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VEHICLE WEIGHT DISTRIBUTION AND OCCUPANT LOADINGS

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ABSTRACT
The Federal Aviation Administration (FAA), Federal Transit Authority (FTA) and Coast Guard instituted or recently proposed an increase in the average passenger weight used to calculate load and conduct safety analysis and tests in multiple modes of transportation. The increased passenger weight requirements were created in response to the Center for Disease Control's (CDC) documented rise in weight among the country's citizens and followed crash or failure incidents in which a cause was overweight equipment. The current certification requirements under CFR 49, Part 567 state that Gross Vehicle Weight Rating (GVWR) of a motor vehicle shall not be less than the sum of the unloaded vehicle weight, rated cargo weight and 150 pounds times the number of designated seating positions. Actual occupant weight distributions versus certified weight per occupant seat causes a potential conflict between a vehicle's in-use weight versus its certified GVWR. This paper is distinct in its contrasting of the 150 pound occupant standard in relation to documented actual occupant weight, clothing, personal items and baggage. A midsized bus example was used to explore the statistical probability that adult passengers and rated cargo would result in weight distributions that exceeded tire load capability, Gross Axle Weight Rating (GAWR), or GVWR. The unreliability of the 150 pounds per designated seat position in producing loaded weight under gross weight ratings was demonstrated for a midsized bus. Results demonstrated that load conditions and usage restrictions are identifiable and decrease the probability of operating in a condition that exceeds a weight rating. Weight assumptions that take into consideration well documented transportation industries baggage weight were identified as potentially confounding additional weight that may contribute to overload of midsized buses.

INTRODUCTION
The current Certification requirements under 49CFRPart 567 state that Gross Vehicle Weight Rating (GVWR) of a motor vehicle shall not be less than the sum of the unloaded vehicle weight, rated cargo weight and 150 pounds times the number of designated seating positions [1]. In describing its understanding of the genesis of the 150 lb standard the Federal Transit Administration (FTA) stated: "Although NHTSA [National Highway Traffic Safety Administration (NHTSA)] did not provide an explanation for this figure [150 pounds] in its 1971 rulemaking documents, NHTSA staff believes their average was based on data derived from the National Health Examination Survey for 1960 - 1962" [2].

The average reported weight from the National Health Survey for 1960 - 1962 for men and women from 18 to 79 years old was 168 pounds and 142 pounds, respectively. The survey reported cumulative percentile for men and women as shown in the top two rows of Table 1 and plotted in Figure 1. Certainly, data from the National Health Survey for 1960 – 1962 would support an average around 150 pounds – though the calculated average for all adults (assuming equal men and women) from the survey was 155 pounds and the calculated median was 153 pounds.

The 150 pound convention for passenger load may also have been derived from longstanding industry practice as demonstrated in the 1934 SAE paper titled, "Weight Distribution of Motor Vehicles," in which two examples of motor coach weight analysis use exactly 150 pounds per passenger [4]. The current FMVSS 110, which specifies tire selection to prevent overload, defines normal occupant weight as 68 kg (150 pounds) and uses 68 kg per designated seat position in the definition of Vehicle Carrying Weight [5].

The Federal Aviation Administration upgraded its Advisory Circular (AC), AC-120-27D, Aircraft Weight and Balance Control in August of 2004 [6]. The AC includes a section on Standard Average Passenger Weights that, according to the AC,

18 - 79 Years	Mean	Percentile (weight in pounds)												
		1th	5th	10th	20th	30th	40th	50th	60th	70th	80th	90th	95th	99th
Men	168	112	126	134	144	152	159	166	173	181	190	205	217	241
Women	142	93	104	111	118	125	131	137	144	152	164	182	199	236
All	155	98	110	119	127	136	145	153	159	169	181	196	213	234

Table 1. Data from the National Health Survey for 1960 - 1962.

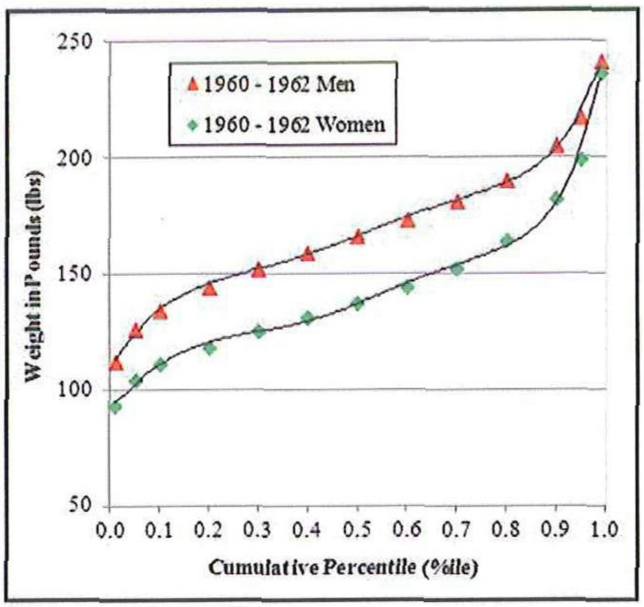

Figure 1. Data from the National Health Survey for 1960 - 1962.

