Occupant Age and Size Characteristics by Seating Location in Tow-Away Crashes Involving Light Vehicles in the United States

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Abstract Data from 1989-2015 NASS-CDS and 2017-2019 CISS were analyzed for exposure of drivers, right-front passengers, second-row passengers and third-row passengers by age, height and weight. The data were analyzed by calendar year (CY) ranges for light vehicles in all crashes. The percentile distribution was modelled by a Beta distribution. The weighted sample included 59,290,000 drivers, 15,384,761 right-front, 9,323,559 second-row, and 433,002 third-row passengers.

The average driver was 76.4 kg and 171.6 cm. The average right-front passenger was 67.8 kg and 165.0 cm. Second-row passengers averaged 45.4 kg and 137.7 cm. The average weight of drivers and right-front passengers increased with time. For example, the average right-front passenger weight was 61.9 kg between 1989 and 1995 and 75.4 kg between 2017 and 2019.

The Beta distribution function is a two-parameter model of distributions. It enables calculation of percentile data on occupants in different seating positions. For example, a 76 kg (± 7.6 kg) driver represents 31.6% of the driver population, and a 102.5 kg (±10.3 kg) driver represents 15.8% of the driver population.

The Beta distribution function provides a simple means to quantify the percentiles of occupants by seating position. It can be used to determine the fraction of occupants covered within a specific range of the height and weight of different crash test dummies.

Keywords Demographics, height, weight, distribution, occupants.

I. INTRODUCTION

The anthropometry of the United States population has changed over time and the demographics (age, sex, weight and height) of passenger vehicle occupants has also changed. For example, the majority of drivers were males in the 1960s; today there are approximately equal numbers of male and female drivers [1]. Changes in passenger vehicle occupants demands a better understanding of occupant demographics in order to interpret safety trends.

Anthropomorphic test devices (ATDs, or “crash test dummies”) have been developed in response to occupant safety needs. Instrumented ATDs provide invaluable data on the loading an occupant experiences in a crash; significant research and development has gone into maximizing and contextualizing the biofidelity of ATDs. ATDs are an important tool for human modeling in a crash when use of a volunteer or a postmortem human subject (PMHS) is inappropriate or impractical. However, a single ATD cannot represent every possible vehicle occupant. Therefore, various ATDs have been introduced over the years to assess front-seat and rear-seat occupant safety, and they have evolved based on safety needs.

The Hybrid III 50th Male is the original member of the Hybrid III series of ATDs. It was designed to represent a 50th percentile male based on its seated height, weight and body segment masses using available anthropometric data. ATDs of other sizes in the Hybrid III family have been developed, such as the Hybrid III 5th Female and the Hybrid III 95th Male, to represent a 5th percentile female and a 95th percentile male, respectively. Child ATDs have subsequently been developed to model pediatric occupants. Additional ATDs were developed for side and rear impact.

The standing and seated height, weight and body segment masses of ATDs match the specific anthropometry of the

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human population at the time. The height and weight of the population are not static values and vary with time and demographics [2]. Perhaps the most extensive study of the anthropometry of the U.S. population is the National Health and Nutrition Examination Survey (NHANES) undertaken by the Centers for Disease Control and Prevention (CDC) and started in 1971.

A survey of the U.S. general population does not necessarily represent a survey of the U.S. passenger vehicle occupant population who are involved in tow-away motor vehicle crashes. The examination of exposed occupants by seating position is relevant for the evaluation of motor vehicle safety, a field that uses ATDs to represent the population of exposed occupants. Traditional look-up tables of anthropometric parameters can be difficult when evaluating how well an existing ATD represents the current population.

In this study, a new method is introduced using the Beta distribution function, a statistical probability distribution function, to quantitatively assess anthropometry and compare it to target height or weight of the anthropometric dataset. The Beta distribution is advantageous because it allows for the calculation of percentile information on occupants in different seating positions exposed to tow-away crashes. The Beta distribution was fitted to data from the 1989-2015 NASS-CDS (National Automotive Sampling System-Crashworthiness Data System) and the 2017-2019 CISS (Crash Investigation Sampling System) databases. This method can be readily translated to other anthropometric databases. The immediate impact of this new approach is in providing a simple mean to quantify the percentiles of passenger vehicle occupants, which is important as new safety technologies and new ATDs are being developed.

II. METHODS

Field data analysis

NASS-CDS and CISS: the Crashworthiness Data System is a national, statistically sampled vehicle crash database consisting of about 5,000 yearly crashes, with the final year of data available in calendar year (CY) 2015. The Crash Investigation Sampling System replaced NASS-CDS in 2016, with the first publicly available data in CY 2017. At the time of this analysis, data were available through CY 2019. In this study, the data were extrapolated to national estimates using weighting factors provided by National Highway Traffic Safety Administration (NHTSA).

Vehicles: passenger cars, SUVs, minivans and pickup trucks were included in the analysis (coded as BODY TYPE values 1-9, 14-20, 30-33, and 30-39).

Calendar year: the data were divided into six CY groups, stratified by the emergence of child safety campaigns by the NHTSA and other organizations, as described in a prior study by Viano and Parenteau [2]: 1989-1995 represents the years before a series of safety campaigns; 1996-1999, 2000-2004, 2005-2009, 2010-2015, and 2017-2019 represent distinct phases in these ongoing campaigns.

Seating position: the seating position for the driver was defined as SEATPOS or SEATLOC = 11 and ROLE = 1, RF passenger as SEATPOS or SEATLOC = 13, second-row passenger (2^{nd}) as SEATPOS or SEATLOC = 21-23, and third-row passenger (3^{rd}) as SEATPOS or SEATLOC = 31-33.

