

# **PASSENGER OBESITY AND REGIONAL AIRCRAFT PERFORMANCE FOR THE MOST CORPULENT STATES IN THE USA**

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## **ABSTRACT**

Obesity affects over 25% of Americans; however, prescribed FAA standard passenger weights for US airlines are based on data compiled 15 years ago. Since increased passenger weight degrades aircraft performance and may lead to a loss of control, the hypothesis herein is that passenger weight under-estimation for states with high obesity rates could potentially lead to a runway overrun or the inability to out climb rising terrain. In terms of the employed methodology, current person weights for the ten most obese states were determined using nationwide data adjusted for state ethnicity. Performance degradation for regional aircraft was assessed by accelerate-stop distance for a rejected take-off and climb gradient. Statistical analyses employed Poisson distributions. The results reveal that obesity rates across all ten states increased ( $p < 0.001$ ) between 2000, the year for which data were captured for standard passenger weights, and 2013. Moreover a 5.4 kilogram gain over the standard weight in current usage was evident. Modelling transport-category aircraft performance demonstrated that under-estimating passenger weights could degrade climb performance potentially leading to a collision with rising terrain and/or a runway excursion in the event of a rejected take-off. In conclusion, caution should be exercised in using standard passenger weights for states prone to obesity.

Keywords: aircraft performance, passenger weight, aircraft weight, transport-category aircraft, obesity, aircraft accident.

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## 1. INTRODUCTION

Obesity (defined as a body mass index of 30 or greater kg/m<sup>2</sup>) (Kelley et al., 2016) is at epidemic proportions affecting more than a quarter of the United States population (Center for Disease Control (CDC), 2015a). Medically, obesity is a major cause of hypertension, diabetes mellitus, heart disease, cerebrovascular disease and osteoarthritis (Malnick and Knobler, 2006).

From an aviation perspective, passenger obesity or, as a corollary, an individual's weight is germane to safe aircraft operations. Aircraft performance in terms of runway length required for take-off and the subsequent climb gradient is a function of aircraft load inclusive of passenger weight (Federal Aviation Administration, 2015b). Increased aircraft weight requires a longer runway for take-off (or stop distance in the event of a rejected take-off) and results in a shallower climb gradient (Federal Aviation Administration, 2008a). Indeed, for transport-category aircraft certification, minimum performance requirements are specified per the Code of Federal Regulations Subparts 25 and 29. Specifically, in the event of engine failure for an aircraft with two power plants, a minimum climb gradient (Federal Aviation Administration, 2008a; Federal Aviation Administration, 2015b), allowing for a mere 35 foot vertical obstacle clearance, is mandatory. This climb gradient is of particular importance at airports with surrounding rising terrain and under conditions (high ambient temperature, high field elevation) that degrade aircraft performance. Also, in the event of a rejected take-off, sufficient distance is required to allow the aircraft to come to a full stop without incurring a runway overrun. Certainly, rejected take-offs are not infrequent; a query of the Aviation Safety Reporting system database (National Aeronautics and Space Administration (NASA), 2015) returned a total of 261 such events by air carrier-operated aircraft for the period between 2001 and 2015. A rejected take-off from a runway whose departure end is immediately followed by descending terrain or water carries an increased potential for loss of life in the event of a runway excursion. Indeed one study reported 400 fatalities associated with 57 rejected take-offs for western-built jet transports through 2003 (Federal Aviation Administration, 2015b). Another concern is that an aircraft operating outside of its weight and balance envelope may experience an in-flight loss of control. In fact, the cause of two fatal aviation accidents (a McDonnell Douglas DC-8 and a Beech 1900 aircraft operating as Arrow Air 1285 and Air Midwest 5481 respectively) was ascribed, at least in part, to an under-estimation of passenger weight and, for the latter, an out-of-centre-of-gravity aircraft. As a consequence of the Air Midwest 5481 accident, the Federal Aviation Administration (FAA) revised upwards the average adult passenger weights (hereafter referred to as standard passenger weights) used by air carriers (per Advisory Circular (AC) 120-27E) to determine aircraft weight and centre of gravity. These

revised weights were based on measurements compiled by the National Health and Nutrition Examination Survey (NHANES) for the years 1999-2000 then the most current data at the time that AC 120-27E was implemented.

