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Predicting Weight Distribution from Occupant Load Using a Monte Carlo Method

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ABSTRACT

The Federal Aviation Administration (FAA) and Coast Guard recently adapted increases in the average passenger weight used to calculate load and conduct safety analysis and tests in multiple modes of transportation. The Federal Transit Authority (FTA) has proposed similar measures. 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 (68 kg) 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. A Monte Carlo method using a midsized bus example was conducted to determine 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. A discrete distribution of occupant weight modeled on the 2006 CDC anthropometric reference data was utilized. The analysis examined buses loaded with fewer occupants than seating positions by assuming a uniform probability that a seat would be occupied. Results demonstrated that load conditions and usage restrictions can be identified that decrease the probability of operating in a condition that exceeds a weight rating.

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].

NHTSA staff members' belief that the 150 pounds average was based upon the National Health Survey for 1960 - 1962 may be correct, but data from a report of the survey [3] did not easily replicate an 150 pound average. 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.

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

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

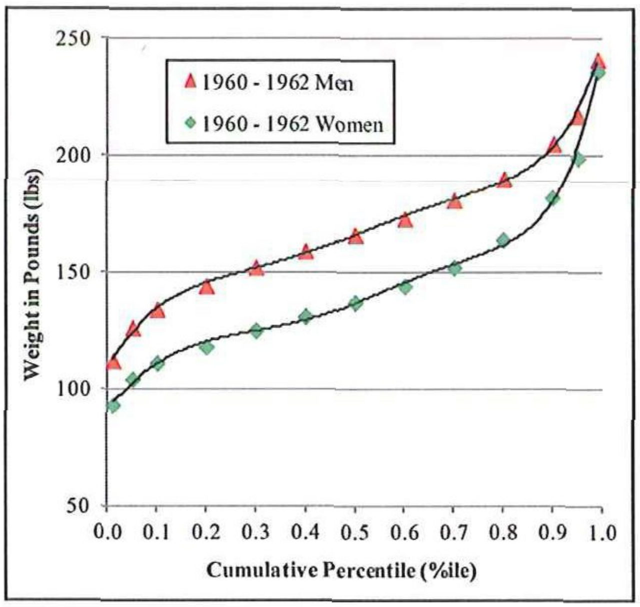

Figure 1. Data from the National Health Survey for 1960 - 1962.

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 used 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-120-27, 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, was based on data from the 1999 and 2000 National Health and Nutrition Examination Survey (NHANES) [7] conducted by the Center for Disease Control (CDC). 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 a 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], reveal 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 average weights 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, prior AAWPP was 160 pounds. This standard excluded vessels operating exclusively on protected waters and carrying a mix of men, women, and children, which 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 amending 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 it 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].

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The 2003-2006 National Health Statistics Report, Anthropometric Reference Data for Children and Adults: United States, 2003-2006, was based upon the 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 numbers of men and women, the calculated average for all adults from the survey was 180 pounds and the calculated median was 174 pounds.

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

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

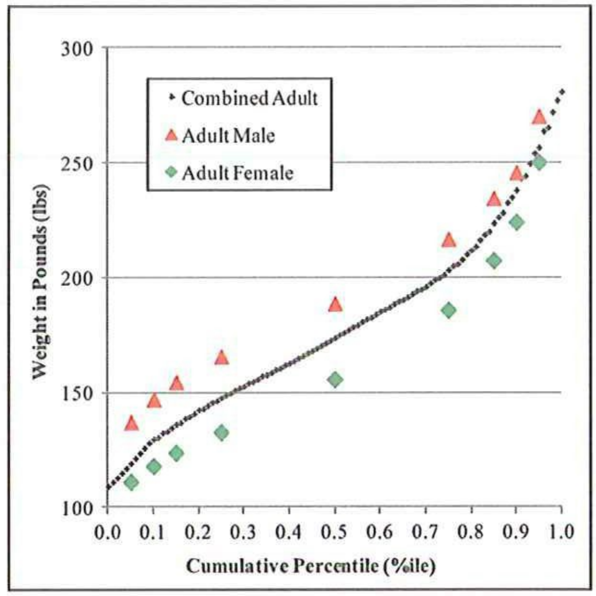

Figure 2. Data from the National Health Survey for 2003 - 2006.

METHOD

The example vehicle that was the subject of this paper was documented by dimensions and weights. The vehicle was a mid-sized bus, which by definition of the Mid-Sized Bus Manufacturing Association (MSBMA) "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 bus was weighed in curb weight condition as defined by Code of Federal Regulations (CFR) 49 571.3: "Curb weight means the weight of a motor vehicle with standard equipment; maximum capacity of engine fuel, oil, and coolant; and, if so equipped, air conditioning and additional weight optional engine [13]." The curb weight condition was obtained by removing all material from the bus that was added after its final stage manufacture and by filling all fluid reservoirs, including the fuel tank, to their full condition. Curb weight is also called the unladen weight. Weight was measured by simultaneously using four 20,000 pound scales with 10 pound precision and calibrated to 10 lb accuracy.

Figure 3. In-use seated mannequin template.

Key bus dimensions, including wheelbase and front and rear track width, were measured. In addition, the location and dimension of overhead and other cargo areas were measured and documented. The position of each designated seat position's occupant center of gravity location was also measured.

Seated occupant center of gravity (CG) was determined by placing a cardboard template of a seated manikin in each seat. The seated manikin template and its corresponding CG were derived from the work of NHTSA's Vehicle Research and Test Center in which they characterize the mass properties, including CG location of a full weight anthropomorphic water dummy used to simulate passenger seating loads in the

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development of test maneuvers for vehicle rollover resistance [14]. A picture of the in-use template is shown in Figure 3.