Weighted data: national estimates for the number of occupants and injuries in each category were made using the Inflation Factor (named RATWGT in the NASS-CDS and CASEWGT in CISS).

Beta distribution: the Beta distribution function is used to fit non-normally distributed data in the health sciences [3-5]. The Beta distribution function is characterized using two parameters (α, β) and a range of values (a, b). The Beta distribution was fit to the percentile distribution for the age, weight and height of occupants in various seating positions in the tow-away crashes using the "BETA.DIST" function in Excel. The "SOLVER" routine was used to optimize the α and β parameters by minimizing the squared error between the data and Beta distribution. The range was selected using the 0.5^{th} and 99.5^{th} percentile range values ± 0.1 unit. In some situations, a more optimal fit was achieved by manually expanding the range of a and b.

Comparison to ATDs: the fitted Beta distribution functions were compared to the height, weight and age of various members of the Hybrid III ATD family to determine how representative each ATD is of passengers by seating position. "Representativeness" was computed by expanding the height, weight and age of each ATD by ±10% and then evaluating the difference in percentiles (value + 10% minus value – 10%) at each seating position using the fitted Beta distribution functions.

III. RESULTS

Figure 1 shows the mean (average) age, weight and height by seating location. For example, the average RF passenger was 67.8 kg, 165.0 cm and 30.5 years. In comparison, the average second-row passenger was 22.4 kg lighter, 27.3 cm shorter and 15.0 years younger, while the average third-row passenger was 29.5 kg lighter, 30.7 cm shorter and 18.8 years younger than the average RF passenger.

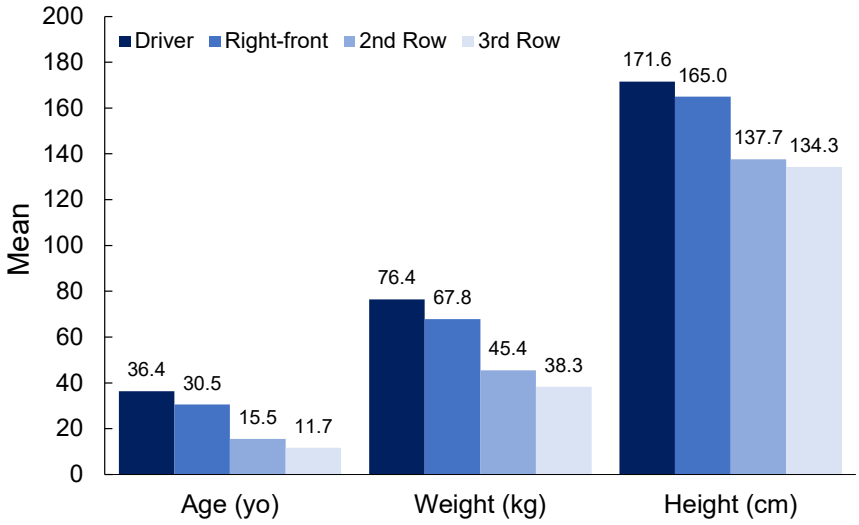

Fig. 1. Average/mean age, weight and height of drivers and passengers in NASS-CDS and CISS data.

Table I shows the mean and 5th, 50th and 95th percentile data from NASS-CDS and CISS. The data were also tabulated by sex for drivers and RF passengers. On average, females were 15.5 kg lighter and 13.5 cm shorter than males when in the driver seat, and 10.5 kg and 9.7 cm, respectively, when seated as a RF passenger.

TABLE I
AVERAGE AGE, WEIGHT AND HEIGHT BY OCCUPANT TYPE AND PERCENTILE IN 1989-2015 NASS-CDS AND 2017-2019 CISS

	Age (yo)				Weight (kg)				Height (cm)			
	Mean	5th	50th	95th	Mean	5th	50th	95th	Mean	5th	50th	95th
Driver	36.4	16.4	31.5	70.8	76.4	51.7	74.9	109.0	171.6	155.0	172.2	188.0
M	36.5	16.5	31.4	71.3	83.6	60.9	81.8	112.8	177.8	164.5	177.9	190.5
F	36.3	16.3	31.6	70.1	68.1	48.0	64.0	101.3	164.3	151.7	164.2	174.9
RF	30.5	8.3	23.3	71.3	67.8	31.4	66.7	103.4	165.0	125.5	167.8	184.4
M	33.7	6.5	21.1	61.5	73.7	25.0	74.9	108.9	170.4	121.9	174.8	188.0
F	26.5	9.8	26.0	74.9	63.2	36.0	60.8	94.8	160.7	135.7	162.9	175.2
2nd Row	15.5	0.3	12.1	50.5	45.4	10.0	45.0	86.0	137.7	65.4	152.0	182.9
M	14.3	0.3	12.3	38.8	48.3	10.9	49.9	90.9	140.8	65.4	159.3	183.3
F	16.7	0.2	11.8	57.8	42.7	10.0	45.0	81.8	134.7	64.6	151.1	170.1
3rd Row	11.7	2.1	8.8	33.7	38.3	13.9	33.4	76.5	134.3	84.6	136.1	172.9
M	10.7	2.1	8.0	26.4	39.0	15.1	31.7	78.5	133.4	75.9	135.3	177.8
F	12.9	2.0	9.5	40.8	37.5	13.7	35.4	70.4	135.2	85.4	139.9	168.0

RF: Right-front passenger, M: Male, F: Female

Figure 2 shows the weight of the driver, the RF passenger, the second-row and third-row passenger per CY group. There was an increase in weight over time for the driver and the RF passenger. The weight of the second-row and third-row passengers remained similar over time.

