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General Aviation Accidents Related to Exceedance of Airplane Weight/Center of Gravity Limits

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ABSTRACT

Background: Obesity, affects a third of the US population and its corollary occupant weight adversely impacts safe flight operations. Increased aircraft weight results in longer takeoff/landing distances, degraded climb gradients and airframe failure may occur in turbulence. In this study, the rate, temporal changes, and lethality of accidents in piston-powered, general aviation aircraft related to exceeding the maximum aircraft weight/center of gravity (CG) limits were determined.

Methods: Nation-wide person body mass were from the National Health and Nutrition Examination Survey. The NTSB database was used to identify accidents related to operation of aircraft outside of their weight/CG envelope. Statistical analyses employed T-tests, proportion tests and a Poisson distribution.

Results: While the average body mass climbed steadily ($p<0.001$) between 1999 and 2014 the rate of accidents related to exceedance of the weight/CG limits did not change ($p=0.072$). However, 57% were fatal, higher ($p<0.001$) than the 21% for mishaps attributed to other causes/factors. The majority (77%) of accidents were due to an overloaded aircraft operating within its CG limits. As to the phase of flight, accidents during takeoff and those occurring enroute carried the lowest (50%) and highest (85%) proportion of fatal accidents respectively.

Conclusion: While the rate of general aviation accidents related to operating an aircraft outside of its weight/CG envelope has not increased over the past 15 years, these types of accidents carry a high risk of fatality. Airmen should be educated as to such risks and to dispel the notion held by some that flights may be safely conducted with an overloaded aircraft within its CG limits.

Highlights:

- the rate of weight/CG-related general aviation accidents is static since 1999,
- weight/CG-related accidents are more often fatal than those due to other causes,
- of all phases of flight, the highest proportion of fatal accidents are enroute,
- the majority of accidents are due to an overloaded aircraft within its CG limits.

Keywords: general aviation accidents, aircraft weight and balance, obesity.

1.0 INTRODUCTION

Obesity (body mass index of $\geq$30 kg/m^2 [Krueger et al., 2014]) is at epidemic proportions in the United States affecting a third of the population (Center for Disease Control [CDC], 2015a; Flegal et al., 2012). Occupant weight, as a corollary of obesity, is germane to safe flight operations (FAA, 2007) especially for general aviation (all civilian aviation apart from operations involving paid passenger transport) where usable payloads are modest. Indeed, the limited usable loads for general aviation (even more restrictive for light sport aircraft [Pagan et al., 2006]) is best exemplified by the four seat Cessna Skyhawk (the most popular single engine aircraft manufactured, which fully fueled, is limited to 600 lbs. for occupants and cargo (Cessna, 2015). For safe flight operations, airplane loading should not exceed the maximum certified weight specifications and be within the center of gravity (CG) limits, data documented by the manufacturer (Federal Aviation Administration [FAA], 2007) as part of aircraft certification.

Increased aircraft weight, whether attributed to the occupants, accompanying cargo or both, adversely affects aircraft performance in a variety of flight parameters. For example, longer takeoff and landing distances are evident for a heavier aircraft and climb gradients are degraded (FAA, 2007, 2008). The consequence of such decreased performance could be a runway excursion (of particular concern when the runway is followed by descending terrain or water) or the inability to clear rising terrain in the flight path. Moreover, airframe failure may occur under turbulent flight conditions where the aircraft is loaded beyond its maximum certified weight or outside of its CG limits (FAA, 2007). Importantly, the aforementioned weight-dependent performance degradation is further exacerbated by a performance penalty associated with an aging aircraft. As of 2014, the average age of the general aviation, single engine aircraft exceeds 30 years (General Aviation Manufacturers Association, 2014). Performance of aging aircraft often diminishes from that stated in the pilot operating handbook/flight manual largely due to airframe deterioration (causing parasitic drag), weight gain (e.g. addition of after-market products, detritus) and reduced engine performance (Airbus, 2002; FAA, 2007). Finally, exceeding the CG limits of an aircraft may make recovery from an aerodynamic stall impossible due to loss of elevator control authority (FAA, 2007).

A final emerging concern is the recent proliferation of non-FAA approved software applications for aircraft weight-CG determinations. These allow for an expedient determination of aircraft weight and CG location in a non-arduous manner compared with a standard loading graph provided in the pilot operating handbook/flight manual. However, these applications utilize a generic aircraft not taking into account modifications (e.g. new avionics, air-conditioner, residual wiring) which alters usable loads/CG limits for the end user.

