An investigation of the impact of the upper-anchor-point location of the shoulder belt on crash protection during wheelchair transportation was conducted using a lumped parameter crash victim simulator. While varying the location of the upper anchor point in each of three directions, the kinematics and injury parameters of the wheelchair occupant, modeled after a Hybrid III test dummy, were determined. Through comparison of these parameters and their associated trends, it was determined that varying the location of the anchor point had a significant impact on occupant crash protection.
INTRODUCTION

A review of research and development in the area of transportation safety produces a very lengthy and successful history. Perhaps one of the most effective safety measures introduced to this industry is the safety belt, or occupant restraint, which alone is estimated to save 5000 lives each year [1]. The design and implementation of restraints and other safety devices in the automotive transportation environment are guided by the Federal Motor Vehicle Safety Standards (FMVSS) as developed by the National Highway Transportation Safety Administration (NHTSA). FMVSS 210 [2], along with several Notices of Proposed Rulemaking (NPRM) to this legislation, specifically addresses occupant crash protection systems. Details such as occupant comfort while wearing safety belts and recommended anchorage points are addressed in these documents. While attempting to maintain optimum crash protection, comfort has been one of the primary focuses of recent NPRM’s since increased occupant comfort is believed to lead to a greater tendency to use safety belts.

Unfortunately for individuals with disabilities, the parameters set forth in these documents were developed primarily with the intent of application to able-bodied drivers and passengers. Individuals who cannot transfer and must use their wheelchair as a seat during vehicle transportation, have not benefited from the research and development that has taken place in the automotive industry. In fact, direct application of FMVSS guidelines, such as the prescribed upper anchor point of the shoulder belt, to public wheelchair transportation may be impractical in some cases. Physical limitations are often imposed by both the wheelchair and a vehicle’s interior structure. To investigate the impact upper-anchor-point limitations introduce to the wheelchair occupant’s crash protection, an analysis employing computer simulations of various anchoring scenarios was conducted.

METHODS

An occupant simulation software system, Dynaman, was used to evaluate the effects of varying the position of the upper anchor point of the occupant restraint. Dynaman models the International Standards Organization’s (ISO) Standard 10542 [3] surrogate wheelchair secured by a four point tiedown system with a 50th percentile male, Hybrid III anthropometric test dummy restrained by shoulder and lap belts. The surrogate wheelchair, a structurally enhanced wheelchair, and it’s associated model, were developed through the efforts of the Society of Automotive Engineers (SAE) and ISO Wheelchair Tiedowns and Occupant Restraints Standards committees with the intent of repeated testing of wheelchair securement systems without the requirement of continuous wheelchair replacement. The model, using a deceleration pulse which simulates a 30 mph, 20 g frontal van impact, has been validated through a series of sled impact tests conducted during the ISO and SAE standards development process [4].

For the purposes of this study, the coordinate system and reference points are as shown by Figures 1 and 2. The coordinate system locates the origin at the
center of the rear edge of the sled/floorboard. The positive x–direction is assigned as forward, while the positive y– and z–directions are established as, to the right taken from the perspective of the occupant, and downward, respectively.

The validated ISO/SAE model sets the upper anchor point of the occupant restraint at \( x=22.65\)”, \( y=–9.9\)” and \( z=–48\)”. However, in an actual transportation vehicle it is not unlikely to find the upper anchor point located on the vehicle’s side-wall or ceiling. In addition, it is impractical to simulate a crash with \( y=–9.9\)” since most adult wheelchairs have a width of at least 28”. Therefore, for these simulations the position of the upper anchor point of the shoulder belt was derived from applying FMVSS defined belt comfort zones [5] to a wheelchair occupant [6], as well as from physical and structural constraints found in the vehicle, which impose limitations on the location of the upper anchor. Considering these factors, a baseline case was developed from which other simulation runs were conducted by varying only one parameter at a time. Accordingly, the coordinates shown in Figures 3 and 4 were utilized in conducting the study. The baseline case in the frontal (yz) plane, fixes the y–coordinate equal to \(–24\)”, allowing for half the typical wheelchair width of 28”, plus a clearance between the wheelchair and vehicle wall of 10”. The z–coordinate was chosen by transforming the FMVSS’s recommended shoulder belt comfort zone to the wheelchair user. The center of this zone yields a 55° angle between the sternum reference horizontal plane and the shoulder belt. This angle in conjunction with the previously defined y–coordinate point, leads to a z–coordinate value of \(–70.5\)”. In the longitudinal plane, as shown by Figure 4, the baseline upper anchor point has been assigned an x–coordinate value of 10.65”, placing it approximately 20” aft of the shoulder’s apex. This x–coordinate was selected as a starting point based upon physical limitations found in vehicles.

