



Effects of Driver Characteristics on Seat Belt Fit

Matthew P. Reed, Sheila M. Ebert
University of Michigan Transportation Research Institute

Jason J. Hallman
Toyota Technical Center USA, Toyota Motor Eng. and Manuf. NA, Inc.

ABSTRACT – A laboratory study of posture and belt fit was conducted with 46 men and 51 women, 61% of whom were age 60 years or older and 32% age 70 years or older. In addition, 28% of the 97 participants were obese, defined as body mass index $\geq 30 \text{ kg/m}^2$. A mockup of a passenger vehicle driver's station was created and five belt anchorage configurations were produced by moving the buckle, outboard-upper (D-ring), and outboard-lower anchorages. An investigator recorded the three-dimensional locations of landmarks on the belt and the participant's body using a coordinate measurement machine. The location of the belt with respect to the underlying skeletal structures was analyzed, along with the length of belt webbing. Using linear regression models, an increase in age from 20 to 80 years resulted in the lap belt positioned 18 mm further forward relative to the pelvis, 26 mm greater lap belt webbing length, and 19 mm greater shoulder belt length. An increase in stature of 350 mm (approximately the range from 5th-percentile female to 95th-percentile male in the U.S. population) was associated with the lap belt 14 mm further forward relative to the pelvis, the shoulder belt 37 mm more outboard relative to the body centerline, and 38 mm less shoulder belt webbing length. Among the driver factors considered, body mass index had the greatest effects. An increase of BMI in 20 kg/m^2 , which spans approximately the central 90% of U.S. adults, was associated with the lap belt being placed 102 mm further forward and 94 mm higher, relative to the pelvis, and increases in lap and shoulder belt webbing length of 276 and 258 mm, respectively. Gender did not have important effects on the analyzed belt fit measures after taking into account stature and body mass index. These results offer important considerations for future crash safety assessments and suggest that further research is needed to consider belt fit for older and obese occupants.

KEYWORDS – Posture, Safety Belts, Belt Fit, Obesity, Aging

INTRODUCTION

Safety belts are the primary component of the occupant restraint systems in modern vehicles and are effective in reducing the risk of death and injury in many types of crashes (Kahane 2000, Glassbrenner and Starnes 2009, Ridella et al. 2012). Belts are effective in all seating positions and for occupants with a wide range of characteristics, including children, young adults, and older adults (Elliot et al. 2006, Glassbrenner and Starnes 2009). However, belt effectiveness varies across age groups, in part due to an increase in risk of belt-induced injury with age (Glassbrenner and Starnes 2009). Older occupants of crash-involved vehicles, particularly older women, are at greater risk of belt-induced thoracic injuries, particularly rib fractures, than

younger occupants (Kent et al. 2004, Ridella et al. 2012). Older occupants may also be at greater risk of abdominal injury than younger occupants (Yaguchi et al 2011, Frampton et al. 2012). In many high-income countries, such as the U.S. and Japan, older occupants are increasing both in absolute numbers and as a fraction of the crash-involved population, highlighting the need for further understanding of the performance of restraint systems for this population.

Obesity is also associated with a higher risk of injury for belted occupants in crashes (Zhu et al. 2006, Viano et al. 2008, Rupp et al. 2013). Contributing to this pattern may be the finding that belt fit is worse for obese occupants than for those of normal weight (Reed et al. 2012). Both sled testing (Kent et al. 2010) and simulation studies (Turkovich et al. 2013) have demonstrated decreased pelvis engagement for obese occupants, and volunteer studies have demonstrated that obese occupants experience belt

Address correspondence to corresponding Matthew Reed,
2901 Baxter Road, Ann Arbor, MI 48109. mreed@umich.edu

routing higher and more forward relative to the bony pelvis than for normal-weight occupants (Reed et al. 2012). Sub-optimal belt fit can be associated with submarining kinematics, in which the lap belt bears on the abdomen rather than the pelvis during a frontal crash (Kent et al. 2010). Submarining can result in abdomen or thorax injuries due to belt loading or lower extremity injuries due to interaction with the vehicle interior when lower-body excursion increases.

In the U.S., the generation of adults now moving past age 65 has the highest prevalence of obesity in history (Flegal et al. 2010). The effects of obesity on body shape are different for older individuals than for younger (Shimokata et al. 1989). These two major population trends may combine to reduce the historical effectiveness of belts as primary restraints. Yet, more complete knowledge of how belts function for both older and obese adults could guide the enhancement of these systems.

In a previous study, Reed et al. (2012) demonstrated that participants with higher BMI placed the lap portion of the belt higher and more forward relative to surface landmarks on the pelvis than leaner participants. In that study, the seat position was fixed, no driving task was simulated, and most participants were below age 40.

The data for the current analysis were extracted from a larger study of posture and belt fit. Ninety-seven men and women with a wide range of age, stature, and body mass, 60% of whom were age 65 years or older, were measured in their normal driving postures in a reconfigurable laboratory mockup. The locations of the belt with respect to bony landmarks were recorded for a range of belt anchorage locations. The resulting data were analyzed to test the effects of occupant and belt factors on belt fit.

METHODS

Vehicle Mockup and Package Condition

Figure 1 shows the vehicle mockup used for testing. A steering wheel and instrument panel from a 2010 sedan were modified for mounting in the laboratory and set up in the left-side drive configuration typical of U.S. vehicles. Accelerator and brake pedals were mounted to an adjustable arm attached to a moveable floor, so that both the fore-aft and vertical relationship between the floor and the steering wheel

could be changed to represent a wide range of vehicle configurations. The pedals were connected to springs so that pressing the pedals produced typical amounts of travel. A seat from a 2010 mid-sized SUV that provided adjustability for height, cushion angle, and seat back angle was installed on a rail system that provided additional fore-aft adjustability. Powered seat mechanisms provided 239 mm of continuous fore-aft adjustability along a track inclined 5 degrees from horizontal, 50 mm of vertical adjustability, and cushion angle adjustment from 11.5 to 17.5 degrees. As is typical of powered seats, cushion angle adjustment was constrained at the highest and lowest seat positions. Seat back angle was continuously adjustable and essentially unlimited (no participant hit the end of the range of travel). The head restraint was removed to provide better access to the participant for measurements.

A seat belt assembly with a sliding latchplate and retractor from the second row of a model year 2010 minivan was mounted on customized fixtures designed to permit adjustment of belt anchorage locations. A second-row belt was used to ensure sufficient webbing length for all package conditions. A rigid buckle stalk was attached to the seat with an adjustable fixture, as shown in Figure 2. The outboard lower anchorage was attached to the mockup, rather than to the seat, simulating a belt mounted to the vehicle body. The retractor and D-ring were mounted to a fixture allowing the D-ring location to be adjusted over a wide range. The belt webbing width was 45 mm.