However, despite the passage of fifteen years, the standard passenger weight (78.9 kg. (174 lbs.) body mass) exclusive of the 16 lbs. (7.3 kg.) carry-on luggage) specified by AC 120-27E for the summer months (an additional 5 lbs. (2.3 kg.) for clothing is added for winter months) is still in current usage. It should be noted that the 86.2 kg. (78.9 + 7.3 kg. carry-on luggage), represents a mean value for male (90.7 kg.) and female (81.2 kg.) passengers. If however, the US population has continued to increase in body mass since 1999-2000, airlines may be under-estimating passenger and hence aircraft weights. Indeed, there is some evidence consistent with this notion. For example, in one report (Krueger et al., 2014) covering a study period extending a decade beyond capture of the NHANES data used to establish standard passenger weights, a trend for an increase in body mass for US-born whites was evident; Hispanics showed the steepest linear increase (Krueger et al., 2014).

In view of these findings the hypothesis herein is that for states carrying the highest obesity rates passenger loads, based on standard passenger weights, under-estimate aircraft weight and thus degrades aircraft performance. To test this hypothesis, the effect of under-estimating passenger load for the ten states with the highest obesity rates on performance of two transport-category aircraft in usage by US regional carriers (which transported 157 million passengers in 2013 an 89% increase over 2000 (Regional Airline Association, 2015)) was determined. Specifically, could usage of standard passenger weights for these states potentially lead to a (i) runway overrun in the event of a rejected take-off and/or (ii) climb gradient insufficient to clear surrounding rising terrain?

## **2. METHODS**

### *2.1 Procedure*

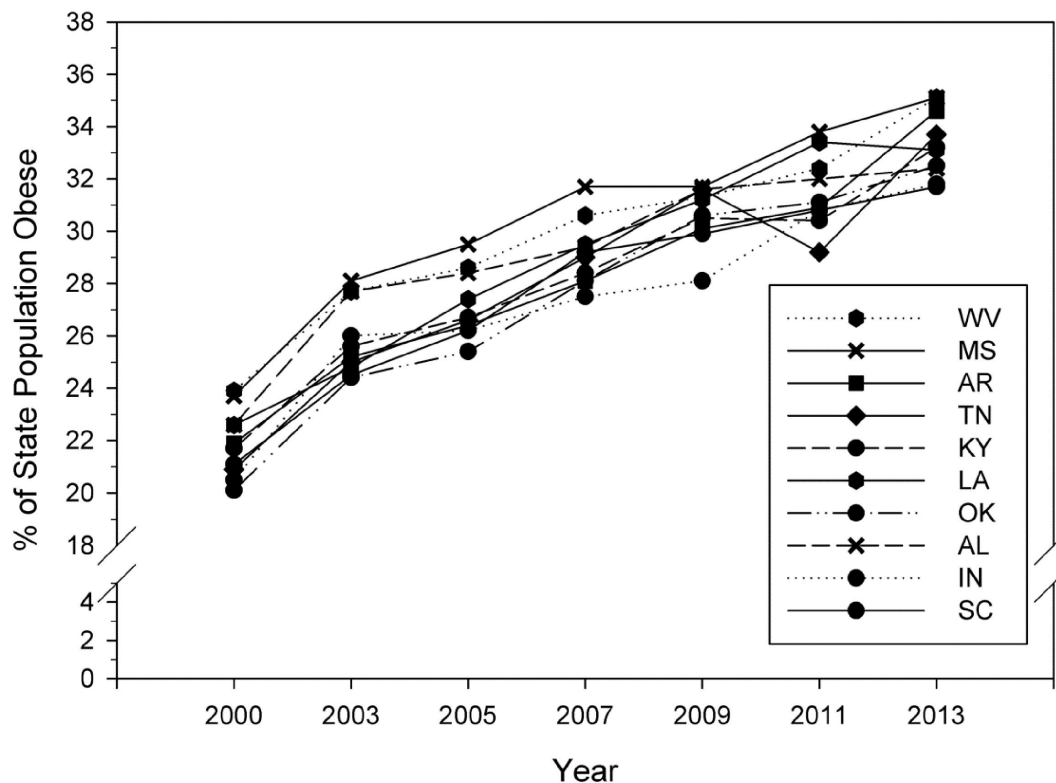
State obesity data were from the State of Obesity Project (Levi et al., 2015) and the Behavioural Risk Factor Surveillance System (BRFSS) (Center for Disease Control (CDC), 2013). Obesity is defined as a body mass index (BMI) of 30 kg/m<sup>2</sup> or greater (Kelley et al., 2016). BRFSS data were downloaded, opened with SPSS (v22) software and exported to Excel.

