# VEHICLE GREENHOUSE SHAPE ANALYSIS FOR DESIGN OF A PARAMETRIC TEST BUCK FOR DYNAMIC ROLLOVER TESTING

**Patrick Foltz**
**Taewung Kim**
**Jason R. Kerrigan**
**Jeff R. Crandall**
Center for Applied Biomechanics, University of Virginia
United States
Paper Number 11-0271

## ABSTRACT

The goal of this study was to define a set of vehicle greenhouse geometries that are representative of the current vehicle fleet for use on a parametric rollover test buck. Greenhouse geometry data for 60 vehicles were taken from New Car Assessment Program (NCAP) test reports and compiled in a database for analysis. The database was then used to determine XYZ coordinates for landmark points that characterized the greenhouse geometries for those 60 vehicles. These landmark-based greenhouse representations were then analyzed and grouped into one of three groups using an Optimization technique. The mean shape was found for each group, and this was used as a representation of the group. These three representative shapes were found to have a maximum variation of 15 degrees in the windshield angle, 120 mm in roof rail height, 119 mm in greenhouse roofline width, and 258 mm in B- to C-pillar length.

## INTRODUCTION

While only accounting for 3% of crashes, more than one-third of vehicle occupant fatalities occur in crashes that involve rollover (NHTSA 2010). Epidemiological, computational, and experimental studies have implicated a variety of vehicle, crash, and occupant parameters affecting occupant fatality and injury risk (c.f. Gloeckner et al. 2006, Hu 2007, and Orlowski et al. 1985). Prioritization of these parameters for effective vehicle design, injury countermeasure development, or dynamic crashworthiness test procedure development, requires a means to assess the effects of adjusting a single parameter independently of the other factors. Computational modeling provides for a means to perform such independent evaluations, but uncertainties regarding the validity of vehicle models in dynamic rollover simulations (Parent et al. 2010) suggest that simulation results should be used only to guide and not define parameter prioritization. While experimental analyses have the benefit of utilizing physical structures, which eliminates concerns regarding validity, parametric analysis of rollover crashes using experimental testing is complicated by variations in multiple parameters between vehicles. For instance, in general, while vehicle A may differ from vehicle B in roof strength, they also may vary in roof shape, roll moment of inertia, mass and a variety of other factors. Thus, any differences in vehicle response cannot be attributed to variations in roof strength any more than they can be attributed to variations in shape, moment of inertia or mass. However, a vehicle-like buck structure that could be configured to match a variety of vehicle geometric, inertial, and strength parameters, while allowing for independent adjustment of individual characteristics, would permit parametric evaluations of vehicle characteristics affecting occupant injury risk in rollover crashes. Use of the parametric rollover buck with a rollover crash test fixture designed for parametric variation of crash characteristics (Kerrigan et al. 2011) and with various occupant surrogates in various positions with various restraints full parametric analyses could be conducted. This study presents methodology and results of a part of a larger research effort aimed at the development of a parametric rollover test buck for use in examining the effect individual vehicle parameters have on vehicle crashworthiness and occupant injury risk.

To ensure that parametric rollover testing yields applicable results, the buck should be representative of the current model vehicle fleet. Thus, the test buck was designed to mimic the current vehicle fleet in four separate categories: exterior geometry, interior (occupant space) geometry, inertial properties, and roof strength. For each of the individual parameters within each group, a range values representative of the current fleet needs to be identified, and a design methodology that permits adjustment of the buck to achieve values within the range needs to be developed. For the inertial properties (including mass, moment of inertia, location of the center of gravity), identification of the parameter ranges for the current fleet can be determined from the literature (Heydinger et al. 1999, Bixel et al. 2010), and buck adjustment can be achieved by designing provisions to add and remove ballast weights from different locations on the vehicle. Similarly, interior geometry (e.g. occupant vertical, lateral and longitudinal headroom, lateral space from occupant to the door structure) can be determined from United States Department of Transportation (USDOT) frontal impact (FI) and side impact (SI) New Car Assessment Program (NCAP) reports, and buck adjustment can be obtained by adjusting the location of the occupant's seat relative to the vehicle's interior structures (door, roof rail, roof, B-pillar, instrument panel, etc). Regarding external (greenhouse) geometry and roof strength, adjustment of the buck to achieve particular values is a more complex problem. Since the buck's greenhouse (pillars and roof) should sustain plastic deformation as a result of a rollover test, parts of the greenhouse, or possibly the entire structure, will need to be replaced between tests. Thus, as an initial effort at identifying the sensitivity of occupant injury risk to changes in roof strength and exterior vehicle shapes, greenhouse structure designs exhibiting three different shapes and three different strengths will be developed. Once the baseline sensitivities are elucidated, an extensive computational modeling effort will be undertaken to complement experimental results, and additional roof structures may be developed.

However, the problem of identification of the ranges of parameters exhibited by the vehicle fleet for strength and shape still exists. Roof strength can be conveniently represented on a linear scale using the strength-to-weight ratio (SWR) determined from a platen test like the Federal Motor Vehicle Safety Standard (FMVSS) No. 216 test. Since this test can be simulated computationally, once greenhouse geometries are identified, specific structural components of the greenhouses can be modified until the structures exhibit the targeted SWR. Thus, the last issue is how to identify three greenhouse geometries that are representative of the current vehicle fleet.

Since greenhouse geometries vary widely between vehicles, and more than three parameters are required (at a minimum) to characterize the geometries, identification of three specific geometries that are representative of the fleet is a challenging problem. It is hypothesized that specific geometries that are at or near the boundaries of vehicle-to-vehicle variation will be required to show significant effects on injury risk when the sensitivity of geometry is examined. The current study combines Generalized Procrustes Analysis (GPA) and a novel optimization technique to group greenhouse geometries from 43 vehicles, spanning 14 different classifications, into three separate groups based on geometric differences and identifies "average" geometries from each group. While it is clear that there are some relationships between greenhouse shape and size that result from the vehicle design process, the procedures presented here normalize vehicle geometries by their size to group vehicles by differences in their shape alone.

# METHODOLOGY

## Greenhouse geometry and landmarks

First, an initial study of original equipment manufacturer (OEM) vehicle classifications was conducted. Vehicle registration data [R.L. Polk & Co] was referenced to determine a ranking of OEMs by number of vehicles registered in the United States in 2008 and 2009. Over 70% of the vehicle fleet was accounted for by the 14 different vehicle makes considered in this study. It was determined that the vehicle classifications used by the manufacturers of these 14 vehicle makes were one of 15 categories: Subcompact, Compact, Midsize Sedan/Coupe, Fullsize Sedan/Coupe, Sports Car, Compact SUV, Compact Crossover, Midsize SUV, Midsize Crossover, Midsize Pickup, Fullsize SUV, Fullsize Pickup, SUT (Pickup-SUV Hybrid), Minivan, and Fullsize Van. Once these 15 categories were determined, at least three vehicles from each category were selected to populate a database. Greenhouse geometry for each of the vehicles was specified using measurements collected from FI and SI NCAP test reports. However, NCAP reports for Fullsize Vans were unavailable, so this group was omitted. Also, in the case of the SUT class, only three vehicles fit into this class (Chevrolet Avalanche, Honda Ridgeline, Explorer Sport Trac), but FI and SI NCAP reports were not available for the Explorer Sport Trac, so only two vehicles were used for this category. In total, 60 vehicles were found encompassing the 14 remaining categories (Table 1, and Table A1).