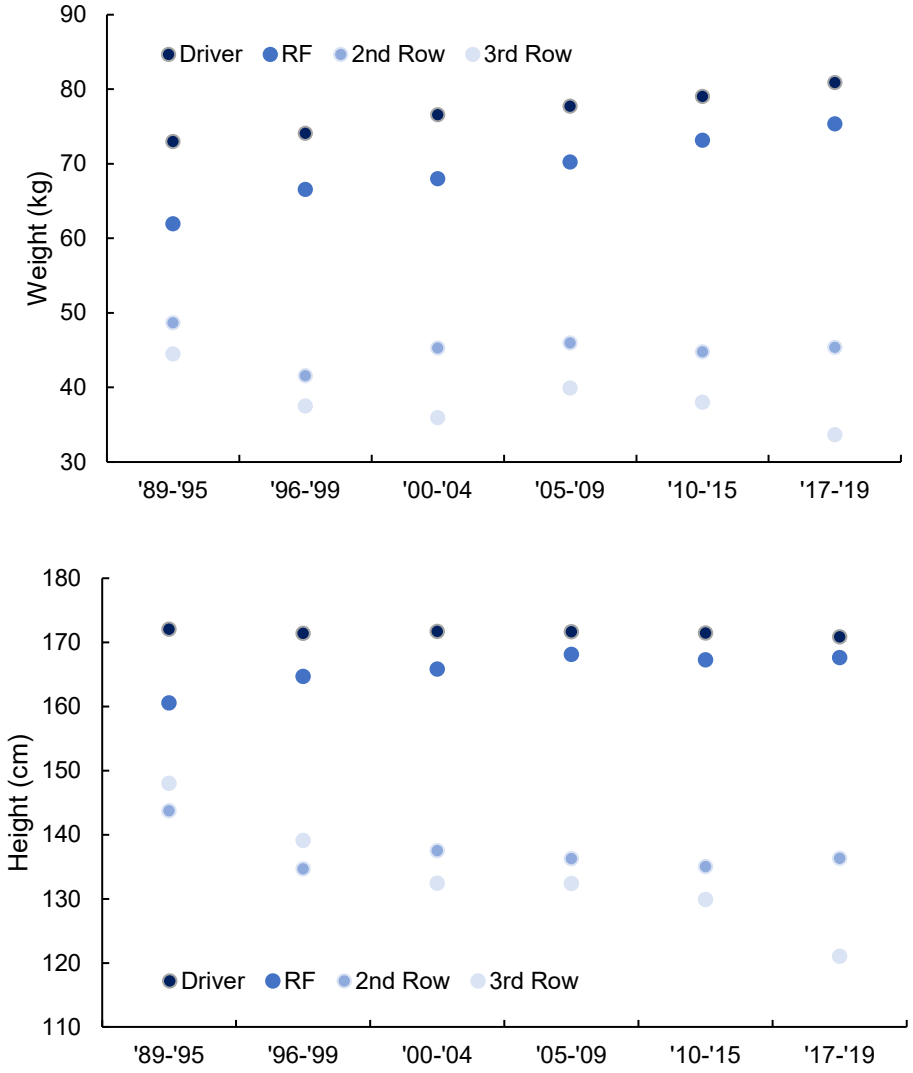

Fig. 2. Average weight and height of RF, second-row and third-row passengers by CY group.

Table II summarizes the Beta distribution fitting parameters derived from the percentile age, weight and height data, stratified by seating location and sex. These parameters can be used to estimate the percentile distribution of any occupant by seating location. For example, Fig. 3 shows the driver age by percentile distribution overlaid with the fitted Beta cumulative distribution function. The alpha (α) and beta (β) were 0.84 and 2.08, respectively. Appendix A provides additional information on the age, height and weight percentile distribution and fitted Beta cumulative distribution function by seating location.

TABLE II

ALPHA (A), BETA (B) AND SUM OF ERROR SQUARED FOR AGE, HEIGHT AND WEIGHT DISTRIBUTION BY SEATING LOCATION AND SEX (DRIVER AND RF PASSENGER ONLY)

	Age (yo)					Weight (kg)					Height (cm)				
	a	b	Alpha (α)	Beta (β)	Sum error-squared	a	b	Alpha (α)	Beta (β)	Sum error-squared	a	b	Alpha (α)	Beta (β)	Sum error-squared
Driver	15.0	86.0	0.84	2.08	0.0041	43.9	140.8	2.10	4.21	0.0035	146.0	196.0	2.66	2.58	0.0047
M	15.0	86.7	0.84	2.10	0.0055	51.4	146.9	2.94	6.00	0.0079	150.8	197.2	5.25	2.10	0.0055
F	15.0	84.0	0.84	1.98	0.0031	42.7	135.1	2.02	5.74	0.010	142.0	183.2	4.57	4.01	0.017
RF	0.0	86.0	1.85	3.89	0.054	8.0	135.3	5.72	6.55	0.012	65.3	194.0	14.6	3.97	0.016
M	0.0	83.6	2.77	6.98	0.037	7.9	135.8	7.02	6.40	0.020	64.0	196.1	20.0	3.95	0.024
F	0.4	87.1	1.51	2.69	0.054	20.0	127.6	7.55	9.50	0.025	69.2	183.0	21.6	4.82	0.016
2nd Row	0.0	67.0	1.09	4.31	0.017	4.9	112.9	1.04	1.76	0.030	50.3	191.0	1.70	1.01	0.056
3rd Row	0.0	78.1	2.28	16.3	0.013	8.5	100.0	1.27	2.76	0.011	53.9	182.0	2.06	1.24	0.015