Currently, there is little peer-reviewed published research on general aviation accidents related to exceeding the allowable certified weight and/or the CG limits. The comprehensive Joseph T. Nall Report (Kenny, 2015) (hereafter referred to as the Nall Report) provides data for only weight-related general aviation accidents which occurred during the takeoff/climb phase of flight and for which density altitude was a factor. Moreover, the high obesity rates for the American population (Flegal et al., 2012) (increasing the potential for aircraft over-loading), the proliferation of non-FAA-approved weights and balance software applications, and the degraded performance associated with aircraft aging are of particular concern. Therefore, the current study was undertaken to determine: the rate, temporal changes, and lethality of accidents in piston-powered, general aviation aircraft related to exceeding the maximum aircraft weight/CG limits.

2.0 MATERIALS AND METHODS

2.1 Procedure

Body mass for persons age 16 years of age or older were derived from measurements made by the National Health and Nutrition Examination Survey (NHANES) (CDC, 2015b), a survey of the non-institutionalized US population. Body mass data were adjusted using the mobile exam center (MEC) exam weight to correct for over-sampling and non-response

(Centers for Disease Control and Prevention, 2016). Records with null weights were deleted from the study.

The NTSB Access database (Oct 2015 release) was downloaded (National Transportation Safety Board, 2015) and queried for accidents in piston-powered (1-2 power plants) airplanes operating under 14 CFR Part 91. The term weight was included in the query of the narrative cause field of the database. Search criteria were used to exclude accidents involving: air medical flights, aerial observation or application, airshows, flight instruction, airdrops, glider tows and flight tests. The narrative causes of the exported data were manually parsed for accidents unrelated to exceedance of aircraft weight/CG limits (e.g. crankshaft counterweight) which were subsequently deleted. To be included in the current study, either an exceedance of the maximum certified gross weight and/or the CG limits had to be cited by the NTSB report (probable cause section) as causal or a factor in the accident. Annual fleet activity for piston-powered general aviation aircraft was obtained from the General Aviation and Part 135 Activity Surveys (FAA, 2015). A fatal accident was any in which one, or more, occupants perished within 30 days of the crash as defined following 49 CFR 830 (Electronic Code of Federal Regulation, 2010).

2.2 Statistical Analysis

All statistical analyses were performed using SPSS (v22) software. A p value of <0.05 was used as cut-off for statistical significance.

An Independent Samples T-test was used to determine if the weighted, average nation-wide person body mass ($\geq$16 years of age) for a specific period differed from the prior period. Equal variances were not assumed when Levene’s Test for Equality of Variances was statistically significant ($p<0.05$).

A generalized linear model with Poisson distribution (log-linear) was employed to determine if the rate of accidents ascribed to exceedance of maximum weights and/or CG changed relative to the initial period (1988-1994). The natural log of the annual fleet activity for piston-powered aircraft averaged over the indicated period was used as an offset.

Contingency tables employed Pearson Chi-Square (2-sided test) to determine where there were statistical differences in proportions. If the expected minimum count was less than five the Fisher's Exact Test was used instead (Field, 2009). P values for cells in multinomial tables were derived from adjusted standardized residuals (Z-scores) in post-hoc testing.

3.0 RESULTS

3.1 Increase in Nation-wide Person Weight in the USA.

Temporal changes in body mass data for the US population was first determined. Towards this end, NHANES data (CDC, 2015b), collected over consecutive two year periods as part of a continuous program implemented in 1999 (CDC, 2015b) were employed. The body mass of the average American steadily climbed over the NHANES continuous program (Figure 1A). For 1999-2000, the average person body mass was 174.3 lbs. increasing to 181.5 for the years 2013-2014. Across the study period, increases in body mass between consecutive periods were strongly statistically significant ($p<0.001$).

3.2 Rate of Accidents Related to Aircraft Weight/CG Limit Deviations.

The increasing body mass of the US population over time raised the question as to whether a parallel climb would be evident for the rate of general aviation accidents ascribed to operating the aircraft outside of its weight/CG envelope. For increased statistical power, accidents were aggregated into 5 year periods. For the initial period (1999-2003), 45 general aviation accidents (2.3/million flight hours) in piston-powered aircraft were related to exceeding the maximum certified weight and/or the CG limits (Figure 1B). However, there was little evidence of a change over time with a comparable rate (2.4/million flight hours) for the most recent period (2009-2013). A rate analysis (Poisson distribution) indicated no change in accident rate between the first and most recent periods ($p=0.072$).

3.3 Lethality of Accidents for which Transgression of Weight/CG Limits was Causal or a Factor.

The prior data indicated no temporal change in the rate of accidents related to operating the aircraft outside of its weight/CG envelope. The next question posed was whether such types of accidents vary in risk of a fatal crash compared with those unrelated to weight/CG exceedance. To answer this question, the fraction of fatal accidents related to exceeding the approved weight and/or CG limits was then compared with that for mishaps ascribed to any other reason. Hereafter, the query period was extended prior to 1999 (the first year of the continuous NHANES survey) to 1988 to increase the robustness of statistical testing. The latter year was chosen due to the limited NTSB database storage in the early 1980s (and prior) which precluded the inclusion of complete narratives (personal communication with Dr. Loren Groff NTSB) required for the current search strategy.