Testing was conducted using a midrange vehicle configuration typical of midsize sedans. The seat height (SAE H30) was 270 mm and the steering wheel center was positioned 550 mm aft of the ball of foot reference point on the accelerator pedal (SAE L6). The steering wheel center was 646 mm above the heel surface (SAE H17).



Figure 1. Vehicle mockup.

Address correspondence to Matthew P. Reed, 2901 Baxter Road, Ann Arbor, Michigan, USA 48109. mreed@umich.edu

Five belt configurations were obtained by manipulating the belt anchorage locations. Table 1 lists the conditions. Because previous work showed that the D-ring location had minimal effect on lap belt fit across a range of lap belt angles, the effects of D-ring location and lap belt angle were examined separately, each at 3 levels. The shoulder belt YZ and XZ angles were manipulated together, creating three D-ring locations: one location high, rearward, and inboard, one location low, forward and outboard, and one midrange location. Figures 2 and 3 illustrate the belt configurations. The lap belt angles were set relative to seating reference point (SgRP) and were equivalent on the inboard (buckle) and outboard sides.

Table 1
Belt Anchorage Conditions

Condition	Lap Belt Angle* (deg)	Shoulder Belt YZ Plane Angle** (deg)	Shoulder Belt XZ Plane Angle** (deg)
DB1	52	21	26.5
DB2	30	21	26.5
DB3	75	21	26.5
DB4	52	17	24.5
DB5	52	24	31.0

* See Figure 2; ** See Figure 3.

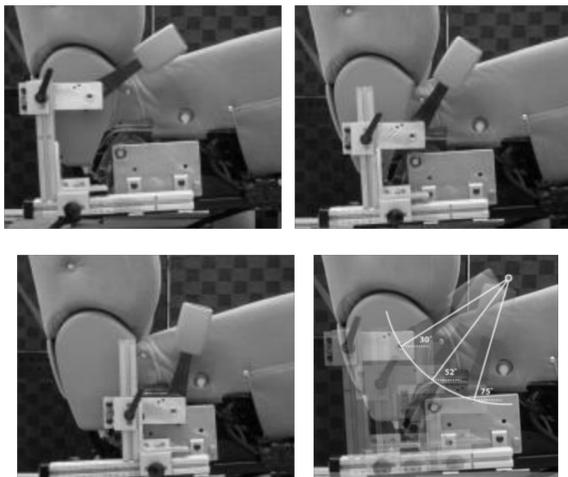


Figure 2. Lap belt buckle anchorage locations for belt fit conditions at 30, 52, and 75 degrees to horizontal.

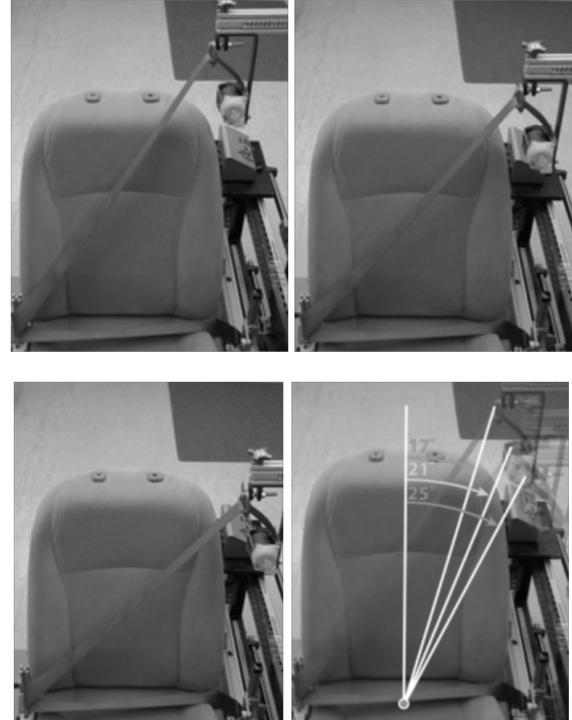


Figure 3. Illustration of shoulder belt conditions with (left to right) YZ angles of 17, 21, and 25 degrees.

Protocol

To protect the rights and welfare of the study participants, the study protocol was approved by Institutional Review Board at the University of Michigan. Participants were recruited by online ads, flyers, and by word of mouth. All participants were licensed drivers, although no minimum driving frequency was required. Participants were screened for medical conditions, such as vision or mobility impairments, that would preclude them from undertaking the required tasks.

On arriving for testing, written informed consent was obtained from each participant. The participant changed into test clothing (loose-fitting short-sleeve shirt and shorts) and standard anthropometric measures were taken, including stature, body weight, and erect sitting height. Self-reported age was recorded.

The investigator used a FARO Arm coordinate digitizer to record the three-dimensional locations of landmarks on the participant’s body as he or she sat in a laboratory *hardseat* shown in Figure 4. The hardseat allows access to posterior landmarks that are useful in quantifying the participant’s skeletal linkage. In particular, both anterior and posterior pelvis landmarks can be accessed in the hardseat.



Figure 4. Subject seated in the laboratory hardseat.

While seated in the driving mockup, the participant was trained in the operation of each seat adjuster and demonstrated use of the components for the investigator. The initial positions of each participant-adjustable component were set to the same midrange values prior to each trial. The participant entered the mockup and adjusted the seat (fore-aft position, vertical position, cushion angle, backrest angle) to obtain a comfortable driving posture. The participant then donned the belt and assumed a normal driving posture.

The investigator used the FARO Arm coordinate digitizer to record the three-dimensional locations of landmarks on the participant's body and on the mockup, seat, and belt. In addition, a stream of points on approximately 5-mm spacing were recorded along the edges of lap and shoulder portions of the belt between the anchorages and latchplate. These data quantify the length of webbing and its routing with respect to the participant.

Posture and Belt Fit Measurements

Following methods used in a previous belt fit study (Reed et al. 2012), lap belt fit was quantified by the fore-aft and vertical location of the upper/rearward margin of the lap portion of the belt at the lateral location of the anterior-superior iliac spine (ASIS) landmarks on the left and right sides of the pelvis (Figure 5). Shoulder belt fit was quantified by the lateral location of the inboard edge of the shoulder portion of the belt relative to the body midline at the height of the suprasternale landmarks (Figure 6). The Y-axis (medial lateral) distance between the body midline and belt is termed shoulder belt score (Reed et al. 2009, Reed et al. 2012, Reed et al. 2013).

A fourth-order Bézier curve was fit to the lap and shoulder belt stream points to smooth measurement error and the length of the resulting curves were calculated.

