Changes in Rider Anthropometrics and the Effect on Rail Car Design

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Abstract

This research takes a quantitative, statistical approach to the best way to account for the growth in rider size and weight over the last 30-40 years and how it affects new light rail car design standards. Case scenarios were created using past and present anthropometric data of the American population, provided by the CDC. Initial recommendations are extrapolated from the findings concerning how the industry should look at the effects of passenger load. The paper concludes with a brief outlook to the future research questions that should be addressed.

I. Introduction

Over the past thirty to forty years the general population of America has been increasing in weight. In turn, the increase affects the amount of area each person takes up and how efficiently he or she can be packed into a finite space. For the rail industry this growth initiates two significant questions: What effect, if any, do these changes have on the way light rail cars need to be designed, and do these changes affect the infrastructure associated with the rail cars?

A. Problem Statement/Description

The need to reevaluate, or at least reexamine, the effects of passenger weight and occupied volume on public transit has been brought forth by new anthropometric data collected by the Center for Disease Control. This data is showing that the U.S. population, on average, has increased in weight and occupied space since the 1970s. Transit vehicle designs operating today are based on the weight data from this 1970s era. Historical reports of this data make it clear that the average weight of the population has indeed risen due to an increase in the weight of the upper 50th percentile. The current standard calls for a passenger weight of 155 pounds; however the current data is showing that the median weight of the population is closer to 182 pounds.

This increase in population weight, and in turn body size, brings forth the question of the effects on passenger weight density, specifically in light rail cars. Does one simply add the extra weight? Do fewer people fit in the car because of the increase in body size therefore creating a smaller total weight? Do the changes in weight and in body area cancel each other out, making the need for a change to the standards null and void? Using today's measurements and assuming a standard body ellipse (Figure 2) to represent each passenger, the researcher were able to calculate both average and relative weight densities per square meter, the standard amount of space referenced in the current ratings.

B. Scope

The scope of this research is limited to the population of the United States of America. Only the adult population, age twenty and older, was considered applicable to transit, using the population survey conducted by the CDC. Within this set, all races and genders were appropriately sampled. The choice not to include children was based upon the assumption that the majority of passengers on transit systems are adults. For the application and conclusions of this data only the AW3 Crush Load rating was considered.

II. Background

A. Current Standards

The current FTA standard, as outlined in the TCRP Report 57, *Track Design Handbook for Light Rail Transit*, uses a rating system to determine static forces of the car on the rail heads. There are five levels – AW0-AW4. All of the loads assume a passenger weight of 155 pounds. The ratings are worded in a way that they can be applied to a variety of car designs, and it is expected that the amount of seating and standing space will be defined by the car builder.

AW0 is used to describe total car weight with no passengers in a revenue service ready condition. AW1 is equal to the weight from AW0 plus the weight of a fully seated passenger load. The next level, AW2, is known as the Design Load, which is equivalent to AW1 plus a standing passenger load with 4 passengers per square meter of suitable standing space. AW3, designated Crush

Load, is AW1 plus a standing passenger load of 6 people per square meter. Finally, AW4, or Structure Design, is AW1 plus a standing passenger load of 8 people per square meter. It is common practice for an agency to make reference to these ratings in a request for proposal for new cars.

B. The CDC Survey

The U.S. Department of Health and Human Services published a report based on the information collected by the National Health and Nutrition Examination Survey periodically until 1994 at no assigned time interval. Since that time, the survey is conducted as a continuous effort with reports to be released every 2 to 4 years to allow for statistically significant sample size to be found and measured. The most current data is for the years between 2007 and 2010.[1] The survey uses household interviews and health examinations to collect the relevant data.

The pertinent information to this research is found in the measurement of weight and waist circumference. The measurements are provided for males and females from ages twenty and up, excluding pregnant women. The CDC provides a statistical breakdown including the sample size, mean, standard error and the 5^{th}, 10^{th}, 15^{th}, 25^{th}, 50^{th}, 75^{th}, 85^{th}, 90^{th} and 95^{th} percentile points. However, the raw data collected is not readily available.

C. Anthropometrics

Anthropometry is the science of measuring the human body with regard to height, weight, and size metrics, comparing relative proportions under normal and abnormal conditions. Anthropomorphic measurements, such as those from the CDC, can be used for medical research, workstation and product design, anthropologic research and various other research efforts.