State-specific average passenger weights were calculated using two independent sources: (a) the NHANES (actual measurements) and (b) BRFSS data (self-reported). Regarding the NHANES, which represents measurements of the non-institutionalized US population, data

for the most recent period available (2011-2012) were obtained from the Centers for Disease Control (Center for Disease Control (CDC), 2015b). Records with null weights and for persons of less than 18 or over 65 years of age were deleted for this study. These nationwide weights were cross-referenced with race to determine a US-wide, ethnic group-specific average weight for individuals in this age range. A state-specific average passenger weight was calculated as follows. First, the ethnic composition of the ten most obese states was obtained from the United States Census Bureau (United States Census Bureau, 2015). Then the aforementioned US-wide, ethnic group-specific average weights were adjusted by mathematical weighting based on the racial group composition for each state.

**Figure 1 – Increasing Obesity Rates Post-Establishment of Standard Passenger Weights**

For the indicated state, the percentage of the surveyed population that was obese (>30 kg/m<sup>2</sup>) is shown.



For BRFSS-derived person weights, data for the most recent year available (2013) were downloaded from the CDC website (Center for Disease Control (CDC), 2013), opened with SPSS software and exported to Excel. The data were then filtered for the ten most obese states (Levi et al., 2015). Records null for weights or corresponding to individuals younger than 18 or older than 65 years of age were deleted. Performance data for two transport-category aircraft, one of medium cabin (50) and the other of large-cabin capacity (86 seats) were used in the study. The performance charts for the Embraer 175 (86 seat maximum capacity) was downloaded from the company website (Embraer, 2013) and exported to a

bitmap image file format. The latter was imported into vector-based graphics software (CorelDraw v X7) allowing for the construction of vertical and horizontal intercept lines to determine the effect of excess weight on runway distance required in the event of a rejected take-off at decision speed ( $V_1$ ). Using a similar strategy, climb gradients in the event of a powerplant failure (at or after  $V_1$ ) were determined for the two engine aircraft of 50 passenger capacity aircraft whose manufacturer kindly provided performance charts but under condition of anonymity.

## *2.2 Statistics*

To determine if obesity rates averaged across the ten most obese states for a particular period differed from the earliest year (2000), a generalized linear model with Poisson distribution was employed adjusting for differences in population sample size for each time period. Statistical analyses were performed using SPSS (v22) software.

## **3. THEORETICAL CONTRIBUTION**

### *3.1 Increase in Obesity Rates for the Upper Ten Obese States.*

Standard passenger weights (per AC 120-27E) prescribed by the FAA are based on nationwide measurements (NHANES) made in 1999-2000. However since this survey represented averages for the entire nation, it is possible that such data under-estimated weights for states with high obesity rates. Moreover, if obesity rates continued to climb after 1999-2000 this might cause further divergence of passenger weights for the most obese states from the values specified in AC 120-27E.

Towards addressing these concerns, obesity rates were first determined for the top ten obese states (WV, MS, AR, TN, KY, LA, OK, AL, IN, SC) (Levi et al., 2015) for the period following the 1999-2000 NHANES survey (Figure 1). For the individual states, comparing data for the 2013 and 2000 surveys, Oklahoma and Tennessee showed the greatest increase in obesity rates (62 and 61% respectively) for their populations. Alabama showed the most modest gain in obesity rate increasing from 22.6% to 32.4% for 2000 and 2013 respectively.