**Table 1. Number of Vehicles Included In Each Classification**

| Vehicle | Number |
|---|---|
| Subcompact | 3 |
| Compact Car | 4 |
| Midsize Sedan/Coupe | 5 |
| Fullsize Sedan/Coupe | 4 |
| Sports Car | 3 |
| Midsize Pickup | 5 |
| Fullsize Pickup | 5 |
| Compact SUV | 3 |
| Compact Crossover SUV | 4 |
| Midsize SUV | 9 |
| Midsize Crossover SUV | 5 |
| Fullsize SUV | 5 |
| Minivan | 3 |
| Pickup/SUV Hybrid | 2 |
| Total Vehicles | 60 |

Eight geometric parameters for each of the 60 vehicles obtained from the FI and SI NCAP reports were added to the database (Figure 1): windshield angle, A- to B-pillar base length measured midline to midline, B- to C-pillar base length measured midline to midline, greenhouse base width from A-pillar edge to A-pillar edge, greenhouse roofline width from A-pillar edge to edge beltline height, roof rail height, and overall roof height (US DOT FI/SI NCAP). From these parameters, the overall greenhouse height was calculated by subtracting the roof height from the beltline height, and the greenhouse rail height was calculated by subtracting the roof rail height from the beltline height (Figure 1). Histograms for each of the greenhouse geometric properties were created to examine differences across the vehicle fleet (Appendix Figure A1).

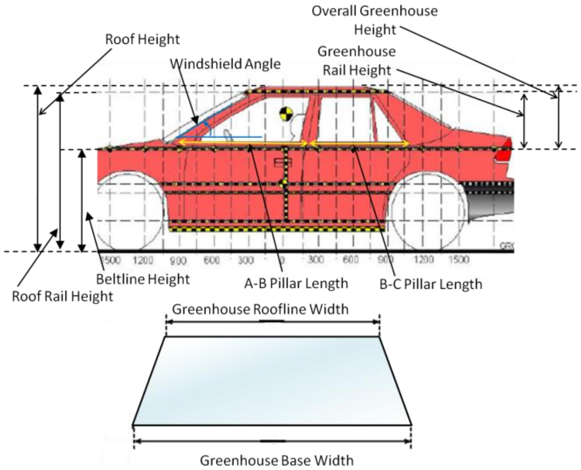


**Figure 1. Vehicle geometric parameters used to characterize greenhouse geometry (US DOT FI/SI NCAP).**

To more easily compare the differences in geometry between vehicles and facilitate grouping optimization (see *Grouping Using Optimization*) data, parameters were expressed as X-, Y-, and Z-coordinates of 18 landmarks on the vehicle (Figure 2). The origin of the coordinate system was located at the center base of the windshield ($L_{16}$), with the X-direction aligned with the longitudinal axis of the vehicle, the Y-direction aligned with the lateral axis of the vehicle, and the Z-direction aligned with the vertical axis of the vehicle. D-pillar geometry was not considered, even though SUVs and some other vehicles have a D-pillar, since front row occupants involved in lateral (barrel) rolls were the primary focus of the buck development. X-, Y-, and Z-coordinates for each of the 18 points on each vehicle were added to the database (Figure 2). Due to the way each of the landmarks were defined, all of the landmark coordinates could be determined from the coordinates of a reduced set of landmarks ($L_1$, $L_4$, $L_5$, $L_6$, and $L_7$) referred to as the critical landmarks.

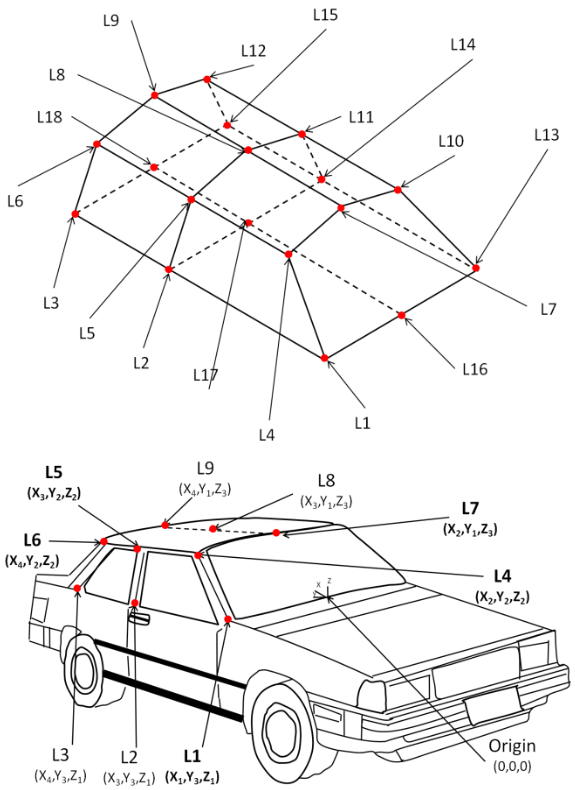


**Figure 2. Top: 18 landmarks used to characterize greenhouse geometry. Bottom: Five particular landmarks (in bold) representing the reduced set of "critical" landmarks.**

While some of the coordinates could be derived directly from the geometric parameters taken from the NCAP reports (Figure 1), some of the landmark coordinates had to be derived. The height of the roof rail ($Z_2$ from point $L_4$ in Figure 2) was calculated by subtracting the beltline height from the roof rail height, the overall greenhouse height ($Z_3$ from point $L_7$ in Figure 2) was derived by subtracting the beltline height from the overall roof height. Finally, the X-coordinate of the point at the top of the A-pillar $X_2$ was calculated using

$$X_2 = \frac{h_{greenhouse}}{\tan(\theta_{windshield})} \quad (1).$$

where $h$ is the height of the roof rail, and $\theta$ is the windshield angle.

From the original 60 vehicles, complete data (all of the measurements from Figure 1) were only found for 52 vehicles. For the vehicles with complete data, not all measurements were included due to inconsistencies in the reported measurements (i.e. the value $X_2$ suggested the top of the A-pillar was between the B- and C-pillars) or because some vehicles lacked a C-pillar. The final set consisted of 43 vehicles, with less than three vehicles in the Subcompact, Compact, Fullsize Sedan and Sports Car categories. However Midsize Sedans, Trucks and SUVs were well represented (Table 2 and Appendix Table A1).