RF: Right-front passenger, M: Male, F: Female

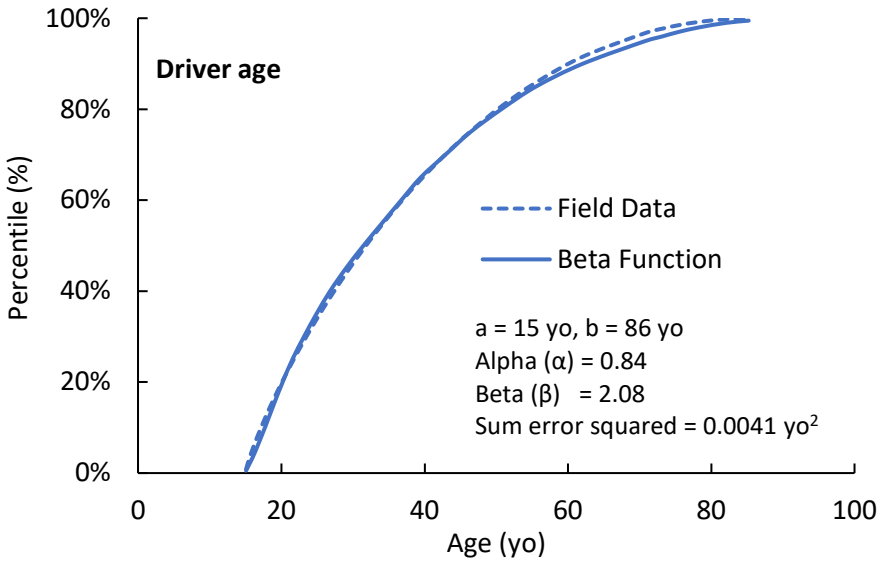

Fig. 3. Driver age percentile distribution and fitted Beta cumulative distribution function.

Table III shows the age, weight and height of selected Hybrid III ATDs. These characteristics (± 10%) were evaluated using the fitted Beta distribution to estimate their corresponding percentile. The results obtained from this study indicate that the weight of the Hybrid III 5th Female ATD corresponds to a 0.90th percentile driver, to a 12.5th percentile RF passenger, to a 56.3rd percentile second-row passenger and to a 70.4th percentile third-row passenger, irrespective of sex. The corresponding height percentiles were 1.40%, 11.1%, 57.2% and 65.9%. Table III also shows how the size and age of various ATDs are representative of occupants in tow-way crashes (height, weight, or age of the ATD ± 10%), termed "representativeness". The ATD representativeness of driver age was not evaluated since there were no drivers less than 15 years old. Additionally, the ages of a 50th and 95th ATD were not defined.

TABLE III

AGE, WEIGHT AND HEIGHT PERCENTILES AND REPRESENTATION OF SELECTED ATDS

	ATD (Hybrid III) (Mertz et al. 2001)											
	95th M		50th M		5th F		10 YO		6 YO		3 YO	
	Percentile	Repr.	Percentile	Repr.	Percentile	Repr.	Percentile	Repr.	Percentile	Repr.	Percentile	Repr.
Age (yo)					13+		10		6		3	
Driver	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
RF	NA	NA	NA	NA	19.1%	8.8%	12.6%	4.1%	5.4%	1.8%	1.6%	0.57%
2nd Row	NA	NA	NA	NA	56.7%	12.8%	46.1%	7.7%	29.2%	5.5%	14.8%	3.0%
3rd Row	NA	NA	NA	NA	75.6%	17.1%	59.7%	12.4%	31.0%	9.3%	9.5%	3.6%
Weight (kg	102.5		78.2		46.7		32.4		20.9		14.5	
Driver	92.2%	15.9%	58.0%	31.2%	0.66%	4.6%	NA	NA	NA	NA	NA	NA
F	98.8%	4.9%	79.9%	25.6%	3.1%	12.5%	NA	NA	NA	NA	NA	NA
M	90.2%	22.3%	41.3%	57.6%	<0	<0	NA	NA	NA	NA	NA	NA
RF	97.9%	8.0%	72.6%	27.8%	12.5%	11.7%	1.7%	2.1%	0.07%	0.13%	0%	0%
F	99.9%	1.4%	87.3%	23.1%	13.8%	15.8%	1.0%	1.8%	0%	0%	0%	0%
M	95.1%	15.0%	57.3%	48.9%	2.2%	20.0%	0.38%	0.63%	0%	0%	0%	0%
2nd Row	98.3%	5.7%	85.8%	11.2%	56.3%	10.7%	38.7%	8.4%	23.0%	5.9%	13.9%	4.2%
3rd Row	>100	0.17%	97.2%	5.5%	70.4%	13.2%	46.6%	12.3%	23.2%	8.8%	10.0%	5.8%
Height (cm	186.4		175.1		151.3		137.4		116.8		95.3	
Driver	93.0%	62.5%	62.7%	89.9%	1.4%	33.1%	NA	NA	NA	NA	NA	NA
F	>100	30.1%	95.8%	81.7%	2.8%	63.0%	NA	NA	NA	NA	NA	NA
M	88.2%	90.4%	36.0%	99.1%	2.2%	0.00%	NA	NA	NA	NA	NA	NA
RF	98.1%	50.4%	74.1%	78.4%	11.1%	43.9%	1.7%	10.8%	0.03%	0.35%	0%	0%
F	>100	28.2%	96.3%	73.3%	10.6%	65.1%	0.6%	10.3%	0%	0.06%	0%	0%
M	91.2%	76.6%	48.2%	93.6%	2.2%	20.0%	0.1%	2.2%	0%	0%	0%	0%
2nd Row	94.6%	26.2%	81.8%	36.6%	57.2%	28.9%	44.6%	23.8%	28.2%	16.8%	14.6%	10.4%
3rd Row	>100	14.3%	93.9%	26.5%	65.9%	35.6%	49.9%	30.2%	29.1%	20.9%	12.8%	11.7%