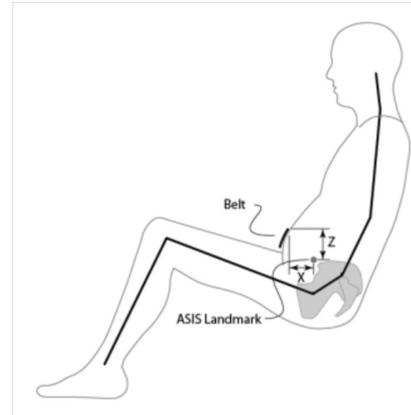


Figure 5. Dependent measures for lap belt fit. The upper/rearward edge of the lap portion of the belt is measured at the lateral position of the right and left anterior-superior iliac spine (ASIS) landmark. The fore-aft (X) coordinate is positive rearward of the ASIS and the vertical coordinate is positive above the ASIS landmark.

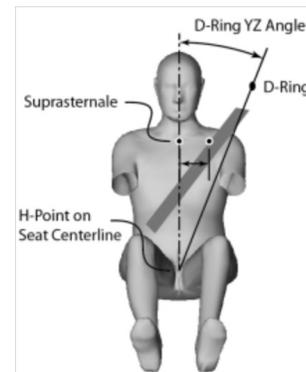


Figure 6. Torso (shoulder) belt fit measurement. Larger positive values indicate more-outboard belt placement. The definition of D-ring YZ Angle is also shown.

Pelvis Flesh Margin Correction

In previous research (Reed et al. 2012), lap belt fit was quantified relative to the measured ASIS landmark locations. However, an examination of the data from the current study suggested that the flesh margins between the bone and the measured landmark locations vary with adiposity, so some adjustments to the measured locations were needed to accurately quantify belt location with respect to the bony pelvis. The calculation of these adjustments was guided by the observation that skeletal dimensions should be largely independent of body mass index in this diverse population. That is, lacking a significant segment of the population with unusual muscle development (e.g., male athletes), BMI is primarily influenced by adiposity, and hence skeletal size should be largely independent of BMI.

Figure 7 illustrates one observation that demonstrated the need for adjustment. In the data from the hardseat, pelvis depth is calculated as the side-view distance between the mean of the left and right posterior-superior iliac spine (PSIS) landmarks and the mean of the left and right ASIS landmarks. Using this metric, a strong relationship with BMI is observed, indicating that increased flesh margins are influencing the estimate of pelvis location and size.

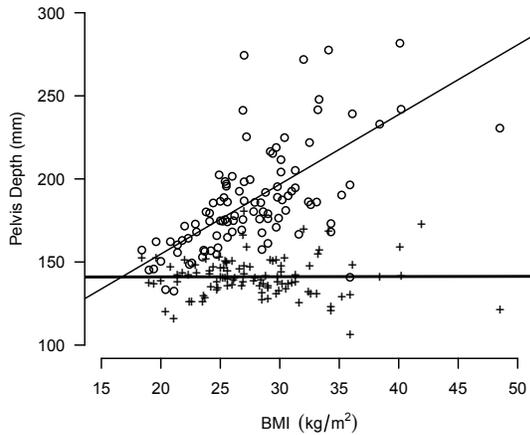


Figure 7. Pelvis depth calculated from surface landmarks (ASIS and PSIS) measured in the hardseat as a function of body mass index. Values corrected for adiposity are shown with + symbols. Lines show least-squares fits to the uncorrected (thin) and corrected (thick) data.

Based on these observations, the following procedures were used to adjust the ASIS and PSIS locations to account for increased flesh margins with high BMI. These calculations were performed using 200 subjects participating in the larger study, which included the 97 subjects used for the current analysis.

1. With the subject seated in the hard seat, the left and right ASIS and PSIS landmark locations were digitized with the experimenter firmly pressing the flesh over the bony landmark (Figure 4). A vector between the midpoint of ASIS landmarks to the midpoint of the PSIS landmarks was constructed. The length of this vector was considered the measured pelvic depth and the direction of the vector to be the pelvic x-axis.
2. The pelvic depth (PD) was adjusted for BMI by subtracting the effect of BMI shown in Equation 1. The adjusted depth was calculated as

$$PD_{adj} = PD_{min} + PD_{meas} - PD_{pred}, \quad [1]$$

where $PD_{min} = 141$ mm is the mean expected PD for the subject with the lowest BMI (17.3 kg/m^2) based on the regression given in Equation 2, PD_{pred} is the PD predicted by Equation 2 for the subject, and PD_{meas} is the measured PD for the subject. For example, consider a participant with a BMI of 30 and a PD_{meas} of 220 mm. From equation 2, PD_{pred} is 197 mm. By equation 1, the adjusted pelvis depth is then $141 + 220 - 197 = 164$ mm.

$$PD_{pred} = 65.6 + 4.38 * BMI, R^2=0.45 \quad [2]$$

3. The mean, standard deviation, and coefficients of variation of the pelvic depths for subjects with a $BMI \geq 24$ ($\mu=141$, $\sigma=28$ mm, $cv=0.202$) were larger than for subjects with a $BMI < 24$ ($\mu=139$, $\sigma=12$ mm, $cv=0.087$). The ratio of coefficients was 0.43. Under the assumption that this increased variance is due to measurement error, the pelvic depths of the subjects with $BMI \geq 24$ were scaled around the mean by multiplying their distance to the mean by this ratio. Following the adjustment, the coefficient of variation for pelvis depth among those with $BMI \geq 24$ was the same as for those with $BMI < 24$.
4. The PSIS flesh margin was set to a vector along the pelvic x-axis with a length of $0.0006 * BMI^3$ mm. This relationship was chosen by adjusting the ASIS flesh margin (described below) until there was no BMI effect on femur to shank ratio or on femur to stature ratio for the sample. The margin varies from 5 mm for a BMI of 20 to 38 mm for a BMI of 40.
5. The ASIS flesh margin was set along the pelvic x-axis to obtain a length between the adjusted mid-PSIS location to the new mid-ASIS location equal to the adjusted pelvic depth.
6. The bispinous (bi-ASIS) breadth (BB) was adjusted for BMI by subtracting the effect of BMI as shown in equation 3. The bispinous breadth predicted by the regression line given in equation 4 (BB_{pred}) was subtracted from the measured bispinous breadth (BB_{meas}) and the result added to 212 mm (BB_{min}), the bispinous breadth obtained from the regression equation at 17.3 BMI (the leanest subject), according to equation [4].

$$BB_{adj} = BB_{min} + BB_{meas} - BB_{pred} \quad [3]$$

$$BB_{pred} = 165.3 + 2.64 * BMI, R^2=0.23 \quad [4]$$

- In the vehicle seat, both the left and right ASIS landmarks were digitized. However, due to steering wheel interference and driver leg being raised to rest the foot on the accelerator, the right ASIS was often more difficult to record reliably. Therefore, the mid-ASIS point was determined from the X and Z (anterior-posterior, and superior-inferior) location of the left ASIS and the lateral (Y) position of the suprasternale landmark. The ASIS flesh margin (X-Y vector) calculated for the subject in the hard seat was then applied to this in-vehicle, mid-ASIS location. The right and left locations of the ASIS were added along the vehicle y-axis using the BMI-adjusted bispinous breadth.