**Table 2.**
**Vehicles for Greenhouse Structure Shape Analysis**

| Vehicle | Number |
|---|---|
| Subcompact | 1 |
| Compact Car | 2 |
| Midsize Sedan/Coupe | 4 |
| Fullsize Sedan/Coupe | 1 |
| Sports Car | 2 |
| Midsize Pickup | 4 |
| Fullsize Pickup | 3 |
| Compact SUV | 3 |
| Compact Crossover SUV | 3 |
| Midsize SUV | 8 |
| Midsize Crossover SUV | 5 |
| Fullsize SUV | 3 |
| Minivan | 2 |
| Pickup/SUV Hybrid | 2 |
| Total with full data | 43 |

## Generalized Procrustes Analysis

Once the vehicle data were organized, Generalized Procrustes Analysis was used to translate and scale each of the greenhouse shapes to prepare the data for grouping optimization by shape (Dryden and Mardia, 1998). Translation of the shapes, and their landmark coordinates, resulted in a set of centered landmarks $L_c$, obtained by

$$L_{c,ni} = L_{ni} - \frac{1}{K}\sum_{j=1}^{K} L_{nj} \quad (2).$$

where $L$ is a vector containing the coordinates of each landmark, $n$ represents the vehicle number from 1 to 43, $K$ is the total number of landmarks (18), and i represents the index of the landmarks from 1 to 18.

This step serves to express each landmark's vector relative to the centroid of points composed using all 18 landmarks for the particular vehicle. While all 18 landmarks were used to compute the centroid, only the five critical landmarks are needed to define the greenhouse geometry (Figure 3).

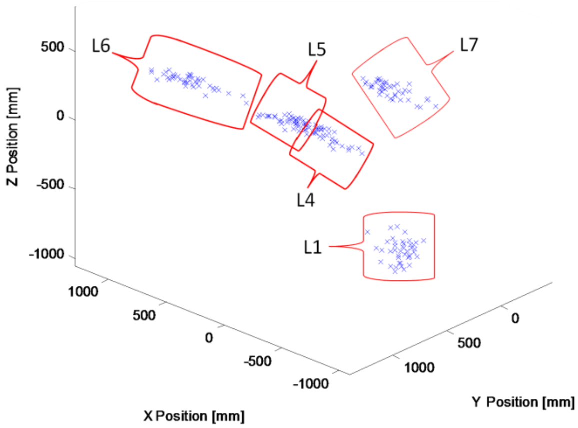


**Figure 3. Centered critical landmark distributions for each of the 43 vehicles.**

Then, each of the centered landmarks were scaled, or normalized, by the size variable $r_n$ (Dryden and Mardia, 1998)

$$r_n = \left(\frac{1}{K}\sum_{j=1}^{K} L_{c,nj}^T L_{c,nj}\right)^{0.5} \quad (3a).$$

$$Q_{ni} = L_{c,ni}/r_n \quad (3b).$$

where $r_n$ was the mean square root error of distances each landmark was from its centroid, and $Q$ were the normalized vectors.

## Grouping using Optimization

Once the landmarks were scaled and aligned with the same origin, three groups of greenhouse geometries were determined by optimization (Equation 4). The optimization relied upon the use of a weighting vector $p_{mn}$, which is similar to the probability that the $n^{th}$ vehicle was included in $m^{th}$ group, which was used as the design variable in this problem. $Q_{nk}$ denoted the position of $k^{th}$ landmark of $n^{th}$ vehicle (the aligned and normalized landmark coordinates) and $\bar{Q}_{mk}$, which was the output of the optimization algorithm, represented mean location of the $k^{th}$ landmarks of the $m^{th}$ group.

*Minimize*

$$\sum_{m=1}^{M}\sum_{k=1}^{K}\sum_{n=1}^{N} p_{mn}\left(Q_{nk} - \bar{Q}_{mk}\right)^T\left(Q_{nk} - \bar{Q}_{mk}\right) \quad (4a).$$

*where*

$$\bar{Q}_{mk} = \sum_{n=1}^{N} p_{mn}\, Q_{nk} / \sum_{n=1}^{N} p_{mn} \quad (4b).$$

*Subject to*

$$\sum_{m=1}^{M} p_{mn} = 1\ (for\ n = 1, \ldots, 43) \quad (4c).$$

$$p_{mn} \geq 0 \quad (4d).$$

It should be noted that if the weights are uniformly distributed (equal) the objective function is maximized and the optimization cannot progress. Therefore, the weights were seeded randomly, and the optimization was performed 50 times with different seed values for the weights. The MATLAB™ function *fmincon* was used to minimize the objective function each time. From the 50 results, the result with the lowest final value for the objective function was used. Then these steps were conducted nine more times to verify that the group weights $p_{mn}$ resulted in the same distribution of groups, which verified the repeatability and robustness of the result.

The resulting weights showed that each vehicle was effectively put into one of the three groups: one value was close to 1, and the other two values were close to 0. Then mean shapes for each group were obtained by a simple average of the normalized coordinates for all of the vehicles in each group. Since the GPA process effectively removed size information from the data, the three mean greenhouses were then scaled back to real coordinates. The landmarks, $\bar{Q}_{mk}$, that are expressed in normalized coordinate system were scaled back to landmarks of the original coordinate system, $\bar{L}_{mk}$, by multiplying the mean size of the 43 vehicles.

$$\bar{L}_{mk} = \bar{Q}_{mk} \cdot \frac{1}{N}\sum_{n}^{N} r_n \quad (5).$$

# RESULTS

Three separate greenhouse shapes were determined (Figure 4). 27, 9, and 7 vehicles were in group 1, group 2, and group 3, respectively (Table A1). All of the greenhouse coordinates were translated so that the

X- and Z-coordinates of $L_{13}$ were aligned at 0 and 0, respectively and so that $L_{16}$ had a Y value of 0 (Figure 5 and Table 3). The resulting coordinates of the mean group shapes were compared with those in the fleet (Figure A1). The geometric parameters defining greenhouse geometry were computed to compare with the fleet (Table 4 and Figure A2). To examine the relationship between size and shape of the greenhouses, the distribution of the size variables for each vehicle (Equation 3a) were compared with the distributions from each group (Figure 6).