RF: Right-front passenger, M: Male, F: Female, NA: Not applicable, Repr.: Representativeness

Figure 4 shows the height and weight of drivers, RF passengers, second-row passengers and third-row passengers exposed to tow-away crashes from NASS-CDS and CISS. Each point represents a 5% increase, from 5% to 95%, for each seating position. The height and weight of six Hybrid III ATDs were plotted with ranges of ±10% shown as bars from the mean value. The population of occupants decreases in height and weight from the driver to the RF passenger to second-row and third-row passengers. The ATDs reasonably cover the demographics of the occupants, with gaps between the 5th female and the 50th male Hybrid III and at the lower extreme.

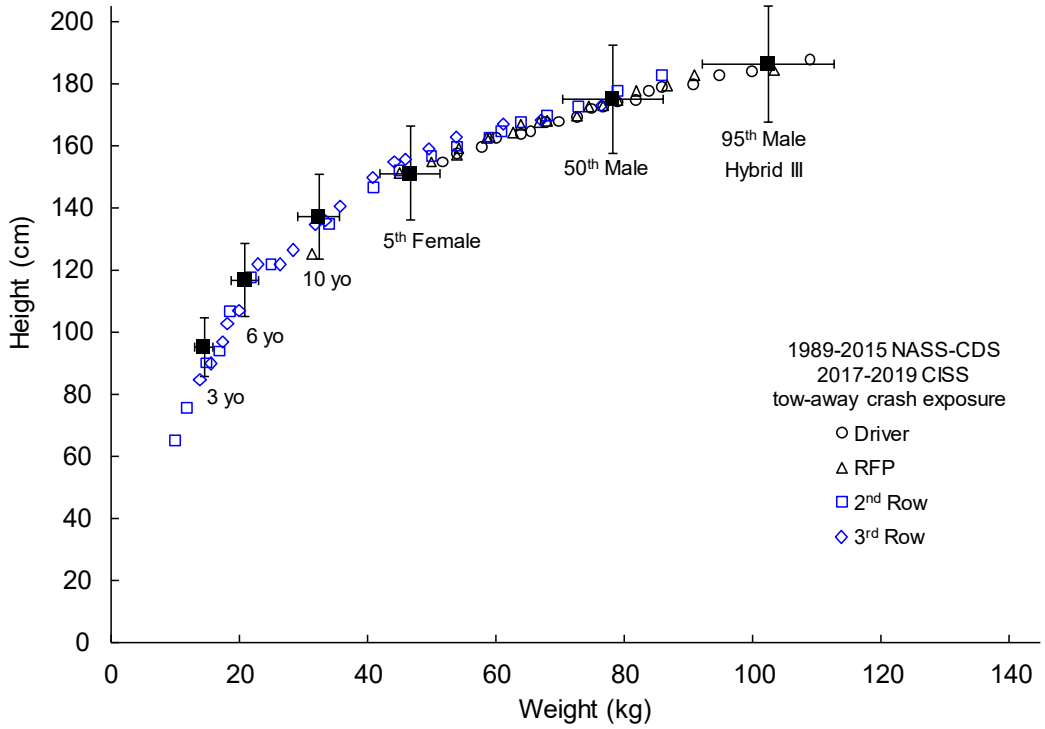

Fig. 4. Height and weight of selected Hybrid III ATDs compared to the percentile size (5th–95th percentile) of occupants by seating position. Bars represent ±10% of the height and weight of each ATD.

Figure 5 is similar to Figure 4 in that it shows the height and weight of drivers, RF passengers, second-row and third-row passengers with the 0.5 to 4th and 96th to 99th percentile added.