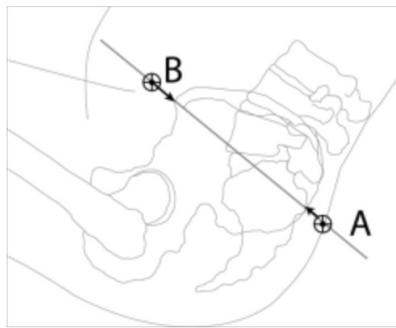


Figure 8. PSIS flesh margin (A) and ASIS flesh margin (B) separating the depressed surface landmark from the underlying bone landmark.

Statistical Analysis

Linear regression analysis was conducted to assess the effects of belt anchorage locations and driver covariates on belt fit. Potential predictors included stature, gender, body mass index, and age. Analyses were conducted using R statistical software package version 2.15.0 (r-project.org).

RESULTS

Participant Anthropometry

Table 2 lists summary statistics for standard anthropometric variables by gender and age. Figures 9, 10, and 11 show bivariate plots, demonstrating minimal relationships among the important covariates. Of the 97 participants, 46 were male and 51 female, 61% were age 60 or greater, and 32% were age 70 or greater. Obese participants (BMI $\geq 30 \text{ kg/m}^2$) were 28% of the sample and distributed approximately evenly across age, stature, and gender, except only three participants below age 40 were obese. Age was slightly correlated with stature ($r = -0.22$) due primarily to short stature among the oldest female participants.

The study population compares favorably to the U.S. adult population with respect to stature and BMI distributions. The mean male and female statures of 1759 and 1601 mm are similar to the U.S. mean values of 1759 and 1621 mm (Fryar et al. 2012). Flegal et al. (2010) report that approximately 33% of U.S. men and 35% of U.S. women are obese (BMI $> 30 \text{ kg/m}^2$). The 95th-percentile BMI is 39.2 and 42 for men and women, respectively (Fryar et al. 2012). The current sample is generally representative of the U.S. population with respect to BMI. The median BMI is 28.4 and 26 for men and women, respectively, and the 95th-percentiles are 38 and 36, respectively. The fraction of obese individuals in the current population (28%) is slightly less than in the general US population (34%).

Table 2
Summary of Standard Anthropometric Measures: Mean (SD)

Measure	Men (N=46)	Women (N=51)
Stature (mm)	1759 (85)	1601 (67)
Body Weight (kg)	87.9 (17)	69.9 (16)
Body Mass Index (kg/m ²)	28.4 (4.9)	27.3 (5.7)
Erect Sitting Height (mm)	913 (40)	845 (42)
Age (years)	58 (19)	59.3 (20)

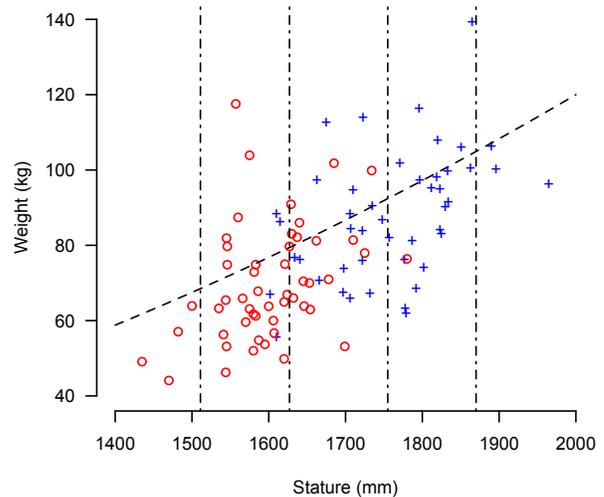


Figure 9. Weight vs. stature for men (+) and women (o). Vertical lines show 5th-percentile female, 50th-percentile female, 50th-percentile male, and 95th-percentile male statures for the U.S. population (Fryar et al. 2012). Dashed curve shows boundary for BMI=30 kg/m². Participants above the curve are obese.

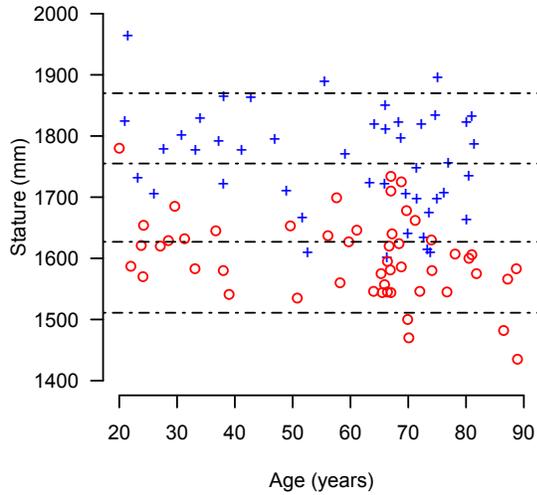


Figure 10. Stature vs. age for men (+) and women (o). Horizontal lines show 5th-percentile female, 50th-percentile female, 50th-percentile male, and 95th-percentile male statures for the U.S. population (Fryar et al. 2012).

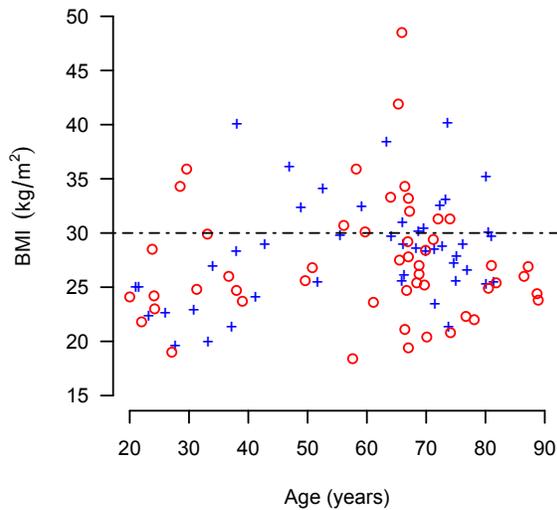


Figure 11. BMI vs. age for men (+) and women (o). Horizontal line shows obesity threshold.

