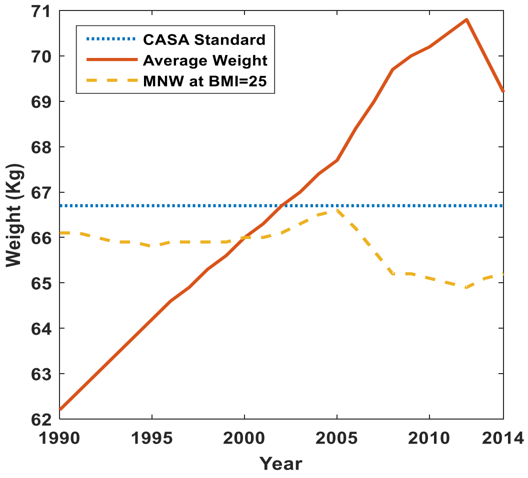

Fig. 3b: Australian female weight comparison

Another anthropometric measurement that directly relates to weight is waist size. There has been an average increase of 6cm and 7 cm in the waist circumference of Australian males and females respectively from 1995 to 2014 [7,23]. Although the size of an adult waist would have no direct effect on the aircraft performance, there would be design consequences for greater variation in a passenger's shape (e.g., ergonomics) that manufactures should take into consideration.

The influence airline passengers' anthropometry has on aircraft fuel performance is not the only aspect that needs to be explored in the aviation sector. Beyond the performance characteristics of aircraft other consequences for larger anthropometric passengers have consequences on airlines. Addition weight may cause aircraft to be unbalanced often resulting in passenger offloads; normal weight passengers seeking for compensations for the inconvenience of being sat next to heavier-larger passengers; debate about the baggage weight-price equality, e.g. premiums for excess baggage for a normal weight passenger when a similar heavier passenger do not pay extra or airline policies charging larger passengers for two tickets [24]. Anthropometrical influence dictates many other important aspects of aircraft design, such as safety requirements and performance characteristics [25]. These aspects rely on the awareness of regulators to timely and accurately update regulations to mirror the increasing trends in passengers' average weight and size.

Conclusion

It is expected that both the prevalence of obesity and demand in air travel increase in Australia for the next years. The data presented in this paper serves to raise awareness for a problem that seems to have been overlooked by stakeholders, having significant effects on the operational efficiency of airlines. Even though the results presented herein are at a preliminary stage, they pave the way for a broader research envisaging assessing the impact of the anthropometric changes of passengers across all the dimensions of the commercial airline sector, contributing to a better understanding on how the current standards and procedures can be revised to improve both the efficiency and safety of commercial aircraft.

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