Obesity rates were then averaged across all ten states for each time-period. The sample size for the combined ten states was 32,626, 69,059 and 72,878 for the years 2000, 2010 and 2013 respectively. For the most recent year (2013) for which data were available, a Poisson distribution showed a highly significant ( $p < 0.001$ ) increase in obesity rate relative to 2000 one of the two consecutive years for which data were captured for establishing standard passenger weights per AC 120-27E. Since a modified survey methodology was implemented in 2011 (Center for Disease Control (CDC), 2013), obesity rates for 2000 and

2010 were also compared. Again, the averaged obesity rate across the ten states was significantly higher for 2010 ( $p < 0.001$ ). These data would suggest that obesity rates for these ten states have continued to climb in the 13 years since establishment of standard passenger weights.

### 3.2 Person Weight Determinations for the Upper Ten Obese States.

While the aforementioned state-specific obesity data are calculated from corresponding weight (and height) data one caveat of using the latter is that they are self-reported rather than measured (Center for Disease Control (CDC), 2013). It is well recognized that individuals often under-estimate their weights likely, in part, due to the perception of social desirability (Shiely et al., 2010). Moreover, such under-estimations have increased over time (Shiely et al., 2010). At the same time, while the NHANES data represent actual weight measurements, they lack state identifiers. Considering these limitations, dual approaches were employed. First, the most current NHANES data (2011-2012) were used to derive average weights per capita for each of the ten most obese states based on their racial composition. As mentioned above different ethnic groups have shown disparate temporal gains in obesity (Flegal et al., 2012; Krueger et al., 2014). Second, state-specific self-reported weights were employed using BRFSS data.

**Table 1 – Average Passenger Weights for the Ten Most Obese States Adjusted for Ethnic Group Composition**

Nationwide (NHANES) weight data for 2011-2012 were cross-referenced with race to determine a US-wide, ethnic group-specific (sample sizes were 1,467, 973 and 1,229 for whites, Hispanics and blacks respectively) average weight for individuals aged 18-65 years. State-specific, average passenger weights were derived by adjusting, by mathematical weighting, the aforementioned US-wide, ethnic group values for the state's racial group composition.

		WV	MS	AR	TN	KY	LA	OK	AL	IN	SC	Average passenger weight (kg.) for the ten most obese states
<b>State Ethnic Group Composition (%)</b>	white	93	48	75	76	86	60	68	66	81	64	
	Hispanic	2	3	6	5	3	5	10	4	6	5	
	Black	4	37	15	17	8	32	8	27	10	28	
	Other	1	12	4	2	3	3	14	3	3	3	
	<b>Average Pax Weight (kg.) Adjusted for State Ethnic Group Composition</b>	<b>83.9</b>	<b>85.5</b>	<b>84.2</b>	<b>84.3</b>	<b>84.0</b>	<b>85.0</b>	<b>83.6</b>	<b>84.8</b>	<b>83.9</b>	<b>84.8</b>	<b>84.4</b>

For the most current NHANES data, the average nationwide weights for the predominant

ethnic groups (ages 18-65 years) were determined to be 83.9, 88.3 and 78.5 kg. for whites, blacks and Hispanics respectively. Ethnic group composition for each state was then used to generate an average person weight for each of the ten states with the highest obesity rates (Table 1). Using this approach, the populations of Oklahoma and Mississippi were determined as having the lowest and highest average weights (83.6 and 85.5 kg. respectively). The mean value across these ten states was computed as 84.4 kg. per capita a 5.5 kg. gain over standard passenger weights (78.9 kg. inclusive of 2.3 kg. for summer clothing but exclusive of the 7.3 kg. assigned to carry-on baggage per AC 120-27E). Interestingly, the aforementioned average passenger weight (84.4 kg.) was close to the 83.9 kg. calculated using the most current BRFSS self-reported data for individuals (n=47,042) 18-65 years of age across the ten most obese states.

### *3.3 Degraded Aircraft Performance with Increased Passenger Weight*

Since aircraft performance diminishes as a function of increased weight (Federal Aviation Administration, 2008b), the adverse impact of under-estimating passenger load on two parameters for a flight carrying passengers fitting the average weight profiles for the top ten obese states was modelled. The studies described below were performed using two separate transport-category aircraft with a 50 and 86 passenger capacity both in usage by regional airlines (Regional Airline Association, 2015). Two high elevation airports (Santa Fe Municipal (KSAF) and Denver International (KDEN)) both served by regional air carriers were selected for this model.