Lap Belt Fit

Left vs. Right

Figure 12 shows a cross plot of the X and Z lap belt fit measures (corrected) between the left and right sides for all trials, showing no apparent bias between the right and left. The left and right X values were correlated with 0.89; the correlation for Z values was 0.83. Two-sample t-tests did not show significant differences between left and right for either measure

($p > 0.25$). Consequently, the left score (measured on the side closest to the investigator) was used for subsequent analysis.

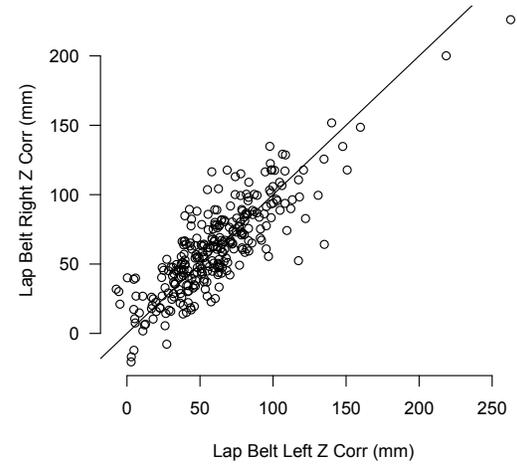
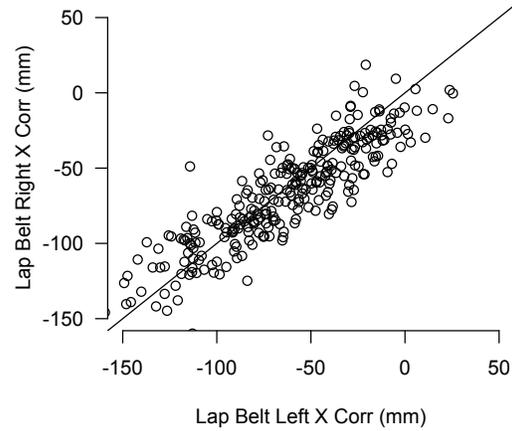


Figure 12. Left vs. right lap belt fit measures along with 1:1 line for all trials.

Lap Belt Fore-aft (X) Location with Respect to the Pelvis

Because the participants were free to select their preferred fore-aft seat position, the outboard lap belt angle was lower (more horizontal) for participants who sat further forward relative to the fixed outboard lower anchorage. Consequently, an effective lap belt angle (ELBA) was used in the analysis. The ELBA was computed as the side-view angle from the anchorage to the seat H-point in the position selected

by the participant. (In contrast, the standard FMVSS 210 measure of lap belt angle is measured to a fixed point located with respect to the seating reference point for the seat position.) To simplify the presentation, ELBA is referred to as lap belt angle. On average, the upper edge of the lap belt was 64 mm forward of and 61 mm higher than the ASIS landmark on the pelvis. Figure 13 shows the lap belt location with respect to ASIS for men and women for all trials. Figure 14 shows images of two trials from one subject, labeled A and B in Figure 13. The nominal lap belt angle was 30 degrees in trial A and 52 degrees in trial B. This participant, with BMI = 38, placed the belt unusually high on his abdomen in these two trials. Figure 15 shows other photos of lap belt fit for a range of occupant sizes.

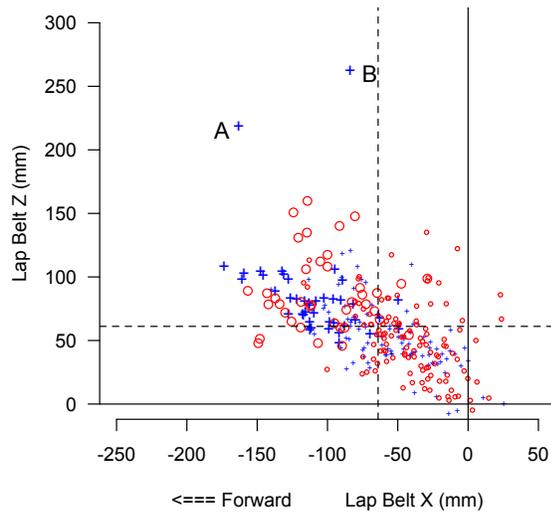


Figure 13. Lap belt location for all trials for men (+) and women (o). The data points are the location of the upper edge of the lap belt at the lateral position of the left bone ASIS landmark relative to the bone ASIS landmark. Obese participants are shown with larger symbols. Images from trials labeled A and B are shown in Figure 13. Dashed lines show the mean values of $X = -64$ mm, $Z = 61$ mm.

A regression analysis was conducted predicting the X and Z lap belt scores with potential predictors stature, BMI, age, and lap belt angle. The three lap-belt trials were included in the analysis for each participant. A second analysis was conducted using gender rather than stature. Second- and third-order interactions were also considered. Effects were considered statistically significant with $p < 0.01$ and considered important if they also increased the adjusted R^2 value by 0.02 or more.



Figure 14. Photos showing lap belt fit for trials labeled A (left) and B (right) in Figure 12. This participant had a BMI of 38 kg/m^2 .



81 YO	38 YO	87 YO
BMI = 26	BMI = 40	BMI = 27
Stature = 1755	Stature = 1865	Stature = 1566

Figure 15. Photos showing lap belt fit for a range of occupant sizes.

For LapBeltX, BMI was by far the most important effect. Equation 3 shows a regression model with main effects of lap belt angle, BMI, stature, and age. Note that lower values (more negative) indicate that the belt is farther from the pelvis. The adjusted R^2 value for this model is 0.57, whereas the adjusted R^2 for a model with only BMI is 0.44. Another useful way to evaluate the importance of the effects is to multiply the estimated effect slope by the range of the variable in the data. For example, the stature slope is -0.042 mm/mm and the range of statures is 535 mm, so the tallest subjects would on average have the lap belt 22 mm further forward than the shortest subjects. In contrast, the BMI slope is $-5 \text{ mm/(kg/m}^2)$ and the range of BMI is 17.3 to 48.5, yielding a difference in LapBeltX across that range of 150 mm. That is, the highest BMI individuals would have the lap belt located, on average, 150 mm further forward relative to the pelvis than the thinnest individuals. An increase in BMI of 10 kg/m^2 is associated with the lap belt being located 51 mm further forward relative to the pelvis, on average. Age had a significant but

smaller effect than BMI. Compared with a typical 20-year-old, a typical 80-year-old had the lap belt located 18 mm further forward after accounting for stature and BMI. Gender was not significant after accounting for stature, and no two- or three-way interactions among the predictors were significant.

$$\text{LapBelt X (mm)} = 156 + 0.297 \text{ ELBA} - 0.30 \text{ Age} - 5.12 \text{ BMI} - 0.04 \text{ Stature},$$

$$R^2_{\text{adj}} = 0.57, \text{ RMSE} = 25.8 \quad [3]$$

Figures 16 and 17 show the univariate effects of BMI on LapBeltX for men and women as well as for older (60+ years) and younger participants. The effects of BMI are not markedly different between these subject groups.