To systematically determine the affect of altering the location of the upper anchor, a number of simulations were run while varying the position along only one axis, while holding the other two coordinates constant. This process was followed for each of the three coordinate axes. For each simulation, data regarding the linear and angular accelerations and the linear displacements of the head were collected over a 240 msec period. Acceleration profiles of the head and upper torso were further used to derive the Head Severity Index (HSI), Head Injury Criterion (HIC) and the Chest Severity Index (CSI). To determine the influence of the upper-anchor-point position, characteristics, trends and peak values of these variables were examined for each simulation. Additionally, traces of head excursions occurring in the horizontal plane were generated and examined as a part of this evaluation. Although acceleration and displacement values for other body segments were observed, the data relative to the head was used in this analysis since often the kinematics of the head and neck are the most critical to the level of injury severity. Forces developed in the occupant restraints (i.e., lap and shoulder belts) were also determined for each simulation.
Using the data described above for each of the shoulder belt anchorage scenarios, it was possible to compare the affects of anchor location on the effectiveness of the occupant restraint system.

**RESULTS**

**VARIATION IN X–COORDINATE**

Three simulations which maintained constant y- and z-coordinates of the upper anchor point at –24" and –70.5", respectively, were run while varying the x-coordinate through 10.65", –1.35" and –13.35". Graphs in Figure 5 and data in Table 1, describing peak values of various parameters with respect to the x-coordinate position, generally show a decrease in parameter values as the anchor point is moved rearward, or aft. Injury criterion such as the HIC and HSI have values as high as 1548 and 1793, respectively, for x=10.65", but are seen to decrease to 765 and 945, respectively, with moving the anchor point rearward to x=–13.35". Changes of this order of magnitude are significant in these injury parameters and may represent the difference between a severe and minor head injury, as the upper HIC limit allowed by the FMVSS in vehicle design is 1000 [2].

Peak relative displacement of the head in the x–direction can also be seen to decrease with moving the upper anchor point rearward. However, upon review of head displacement in the y–direction, Table 1 and Figure 5 show an initial decrease, followed by an increase with a more rearward position (x=–13.35") of the upper anchor point. To further analyze this head motion, head excursion in the xy, horizontal plane, was plotted over the entire 240 msec duration, and is shown in Figure 6. This plot shows a slight decrease in the x–directional displacement as the anchor is moved rearward. It is easy to see from this figure that the head excursion pattern in the xy plane is minimized for the case of x=–1.35 when comparing these simulation runs.

A review of the resultant linear acceleration of the head, as denoted by $G_r$, also shows a desirable decrease as the anchor point is moved rearward. The peak resultant linear acceleration at the most rearward anchor point is 58.6 g’s, while in the most forward position it increases to 67.3 g’s. Although this only represents the peak acceleration values, it can be concluded that the duration of higher accelerations is also reduced by moving the anchor rearward as is evidenced by the sharp decline in the HIC value which is proportional to the integral of acceleration taken over a period of time which maximizes HIC.

Figure 5 also indicates that the shoulder belt forces decrease with moving the anchor point rearward. These forces range from a high of 2100 lbs. with the anchor point in the most forward position (x=10.65") to a low of 1900 lbs. when the anchor is in the aft most position of x=–13.35.