Surprisingly, of the accidents for which deviation beyond the allowable weight and/or CG limits was deemed causal or contributory, 57% were fatal (Figure 2). This was substantially higher ($p<0.001$) than the 21% for accidents unrelated to operating the aircraft outside of its weight/CG envelope.

3.4 Segregation of Accidents into those Ascribed to Exceedance of Maximum Weight or CG Limits.

The proportion of accidents related to either exceeding the maximum allowable weight, CG limit or both was then determined. Of the accidents related to operations outside of the weight/CG envelope, 266 could be categorized without ambiguity. Interestingly, the overwhelming majority (77%) of accidents were related to an overloaded aircraft operating within its CG (Figure 3). In contrast, the minority (5%) of accidents were solely ascribed to a CG located forward or aft of the designated limits (i.e. not exceeding the certified aircraft maximum weight). The low fraction of accidents ascribed to the latter scenario could reflect the fact that pilots sit at stations with set arms with the consequence that heavier pilots would not lead to an aircraft outside of its CG limits. A combination of both factors accounted for the remaining 18% of the accidents.

3.5 Fatal Accident Proportion as a Function of Excess Weight.

Anecdotally (Cook, 2015) some general aviation pilots consider operating an aircraft weighing in excess of that for which it is certified but which is within its CG limits to be safe. To address this premise, the fraction of fatal accidents was determined as a function of excess weight. Accidents related to weight in excess of that certified for the aircraft (for which the aircraft was within its CG limits) were separated into quartiles based on this parameter. From the NTSB records, the excess weight over that allowable could be quantified for 183 accidents. Interestingly, the proportion of fatal accidents (Figure 4) corresponding to aircraft in the two lowest quartiles of excess weight was higher than the third and fourth quartiles (123-230 and >230 lbs.). In fact post-hoc analysis indicated that the 123-230 lbs. overweight group was under-represented for fatal accidents (p=0.021). These data would argue against the contention that lower loads in excess of that for which the aircraft is certified are associated with a decreased risk of a fatal accident.

3.6 Categorization of Weight/CG-Related Accidents by Phase of Flight.

Accidents were then categorized by phase of flight. Not unexpectedly, the majority (77%) of all accidents related to operating the aircraft outside of its weight/CG envelope occurred during the takeoff-climb phase (Table 1). However, somewhat surprisingly, this phase of flight carried the lowest fatality rate (50%). In contrast, while accidents during the approach/landing phase were far fewer (8%) a substantially higher percentage of these mishaps were fatal (78%). Similarly, accidents occurring enroute comprised only 15% of all the accidents but nevertheless carried the highest proportion of fatal accidents (85%). In post-hoc testing, fatal accidents were over-represented in both the approach-landing (p=0.004) and enroute (p<0.001) flight phases.

4.0 DISCUSSION

It was initially hypothesized that high obesity rates for the US population combined with a proliferation of non-certified FAA software applications for weight/balance calculations and degraded performance of an aging general aviation fleet would conspire to increase the rate of accidents related to exceedance of weight/CG limits. However, there was little evidence of such a trend at least for piston-powered aircraft operating under 14 CFR Part 91 regulations. Nevertheless, the high fraction of fatal accidents (50-85% depending on the phase of flight) related to over-loading and/or deviating from the CG limits of the aircraft was surprising and disconcerting as these proportions are well above the 18-22% cited for all causes of general aviation accidents (Kenny, 2015; Wiegmann and Taneja, 2003).

The high proportion of fatal accidents related to operating the aircraft outside of its weight/CG envelope merits discussion. Several potential reasons could contribute to the lethality of such accidents. First, increased aircraft weight demands increased lift; as a corollary landing speed increases (FAA, 2008). Consequently and since the impact force exerted on the occupants is a square of the velocity (Freitas, 2014), crash forces exerted on occupants of an aircraft loaded beyond its maximum certified weight is increased. Second, a degraded climb gradient could result in controlled flight into terrain which carries a 12 fold elevated risk of a fatal outcome (Thomas et al., 2000) at least for air taxi operations in Alaska. Third, an aerodynamically stalled condition for an aircraft loaded outside of its aft CG limit (FAA, 2007) may lead to a “flat spin” a condition difficult to recover from. Finally, airframe failure may occur under turbulent flight conditions where the aircraft is loaded beyond its maximum certified weight (FAA, 2007).

Noteworthy was that the majority of accidents for which the aircraft was loaded beyond its approved maximum weight but within its CG limits were fatal. Anecdotally, a misconception among some general aviation pilots (Cook, 2015) is that an over-gross aircraft within its CG limits may be operated safely. However, there was little evidence to support such a contention insofar as the fraction of fatal accidents was not diminished for a lightly over-loaded aircraft compared with a heavily overloaded aircraft.