When applied to designing work stations or other areas that involve a human element, the goal of anthropometrics is to account for the best representation of the population that will be subject to your design, within budgetary reason. Figure 1 shows a graphic representation of the possible ways to accomplish this goal, known as Design Types. The bell curve represents the entire population, and the shaded regions are the portion of that population that will be considered or eliminated in the design criteria. This research attempts to collect and analyze current anthropometric data to make an educated recommendation as to the most appropriate design type for light rail cars.

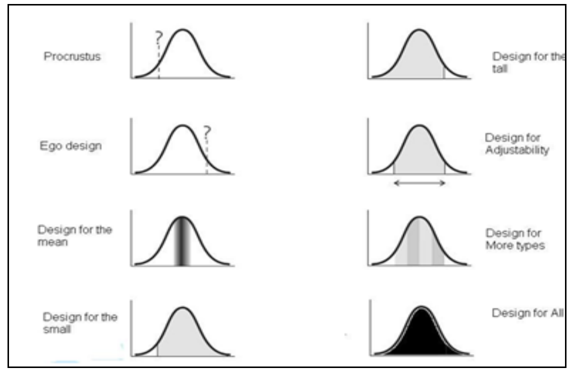

Figure 1: Design for Population Types

To consider every type of person in the population - tall, short, heavy, light, et cetera - is called "Design for All." It is a difficult, time-consuming and expensive option due to the need to conduct a nearly infinite number of simulations that in the end would increase the likelihood of over-engineering the final product.

The current AW-series standard is a representation of "Design for the Mean." The industry assumes a single average weight and size for all passengers and standards are created around this assumption. While the application is valid, graphically one can see that it does limit the body types considered, a particularly important consideration for analysis of standing passengers. Depending on the variation and range of the population this may or may not make a significant difference in the final design, but the effects should be considered.

"Designing for More Types" is the approach of setting the bounds of one's curve and designing to fit that portion of the population (i.e. 5^{th} to 95^{th} percentile). This is a feasible option that would account for the effects of most passenger type combinations, but excludes extreme cases. The threshold for what percentage of the population "more types" encompasses is up to the designer or industry defining the standard. This research hopes to shed light on the different results and variations if one looks at a broader spectrum of the population instead of keeping with the current average assumption.

III. Methodology

The initial approach examined the effect of simply raising the average passenger weight from 155 pounds to 182 pounds, the new CDC average value, using the standard AW-series specification for passenger density measured in persons per meter^2. This results in an overall increase in weight and

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[1] Reference to the CDC data taken between the years 2007-2010 will be known as Current CDC data and between the years 1988-1994 known as Past CDC data.

assumes that the number of people that fit in the car does not change.

The initial approach leaves certain factors untouched. Most notably, it does not consider a variable packing density influenced by the increasing size of passengers; instead it assumes anyone of any weight will occupy the same area, keeping occupancy density fixed. In other words, it is assumed that under the AW3 crush load scenario, six passengers weighing 155 pounds take up the same amount of space as six passengers weighing 182 pounds.

The second major issue is that using an average weight ignores all the possible variation of sizes found within the general population. According to the most recent CDC survey 95% of Americans fall somewhere between 123 and 264 pounds, a difference of approximately 140 pounds. How much does this variation impact the final results? A comparison of these assumed factors versus "realistic" scenarios should test the validity of those assumptions.

In order to account for not only the variation of passenger weight, but also the variation of the occupied area, a standard body shape is needed. The shape chosen was John J. Fruin's standard body ellipse, shown in Figure 2. This ellipse was created using near maximum dimensions of a person measured in width vs. depth, plus added space for clothing, body sway, and personal space expectations.[2] This ellipse has been used to determine capacities of U.S. army vehicles, New York Subway cars, and is used in the design of sidewalks and other pedestrian walkways.[3]

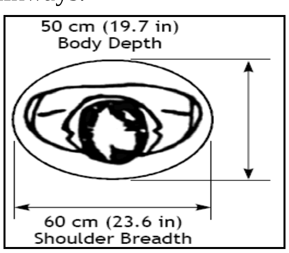

Figure 2: Standard Body Ellipse

To produce varying body sizes, circumference data from the CDC was related to body depth of the Fruin ellipse, while maintaining a constant ratio of shoulder breadth to body depth. The ratio is 1:1.2. Since Fruin's person was considered to be created from near maximum dimensions (90th percentile), variations from this point were made between the 95th and 5th percentiles. Using CDC data for body depths, nine points were chosen to represent the spread in body sizes. The CDC data, which is reported in waist circumference, was related to body depth. The results are shown in Table 1.The cells of the matrix, which represent area, were calculated using the formula for the area of an ellipse.