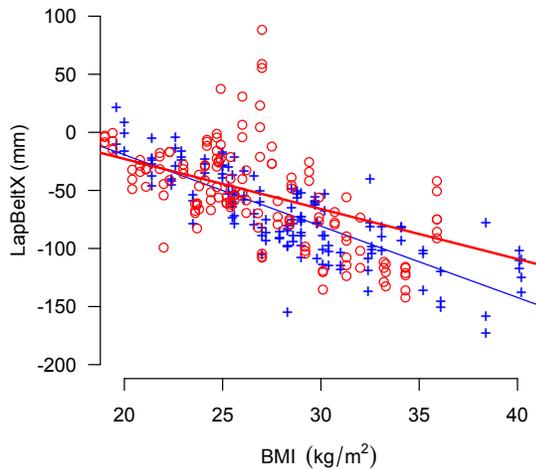


Figure 16. Effect of BMI on LapBeltX for men (+, thin line) and women (o, thick line).

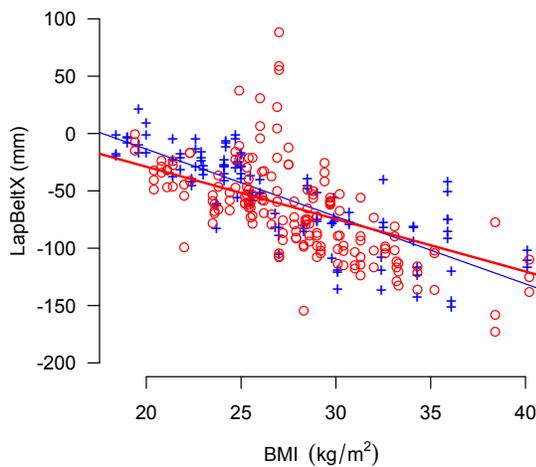


Figure 17. Effect of BMI on LapBeltX for men and women younger (+, thin line) and older (o, thick line) than 60 years.

Lap Belt Vertical (Z) Location with Respect to the Pelvis

Of the variables analyzed, only BMI was a significant predictor of LapBeltZ, with higher BMI associated with higher belt position relative to the pelvis. Lap belt angle, stature, gender, and various two- and three-way interactions were not significant. The BMI regression was

$$\text{LapBeltZ (mm)} = -70.1 + 4.7 \text{ BMI}, R^2 = 0.52,$$

$$\text{RMSE} = 22.9 \quad [3]$$

The slope is similar to the slope for LapBeltX, indicating that increasing BMI moves the belt forward and upward relative to the pelvis at approximately a 45-degree angle to horizontal (see Figure 13). The range of BMI among the participants produces an average change in LapBeltZ of 135 mm. Increasing BMI by 10 kg/m² moves the belt up by 47 mm, on average, or approximately the full width of the belt.

Shoulder Belt Fit

The *shoulder belt score* quantifies the location of the inner edge of the belt relative to the torso centerline at the height of the suprasternale landmark (see Figure 6). Shoulder belt score was analyzed for conditions DB1, DB4, and DB5. In addition to subject covariates, YZ belt angle (see Figure 6) was included as a potential predictor. Linear regression analysis showed that shoulder belt score was not significantly associated with BMI or age, but a significant interaction was observed between stature and the YZ belt angle. Figure 18 shows the relationship. When the D-ring (upper anchorage) is more outboard, producing a larger YZ plane belt angle, the effect of stature on the lateral position of the belt is more pronounced. The shoulder belt score can be predicted from Equation 5.

$$\text{Shoulder Belt Score (mm)} = 338 - 22.3 \text{ YZAngle} - 0.284 \text{ Stature} + 0.0189 \text{ YZAngle} * \text{Stature}, R^2_{\text{adj}} = 0.60, \text{ RMSE} = 24.4 \quad [5]$$

Lap Belt Webbing Length

The length of belt webbing between the outboard lower anchorage and the latchplate was calculated from points digitized along the upper/rearward surface of the belt. Because the outer anchorage was attached to the mockup (to simulate an anchorage attached to the vehicle body), the webbing length was strongly affected by driver-selected seat position. Seat position was quantified as the fore-aft position

of the seat H-point relative to the ball-of-foot reference point (see SAE J1100).

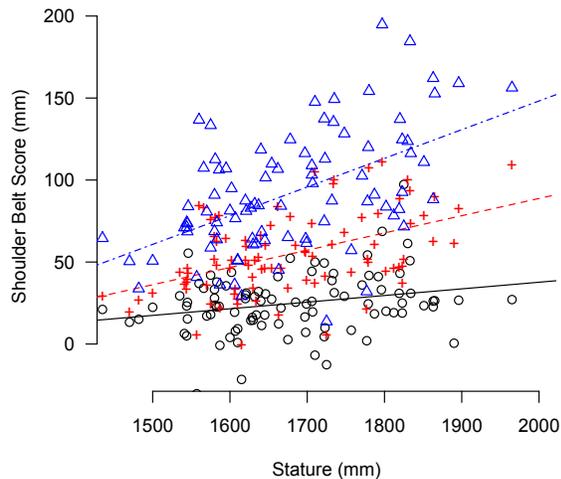


Figure 18. Interaction between stature and YZ belt angle on shoulder belt score for YZ belt angles of 17 degrees (o, —), 21 degrees (+, - -), and 24 degrees (Δ , - - -).

A linear regression analysis was conducted to quantify the effects of subject covariates and lap belt angle on webbing length. Seat position, stature, and BMI had significant effects. Equation 6 shows a regression function using seat position and BMI, demonstrating that more-forward seat positions and higher BMI are associated with greater lap belt length. On average, an increase in BMI of 10 kg/m² is associated with 138 mm greater lap belt length. The average webbing length is 914 mm, so 138 mm is 15% of the mean. Age had a smaller but significant effect, with 60 years adding 26 mm of lap belt webbing, on average.

$$\begin{aligned} \text{Lap Belt Length (mm)} &= 901 - 0.455 \text{ SeatPositionX} \\ &+ 13.8 \text{ BMI} + 0.431 \text{ Age}, \\ R^2_{\text{adj}} &= 0.68, \text{ RMSE} = 48 \end{aligned} \quad [6]$$

Equation 7 shows a similar model using stature rather than seat position. Taller stature is associated with reduced webbing length, because the driver is sitting more rearward on average, closer to the outboard anchorage. The BMI and age effects are similar, with the small differences with Equation 6 due to correlations among the predictors.

$$\begin{aligned} \text{Lap Belt Length (mm)} &= 719 - 0.107 \text{ Stature} + 12.9 \\ &\text{BMI} + 0.32 \text{ Age}, \\ R^2_{\text{adj}} &= 0.65, \text{ RMSE} = 50 \end{aligned} \quad [7]$$

Shoulder Belt Webbing Length

A linear regression analysis was conducted to assess the effects of YZ belt angle and subject covariates on the length of the belt between the D-ring (upper outboard anchorage) and the latchplate at the buckle. Fore-aft seat position was also considered as a covariate, since a more-forward seat position would result in a larger length of webbing being pulled from the retractor.