The first question posed was whether under-estimating passenger weights could potentially lead to a runway over-run in the event of a rejected take-off. Pilots and their despatchers are required to determine that the runway assigned for take-off is of sufficient length to allow a full stop in the event of a rejected take-off at decision speed (V1). This calculation is of importance when the departure end lacks an engineered material arresting system and is followed by water or descending terrain.

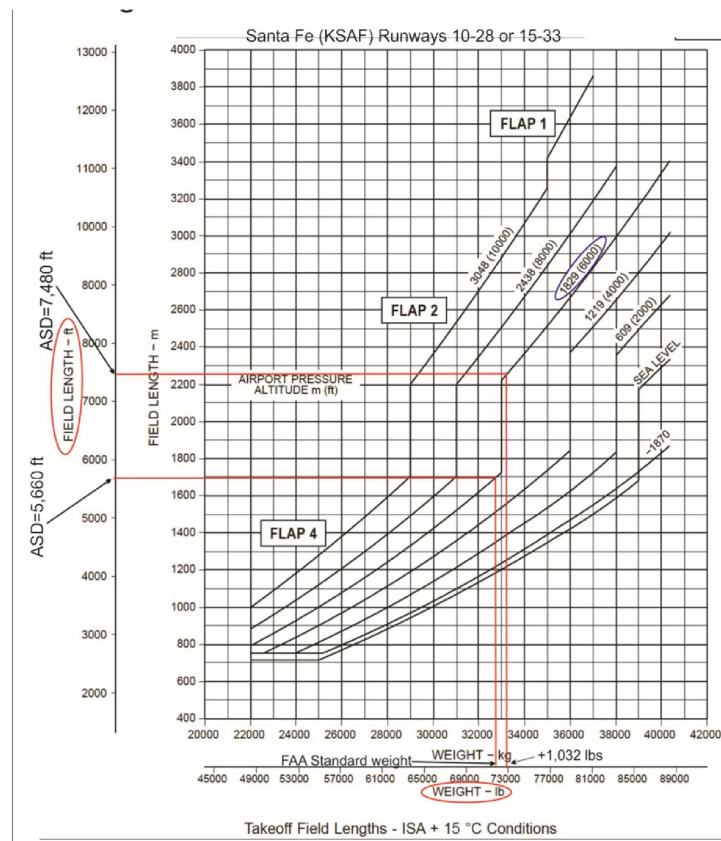
In this scenario, the performance of an Embraer 175, with a maximum seating capacity of 86, departing from Santa Fe Municipal airport (1,829 metres field elevation) under conditions (15°C higher than standard temperature) that degrade performance was modelled. Runways 15-33 and 10-28 are approximately 1,920 metres in length (Federal Aviation Administration, 2015a) and a 21 metre drop in terrain lies beyond the departure end of runway 10 as determined from Google Earth imagery. Using standard passenger weights and for an aircraft at full occupancy and at a take-off weight of 32,568 kilogrammes, the accelerate-stop distance (ASD) was computed at 1,725 metres (Figure 2), well within the 1,920 metres length of either of these runways in the event of a rejected



take-off at V1. However, adjusting for the additional 468 kilogrammes (86 passengers X 5.44 kilogram each) would now require approximately 2,280 metres and consequently a runway excursion for either of these two airstrips. For a departure from runway 10, the aircraft would continue its roll down a 21-metre embankment. It should be noted that these take-off weights are below the maximum take-off weight (40, 370 kilogram) specified (Embraer, 2013) for this aircraft.

**Figure 2 – Increased Accelerate-Stop Distance for a Transport-Category Aircraft Based on Passenger Weight Under-Estimation**

The performance of an Embraer 175 (86 seat capacity) aircraft departing from Santa Fe airport (field elevation 1,920 m) was determined using the corresponding performance chart (red lines). The conditions were 15°C over standard temperature using standard weights or with an additional 468 kg. (5.44 kg. X 86 passengers). For the purpose of this calculation, field elevation was approximated to 1,829 m. A rejected take-off at decision speed (V1) was assumed. The accelerate-stop (ASD) distances under these conditions are shown on the y axis.