was based on data from the 1999 and 2000 National Health and Nutrition Examination Survey (NHANES) conducted by the Center for Disease Control (CDC). NHANES data are the primary source of body measurement and related health and nutrition data for the civilian, noninstitutionalized U.S. population [7]. The Standard Average Adult passenger weight was 190 pounds. Average Adult Male and Female Passenger weight was 200 pounds and 179 pounds, respectively. Child weight (2 years to less than 13 years of age) was 82 pounds. According to the Advisory Circular, "the standard average passenger weights include 5 pounds for summer clothing, 10 pounds for winter clothing, and a 16-pound allowance for personal items and carry-on bags." Where no gender is given, the standard average passenger weights are based on the assumption that 50 percent of passengers are male and 50 percent of passengers are female. The AC also requires checked baggage average weight of at least 30 pounds.

By stripping away included weights, the average weights of FAA AC-120-27D, later duplicated in AC-120-27E (6/10/05) [8], revealed an assumed average adult passenger weight of 169 pounds and average male and female adult passenger weights of 179 pounds and 158 pounds, respectively. Youth above 12 years of age are treated as adults and children 2 years to 12 years of age have a unique average weight of 82 pounds and 87 pounds in summer and winter, respectively.

In December 2010 the United States Coast Guard amended its regulations governing the Assumed Average Weight per Person (AAWPP) to 185 pounds. Under Title 46 of the CFR the prior AAWPP was 160 pounds, except vessels operating exclusively on protected waters and carrying a mix of men, women, and children could use an AAWPP of 140 pounds per person. A weight of 75 kilograms (165 pounds) per person was required for damage stability calculations. According to the Coast Guard the prior weights were established in the 1960s and had not been updated since. The Coast Guard noted, "Updating regulations to more accurately reflect today's average weight per person will maintain intended safety levels by accounting for this weight increase" [9].

In March 2011 The Federal Transit Administration (FTA) proposed to amend its bus testing regulation to more accurately reflect average passenger weights and actual transit vehicle loads. Specifically, FTA proposed to change the average passenger weight from 150 pounds to 175 pounds. In addition, because greater passenger weight was associated with greater passenger space requirements, the FTA proposed to change the floor space occupied per standing passenger from 1.5 to 1.75 square feet. The FTA noted that the establishment of a more accurate average passenger weight was of Department-wide [USDOT) interest, and initiated a new average passenger weight only after consultations within the Department. To avoid conflicts with NHTSA's definition of Gross Vehicle Weight FTA proposed a new definition, "fully loaded weight," which incorporated the heavier and wider dimensions of the average transit bus rider [10].

The 2003-2006 National Health Statistics Report, Anthropometric Reference Data for Children and Adults: United States, 2003–2006, was based upon the National Health and Nutrition Examination Surveys (NHANES) and reported the average weight for men and women, 20 years and over, as 195 pounds and 165 pounds, respectively [11]. The survey reported cumulative percentile for men and women as shown in the top two rows of Table 2 and plotted in Figure 2. Assuming equal men and women, the calculated average for all adults from the survey was 180 pounds, and the calculated median was 174 pounds. The Anthropometric Reference Data comes from the National Health and Nutrition Examination Surveys NHANES conducted by the Centers for Disease Control and Prevention's National Center for Health Statistics (NCHS).

20 Years and over	Mean	Percentile (weight in pounds)								
		5th	10th	15th	25th	50th	75th	85th	90th	95th
Men	195	137	147	155	166	189	217	235	246	270
Women	165	111	118	124	133	156	186	208	224	250
All	180	119	130	136	148	174	203	224	238	257

Table 2. Data from the National Health Survey for 2003 - 2006.