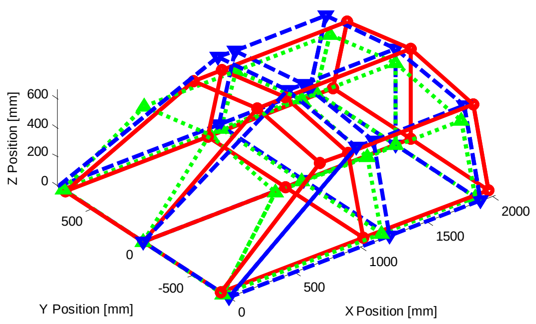


**Figure 4. 3-D view of the 18 landmarks for each of the three average greenhouses.**

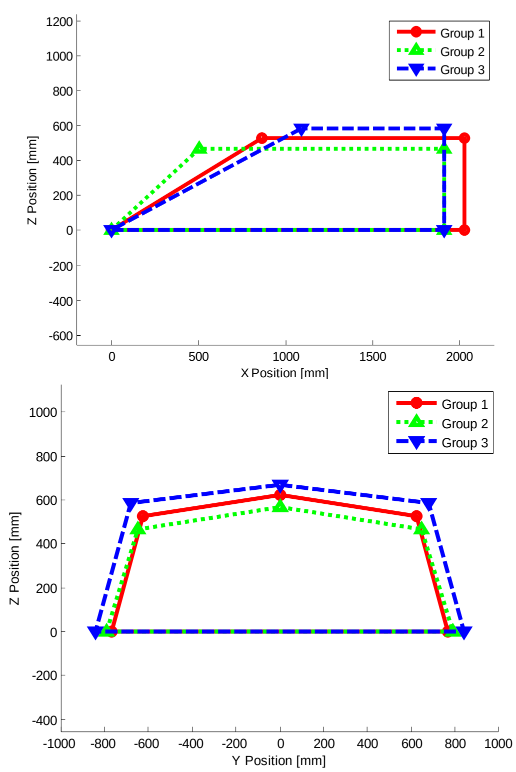


**Figure 5. Front (top) and side (bottom) views of the group average greenhouses.**

**Table 3.**
**Coordinates for the Critical Landmarks [mm]**

| | $L_1$ | $L_4$ | $L_5$ | $L_6$ | $L_7$ |
|---|---|---|---|---|---|
| Group 1 (n=27) | | | | | |
| **X** | 0 | 863 | 1075 | 2027 | 863 |
| **Y** | 767 | 623 | 623 | 623 | 0 |
| **Z** | 0 | 528 | 528 | 528 | 624 |
| Group 2 (n=9) | | | | | |
| | $L_1$ | $L_4$ | $L_5$ | $L_6$ | $L_7$ |
| **X** | 0 | 503 | 1197 | 1913 | 503 |
| **Y** | 791 | 648 | 648 | 648 | 0 |
| **Z** | 0 | 466 | 466 | 466 | 570 |
| Group 3 (n=7) | | | | | |
| | $L_1$ | $L_4$ | $L_5$ | $L_6$ | $L_7$ |
| **X** | 0 | 1090 | 1217 | 1910 | 1090 |
| **Y** | 843 | 682 | 682 | 682 | 0 |
| **Z** | 0 | 586 | 586 | 586 | 669 |

**Table 4.**
**Geometric parameters for the three averaged greenhouses**

| | Group 1 | Group 2 | Group 3 |
|---|---|---|---|
| Roof rail height (mm) | 528 | 466 | 586 |
| Overall roof height (mm) | 624 | 570 | 669 |
| AB pillar length (mm) | 212 | 694 | 127 |
| BC pillar length (mm) | 951 | 716 | 693 |
| Greenhouse roofline width (mm) | 1246 | 1296 | 1365 |
| Greenhouse base width (mm) | 1535 | 1581 | 1686 |
| Windshield angle (deg) | 31 | 43 | 28 |

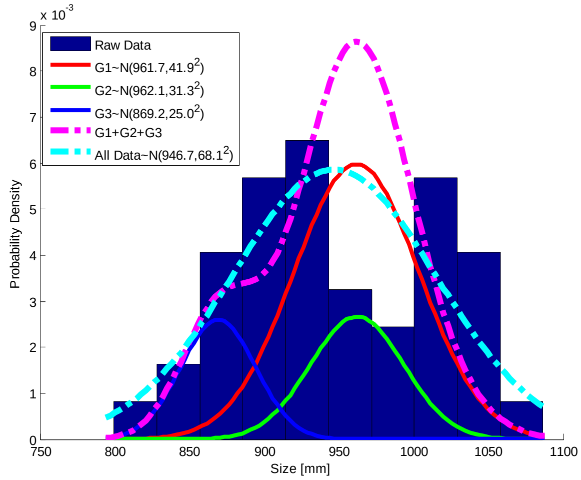


**Figure 6. Distribution of the size variables for each group compared to all vehicles.**

## DISCUSSION

While the optimization problem defined in this study was not designed specifically to obtain unity for one of the elements of the weight vector for each vehicle, the resulting weight vectors showed that each vehicle was completely secluded to one of the three groups. This suggested that the optimization technique succeeded in effectively grouping the greenhouse shapes. After multiplying the mean greenhouse shapes by the same scale factor, it could be seen that group 3 had the tallest roof and greenhouse, but the shortest distance on the roof rail from the A-pillar to the C-pillar (AB Pillar Length + BC Pillar length) and the lowest windshield angle. Whereas group 2 had the lowest greenhouse and roof height, but the longest A-pillar to C-pillar length and highest windshield angle.

Despite the appearance of greater height in group 3, which is an indication only of its shape, the average size variable for the vehicles in group 3 was lower than that of the vehicles in groups 1 and 2 (Figure 6). While the vehicles in group 3 (only one Midsize Sedan, a Fullsize Pickup, a Midsize Pickup, a Midsize SUV, and three Midsize Crossovers (see Table A1) are typically referred to as larger vehicles, their average greenhouse size variable (Figure 6) was actually smaller because much of the size variable is based on the greenhouse length in the X-direction, which is typically larger in sedans than in trucks and SUVs. While group 1 and group 2 showed differences in shape, their average size variables were nearly identical (with a higher variance in group 1) suggesting that for vehicles in these groups, relationships between size and shape could not be determined from the current study. In other words, the current study did not show that there were relationships between size and shape for the vehicles in groups 1 and 2. However, since the size of group 3 vehicles was actually smaller than that of the other groups, it appears that the shape characteristics of group 3 are not independent of size.

This study identified the distributions (Figures A1 and A2) of the greenhouse shapes of a variety of vehicles in the fleet. It successfully separated the geometric characteristics of size and shape to group vehicles based on their shape. To create a series of greenhouses for a rollover test buck, shape characteristics (or the mean shapes of each group) could be paired with certain vehicle sizes (using the data from Figure 6) to develop a series of roofs that span differences in the fleet in terms of vehicle shape and size. However, since data for shape and size have been separated, if three values of shape are paired with three values of size, nine roof geometries would need to be developed for each level of strength chosen. This will result in a cumbersome number of roof variations for a parametric analysis of the effects of roof strength and geometry on occupant injury risk. Additionally, it seems that this approach could result in unrealistic greenhouse geometries since a large size could be paired with a shape to create a greenhouse that is not available in the fleet. It is hypothesized that the effects greenhouse geometry has on occupant injury risk can only be seen by examining geometries that are at the boundaries of the distribution. Thus, it may make more sense to use the data from this study to determine the specific vehicle geometries that are at the boundaries of greenhouse geometry distributions for parametric examinations. As a next step, computational simulations could be used to examine how to determine which factors of greenhouse geometry are most important for rollover analyses.

## CONCLUSION

This study aimed to identify three different greenhouse shapes that are representative of the current vehicle fleet. The fleet was surveyed, and a novel optimization algorithm was used to determine three different geometries by minimizing the sum of the weighted distances between individual vehicle landmarks and the three group averaged geometries. The process separated the effect of greenhouse size from greenhouse shape to group geometries by shape only and permitted separate quantification of the distribution of greenhouse size. The result yielded three different mean greenhouses that are representative of the fleet in terms of differences shape. Additionally, the distribution of a variety of greenhouse geometric parameters for 43 vehicles in the fleet is presented. The next step in this work is to examine how these average shapes, coupled with appropriate sizes, compare to real vehicles in the fleet, and to determine how differences in greenhouse geometry affect occupant injury risk through experimental testing and computational analysis.