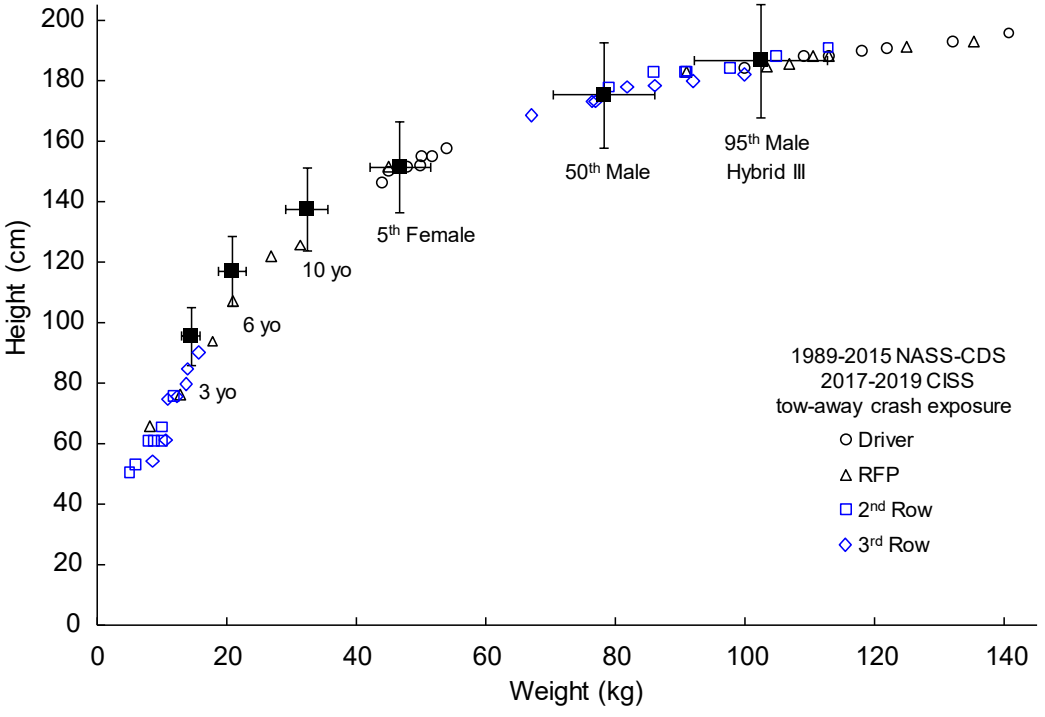

Fig. 5. Height and weight of selected Hybrid III ATDs compared to the percentile size (0.5th–99.5th percentile) of occupants by seating position. Bars represent ±10% of the height and weight of each ATD.

IV. DISCUSSION

The size, weight and age of occupants in each seating position is important information for vehicle crash safety as it enables the tailoring of designs and the optimization of restraint technologies. Occupant safety engineers, including ATD designers, may be limited to using tables of percentiles of anthropometric data using population surveys, which do not necessarily represent occupant sizes and their differences by seated location.

This study provides a means to assess the percentile representation of various occupant sizes and ages by seating location using US tow-away crash data for light vehicles. For example, the height of the Hybrid III 5th Female ATD corresponds to a 1.4th percentile driver, a 11.1st percentile RF passenger, a 57.2nd percentile second-row passenger and a 65.9th percentile third-row passenger. Overall, its height (± 10%) represents 33.1% of drivers, 43.9% of RF passengers, 28.9% of second-row passengers and 35.6% of third-row passengers. Its weight represents 4.6% of drivers, 11.7% of RF passengers, 10.7% of second-row passengers and 13.2% of third-row passengers. The height of the 5th Female ATD seems to be an approximately representative match to evaluate the safety of airbags for small-statured adults and teenagers seated in the RF passenger seats, but this ATD may be light, in particular when considering that the weight of front-seat occupants has increased with each CY. The height and weight of the Hybrid III 5th Female ATD were originally selected to represent a 5th percentile female adult (65 FR 10961). The Hybrid III 5th Female was adopted on 1 March 2000 (NHTSA, final rule, 2000), and specifications were added to 49 CFR Part 572 as Subpart O. The Hybrid III 5th Female is commonly used in frontal crash testing, and a side-impact version of the 5th Female is used in side-impact testing. This study quantifies the representativeness the Hybrid III 5th Female ATD for the driving and passenger populations.

Schneider [6] evaluated results from the National Crash Severity Study (NCSS) and found that about 50% of drivers and passengers have heights within 10 cm of the Hybrid III 5th Female, though their weights were spread over a wider range. According to Shams *et al*. [7], over 22% of female occupants involved in 1995–2001 tow-away crashes were 157 cm in stature or less, and over 2.5% of the females experienced serious and fatal injuries. The authors concluded that 5th percentile female size is representative of a significant proportion of seriously injured occupants.

The height of the Hybrid III 10 YO ATD is representative of 23.8% of second-row occupants, and the Hybrid III 6 YO ATD represents 16.8% of second-row occupants. In recent years, there has been increasing focus on rear-seat occupant safety. The increased interest is related, at least in part, to improvements in front-seat occupant safety that have not been translated as extensively to the rear seating positions (e.g. improvements in vehicle structures and implementation of advanced restraint systems). This interest may result in crash testing using smaller-sized ATDs in second- and third-row seats.

Viano and Parenteau [2] analyzed NASS-CDS and CISS data by seating location and calendar years and observed a decrease in 0–7 yo children using the right-front (RF) seat over time. Data from the most recent CYs showed that children up to 7 yo are no longer riding in the RF seat unless there is no other option. Children aged 8–12 yo are still using the RF seat but at a lower rate. The authors concluded that change in use of the RF seat for children provides evidence that safety campaigns on placing young children in rear seats continue to be successful in the US. They suggested that the decrease was associated with the nationwide public information efforts, starting in 1996, to move children to rear seats. This study demonstrates the smaller stature of second- and third-row occupants compared to front-row occupants.

V. CONCLUSIONS

This study determined the distribution in height, weight and age of the driver, the RF passenger and the second-row and third-row passengers in tow-away crashes using 1989-2015 NASS-CDS and 2017-2019 CISS data. The average driver was 76.4 kg and 171.6 cm, the average RF passenger was 67.8 kg and 165.0 cm, the average second-row passenger was 45.4 kg and 137.7 cm, and the average third-row passenger was 38.3 kg and 134.3 cm. The percentile distributions were determined and modelled by Beta distribution functions, which provided a good fit.

The Beta distribution function provides a simple means to quantify the percentiles of light vehicle occupants involved in tow-away crashes by seating position. It can be used to determine the fraction of occupants covered within a specific range of the height and weight of different ATDs used for crash testing. Within 10%, the Hybrid III 95th Male represents 15.9%, the Hybrid III 50th Male represents 31.2%, and the Hybrid III 5th Female represents 4.6% of drivers by weight; whereas the Hybrid III 95th Male represents 5.7%, the Hybrid III 50th Male represents 11.2%, the Hybrid III 5th Female represents 10.7%, the Hybrid III 10 YO represents 8.4%, the Hybrid III 6 YO represents 5.9%, and the Hybrid III 3 YO represents 4.2% of second-row occupants by weight.

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Appendix A: Age, height and weight percentile distribution and fitted Beta cumulative distribution function.