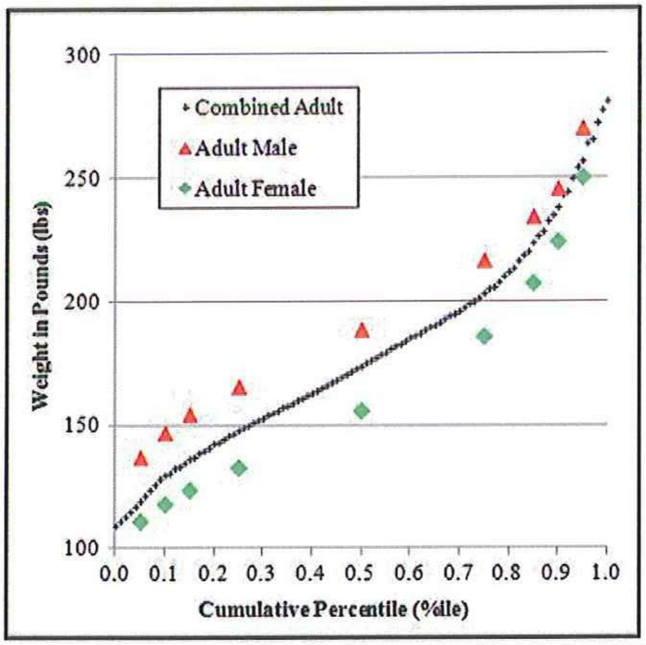

Figure 2. Data from the National Health Survey for 2003 - 2006.

METHOD

The example vehicles in this paper were 41-passenger mid-sized buses with GVWR of 26,000 pounds and a front and rear GAWRs of 10,000 pounds and 17,500 pounds, respectively. An actual bus of this type had a rated cargo load of 60 pounds. The buses had overhead cargo racks and rear storage. The overhead storage area was 20 inches deep and 12 inches tall and ran the length of the bus on both sides. The rear storage compartment, accessed by a 3 ft wide by 5 ft tall rear located door, was 3 ½ ft deep, 8 ft wide and 7 ft tall or 196 cubic feet (1466 liquid gallons) in volume. According to the Mid-Sized Bus Manufacturing Association (MSBMA) a mid-sized bus "means a motor vehicle designed to carry passengers built on a cutaway or rail chassis or on monocoque construction, under 40 feet (12.2 m) in length and having a gross vehicle weight rating class of VII (26,001 - 33,000 lb) (11,794 - 14,969 kg) or less" [12].

The model for occupant weight used the 2003-2006 CDC's Anthropometric Reference Data. Anthropometric weight statistics were reported separately for men and women (Table 2). A separate polynomial curve fit for men and women of the population's reported weight cumulative percentile was made. From the equation describing each curve fit, a combined model of an equal male to female population was statistically analyzed to generate a discrete distribution. The model of the combined population is shown in Figure 2 as the combined adult.

Prediction of the bus weight distribution from occupant load used a Monte Carlo analysis in a Microsoft Excel spreadsheet. The use of Excel spreadsheets in performing Monte Carlo analysis was described by Bartlett in his 2003 SAE Paper [15]. Weight distribution was calculated in two modules. The first module used the spreadsheet to randomly simulate, utilizing a uniform distribution, the position of empty passenger seats. If all seats were occupied, the first module was not employed. The second module assigned occupant weight for occupied seats using the discrete weight distribution of the passenger population. The method was described in more detail in the SAE Paper, "Predicting Weight Distribution from Occupant Load Using a Monte Carlo Method [16]."

In addition to the weight of occupant load, the weight of cargo load was simulated consistent with the weight rating requirements of the MSBMA Recommended Practice, Weight Distribution and Payload [12]. The Recommended Practice requires 25 pounds per occupant when a cargo compartment is present and 5 pounds per occupant when an overhead cargo rack is present. The cargo load in the cargo compartment was simulated at the center of the cargo area floor. Overhead cargo was simulated with the occupant in each occupied seat.

From the cargo and occupant load a calculation based upon Newtonian physics was performed to yield the weight per axle and weight per tire. For the dual rear wheel axle the weight per tire was calculated at the center of the inner and outer track width and divided by two (2). The calculations for load distribution were described by Sparks in his 1990 SAE Paper, Utility Vehicle Weight Problems and Design Considerations [17] and are embodied in publically available spreadsheet-based software sold by the National Truck Equipment Association (NTEA) [18].

RESULTS

Statistics of the combined adult weight model used in the simulation analysis were reported in the bottom row of Table 1 and Table 2 for 1960-62 and 2003-06, respectively. The lookup table in the simulation analysis that described the discrete distribution of the weight model had one percentile gradations.