Table 1: Area Needed for a Single Standee (in^2)

SB/BD	20.83	20	19.17	18.33	17.5	16.67	15.83	15	14.17
25	408.9	392.5	376.1	359.8	343.4	327.1	310.7	294.4	278.0
24	392.5	376.8	361.1	345.4	329.7	314.0	298.3	282.6	266.9
23	376.1	361.1	346.1	331.0	316.0	300.9	285.9	270.8	255.8
22	359.8	345.4	331.0	316.6	302.2	287.8	273.4	259.1	244.7
21	343.4	329.7	316.0	302.2	288.5	274.8	261.0	247.3	233.5
20	327.1	314.0	300.9	287.8	274.8	261.7	248.6	235.5	222.4
19	310.7	298.3	285.9	273.4	261.0	248.6	236.2	223.7	211.3
18	294.4	282.6	270.8	259.1	247.3	235.5	223.7	212.0	200.2
17	278.0	266.9	255.8	244.7	233.5	222.4	211.3	200.2	189.1

Although the complete set of raw data was not provided in the CDC survey report from which to pull a random selection of potential passengers, a random sample could be created with the employment of the average and standard deviation of the CDC data, which was known. Prior to creating a random sample, some assurance is needed that the data is generally normally distributed. From the percentile values provided by the CDC, a test for normality could be performed using a simple test statistic, the "skewness." Skewness values between -0.5 and +0.5 typically reflect a distribution that can be assumed normal. The current survey information and the oldest comparable data were tested using values for the various percentiles, resulting with skews of 0.2 and 0.35, respectively. Based on this the data could be considered normally distributed, at least to a reasonable approximation. With this assumption the researcher was able to use the computed average and standard deviation to generate random weights.

Using MATLAB, a selection of 10,000 random, normally distributed passenger weights, based on an average of 182 pounds and a standard deviation of 50.84 pounds, was generated. From this set only values between the 5th and 95th percentiles were kept, producing a dataset of approximately 8,000. Through the use of random passenger weights and their correlated body size from Table 1, the total occupancy densities and weights were calculated.

Since the AW4 rating assumes a maximum passenger load of eight people, the researcher pulled 8 passengers at a time and conducted a "fit test." These eight people represent a random set of passengers chosen from the general American population that could be found boarding a car. One

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[2] http://www.newyorker.com/reporting/2008 /04/21/080421fa_fact_paumgarten?currentPage=all
[3] http://www.fhwa.dot.gov/publications/research /safety/pedbike/98107/section2.cfm

thousand iterations were performed, a statistically significant amount.

A fit test was conducted to determine the maximum number of these eight passengers that would fit into a square meter space (1555.2 in^2). As each person's area was cumulatively added a test was performed to see if the total exceeded the space available. If it did not, the next passenger was tested, until the maximum number of people was found.

The procedure above was extended to compute the total weight of a typical car with both seated and standing passenger space. A sample car was used that had a seated capacity of 70 passengers and 29.3 square meters of standing space. Since case scenarios had already been generated on a single square meter basis, randomly choosing 29 of these cases would fill the standing space of the car and show the effects of various passenger combinations. This was done for both past and current data sets to allow for comparison.

IV. Results and Analysis

The randomized sampling of weights resulted in fit test results that revealed that the most frequent number of whole passengers seen to fit per square meter was five, for both current and past data. The maximum amount of people was 6 and the minimum 4. This was true for both past and current data; however the frequency distribution of the maximum number of passengers varied. Variation was also seen when partial passengers were considered (i.e. 5.3) and the total weight was calculated. The analysis shows that since the size of an individual typically increases with weight each individual does weigh more, but fewer can be packed into the same limited space. This resulted in lower total weight per square meter, even though the individuals may have been heavier.