## ACKNOWLEDGMENTS

This study was supported by the National Highway Traffic Safety Administration (NHTSA) under Cooperative Agreement No. DTNH22-09-H-00247. Views or opinions expressed or implied are those of the authors and are not necessarily representative of the views or opinions of the NHTSA.

## REFERENCES

Arora J. (2004) Introduction to Optimum Design. Academic Press; 2nd edition (May 19, 2004).

Bixel RA, Heydinger GJ, Guenther DA. (2010) Measured vehicle center-of-gravity locations – including NHTSA's data through 2008 NCAP. Society of Automotive Engineers (SAE). Paper Number 2010-01-0086. Warrendale, PA.

Dryden, IL, Mardia, KV. (1998) Statistical Shape Analysis. Chichester, New York

Gloeckner DC, Moore TLA, Steffey D, Bare C, Corrigan CF. (2006) Implications of vehicle roll direction on occupant ejection and injury risk. 50th Annual Proceedings of the Association for the Advancement of Automotive Medicine.

Heydinger GJ, Bixel RA, Garrott WR, Pyne M, Howe JG, Guenther DA. (1999) Measured vehicle inertial parameters – NHTSA's data through November 1998. Society of Automotive Engineers (SAE). Paper Number 1999-01-1336. Warrendale, PA.

Hu J. (2007) Neck injury mechanism in rollover crashes – a systematic approach for improving rollover neck protection. PhD. Dissertation. Wayne State University. Detroit, MI.

Kerrigan JR, Jordan A, Parent D, Zhang Q, Funk J, Dennis NJ, Overby B, Bolton J, Crandall J. (2011) Design of a dynamic rollover test system. Society of Automotive Engineers (SAE). Paper Number 2011-01-1116. Warrendale, PA.

National Highway Traffic Safety Administration (NHTSA). (2010) Traffic Safety Facts 2008—A compilation of motor vehicle crash data from the fatality analysis reporting system and the general estimate system. Early Edition. DOT HS 811 170. http://www-nrd.nhtsa.dot.gov/Pubs/811170.PDF

Orlowski KF, Bundorf RT, Moffat EA. (1985) Rollover crash tests-the influence of roof strength on injury mechanics. Proceedings of the 29th Stapp Car Crash Conference. SAE Paper 851734. Society of Automotive Engineers, Warrendale, PA.

Parent DP, Kerrigan JR, Crandall JR. (2010) Comprehensive computational rollover sensitivity study part 1: influence or vehicle pre-crash parameters on crash kinematics and roof crush. Proceedings of the International Crashworthiness Conference, Paper 2010-010. Washington DC, USA.

US Department of Transportation. (2004-2010). "*New Car Assessment Program (NCAP) Frontal Barrier Impact Test"*. Retrieved from www.regulations.gov

US Department of Transportation. (2004-2010). *"New Car Assessment Program (NCAP Side Barrier Impact Test."* Retrieved from www.regulations.gov

## APPENDIX

**Table A1.**
**Vehicles examined, with report numbers for the FI and SI NCAP. Vehicles marked "excluded" could not be included in the analysis due to a lack of sufficient information.**

| Vehicle: Make/Model/ Year | FI NCAP Report Docket Number [1] | SI NCAP Report Docket Number [2] | Type | Group |
|---|---|---|---|---|
| Acura/RL/2005 | NHTSA-1999-4962-0281 | NHTSA-1998-3835-0247 | Fullsize Sedan/Coupe | Excluded |
| BMW/5Series/2008 | NHTSA-1999-4962-0439 | NHTSA-1998-3835-0395 | Fullsize Sedan/Coupe | **1** |
| BMW/Z4/2003 | NHTSA-1999-4962-0223 | NHTSA-1998-3835-0207 | Sports Car | Excluded |
| Cadillac/CTS/2008 | NHTSA-1999-4962-0469 | NHTSA-1998-3835-0410 | Midsize Sedan/Coupe | **3** |
| Cadillac/SRX/2010 | NHTSA-1999-4962-0530 | NHTSA-1998-3835-0497 | Midsize Crossover | **3** |
| Chevrolet/Avalanche/2007 | NHTSA-1999-4962-0389 | NHTSA-1998-3835-0384 | Fullsize SUV | **1** |
| Chevrolet/Aveo/2004 | NHTSA-1999-4962-0370 | NHTSA-1998-3835-0232 | Compact | Excluded |
| Chevrolet/Camaro/2010 | NHTSA-1999-4962-0512 | NHTSA-1998-3835-0471 | Sports Car | **2** |
| Chevrolet/Colorado/2006 | NHTSA-1999-4962-0345 | NHTSA-1998-3835-0262 | Midsize Pickup | **2** |
| Chevrolet/Equinox/2005 | NHTSA-1999-4962-0264 | NHTSA-1998-3835-0227 | Midsize SUV | **1** |
| Chevrolet/Malibu/2008 | NHTSA-1999-4962-0467 | NHTSA-1998-3835-0429 | Fullsize Sedan/Coupe | Excluded |
| Chevrolet/Silverado/2007 | NHTSA-1999-4962-0406 | NHTSA-1998-3835-0386 | Fullsize Pickup | **2** |
| Chevrolet/Suburban/2007 | NHTSA-1999-4962-0362 | NHTSA-1998-3835-0379 | Fullsize SUV | **1** |
| Chevrolet/Tahoe/2007 | NHTSA-1999-4962-0349 | NHTSA-1998-3835-0382 | Fullsize SUV | **1** |
| Dodge/Caliber/2007 | NHTSA-1999-4962-0361 | NHTSA-1998-3835-0323 | Compact Crossover | **1** |
| Dodge/Dakota/2005 | NHTSA-1999-4962-0298 | NHTSA-1998-3835-0263 | Midsize Pickup | **2** |
| Dodge/Grand Caravan/2008 | NHTSA-1999-4962-0445 | NHTSA-1998-3835-0415 | Minivan | **1** |
| Dodge/Journey/2009 | NHTSA-1999-4962-0457 | NHTSA-1998-3835-0421 | Compact SUV | **1** |
| Dodge/Nitro/2007 | NHTSA-1999-4962-0392 | NHTSA-1998-3835-0345 | Compact Crossover | **1** |
| Dodge/Ram1500/2009 | NHTSA-1999-4962-0492 | N/A | Fullsize Pickup | Excluded |
| Ford/Escape/2008 | NHTSA-1999-4962-0424 | NHTSA-1998-3835-0364 | Compact SUV | **1** |
| Ford/Expedition/2006 | NHTSA-1999-4962-0226 | NHTSA-1998-3835-0016 | Fullsize SUV | **1** |
| Ford/Explorer/2002 | NHTSA-1999-4962-0147 | NHTSA-1998-3835-0185 | Midsize SUV | Excluded |
| Ford/F-150/2009 | NHTSA-1999-4962-0496 | NHTSA-1998-3835-0459 | Fullsize Pickup | **3** |
| Ford/Flex/2009 | NHTSA-1999-4962-0471 | NHTSA-1998-3835-0435 | Midsize Crossover | **1** |
| Ford/Fusion/2008 | NHTSA-1999-4962-0434 | NHTSA-1998-3835-0297 | Midsize Sedan/Coupe | **1** |
| Ford/Mustang/2010 | NHTSA-1999-4962-0501 | NHTSA-1998-3835-0477 | Sports Car | **2** |
| Ford/Ranger/2007 | NHTSA-1999-4962-0383 | NHTSA-1998-3835-0020 | Midsize Pickup | Excluded |
| Honda/Element/2007 | NHTSA-1999-4962-0216 | NHTSA-1998-3835-0346 | Compact SUV | **2** |
| Honda/Fit/2009 | NHTSA-1999-4962-0488 | NHTSA-1998-3835-0457 | Subcompact | Excluded |
| Honda/Odyssey/2005 | NHTSA-1999-4962-0292 | NHTSA-1998-3835-0257 | Minivan | Excluded |
| Honda/Pilot/2008 | NHTSA-1999-4962-0476 | NHTSA-1998-3835-0440 | Midsize SUV | **1** |
| Honda/Ridgeline/2006 | NHTSA-1999-4962-0312 | NHTSA-1998-3835-0328 | Fullsize SUT | **2** |
| Kia/Borrego/2009 | NHTSA-1999-4962-0484 | NHTSA-1998-3835-0449 | Midsize Crossover | **1** |
| Kia/Forte/2010 | NHTSA-1999-4962-0519 | NHTSA-1998-3835-0476 | Midsize Sedan/Coupe | Excluded |
| Kia/Optima/2006 | NHTSA-1999-4962-0393 | NHTSA-1998-3835-0339 | Fullsize Sedan/Coupe | Excluded |
| Kia/Rio/2006 | NHTSA-1999-4962-0324 | NHTSA-1998-3835-0327 | Compact | **1** |
| Kia/Rondo/2007 | NHTSA-1999-4962-0409 | NHTSA-1998-3835-0358 | Midsize Crossover | **3** |
| Kia/Sedona/2006 | NHTSA-1999-4962-0344 | NHTSA-1998-3835-0314 | Minivan | **1** |
| Kia/Soul/2010 | NHTSA-1999-4962-0502 | NHTSA-1998-3835-0463 | Compact Crossover | **1** |
| Kia/Sportage/2007 | NHTSA-1999-4962-0403 | NHTSA-1998-3835-0348 | Midsize SUV | **1** |
| Lincoln/MKS/2009 | NHTSA-1999-4962-0491 | NHTSA-1998-3835-0444 | Fullsize Sedan/Coupe | **1** |