The bus weight distribution was first calculated assuming a 150 pound occupant in each designated seat position and a rated cargo load of 60 pounds centered in the rear cargo area. Under this condition the bus was 670 pounds over the GVWR and 413 pounds over the Gross Rear Axle Weight Rating (GRAWR).

Exceeding the weight ratings was not in compliance with requirements of 49CFR567, FMVSS120 and Federal Motor Vehicle Safety Standards (FMVSS) that reference Gross Weight Ratings. FMVSS were promulgated by the National Highway Traffic Safety Administration (NHTSA) under authority of the National Traffic and Motor Vehicle Safety Act and, by definition, are minimum standards for motor vehicle or motor vehicle equipment performance [20]. Not meeting the requirements of these Federal requirements means the vehicle was not legally sold and not certifiably free of unreasonable dangers that the FMVSSs were promulgated to prevent. The MSBMA noted that, "NHTSA has indicated that the Agency considers it to be a safety defect for a manufacturer to produce a vehicle that would be overloaded by design in carrying it's (sp) intended payload" [21]. Overweight conditions have been noted previously in other similar buses as indicated by the article, "Exceeding the Gross Vehicle Weight on a Bus," in which the author stated, "I do not know of a state where you can operate a bus fully loaded with passengers, fuel, bags, ADA equipment, when that bus is heavier than its chassis manufacturer rating" [22].

Since the 150 pound per designated seat position was related to the 1960-1962 CDC anthropometric statistics, an analysis using a discrete distribution of the combined adult population from the 1960-1962 data was conducted. Statistics for the combined 1960-1962 population weight model were shown at the last line of Figure 1. In this analysis, like the analysis assuming 150 pounds per seat, each seat was modeled as occupied and a rated cargo load of 60 pounds was modeled centered in the rear cargo area. In this simulation the average result was a loaded bus that was overweight by 1093 pounds (SD = 197 pounds) with a rear axle that was overweight by 759 pounds (SD = 173 pounds). In other words, according to the simulation, when carrying 1960-1962 era adult male and female passengers about 15 percent of the time the bus will exceed the GVWR by 1297 pounds and exceed the GRAWR by 938 pounds. The simulation predicted zero chance, for the modeled loading, that the bus would be operated at weight under the GVWR or GRAWR.

A final comparison was made using a discrete distribution of the combined adult population using the 2003-2006 CDC anthropometric statistics. Each seat was modeled as occupied and a rated cargo load of 60 pounds was modeled centered in the rear cargo area. Statistics for the combined 2003-2006 population weight model were shown at the last line of Figure 2. In this simulation on average the bus was overweight by 2079 pounds (SD = 260 pounds) with a rear axle that was overweight by 1569 pounds (SD = 230 pounds). In other words, according to the simulation, when carrying 2003-2006 era adult male and female passengers about 15 percent of the time the bus will exceed the GVWR by 2349 pounds and exceed the GRAWR by 1809 pounds. If the MSBMA recommended rated load per passenger (30 pounds per passenger for the buses cargo space) was simulated, the gross overweight condition was increased by 1200 pounds.

For illustrative purposes an analysis was undertaken to uncover restrictions in loading of the bus that might optimize its occupant and cargo carrying capability, and reduce overweight operations. For the modeled bus using the combined adult population weight distribution, no restrictions on seating location, 25 pounds rear cargo per occupant and five pounds overhead cargo per occupant, the condition with an average simulated rear axle weight under the Gross Rear Axle Weight Rating (GRAWR) occurred by modeling the carrying of no less than 16 fewer passengers than seating capacity or a total of 25 adult passengers. In other words, roughly half the time that the bus is used to carry adult men and woman with 16 empty seats, it will be overweight on the rear axle.

In instances when the bus can be used by blocking the rear row of five seats and not carry any stowed cargo the maximum capacity assuming the combined adult population weight distribution is no less than 11 fewer passengers than the seating capacity or a total of 30 adult passengers. In this condition the GVWR limits the maximum number of passengers.

The maximum seat capacity with cargo can be achieved by moving the contents of the rear cargo compartment to the position of the front row seats and blocking the rear row of five seats. Under this condition no fewer than 15 fewer passengers than seating capacity or a total of 26 passengers and cargo can be carried without producing an average simulated weight greater than a limiting maximum weight rating. In this case of maximum seating with cargo the GVWR limits the maximum number of passengers.