A histogram plot of the variation of the total weight per square meter was generated as shown in Figure 3. The graph shows the frequency of total weight using bin increments of 0.46 lbs/ft^2 from 84.1 to 92.8 lbs/ft^2, inclusive. The histogram is best fit to a normal distribution, shown in red, with an average of 88.9 lbs/ft^2 and a standard deviation of 1.64 lb/ft^2.

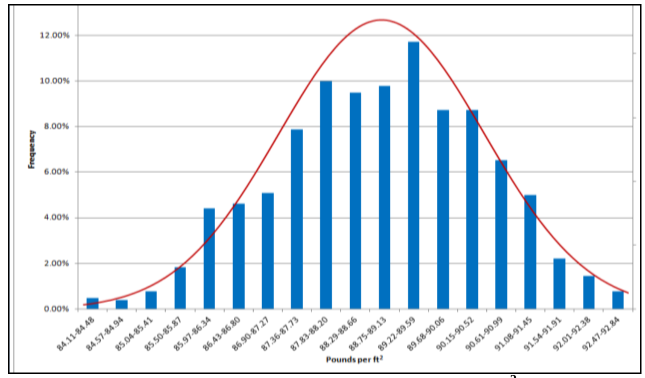

Figure 3: Frequency of Expected Weights per ft^2

The final analysis was to look at passenger loading affects in a full car scenario. A hypothetical car was used that had 29 square meters of standing space and seating capacity of 75. Seated passengers were assumed to be 182 pounds each, and 29 random standing passenger scenarios were selected to fill the car. The weights were summed along with a car weight of 105,000 pounds. The same process was done for comparison to past data with an assumed seated passenger weight of 155 pounds. Figure 4 shows the results of these total loads.

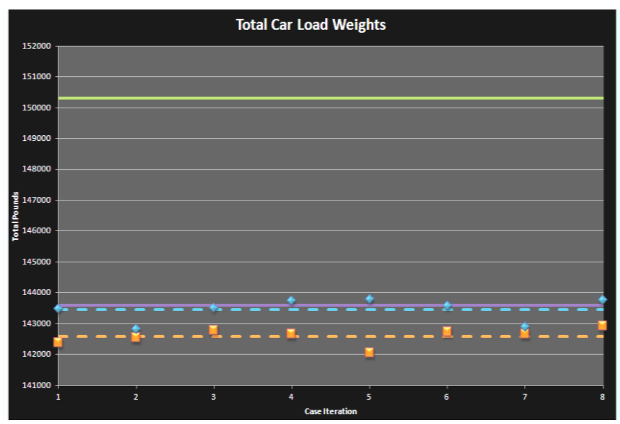

Figure 4: Total Car Load Weights

The figure shows that while the researcher saw a decrease in total standing passenger weight due to an increase in body size and occupied area, the increased weight of the seated passengers has enough of an impact to still increase the total car weight

The bottom portion of the figure represents the total car weights when random scenarios were used to generate passenger standing loads. The purple and green lines use the assumption that everyone weighs either 155 or 182 pounds, respectively, and that one can always fit 6 passengers per standing square meter of space, equivalent to AW3.

V. Discussion

The initial question proposed at the outset of this research was what effect, if any, do the changes in population weight have on the way light rail cars need to be designed? There is indeed an effect and it presents itself in two ways; through the seated passenger and the standee.

The current standards state each passenger should be an assumed 155 pounds, the median weight from the 1970s. The average weight in that decade was approximately 158 pounds. Today the average is 182 pounds, an increase of 24 pounds. For every seated passenger one must add that 24 pounds, since the person will still occupy the same amount of seating capacity. This change can easily be reflected by the AW ratings with an increased weight.

The manifestation of the weight affect is different for the standee and ties back to the second question proposed. How should one design rail cars - for the “average” or for “more types”? The research took the stance of evaluating the standees not just from a weight perspective but from a packing density one as well, yielding interesting results.

We know that the average individual has increased in weight. However, by taking into consideration the changes in body area corresponding to those changes, it was seen that the total weight per square foot of standing space has actually decreased. This change cannot be accounted for in the current design approach and thus the researcher sought to create an alternative recommendation.

For additional insights, the researcher chose to look at other industries with similar concerns to see what approach they have taken.