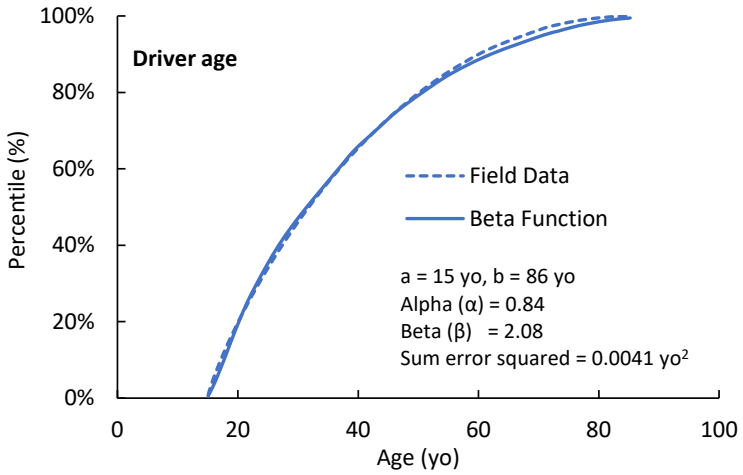

Figure A1: Driver age percentile distribution and fitted Beta cumulative distribution function.

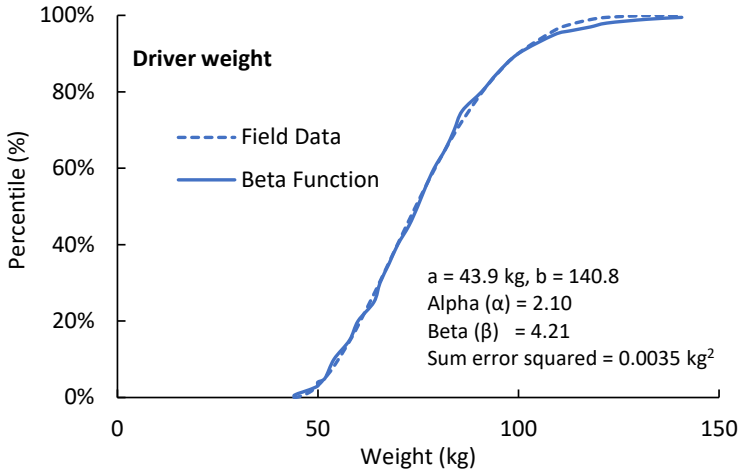

Figure A2: Driver weight percentile distribution and fitted Beta cumulative distribution function.

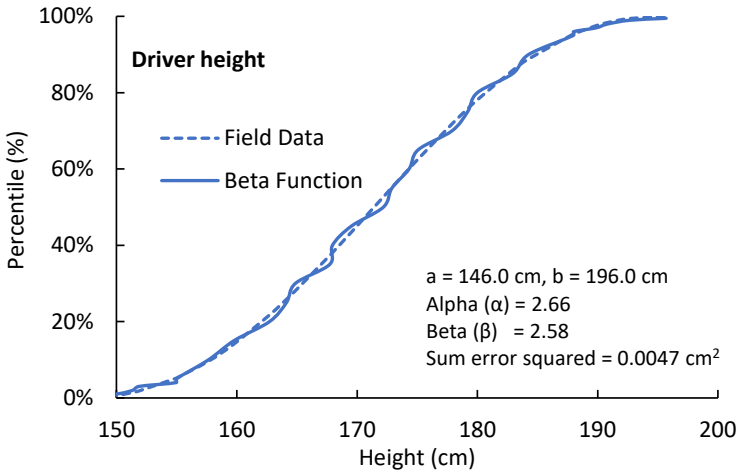

Figure A3: Driver height percentile distribution and fitted Beta cumulative distribution function.

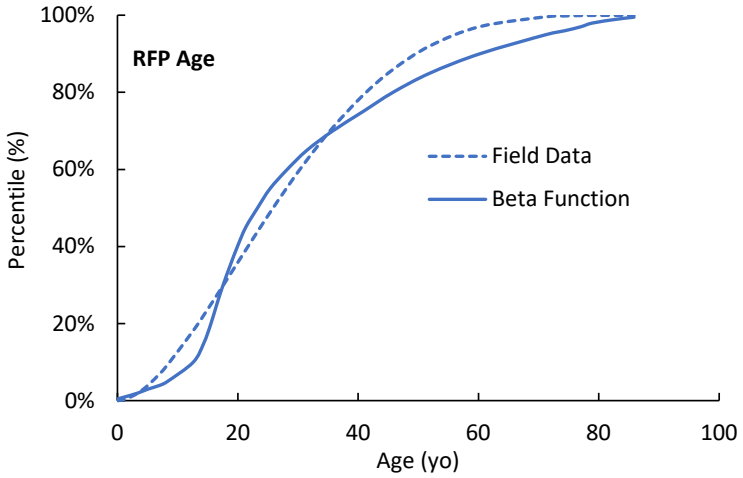

Figure A4: Right-front passenger age percentile distribution and fitted Beta cumulative distribution function.