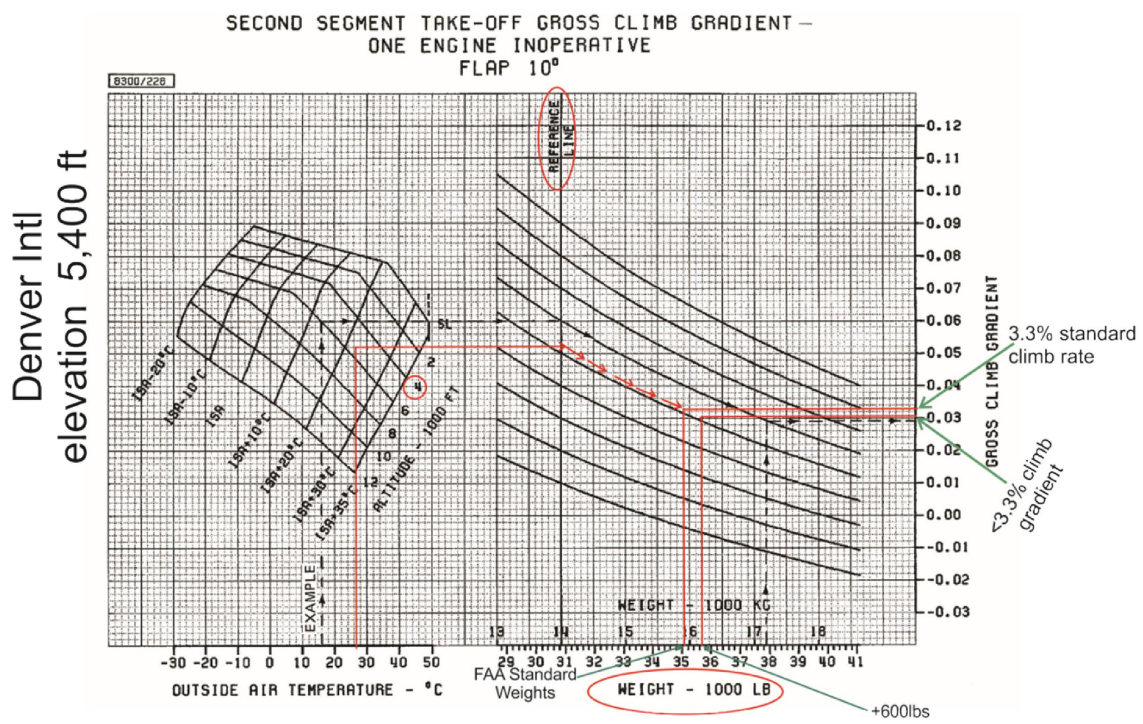
The second question asked was whether the 5.44 kilogrammes excess weight per passenger could diminish climb performance such that the flight path on departure intersects with rising terrain in the event of an engine failure for an aircraft with two power plants. A scenario involving a charted departure procedure (Denver Eight (Federal Aviation Administration, 2015c)) from Denver International airport (elevation 1,646 metres) at a temperature of 28°C and requiring a standard (Federal Aviation Administration, 2014) climb



gradient (61 metres per nautical mile equivalent to 3.3%) was created. For the 50 passenger seat capacity aircraft at full occupancy and at a take-off weight of 15,921 kilogrammes (inclusive of standard passenger weights), the 3.3% climb gradient was met (Figure 3). However, addition of 272 kilograms (50 passengers X 5.44 kilogram each) yielded a gross climb gradient less than the required 3.3% potentially leading to a collision with surrounding rising terrain. Again, the aircraft weight inclusive of the increased passenger load was within the maximum take-off weight limit (19,461 kilogram) specified for this aircraft.