| Vehicle: Make/Model/ Year | FI NCAP Report Docket Number [1] | SI NCAP Report Docket Number [2] | Type | Group |
|---|---|---|---|---|
| Mazda/3/2010 | NHTSA-1999-4962-0537 | NHTSA-1998-3835-0465 | Compact | **1** |
| Mitsubishi/Lancer/2008 | NHTSA-1999-4962-0416 | NHTSA-1998-3835-0373 | Compact | Excluded |
| Nissan/Armada/2006 | NHTSA-1999-4962-0325 | N/A | Fullsize SUV | Excluded |
| Nissan/Cube/2009 | NHTSA-1999-4962-0511 | NHTSA-1998-3835-0470 | Compact Crossover | Excluded |
| Nissan/Frontier/2006 | NHTSA-1999-4962-0355 | NHTSA-1998-3835-0308 | Midsize Pickup | **3** |
| Nissan/Murano/2009 | NHTSA-1999-4962-0461 | NHTSA-1998-3835-0422 | Midsize Crossover | **3** |
| Nissan/Pathfinder/2005 | NHTSA-1999-4962-0300 | NHTSA-1998-3835-0251 | Midsize SUV | **3** |
| Nissan/Titan/2006 | NHTSA-1999-4962-0343 | N/A | Fullsize Pickup | Excluded |
| Nissan/Xterra/2005 | NHTSA-1999-4962-0313 | NHTSA-1998-3835-0276 | Midsize SUV | **1** |
| Smart/ForTwo/2008 | NHTSA-1999-4962-0455 | NHTSA-1998-3835-0420 | Subcompact | Excluded |
| Toyota/4Runner/2010 | NHTSA-1999-4962-0533 | NHTSA-1998-3835-0500 | Midsize SUV | **1** |
| Toyota/FJ/2007 | NHTSA-1999-4962-0358 | NHTSA-1998-3835-0311 | Midsize SUV | **2** |
| Toyota/Highlander/2008 | NHTSA-1999-4962-0442 | NHTSA-1998-3835-0402 | Midsize SUV | **1** |
| Toyota/Sequoia/2008 | NHTSA-1999-4962-0464 | N/A | Fullsize SUV | Excluded |
| Toyota/Tacoma/2006 | NHTSA-1999-4962-0353 | NHTSA-1998-3835-0304 | Midsize Pickup | **1** |
| Toyota/Tundra/2006 | NHTSA-1999-4962-0278 | NHTSA-1998-3835-0150 | Fullsize Pickup | **2** |
| Toyota/Venza/2009 | NHTSA-1999-4962-0498 | NHTSA-1998-3835-0467 | Midsize Crossover | **1** |
| Toyota/Yaris/2008 | NHTSA-1999-4962-0438 | NHTSA-1998-3835-0456 | Subcompact | **1** |