**VARIATION IN THE Y–COORDINATE**

As with the simulations to evaluate the affects of varying the anchor point’s x–coordinate, a similar set of simulations was conducted to evaluate the impact of changing the anchor point’s y–coordinate location. In this case, the values of the x- and z-coordinates were maintained (at x=10.65" and z=–70.5") while...
simulations were run for \( y = -19.6^\circ, -24^\circ, \) and \(-28.5^\circ\). These values of \( y \) were arrived at by varying 5° clockwise, 0°, and 5° counterclockwise from the FMVSS optimum comfort angle of 55°, as measured from the sternum reference horizontal plane to the shoulder belt. Therefore, simulations were conducted at belt angles of 50°, 55° and 60° as viewed from the frontal plane. Graphs similar to those generated for variation in the \( x \)-direction are shown for changes in the \( y \)-direction in Figure 7, with data presented in Table 2. A corresponding trace of head excursions is provided in Figure 8.

With \( y = -19.6^\circ \) being the point closest to the occupant’s medial plane, and \( y = -28.5^\circ \) the farthest from the medial plane, it can be seen from Figure 7 that moving the anchor point away from the medial plane results in a noticeable increase in the head’s \( y \)-displacement. Figure 8, which provides detail of the actual motion of the head, shows the increased excursion to the occupant’s right side (\( y \) direction) when the anchor point is moved outward. Such motion occurs since the shoulder belt is positioned below the apex of the left shoulder, allowing the shoulder to freely rotate on impact. The same figures, along with Table 2, also indicate an increase in the \( x \)-displacement of the head with an outward movement of the anchor point. Injury parameters for this set of simulations show negligible variation with changing the anchor position.

**VARIATION IN Z-COORDINATE**

Simulations to evaluate the affect of moving the upper anchor point either upward or downward from the baseline case were conducted with \( x = 10.65^\circ \) and \( y = -24^\circ \). \( Z \)-coordinate points were derived by varying 5° in either direction from the FMVSS recommended shoulder belt comfort angle of 55° as measured from the sternum reference horizontal plane.

Table 3 and Figure 9 show the tabular and graphical results found while varying the upper anchor point’s \( z \)-coordinate. Increasing the height of the anchor point produces increases in most parameters except head excursion in the \( y \)-direction. Noticeable increase occurs in the head’s angular acceleration about the \( y \)-axis with raising the anchor point. In fact, the anchor position where \( x = 10.65^\circ, y = -24^\circ \) and \( z = -74^\circ \) produces an angular acceleration of the head about the \( y \)-axis equal to 684 rev/sec\(^2\), the largest of all evaluated positions. Similarly, head injury parameters are also the largest with HSI=2045 and HIC=1712, when the anchor is at this same position, \( z = -74^\circ \).

Upon reviewing the head displacement pattern in the horizontal plane, shown in Figure 10, it is seen that having the shoulder belt’s anchor point in the highest position (i.e., \( z = -74^\circ \)) and a belt angle of 60° provides the greatest restriction to head excursion in the \( y \)-direction. When the anchor point is lowered to \( z = -64^\circ \) (belt angle = 50°), the shoulder belt no longer passes over the clavicle and instead crosses the torso below the acromion (shoulder apex), which allows the shoulder to rotate free from the belt resulting in increased head excursion in the transverse plane. Head excursion in the \( y \)-direction, associated with the low anchor point \((z = -64^\circ)\), is 6.4", whereas the highest
anchor point \((z=-74")\) produces head excursions of 2.8”.

**DISCUSSION**

**VARIATION IN X–COORDINATE**

As indicated by the results obtained, moving the upper anchor point of the shoulder belt rearward improves wheelchair occupant crash protection. Decreases occurring in the linear and angular acceleration of the head when the anchor point is moved rearward are significant and could represent a difference in the severity of an injury in such a crash. This most rearward positioning locates the shoulder belt such that contact with the shoulder is increased which serves to better couple the occupant with the vehicle. A closer coupling of the occupant and vehicle through the restraint system will ultimately increase the occupant’s potential for “riding down the crash” at the same rate as the vehicle structure, thereby reducing the amplitude of the occupant’s crash pulse. In effect, moving the shoulder belt anchor point rearward serves to approach the anchoring configuration of an integrated seat which anchors the shoulder belt just above the occupant’s shoulder and has been shown to provide improved crash protection [7].

Although it is interesting to simulate and review the affects of various anchor points in the direction parallel to travel, outside of the laboratory, transporters are usually limited in the availability of structurally suitable anchor points. Bus and van window locations, positioning of seating, and the vehicle’s structural integrity often reduce anchor point possibilities to those other than optimal.