Considering the ascendency in obesity for the US population the observation that this trend was not paralleled by a temporal rise in general aviation accidents related to transgression of the aircraft weight/CG limits was unexpected. Furthermore, the proportion of all accidents related to aircraft weight limit deviations was not elevated for the ten states with the highest obesity rates in comparison with the ten least obese states (data not shown). Several factors might explain these unexpected findings. First is that airmen are practicing due diligence as part of the pre-flight weight/CG calculations mandated per 14 CFR91.103. Another more plausible explanation is that, unlike revenue-driven operations conducted under 14 CFR Part 121, general aviation activity may be predominated by operations made at less than full occupancy (e.g. two of four occupied seats). In such an instance the aircraft weight, inclusive of obese occupant(s), may still be within the maximum allowable weight.

Although the author is unaware of any peer-reviewed publications on the subject of general aviation accidents related to aircraft weight/CG limit exceedance, according to Kenny, data on total and fatal accidents regarding aircraft overloading is available via the Nall Report (Kenny, 2015). Indeed, the 22rd-24th editions of this report covering general aviation accidents over the 2010-2012 period documented that for mishaps related to operating an aircraft outside of its weight/CG envelope, 13% (4 of 31) were fatal. This proportion was lower than the 57% for the period spanning the current study. Several reasons could contribute to this divergence: (a) differing search strategies, (b) and/or varying time frames, (c) and/or the Nall Report restricting its count to accidents during the climb phase of flight for which density altitude was involved. Indeed, the present study showed that the lowest fraction of fatal accidents was evident for the take-off-climb phase. In contrast, accidents occurring enroute, not addressed by the Nall Report, carried the highest proportion of fatal accidents (85%).

The current study was not without its limitations. First, it represented a retrospective investigation. Second, it was often unclear from the NTSB report whether the exceedance of the aircraft weight limits was due to the human occupants or the cargo itself. Third, if there was a bias in the number of totally destructive (and hence fatal) accidents towards the higher end of the excess weight spectrum (Figure 4) assessments of weights for the corresponding subset of accidents may not have been possible. Such a scenario would lead to an under-representation of the number of fatal accidents at higher loads in excess of the maximum approved (Figure 4). Finally, it is possible that the search strategy used herein missed reports related to aircraft weight/CG limit deviations.

In conclusion the rate of general aviation accidents in which the aircraft was operated outside of its weight/CG envelope was static over time. Nevertheless, and importantly, these types of accidents carry a higher risk of fatality compared with mishaps resulting from other causes. Increased emphasis needs to be placed on airman education to dispel the notion held by some (Cook, 2015) that flight operations with an overloaded aircraft within its CG limits are safe as well as the limitations of using non FAA-approved weight/CG software applications. As a final note, airmen should exercise caution in using self-reported occupant weights for weight/balance determinations as these often represent under-estimates (Shiely et al., 2010).

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FIGURE LEGENDS

Figure 1.Increase in Nation-Wide Body Mass and Rate of General Aviation Accidents Related to Operations Outside of the Weight/CG Envelope.

PANEL A. Average body mass (lbs.) for Americans 16 years of age and older are shown for the indicated periods. Population sample sizes for the 1999-2000, 2003-2004, 2005-2006, 2009-2010 and 2013-2014 periods were 5,487, 5,791, 5,807, 6,649 and 6,199 respectively. A T-test was used to determine if the average (weighted) body mass per capita differed statistically between consecutive time frames. * p<0.001. PANEL B. The accident rate for aircraft operating outside of the weight/CG envelope is shown for the indicated periods. A Poisson distribution was used to determine if the rate of accidents differed between the initial (1999-2003) and the final (2009-2013) time periods. n, accident count.

Figure 2. Fatal Outcome for Accidents Related or Unrelated to Weight/CG Exceedance.

Accidents related (Weight/CG Limit Exceedance) or unrelated (Unrelated to Weight/CG Exceedance) to exceedance of the maximum aircraft weight and/or CG limits were categorized as fatal or non-fatal. The percentage of fatal accidents is shown. n, number of fatal accidents. A contingency table (Pearson Chi-Square) was used to determine if the difference in proportion of fatal accidents was statistically significant between the two groups.

Figure 3. Categorization of Accidents based on Exceedance of Maximum Weight or CG Limits.

Accidents related to operating the aircraft outside of its weight/CG envelope were categorized as exceeding the maximum allowable weight, CG limits or both. Seven cases were excluded from the analysis due to ambiguities in the NTSB report. n, accident count for the indicated category.

Figure 4. Relationship between Variations in Excess Aircraft Weight and Fatal Accidents.