Due to the test conditions, shoulder belt webbing length was significantly affected by YZ belt angle, which moves the upper anchorage outward and rearward. Fore-aft seat position also had a strong effect. After accounting for YZ belt angle and seat position, BMI and Age had significant effects, as shown in Equation 8. BMI and Age were also significant when stature rather than seat position was included in the model (Equation 9). No second- or third-order interactions were significant. Gender was not significant after accounting for either stature or fore-aft seat position (which is strongly associated with stature). Due to correlations among the predictors, the coefficients for some factors are different depending on the terms included in the model. After accounting for seat position and belt angle (D-ring location), an increase in BMI of 10 kg/m² is associated with 44 mm of additional belt webbing length. Including stature rather than seat position in the model decreases the BMI affect to 30 mm per 10 kg/m². Age has a smaller but significant, positive effect on belt webbing length, with an increase in age from 20 to 80 associated with an average increase in shoulder belt webbing length of 21 to 50 mm, depending on whether stature is included in the model.

$$\begin{aligned} \text{Shoulder Belt Length (mm)} &= 1658 - 0.6659 \\ \text{SeatPositionX} - 16.8 \text{ YZBeltAngle} &+ 4.44 \text{ BMI} + 0.5 \\ \text{Age}, R^2_{\text{adj}} &= 0.70, \text{ RMSE} = 39 \end{aligned} \quad [8]$$

$$\begin{aligned} \text{Shoulder Belt Length (mm)} &= 1493 - 0.213 \text{ Stature} - \\ 16.7 \text{ YZBeltAngle} &+ 3.09 \text{ BMI} + 0.21 \text{ Age}, R^2_{\text{adj}} = \\ 0.63, \text{ RMSE} &= 43 \end{aligned} \quad [9]$$

DISCUSSION

Summary

This study is the first examination of driver belt fit to take into account age and the effects of adiposity on driver belt fit measurements. Body mass index was the most important factor determining lap belt fit, and higher BMI was associated with a greater length of

webbing pulled from the retractor, irrespective of seat position or stature.

The shoulder belt fit analysis illustrated strong effects of the upper anchorage location but did not reveal important interactions with participant characteristics. This indicates that the effects of changes in belt anchorage on belt routing relative to the shoulder are similar across occupants, after taking into account the geometric effects of shoulder height (expressed in this analysis as stature). Notably, BMI and age were not important predictors of shoulder belt fit, nor were interactions with the test conditions important.

Table 3 and Figure 19 summarize the findings of the statistical analysis. To compare the relative importance of the driver factors, each effect slope was multiplied by a value spanning a large fraction of the range of the factor in the population. For stature and BMI, 350 mm and 20 kg/m² span approximately the central 90% of the U.S. adult population on those measures (Fryar et al. 2012). For age, 60 years spans age 20 to age 80. Using these metrics, BMI is by far the most important of these three factors in influencing the range of belt fit in the driver population.

Table 3
Effects of Driver Factors on Belt Fit (mm)

Variable (mm)	Stature		BMI		Age	
	Slope (mm/mm)	Population Effect over 350 mm*	Slope (mm/(kg/m ²))	Population Effect over 20 kg/m ² *	Slope (mm/yr)	Population effect over 60 years
Lap Belt X†	-0.04	-14	-5.12	-102.4	-0.30	-18
Lap Belt Z			4.7	94		
Shoulder Belt Score	0.105††	36.8				
Lap Belt Length			13.8	276	0.431	25.9
Shoulder Belt Length	-0.107	-37.5	12.9	258	0.32	19.2

* Approximate range of central 90% of the U.S. adult population (Fryar et al. 2012)

† Lower (more negative) values indicate that the belt is further forward relative to the pelvis.

†† This coefficient was fit without interaction with D-ring location and so differs from Equation 5.

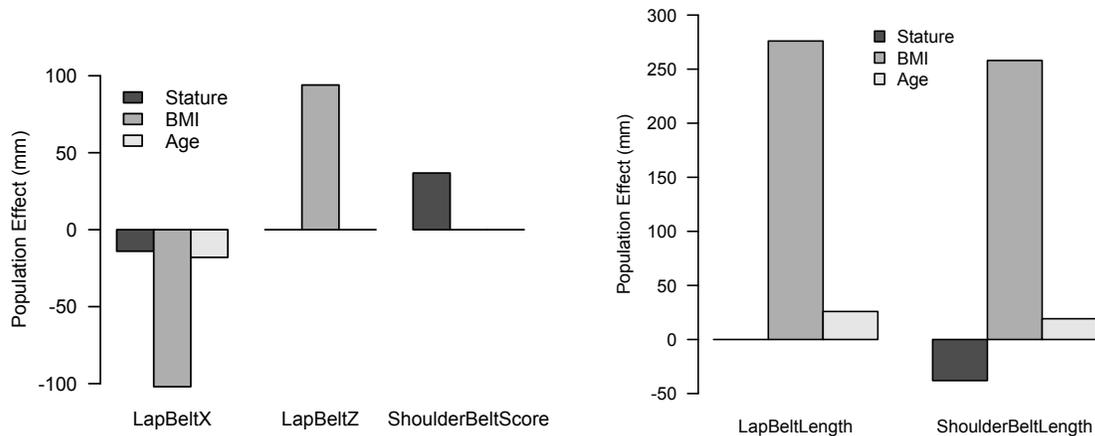


Figure 19. Population effects of stature, BMI, and age on belt fit measures (mm). Stature effect is over 350 mm, BMI effect is over 20 kg/m², and age effect is over 60 years (see Table 3).

The most important finding is that this study population frequently placed the lap portion of the belt above and well forward of the bony pelvis. In a previous study using a fixed-position seat, Reed et al. (2012) examined the belt location relative to the digitized ASIS surface landmark locations. The current analysis used anatomical relationships to adjust the estimated flesh margin thickness at the ASIS to account for the effects of adiposity and to express the belt fit relative to the bony pelvis. The new results suggest that the belt is considerably further forward relative to the pelvis than reported in the earlier study, due to the soft tissue lying over the ASIS.