**VARIATION IN Y–COORDINATE**

Review of results which move the upper anchor point inboard or outboard in the frontal plane indicate that a more inboard positioning of this point, ensuring that the belt crosses the clavicle, significantly reduces the head’s excursion in the y-direction. With moving the anchor point outboard, the shoulder belt no longer passes over the clavicle, but instead crosses the upper torso at a point below the shoulder. This positioning permits the shoulder to rotate freely, resulting in increased head and upper torso excursions.

Linear accelerations of the head vary across simulations which alter the anchor point’s y-coordinate. Injury parameters and angular acceleration of the head decrease slightly due to moving the anchor point outboard since less force is applied by the shoulder restraint in this scenario.

Varying the anchor point in the y-direction, or perpendicular to the direction of travel, is also often limited in actual transport situations due to the physical constraints presented by the wheelchair and vehicle. Factors such as the wheelchair width and it’s positioning relative to the vehicle’s outside wall influence the location of the upper anchor point of the shoulder belt in the transverse plane. For example, if a 22” wide wheelchair is to be transported forward facing in an ADA compliant space of 30” wide x 48” long, with it’s inboard wheel aligned with the bus aisle, then the y-coordinate of the anchor point (on the outside wall)
will be set at –19”. Obviously, changing any of these characteristics will cause a corresponding change in the anchor point’s y-coordinate.

**VARIATION IN Z–COORDINATE**

Varying the shoulder belt angle through 50, 55 and 60 degrees by adjusting the height of the anchor point shows that a higher anchor point location, causing the shoulder belt to cross the torso closer to the neck, produces an increase in head accelerations and injury parameters. Angular acceleration of the head about the y-axis of 684 rev/sec², and a HIC value of 1712 are of the highest values produced for all simulations, and are thought to be unacceptable based upon the FMVSS limit of 1000 for HIC. However, a lower anchor point (z=–65.1”) allows for increased head excursion in the y-direction since, as found with moving the anchor point outboard, the shoulder belt no longer crosses the torso at the center of the clavicle, instead passing outboard of the midpoint of the clavicle.

As with variations in the anchor point’s x- and y-coordinates, only limited options exist to locate the anchor’s height in an actual transit situation. Typically in fixed route or paratransit vehicles, the anchor point will be secured to vertical stanchions separating windows, or to the structure just above the window, depending upon the structural strength of these members. Where suitable vertical structure is not available for anchoring, the anchor’s height is then often limited to a point above the windows. In buses this point is likely to be 5 feet above the floor, or higher, causing a less than desirable anchoring condition for women and children who typically have shorter sitting heights.

**CONCLUSIONS**

As indicated by the results obtained, moving the upper anchor point of the shoulder belt rearward, producing a shallow belt angle beyond the shoulder in the xz (longitudinal) plane, improves the wheelchair occupant crash protection. Decreases occurring in the head’s linear acceleration when the anchor point is moved rearward are significant and could represent a difference in the severity of an injury as evidenced by the changes in injury parameters. The most rearward positioning locates the shoulder belt such that contact with the shoulder is increased which serves to better couple the occupant with the vehicle. A closer coupling of the occupant and vehicle through the restraint system will increase the occupant’s potential for “riding down the crash” at the same rate as the vehicle structure, thereby reducing the occupant crash pulse. In effect, moving the shoulder belt anchor point rearward serves to approach the anchoring configuration of an integrated seat which anchors the shoulder belt just above the occupant’s shoulder, providing improved crash protection.