The model for occupant weight used the 2003-2006 Center for Disease Control and Prevention's (CDC) Anthropometric Reference Data. 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). NHANES data are the primary source of body measurement and related health and nutrition data for the civilian, noninstitutionalized U.S. population [11].

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 in one percentile bins. The model of the combined population is shown in Figure 2 as the combined adult.

Prediction of the bus weight distribution 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, Conducting Monte Carlo Analysis with Spread Sheet Programs. According to Bartlett, a Monte Carlo analysis evaluates the constitutive equations of an analysis many times, each time selecting the variable values based on their specified probability. The series of trials generates a group of possible results (a sample). A range of the results that fall into selected intervals about the median is lower than what would be generated by a simple worst-or-best case approach [15].

Weight distribution is calculated in two modules. The first module uses the spreadsheet to simulate the position of empty seats by assigning uniformly distributed random numbers to each seat position. This operation is accomplished using the RAND() function in Excel. Next, each set of random numbers is ranked using Excel's RANK() function. These processes result in a random listing of integers from one (1) to the number of passenger seat positions. Finally, the numbers associated with each seat are filtered using the Excel IF() function. For seats assigned numbers less than or equal to the number of modeled empty seats, the seat is reassigned a zero (0); all other seats are assigned a one (1). The result for each simulation is a unique passenger seat occupancy distribution represented numerically by a zero (0) or one (1) at each seat location.

The module that calculates occupant weight starts by assigning a uniform distribution of random numbers between zero (0) and one (1) for each seat of the bus. A weight for each occupied seat is then calculated using the Excel VLOOKUP() function for which the pointing variable is the random number assigned to each seat and the look up table is the discrete weight distribution of the passenger population of interest. By multiplying the results of the empty/occupied seat module (0 or 1) by the result of the occupant weight module, a unique weight distribution is modeled in each simulation.

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 [16] and are embodied in publically available, spreadsheet-based software sold by the National Truck Equipment Association (NTEA) [17].

RESULTS

Statistics of the combined adult weight model used in the simulation analysis are 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 calculated assuming a 150 pound occupant in each designated seat position and 60 pounds centered in the rear cargo area. Sixty pounds of cargo was listed on a door placard. 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 a defect as governed by 49CFR567, FMVSS 120 and FMVSS's that reference Gross Weight Ratings. Overweight conditions has been noted previously in other similar buses as indicated by the article "Exceeding the Gross Vehicle Weight on a Bus" [19] 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."

Since the 150 pound per designated seat position was related to the 1960-1962 CDC anthropometric statistics, an analysis

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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 is 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 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 by759 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 is made using a discrete distribution of the combined adult population using the 2003-2006 CDC anthropometric statistics. Statistics for the combined 2003-2006 population weight model was shown at the last line of Figure 2. In this simulation the average result was a loaded bus that 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. Histograms of the simulated rear axle weight result are shown as an illustration of findings and for comparative purposes in Figure 4.

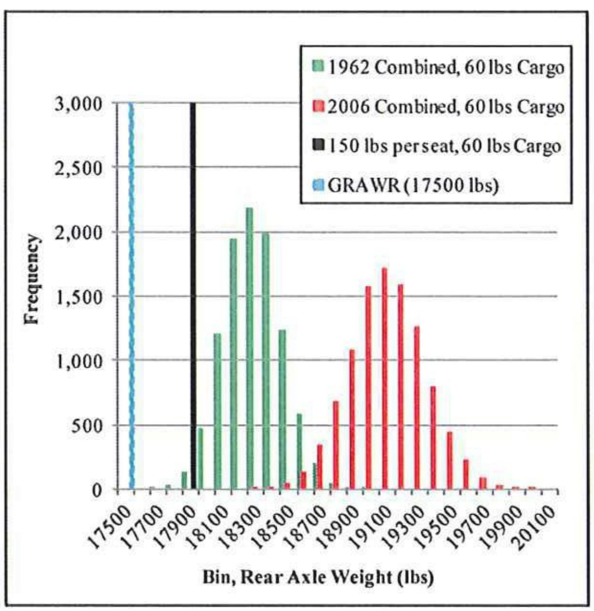

Figure 4. Histogram of rear axle weight based upon simulation of combined 1960-1962 and 2003-2006 adult populations with 60 pounds of rear cargo.

For illustrative purposes an analysis was undertaken to uncover restrictions in loading of the bus that might optimize its occupant and cargo carrying capability but 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 a simulated rear axle weight average 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 men and woman adults with 16 empty seats it will be within weight rating of 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 less 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 [18]. 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 carryon 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 that each government agency is modeling 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

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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 that is below or equal to the actual population weight distribution will result in instances of occupant weight significantly exceeding expectations.

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 [8]. 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 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 an average weight criterion. As a result, roughly half of the simulated load conditions resulted in an overload condition and half did not result in an overload condition. Average load 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 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 an underlying element.

SUMMARY/CONCLUSIONS

A method is described for combining reported U.S. population weight distributions into a statistically derived model. The model is 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 in a model in an Excel spreadsheet that randomly selects occupied seats in instances when the bus was not full of occupants and randomly assigns occupant weights according to the statistically derived combined weight distribution.

The examples illustrated how for a vehicle that was certified in accordance with 49CFR567 - in other words, certified under requirements of 150 pounds per designated seat position - guidelines for bus use assuming an actual population weight distribution could be evaluated. In general for the configuration of the example bus, restricting weight at the back of the bus increased its occupant carrying capability.

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