However, the effects of BMI on belt fit are similar between the studies. For fore-aft lap belt fit, the coefficient of BMI was $-4.3 \text{ mm}/(\text{kg}/\text{m}^2)$ in Reed et al. (2012) and -5.1 in the current study. This suggests that the flesh-margin estimates in the current work, which used BMI as an input, did not excessively inflate the BMI effects.

This study included a large percentage of older drivers as well as a broad range of ages, allowing direct tests of age effects and potential interactions with test variables and subject covariates. However, only relatively small age effects were observed, after accounting for the other variables. Increasing age was associated with higher and more-forward lap belt position and increased belt webbing length, but age did not affect shoulder belt fit. The effects of age were much smaller than the effects of BMI.

Gender effects are difficult to study because of the average body size differences between men and women. However, after accounting for stature and BMI, gender was not significantly associated with the outcome measures. This finding is consistent with Reed et al. (2012) as well as earlier studies of belt fit (Newman et al. 1984, Wells et al. 1986).

Limitations

This study is limited in several important respects. Testing was conducted in a laboratory environment that did not fully replicate the geometry of a vehicle. The static environment meant that the effects of vehicle ride motion on belt fit were not taken into account. The mockup used a single vehicle seat and belt assembly. A different seat or belt might have produced different results. Testing was conducted in a single vehicle package (geometric relationship among the pedals, seat, and steering wheel). A different vehicle layout might influence the results. The participants wore similar, close-fitting clothing provided by the experimenters. Ordinary clothing

worn during driving might change belt fit, likely increasing belt distance from the ASIS.

The participants in this study at a University laboratory may not be representative of the general population with respect to physical fitness or experience with and attentiveness to belt use. Since the participants knew that belt position was being measured, they may have positioned the belt more advantageously than the normally would in their own vehicles. The data reported here were measured with after the driver entered the mockup and adjusted the seat a single time with the belt donned repeatedly across the five randomized test conditions. If the participant exited the mockup between trials, additional variability in posture and position would be expected, which might reduce the statistical significance of the findings.

The lap belt fit assessment was based on estimated bony landmark (ASIS) locations rather than measured surface landmarks as in the preceding work. The advantage of this method is that it compensates for the effects of adiposity on the flesh margin at the ASIS. However, the method has not been validated using direct measurements. Instead, the measured ASIS locations were adjusted under the assumption that pelvis and lower-extremity bone size is independent of BMI. Because the adjustment procedure is based on BMI, it magnifies the BMI effects on lap belt fit relative to the pelvis. However, the slope of the BMI effect on fore-aft lap belt location relative to the pelvis was similar to the value found in the previous study (Reed et al. 2012), suggesting that the adjustment did not bias the results dramatically.

In this study, belt fit was characterized by a small number of linear geometric variables, along with measures of belt webbing length. The relationships between these variables and the dynamic belt interaction with the occupant will depend on many factors not measured. For example, the measure of lap belt fit is based on a single measurement of the belt location relative to the pelvis. Examination of the belt contours shows that the belt can extend substantially further forward than this point as it routes around the bellies of higher-BMI occupants. Consequently, the belt fit values relative to the bony pelvis at the lateral location of the ASIS may underestimate the amount of excursion that is needed before the lap belt would provide substantial restraint. That is, the lower abdomen tissue would need to be displaced so that the belt was approximately flat across the front of the pelvis

before the restraint force could reach the desired levels.

To save test time, the data used in this study were gathered after the driver entered the mockup and adjusted the seat a single time. If the driver had exited and re-entered the mockup between trials, postural variability may have increased, affecting the statistical hypothesis tests. However, the magnitude of the trends with respect to occupant and belt factors would likely have been similar.

Implications

For many study volunteers, the lap belt location relative to the pelvis differs from the close fit obtained with anthropomorphic test devices (ATDs) used in vehicle crash testing and restraint system optimization. The adult ATDs used for regulatory tests in the U.S., the so-called 50th-percentile male and 5th-percentile female Hybrid-III ATDs, represent relatively lean individuals. Reed and Rupp (2013) compared the reference stature and body weight for the Hybrid-III adult ATDs to current values at the target percentiles for the U.S. population. The 50th-percentile male body weight is now 85.4 kg, compared with the target value for the midsize-male ATD of 78.2 kg. The target value is now the 33rd-percentile; two-thirds of U.S. adult men have body weight greater than the reference value for the “50th-percentile male” ATD. Expressed in terms of BMI, the midsize-male Hybrid-III ATD, with a reference stature of 1751 mm, has a BMI of $78.2/(1.751)^2 = 2.5 \text{ kg/m}^2$. In contrast, the median male BMI is currently 27.5.

The belt locations measured in this study could affect restraint system performance in several ways.

1. The lap belt was an average of 64 mm forward of the bony pelvis at the ASIS for the study population. In a frontal crash, the occupant would need to translate forward by most of this amount before a significant amount of lap belt restraint force would be generated. Depending on the initial clearance between the knees and knee bolster, and between the lower chest and the steering wheel, this could markedly change the load sharing between the belt, bolster, and airbag.
2. On average, the lap portion of the belt lay fully above the ASIS landmark on the bony pelvis (mean LapBeltZ value of 61 mm and a 45-mm-wide belt). Although the belt would tend to pull downward relative to the pelvis during the early stages of a frontal crash event, this high initial

position may make it less likely that the belt will “catch” the pelvis. Kent et al. 2010, in rear-seat tests with high-BMI occupants, showed adverse effects of this lap belt fit, with submarining kinematics resulting.

3. The net effect of increased BMI is to add slack to the belt system, moving the belt above and forward of the pelvis and increasing the amount of webbing pulled from the retractor. These trends may increase occupant excursions during frontal crashes and delay the application of significant belt forces onto the occupant.

These findings highlight the challenge in providing good belt restraint for occupants with a wide range of body size and shape. Changing lap belt angle had only small effects on lap belt fit, compared with BMI. In many cases, a different belt donning procedure that placed the lap belt lower, and pulled it tighter, might have produced better belt fit scores. This was particularly apparent for some trials with high, forward lap belt locations that resulted from the participant routing the belt across the abdomen rather than on the thighs, below the abdominal protrusion. However, for many higher BMI individuals, the abdomen protrusion extends to the thighs, providing little opportunity to place the belt closer to the pelvis. Although greater attention to proper belt positioning would help some drivers to obtain better belt fit, further study of belt design may be needed to ensure good belt performance across the population.

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