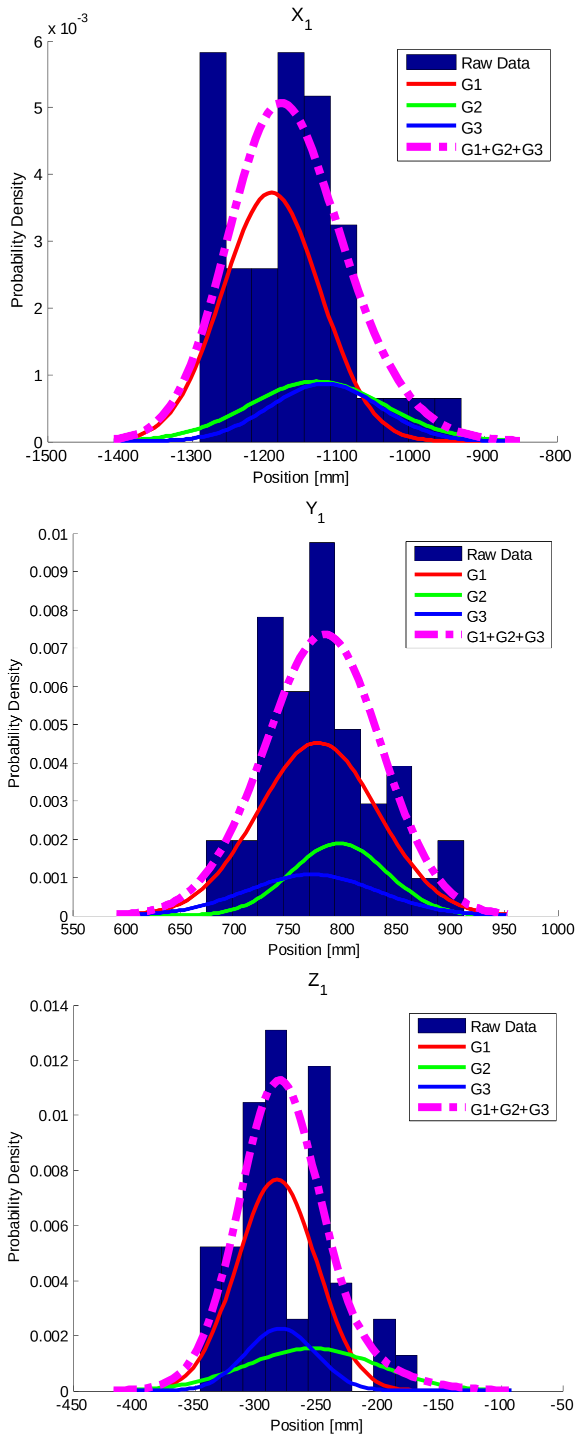


**Figure A1. Distributions of each of the vehicle greenhouse critical landmarks for the 43 vehicles included in the optimization study (Cont'd).**

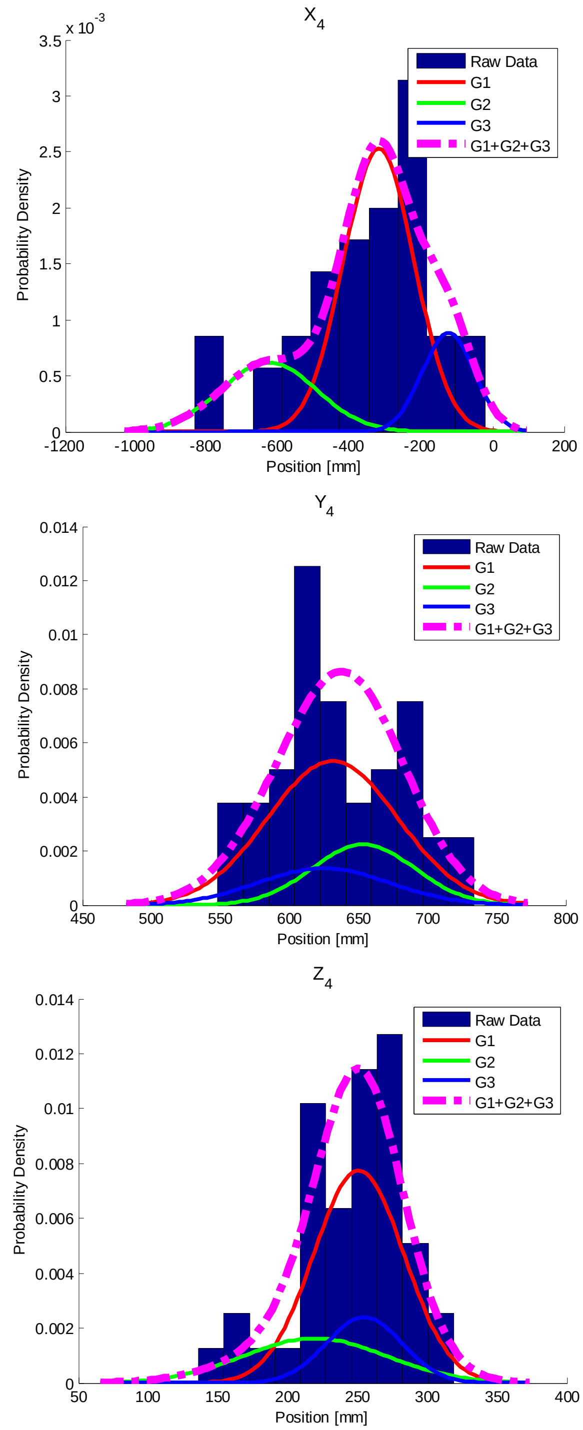


**Figure A1. Distributions of each of the vehicle greenhouse critical landmarks for the 43 vehicles included in the optimization study (Cont'd).**

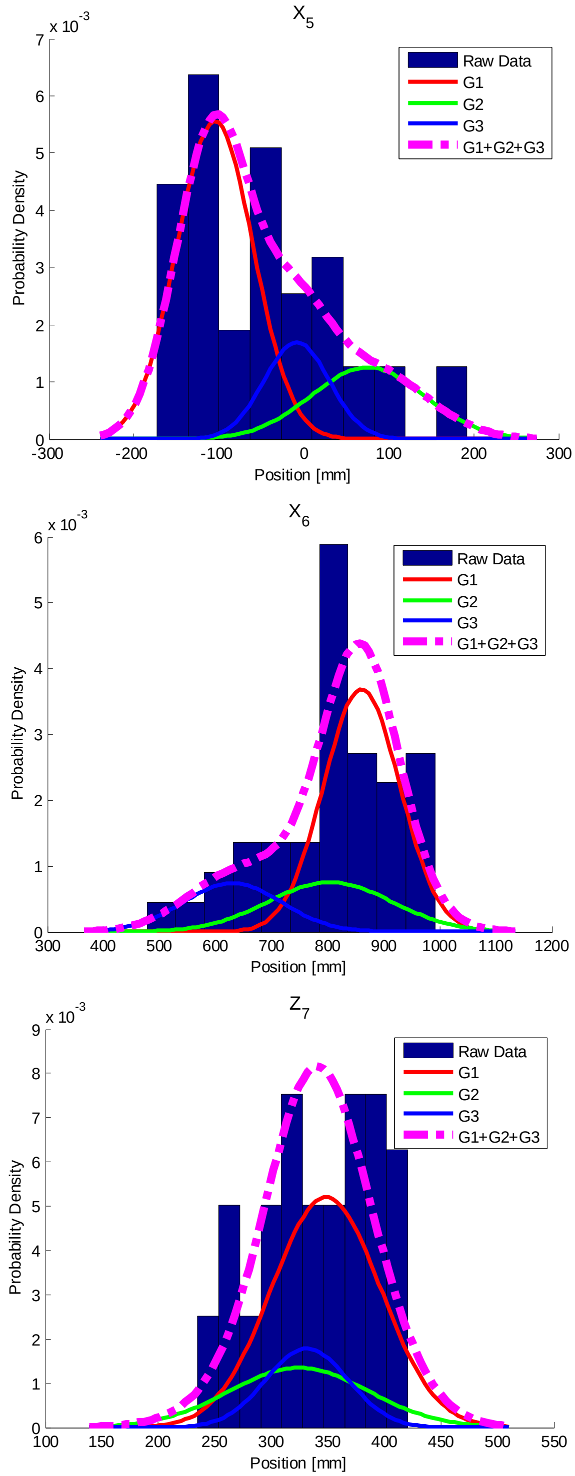


**Figure A1. Distributions of each of the vehicle greenhouse critical landmarks for the 43 vehicles included in the optimization study.**