A. Federal Aviation Administration

The aviation industry has to take similar considerations when it comes to passenger anthropometrics. Aircraft do not have to consider standees, so the comparison is not exact, but the researcher still considered it of value. The regulating body for the industry is the Federal Aviation Administration (FAA). In 2004 the FAA released its most up to date advisory circular, AC 120-27D, addressing aircraft weight and balance control. This update was in reaction to not only the trend of the growing population, but also to at least one aircraft crash that resulted in 21 fatalities.[4]

The FAA classifies aircraft into four cabin sizes; large, medium, small, and non-eligible. Based upon the cabin size, which represents a sample size, the FAA specifies the methodology to be applied to passenger weight and cabin balance.

Statistical study dictates that the smaller one’s sample size the more the average of the sample will deviate from the average of the population. Due to the size of a large cabin aircraft they are permitted to use standard average weights for passengers.

Since most rail cars are expected to hold as many passengers as a large-cabin aircraft, this was the focus of the comparison. Table 5 outlines these standard average passenger weights. The weight per passenger includes 5 to 10 pounds for summer and winter clothing, respectively. This is why the table shows weights that are higher than the aforementioned 182 pounds per passenger[5].

Table 2: FAA Standard Passenger Weights

Average Passenger Weight	Weight Per Passenger
Summer Weights	
Average passenger weight	184 lb
Average male passenger weight	194 lb
Average female passenger weight	173 lb
Child weight (2 years to less than 13 years of age)	76 lb
Winter Weights	
Average passenger weight	189 lb
Average male passenger weight	199 lb
Average female passenger weight	178 lb
Child weight (2 years to less than 13 years of age)	81 lb

The insight into another industry approach brought to light the need to account for clothing and personal items in the final weight recommendations. The FAA has a similar table to that of Table 2 which includes a carryon bag weight included, adding 16 pounds per passenger. This bag weight is an average found by considering factors such as heavier bags and passengers that carry no bags. The consideration to include weight factors will be reflected in the conclusions and recommendations section.

VI. Conclusions and Recommendations

In regards to seated passengers the current use of an average, or expected, weight per person assumption is valid. These passengers will vary in weight, but the expected value is an accurate representation for structural design needs. The research has concluded that 182 pounds is the appropriate weight to assume for the current population.

Standing passengers have the extra factor of a packing density issue which does not allow for the application of the same assumptions as seated passengers. Based upon the analysis done a better assumption in this instance would be to use an average, or expected, weight per square foot of standing space. This would account for multiple variations of body types and weights that combine together to make a single point or range that is most likely to occur.

An important facet of this research is the time sensitivity of the data. The population size has grown in the last 30 years, without question, but how

[4] http://usatoday30.usatoday.com/travel /news/2003/05/01-weight.htm

[5] Data shown assumes an average passenger weight of 179lb from the 2003-2006 CDC data.

much will it grow in the next 5 or 10? Is there a point where the growth will reach a plateau? If the data continues to shift, the recommendations and conclusions from this research would shift as well.

The methods remain valid; however it may behoove the industry to revisit the data that is used in the calculations to watch for significant changes. One way to address this change would be through an APTA Standard which requires that the information contained be reviewed every 5 years.

A second approach would be to conduct a sensitivity analysis, the depth and complexity of which is yet to be determined, to see how much the population would need to grow for the industry to feel negative effects in an established design specification. This would help establish an industry wide safety factor or confirm that building to an AW4 level is sufficient.

The last consideration would be of seasonal clothing and personal baggage items, brought forth by the FAA. While most passengers would not be carrying large carryon bags for multi-day trips as they do on flights, commuter bags can be quite heavy. The researcher's suggestion would be to add 10 pounds of personal items and 7 pounds for year round clothing. The seated passenger weight would thus be 199 pounds and the standing weight would be 106 lbs/ft^2

Equation 1 shows the application of these two recommendations in the calculation of total car weight.

$$Total = (199 * Seat\ Cap.) + (106 * ft^2 stand\ space) + (Car\ Weight)$$

Equation 1: Calculating Total Car Weight

All of the conclusions and specific numerical recommendations are based on the most up to date CDC survey data, 2007-2010. However, if the trend of the population is to continue to grow these recommendations would no longer be valid. The application of this data needs to consider the full life cycle of the car, designing for today's and tomorrow's population statistics. The best solution to the time sensitivity affect, however, is a topic that needs further research and consideration.