When comparing the results of all conducted simulations, it is seen that for a 50th percentile male, or Hybrid III dummy undergoing a 30 mph, 20 g frontal crash, an upper anchor point with coordinates x=–13.35”, y=–24” and z=–70.5” provides the best crash protection. This anchor point produces a shoulder belt angle of 55° with a horizontal plane taken through the
sternum reference, and is located approximately 43” behind the occupant’s shoulder, resulting in a belt angle of 27˚ in the xz plane. With the upper anchor point in this location, the resulting HIC value of 765, and the head acceleration in the z-direction of 53.5 g’s, are within existing FMVSS HIC requirements of 1000 and proposed safety standards of Gz less than 70 g’s. Conversely, many of the other modeled anchor points do not meet these requirements. Additionally, this anchor point is optimal in that it limits the resultant head displacement to 7.5”, the smallest excursion of all modeled anchor points. It is the shallow 27˚ belt angle in the xz plane produced by this anchor point location that yields the desirable occupant dynamics. Therefore moving the anchor closer to the occupant in the x-direction (i.e., forward) will produce similar occupant dynamics as long as the height of the anchor is adjusted to maintain the same 27˚ xz plane belt angle. However, as with any complex analytical model, results of the findings should be verified through the use of actual sled impact testing.

Although this model has been developed based upon the Hybrid III dummy which represents a 50th percentile male, it is common to find wheelchair occupants of size and stature other than that of the 50th percentile male. Altering the physical characteristics of the occupant to represent a smaller individual or child could have a significant impact on the crash protection offered by these same anchor points. Therefore, similar models should be compiled and validated through sled testing to simulate wheelchair occupants other than the 50th percentile male. Furthermore, models representing actual production wheelchairs rather than the surrogate wheelchair used in this study should also be conducted to provide a more realistic simulation. Additional useful information can also be gained by subjecting these same models to oblique frontal crashes, since in many crash scenarios impact is at an angle other than zero degrees.

However, important findings regarding wheelchair transportation safety can be inferred from this study which utilizes the surrogate wheelchair model:

1. Anchoring conditions which may be found in fixed or demand route vehicles may produce HIC values in excess of the FMVSS allowable limit of 1000.
2. Variations in the location of the upper anchor point of the shoulder belt lead to notable changes in the effectiveness of the occupant restraint, and hence, occupant dynamics. Occupant dynamics associated with certain anchoring configurations are indicative of lap and shoulder belts not providing the level of protection anticipated from these restraints.
3. Relocating the anchor point rearward, creating a shallow belt angle in the longitudinal plane beyond the shoulder, improves crash protection. Therefore, increasing the anchor point height should be coupled with moving the point rearward to maintain a shallow angle beyond the shoulder.
4. Standards which prescribe allowable forward head excursion should also be concerned with head excursions which occur in a direction perpendicular to the line of travel since certain anchoring conditions may exacerbate this head displacement.
5. Although variations in physical size of the occupant
were not explored as a part of this study, a fixed
shoulder belt anchor point will lead to variations in
occupant belt fit with different sized occupants. These
variations in belt fit will produce differing, and in some
cases undesirable, levels of crash protection. In
circumstances where the occupant size varies (as is the
case with most public transportation environments), it
is recommended that an adjustable anchor point be
provided to allow for optimal positioning.

Since in public transportation the shoulder belt anchor
point is generally located and permanently fixed at the
time of installation, it is of paramount importance that
additional study and testing of the shoulder belt’s point
of anchorage be conducted, as it can have a large impact
on the wheelchair occupant crash protection. Through
research and standards development regarding
wheelchair transportation, studies such as this must
be conducted in an effort to optimize the location of
the upper anchor point so that we can begin to offer
those being transported in wheelchairs the same level
of safety afforded to the able-bodied transit rider.

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Note: Drawings not to scale

Figure 1. Coordinate System Origin—Transverse Plane

Figure 2. Coordinate System Origin—Longitudinal Plane
Figure 3. Variations in Upper Anchor Point–Transverse Plane

Figure 4. Variations in Upper Anchor Point–Longitudinal Plane
Figure 5. Affects of Varying Upper Anchor Point in X-Direction
Figure 6. Head Excursion in the Horizontal (XY) Plane- Variance of Anchor Point X-Coordinate
Figure 7. Affects of Varying Upper Anchor Point in Y-Direction
Figure 8. Head Excursion in Horizontal (XY) Plane- Variance in Y-Coordinate
Figure 9. Affects of Varying Upper Anchor Point in Z-Direction
Figure 10. Head Excursion in Horizontal (XY) Plane - Variance of Anchor Point Z-Coordinate
Technical Report #4

THE AFFECTS OF SHOULDER BELT ANCHOR POSITION ON WHEELCHAIR TRANSPORTATION SAFETY

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January 1995