**Figure 3 – Diminished Climb Performance for a Transport-Category Aircraft Based on Passenger Weight Under-Estimation**

The climb performance for a medium-cabin size, two-engine, transport-category aircraft (50 seat capacity) departing from Denver International airport (field elevation 1,646 m) via the charted (Denver Eight) procedure (which requires a standard (3.3%) climb gradient) was determined using the indicated performance chart (red lines). Conditions were an ambient temperature of 28°C, a powerplant failing at or after V1 and with either standard passenger weights or with an additional 272 kg. (50 passengers X 5.44 kg. each). The corresponding gross climb gradients are shown on the right hand y axis.



#### 4. SUMMARY AND CONCLUSIONS

The study herein indicates that use of standard passenger weights may lead to underestimates for aircraft operating out of states with the highest obesity rates. In turn, and of relevance to airline operations at high altitude airports, such an underestimation could potentially lead to a runway overrun or, in the event of engine failure, the inability to clear

rising terrain or obstacles.

Standard passenger weights, in current usage, are based on nation-wide measurements made in 1999-2000. However, these nation-wide data do not take state-specific differences into account. The present study indicates that the standard passenger weight of 78.9 kg. (excluding 7.3 kg. for carry-on luggage) under-estimates by 5.4 kg. the average passenger weight for the ten most obese states. For the most obese state (Mississippi) this under-estimation rises to 6.4 kg. per capita.

The conclusions herein are based on conservative estimates in two respects. First, obese state-specific passenger weights employed in this study from the NHANES data were generated using nation-wide average weights for the major ethnic groups adjusted for the state's racial group composition. The fact that the NHANES data were almost identical (84.4 vs. 83.9 kg.) to the self-reported BRFSS weights and that self-reported data almost invariably represent under-estimations (Shiely et al., 2010) argue in favour of this point. Second, the current study assumed "book value" aircraft performance, computed by the manufacturer for a new aircraft. Time in service however results in aircraft performance degradation (increased drag due to e.g. ill-fitting seals, slats, flaps, bird strikes) (Airbus, 2002) which in turn would create longer accelerate-stop distances and a more shallow climb gradient.

Although airlines have curtailment programs which are more restrictive than the loading envelope generated by the aircraft manufacturer, it is unlikely that such a program compensates for the aforementioned weight under-estimations. Curtailment programs are not designed regarding passenger over-loading. Typically, such programs are utilized to consider in-flight movement of passenger/crew or service carts, fuel transfer/usage or for cargo or seating variation (AC 120-27E Section 3).

The author is aware of several limitations of this study. First, the passenger manifest might also include individuals from states for which obesity rates are lower. In such cases, the degraded aircraft performance calculated herein would be offset by the lighter passenger load. Second, the flight models herein assume that passengers are comprised entirely of persons aged 18-65 years of age. The lower age limit is probably not unreasonable for operations during periods when schools are in session. Conversely, the upper limit of 65 years of age may be conservative due to increasing longevity of the US population (National Institute on Aging, 2011). However, re-analysis of NHANES data increasing the upper age to 70 years revealed no change in the derived state weights. Third, there is the assumption that passengers across all socio-economic levels have an equal opportunity to fly. This may

not be the case despite the 45% decline in air fares prices (in real-terms) since airline deregulation (Smith and Cox, 2008). Accordingly, if there is skewing of the average passenger weight data towards lower social-economic groups and such individuals have a lower financial access to this transportation mode the adverse impact on aircraft performance calculated herein would be over-estimated.

Nevertheless, it is well recognized that aviation accidents are often due to an adverse conjunction of multiple active (e.g. high altitude airport, high ambient temperature, an aircraft at full occupancy) and latent (e.g. passenger load deviating from standard passenger weights) causal factors (Reason, 1990), each one necessary but singly insufficient to yield a mishap. While for most flights one, or more of these conditions, would not be met, a convergence of these factors, (considering the high volume of regional airline operations -4.38 million for 2013 (Regional Airline Association, 2015)), could create a trajectory of opportunity ultimately culminating in an accident (Reason, 1990).

Taken together the data suggest that caution should be exercised in using standard passenger weights based on nationwide measurements for states prone to obesity. Strategies to address this issue include operators utilizing an on-board weight and balance system or implementing a region-specific survey of passenger weights per AC 120-27E. Moreover with a trend for increasing obesity across many developed countries (Ono et al., 2015), the findings herein likely impact operations for carriers outside the confines of the United States.

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