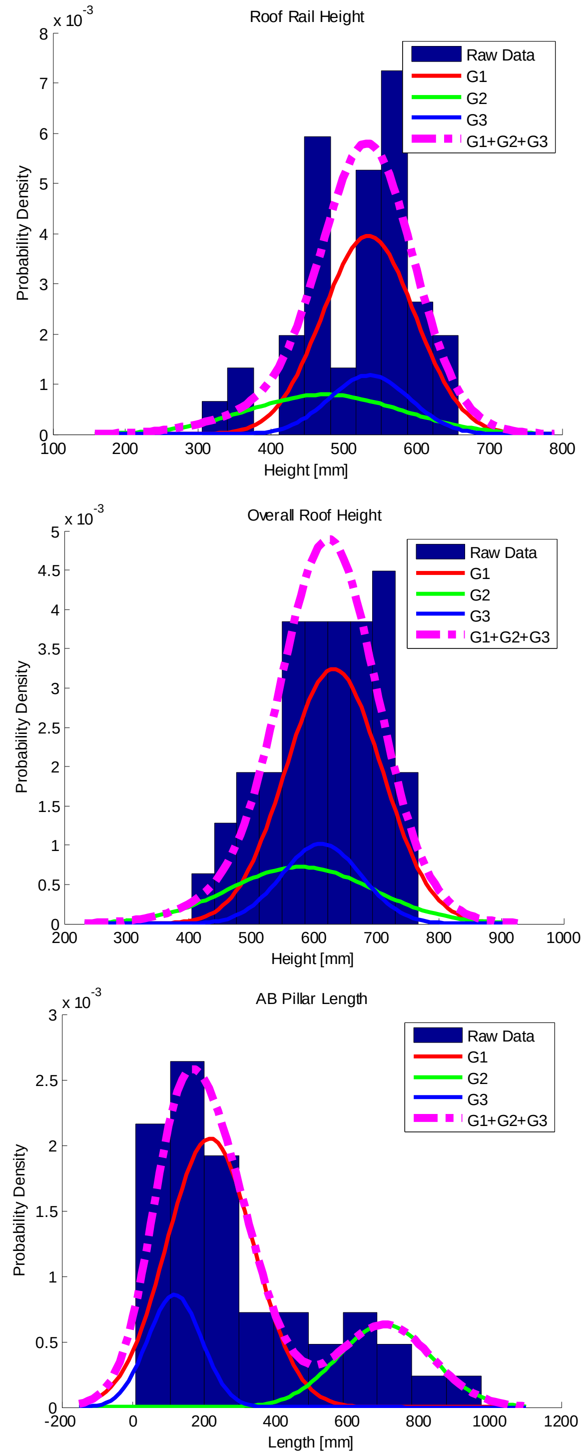


**Figure A2. Distributions of each of the vehicle greenhouse geometric parameters for the 43 vehicles included in the optimization study (Cont'd).**

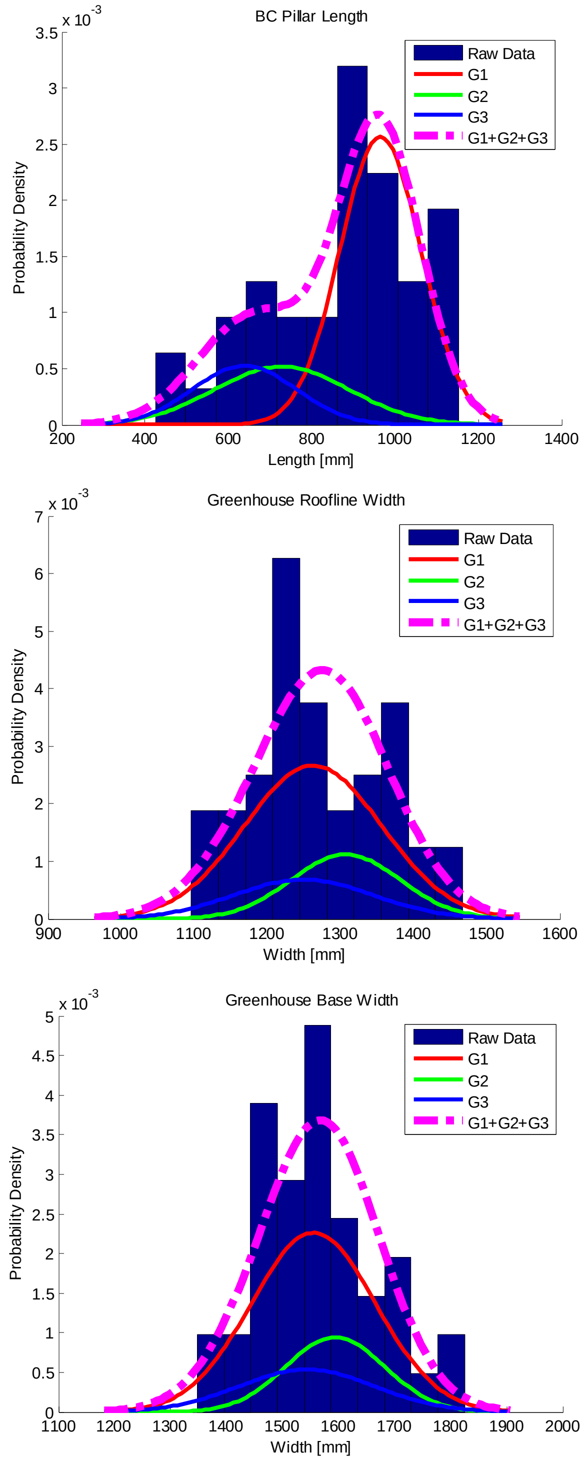


**Figure A2. Distributions of each of the vehicle greenhouse geometric parameters for the 43 vehicles included in the optimization study (Cont'd).**

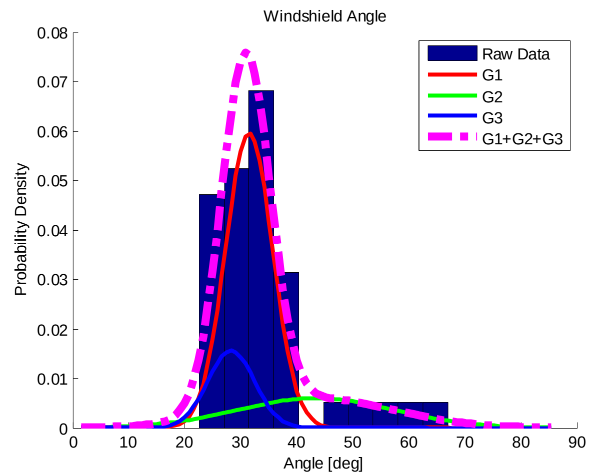


**Figure A2. Distributions of each of the vehicle greenhouse geometric parameters for the 43 vehicles included in the optimization study.**