Accidents related to a weight in excess of that for which the aircraft was certified (but for which the airplane was within its CG limit) were divided into quartiles based on the amount of excess weight. The values above the column indicated the percentage of fatal accidents for the corresponding quartile. A Pearson Chi-Square indicated an overall difference in proportions (p=0.014).

TABLE LEGEND

Table 1. Phase of Flight and Fatal Accidents.

Accidents related to operation of the aircraft outside of its weight/CG envelope were categorized by phase of flight. The enroute phase included maneuvering aircraft. A Pearson Chi-Square test indicated an overall difference in proportion of fatal accidents for the three phases of flight ($p<0.001$). The contribution of each cell (phase of flight) to the overall difference in proportions was determined using adjusted residuals (z-scores) in post-hoc testing to derive a p value.

Figure 1

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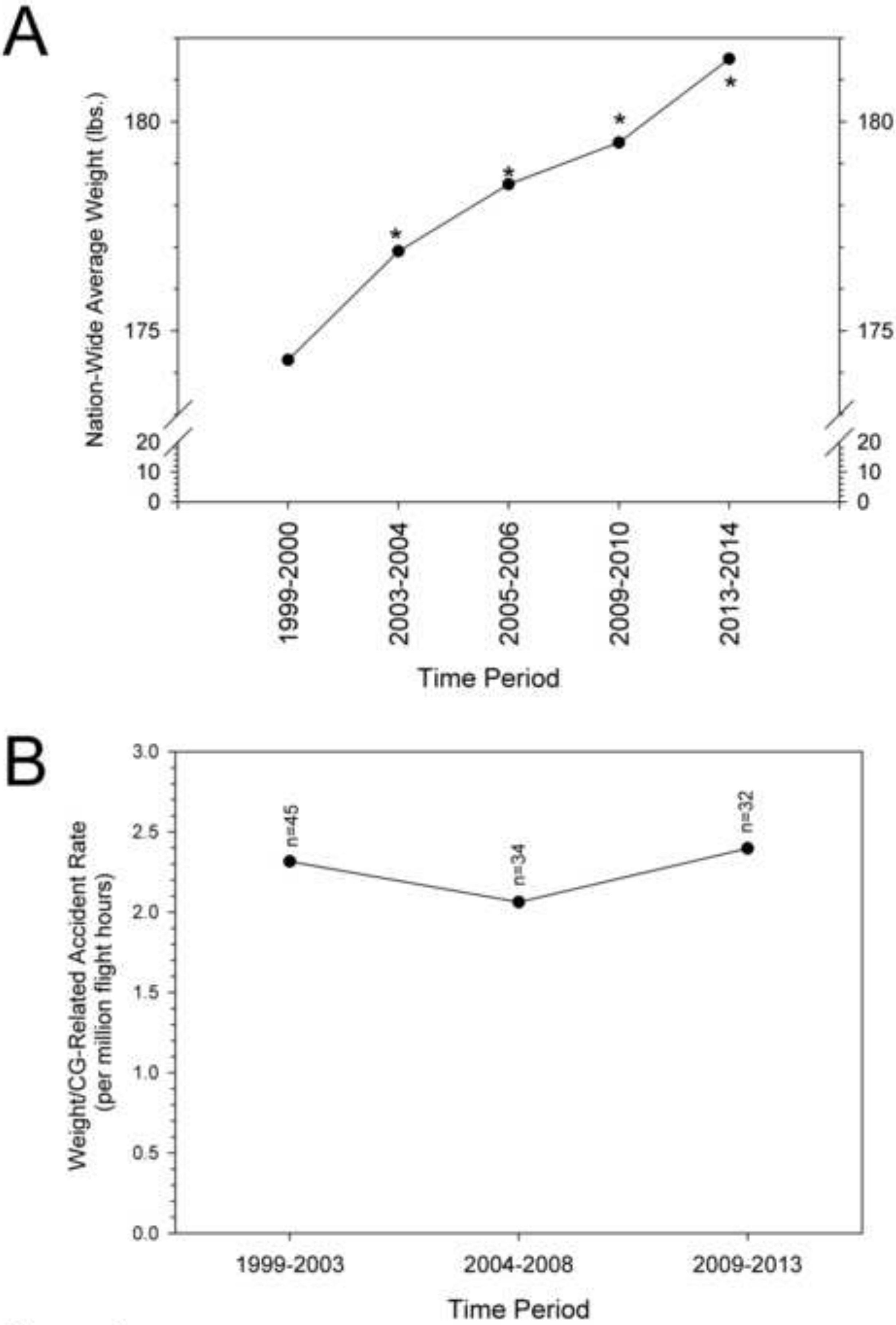