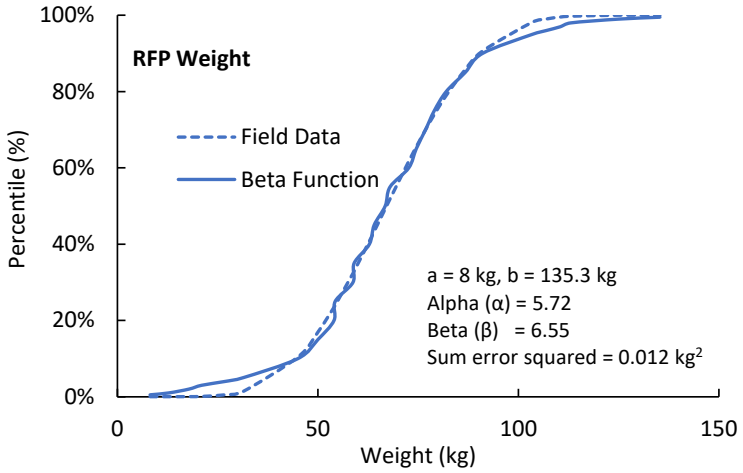

Figure A5: Right-front passenger weight percentile distribution and fitted Beta cumulative distribution function.

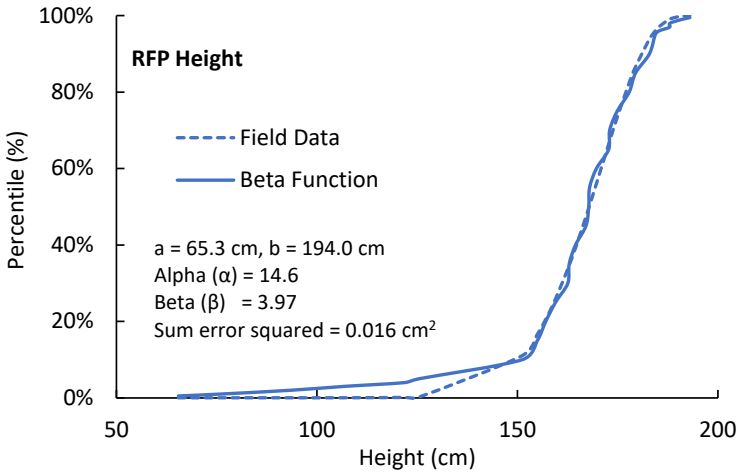

Figure A6: Right-front passenger height percentile distribution and fitted Beta cumulative distribution function.

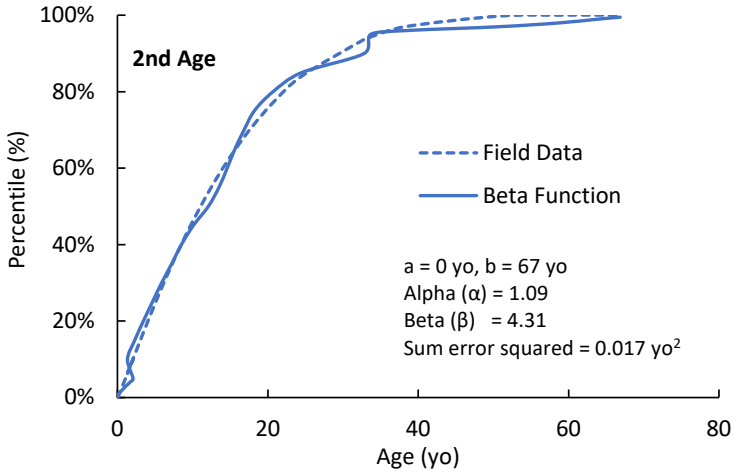

Figure A7: 2nd row passenger age percentile distribution and fitted Beta cumulative distribution function.

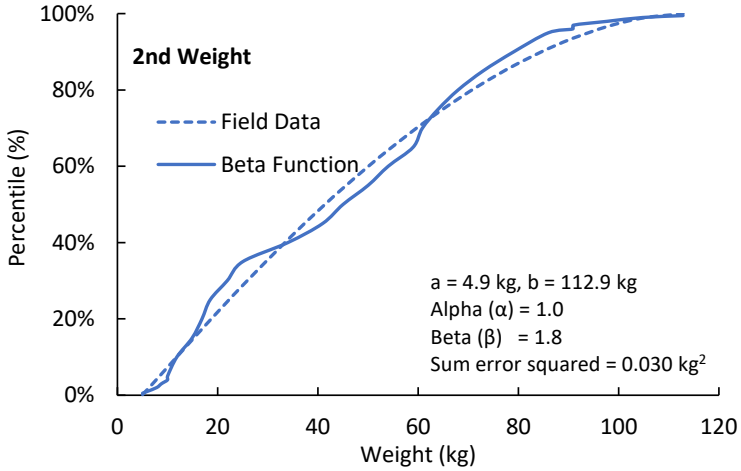

Figure A8: 2nd row passenger weight percentile distribution and fitted Beta cumulative distribution function.

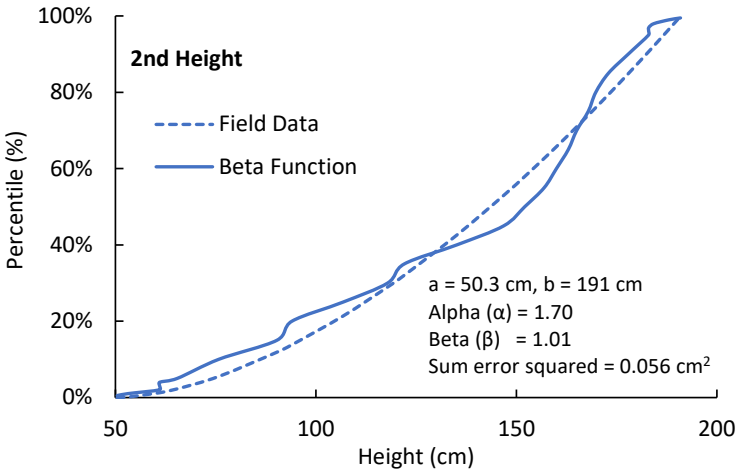

Figure A9: 2nd row passenger height percentile distribution and fitted Beta cumulative distribution function.