DISCUSSION

The NHANES anthropometric weight data is obtained with subjects wearing a standard examination gown, which consists of a disposable shirt, pants, and slippers. Only underpants are worn beneath the gown [19]. The reported NHANES anthropometric weights appear to be effectively unclothed weights. Assuming equal men and women, the calculated average for all adults from the 2003-2006 survey was 180 pounds. The FAA average adult passenger weight, adjusted for clothing and carry on baggage, was 169 pounds. Without adjustment for clothing or baggage, the Coast Guard required 185 pounds, and the FTA proposed 175 pounds for its required testing. It is possible that the population modeled by each government agency differs from the general population represented by the NHANES data. The use of 150 pounds for occupant weight, except for its long standing inclusion in Federal Vehicle Certification requirements, was not supported by modern surveys of the U.S. population.

The distribution of adult weight was not symmetrical about the median. Using an average adult weight and standard deviation, assuming a normal distribution will result in simulations that underestimate the probability of an overweight condition. A demonstration of this phenomenon was the observation that the median weight of the NHANES adult men population was six pounds lighter than the average weight, and the median weight of the NHANES adult women population was nine pounds lighter than the average weight. Assuming average weight and not the underlying population distribution will result in instances of occupant weight significantly exceeding expectations.

The method for describing and simulating occupant weight distribution could be applied to unique populations. For example, a unique distribution could be developed for children in a narrow age group or sports teams. The weight distribution for high school varsity football players would be different from a church's preschool population; both would be different from a general population of youth. The 49CFR567 provides that school bus GVWRs be not less than the sum of the unloaded vehicle weight and rated cargo load where the minimum occupant weight allowance, "shall be 120 pounds per passenger and 150 pounds for the driver [1]."

All simulations described in this paper assume independent random selection of occupied seats and occupant weights. One should consider that these variables may be dependant. For example, a passenger population that draws from a common community might be more likely to sit next to each other and, in instances of related passengers, body size may be more likely similar.

In the example of this study, an average baggage weight associated with the type of cargo compartment was utilized. Twenty-five pounds per occupant in the cargo compartment was modeled, and five pounds per occupant was added as required by the MSBMA Recommended Practice because the bus had a storage area and overhead storage, respectively. The FAA's CA-120-27E included 16 pounds per average occupant weight for in-cabin personal items and 30 pounds per checked baggage stored in the luggage compartment. Data from the FAA, based upon its analysis of several surveys conducted on 10 to 19 seat airplanes, reported personal items on average weighed 15.1 pounds with a standard deviation of 8.2 pounds; checked bags on average weighed 28.9 pounds with a standard deviation of 10.8 pounds and; heavy checked bags on average weighed 58.7 pounds with a standard deviation of 7.2 pounds. The use of a normal distribution for per-occupant cargo would be an improvement to simulations of possible load distributions. Further, since it is unlikely that a cargo load's center of gravity location is always positioned at the center of a cargo area, a distribution of cargo CG location should be considered.

The examination of occupant and cargo conditions that resulted in overload used average simulated weight as the evaluation criteria. Meaning, for a given condition or assumption, roughly half of the simulated loads resulted in overload and half did not result in overload. Average simulated weight was used consistent with regulatory requirements that sanction use of average weight, but the paper does not provide analysis that substantiates the adequacy or inadequacy of the use of average weight or an average weight criteria. The simulation method allows for the computation of statistical percentiles of predicted weight for given vehicle occupancies. For example, it is possible to determine the occupancy and loading characteristics that would produce vehicle weights within one standard deviation, or at approximately the 85 percentile, of the average weight.

This paper addresses the modeling of occupant weight distributions and simulation of vehicle weights in comparison to maximum weight ratings of a mid-sized bus's components. The paper does not attempt to address the legal or safety implications of exceeding or complying with maximum weight ratings or the effectiveness of current standards that used average weight as a constitute.

CONCLUSION

A method was described for combining reported U.S. population weight distributions into a statistically derived model. The model was based upon combining polynomial curve fits of male and female weight data and generating a table with one percentile increments for use in simulations of a mid-sized bus weight.

Simulations of a mid-sized bus weight were conducted. The simulations assumed a bus full of occupants using a variety of occupant weight models and randomly selected occupied seats in instances when the bus was not full of occupants. The simulations randomly assigned occupant weights according to the statistically derived combined weight distribution.

Examples illustrated how for a vehicle certified in accordance with 49CFR567 guidelines - in other words, certified under requirements of 150 pounds per designated seat position - a real population weight distribution could be evaluated and legal usage can be determined. In general for the configuration of the example bus, restricting weight at the back of the bus maximized its legal occupant carrying capability.

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