Figure 1

Figure 2

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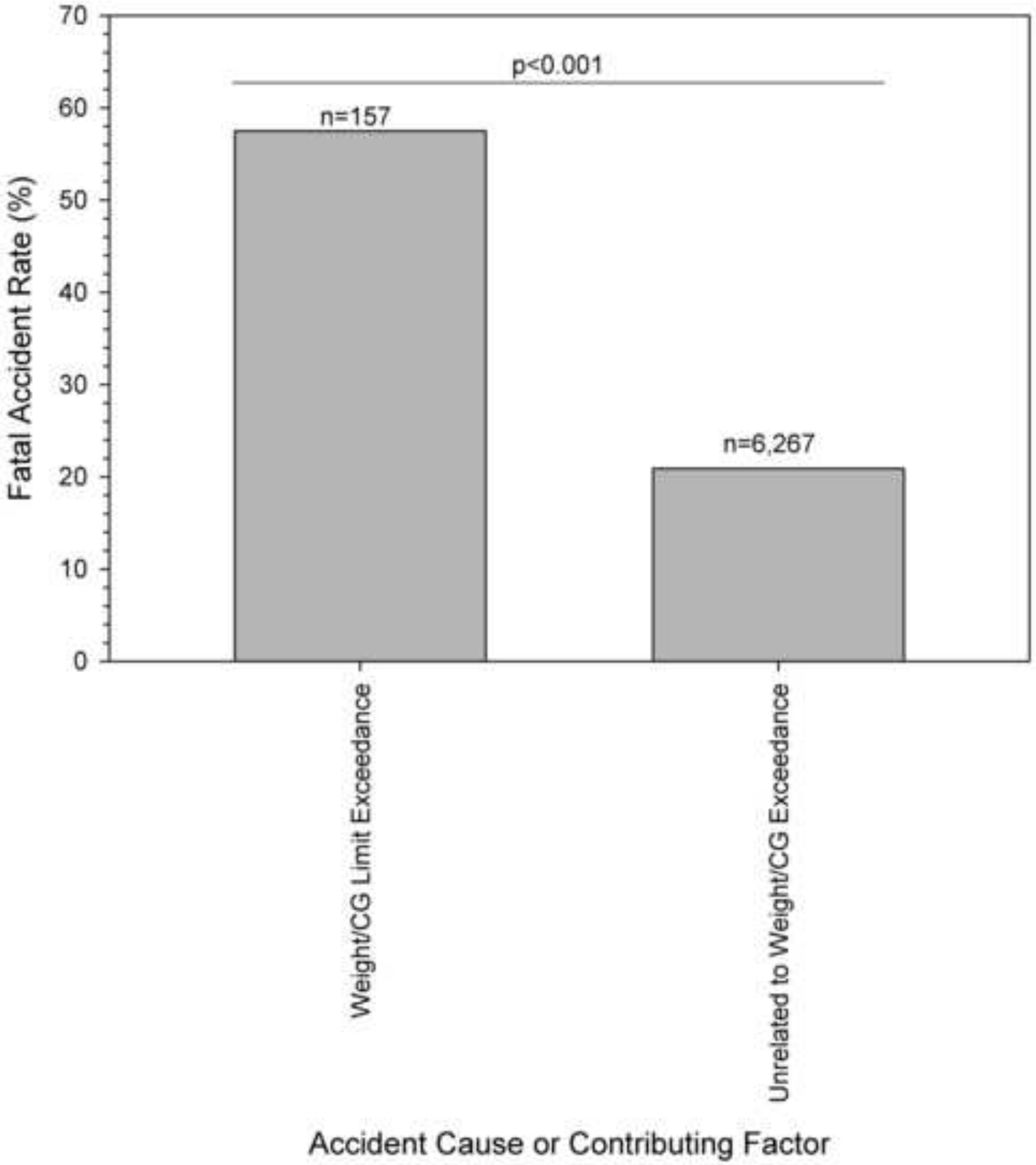
Figure 2



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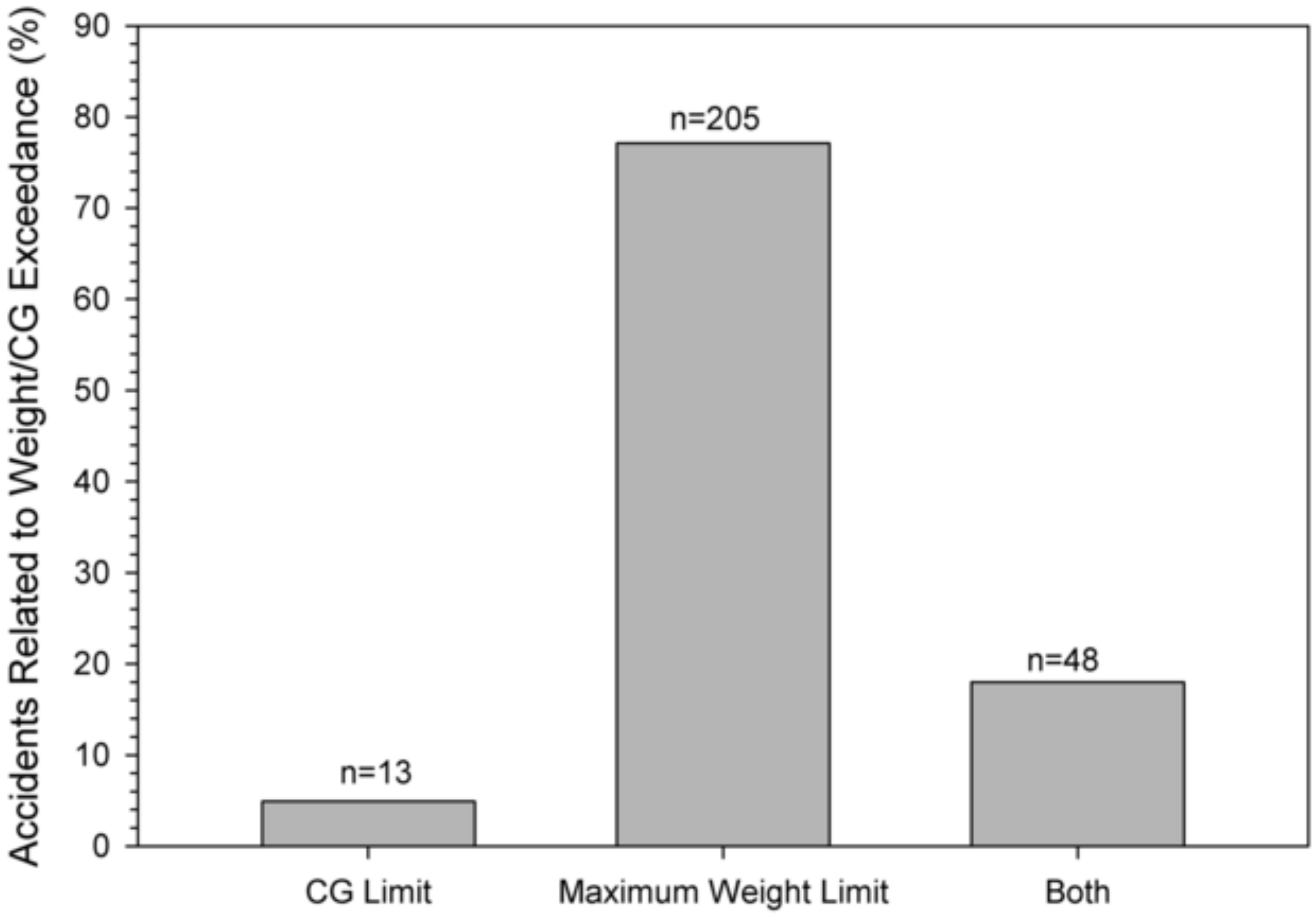

Figure 3

Figure 4

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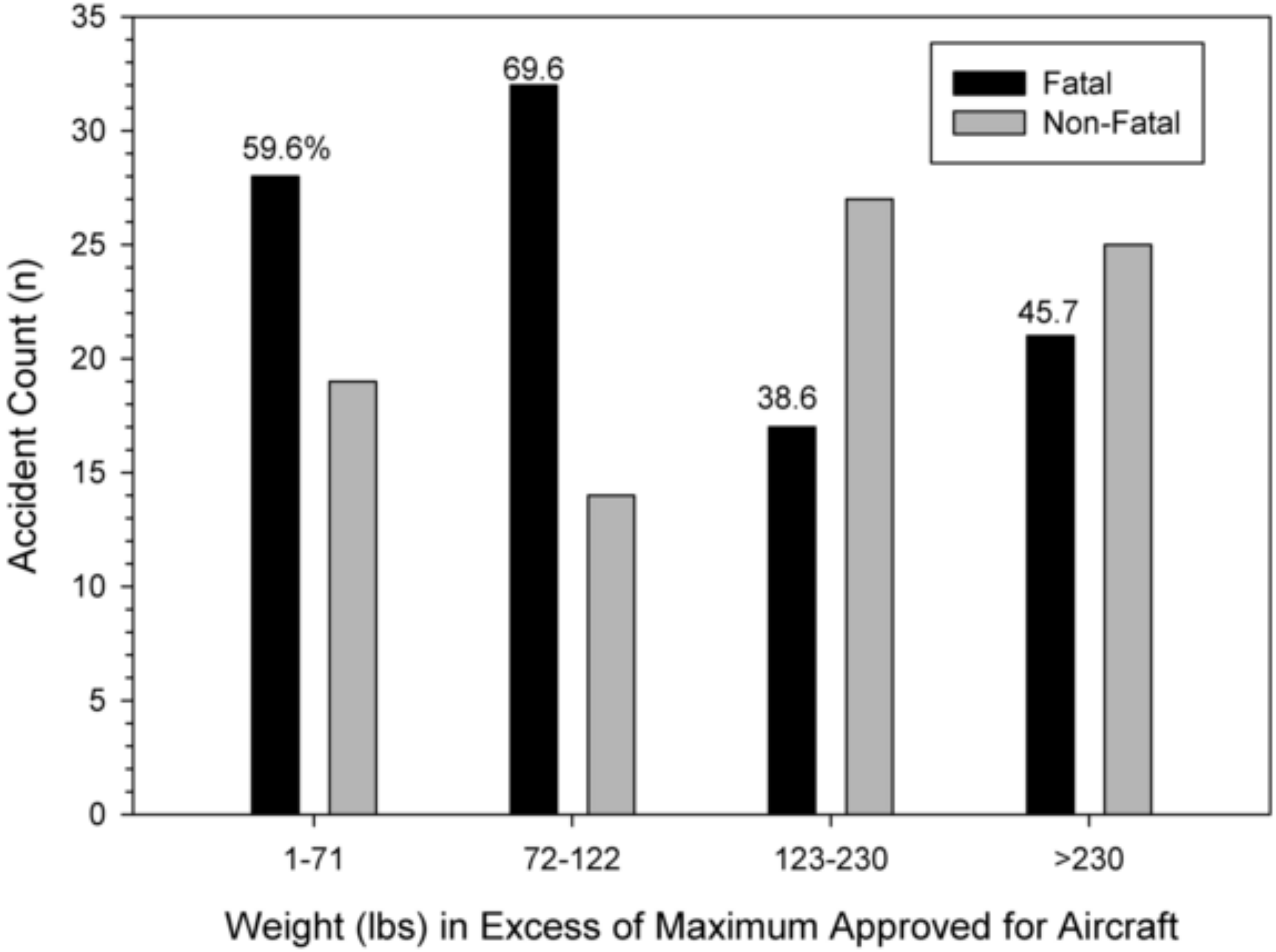

Figure 4

Table 1

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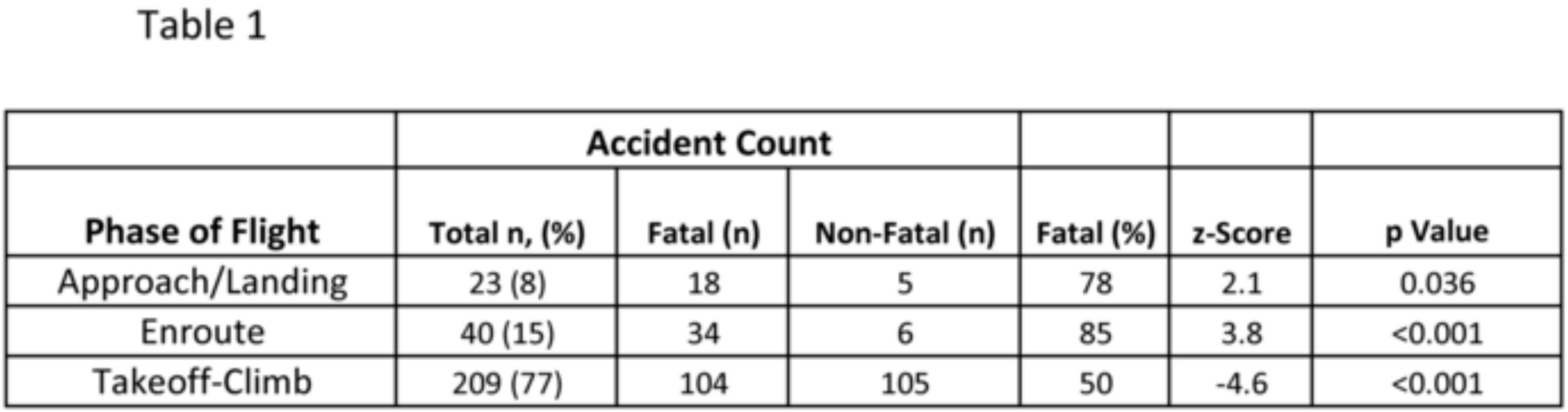

Table 1

	Accident Count					
Phase of Flight	**Total n, (%)**	**Fatal (n)**	**Non-Fatal (n)**	**Fatal (%)**	**z-Score**	**p Value**
Approach/Landing	23 (8)	18	5	78	2.1	0.036
Enroute	40 (15)	34	6	85	3.8	<0.001
Takeoff-Climb	209 (77)	104	105	50	-4.6	<0.001