ASSESSING THE PERFORMANCE OF STEERING WHEEL AIR BAGS FOR DRIVERS SEATED IN WHEELCHAIRS DURING FRONTAL CRASH TESTS

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ABSTRACT

In an effort to improve crash protection for drivers seated in wheelchairs, a recent study by the University of Michigan Transportation Research Institute (UMTRI) conducted 48-km/h frontal sled tests and computer simulations for midsize-male and small female anthropomorphic test devices (ATDs), seated in wheelchairs in the driver position of a minivan. The tests and simulations used various seat belt configurations, including good and poor belt fit, and no belt restraints. The computer models that were validated using results from the sled tests were conducted with and without air bag deployment to investigate the potential benefits of steering wheel air bags for drivers seated in wheelchairs and the potential risks of being injured by deploying air bags. The results of the UMTRI sled tests and computer simulations showed that the deployment energy of advanced steering wheel air bags was not a concern with regard to causing serious injuries to drivers seated in wheelchairs. Rather, frontal steering wheel air bags were generally found to reduce the risk of serious injuries by preventing driver contact with the steering wheel and upper instrument panel that can occur when the air bag is deactivated. The results of the UMTRI study therefore suggest that steering wheel air bags generally enhance frontal crash protection for drivers seated in wheelchairs and should rarely be deactivated.

To support the results of the UMTRI study, two 2015 Dodge Caravan BraunAbility EVII Conversion Vans, altered to accommodate drivers seated in power wheelchairs, were crash tested by conducting 48-km/h full-width frontal barrier tests with a Hybrid III 50th percentile male ATD seated in power wheelchairs in the driver position. In one crash test the frontal air bags (steering wheel and knee bolster air bags) were suppressed and in the second test both air bags deployed. Wheelchairs selected met the requirements of ANSI/RESNA WC-4: Section 19 (WC19), which is the industry standard in the U.S. for wheelchairs used as seats in vehicles. This standard requires wheelchairs to be successfully tested in a 48-km/h frontal sled test using a 4-point strap-type tiedown system to secure the occupied wheelchair. However, in the vehicle crash tests, the wheelchairs were secured in the driver position by a commercial docking-securement device that complies with industry standard ANSI/RESNA WC-4: Section 18 (WC18), *Wheelchair Tiedown and Occupant Restraint Systems for Use in Motor Vehicles*. Also, in both vehicle tests, the crash-test dummies were restrained by properly positioned lap/shoulder belts that were facilitated by using wheelchairs with arm supports that are cantilevered off the wheelchair back-support posts and are therefore open at the front and underneath.

Results for the two vehicle crash tests were compared to assess differences in injury risk for the 50th percentile male ATD with and without air bag deployment based on injury assessment values (IAVs). The frontal crash performance of the wheelchairs and docking securement devices were also assessed. Differences in the kinematic and kinetic responses of the ATD are described and the results are compared to results from the UMTRI sled tests and computer simulations. Results for the vehicle crash tests are directionally consistent with the findings from the UMTRI study. The kinematics of the ATD in the vehicle crash test where the frontal steering wheel air bag deployed are more controlled and the deploying air bag did not cause risk of serious injury.

INTRODUCTION

Significant improvements in frontal crash protection for vehicle occupants have been made over the years due to several factors, including Federal Motor Vehicle Safety Standards (FMVSS) and consumer information programs. In addition, federal legislation, such as the Americans with Disability Act of 1990 and the Individuals with Disability Education Act of 1997 [ADA, 1990; IDEA, 1997], has improved access to motor-vehicle transportation for people with disabilities, and particularly for people who use wheelchairs. As a result, increased numbers of children and adults are now traveling in motor vehicles while seated in wheelchairs [Bureau of Transportation Statistics, 2012].

There are also data indicating that vehicle occupants who travel seated in wheelchairs are at significantly greater risk of serious-to-fatal injuries than occupants using the original vehicle equipment manufacturer's seats and restraint systems. For example, the National Highway Traffic Safety Administration's (NHTSA) National Center for Statistics and Analysis examined data from the Consumer Product Safety Commission's National Electronic Injury Surveillance System database and estimated that, between 1991 and 1995, about 2,294 injuries/deaths occurred to occupants seated in wheelchairs as a result of "improper securement" [NHTSA, 1997]. In a survey of 596 wheelchair users in 45 states conducted by researchers at the University of Pittsburgh, it was found that 26 percent of the respondents remained seated in their wheelchairs while driving personal vehicles, and that drivers seated in wheelchairs had significantly higher frequencies of crash involvement than wheelchair users who transfer to drive from the vehicle seat [Songer et al., 2004 and 2005; Fitzgerald and Songer, 2007]. Also, in a convenience sample of 69 crash and non-crash events (e.g., sudden vehicle braking) involving 74 occupants seated in wheelchairs, including 21 drivers of personal vehicles, 24 occupants (32 percent) sustained serious-to-fatal injuries, many of which occurred in moderate, minor, and non-crash events [Schneider et al., 2016].

While people who use wheelchairs for improved mobility should transfer to the vehicle seat whenever it is feasible and safe to do, transfer is not feasible or safe for a large proportion of the approximately two-million people in the United States who use wheelchairs. Upon recognizing the safety problem for travelers seated in wheelchairs, and that the dynamic crash performance requirements of FMVSS No. 208: *Occupant protection* [49 CFR 571.208] do not apply to wheelchairs and wheelchair securement systems, or to aftermarket seat belts installed by vehicle modifiers for use by occupants seated in wheelchairs, national and international industry standards, known as wheelchair transportation safety (WTS) standards, have been developed for these products [Schneider et al., 2008]. The latest versions of WTS standards in the United States are contained in Volume 4 of ANSI/RESNA wheelchair standards: *Wheelchairs and Transportation* [ANSI/RESNA, 2012]. At the current time, Volume 4 includes the following three sections:

- Section 18 (WC18): *Wheelchair tiedown and occupant restraint systems (WTORS) for use in motor vehicles*
- Section 19 (WC19): *Wheelchairs used as seats in motor vehicles*
- Section 20 (WC20): *Wheelchair seating systems for use in motor vehicles*

The primary focus of these industry standards is on people who travel as passengers in motor vehicles. For example, WC19 requires that wheelchairs provide four easily accessible securement points for manual attachment of tiedown straps by an attendant or caregiver, and that wheelchairs are crash tested using a 48-km/h frontal-impact sled test for which the deceleration pulse must fall within a specified corridor that exceeds 20 *g* for more than 15 milliseconds (ms). WC19 requires that this frontal-impact sled test is conducted with the wheelchair loaded by an appropriate-size anthropomorphic test device (ATD), or crash-test dummy, restrained by a lap/shoudler belt with commercially available wheelchair-anchored lap belt, and with the wheelchair secured by a four-point, strap-type tiedown system attached to the manufacturer-designated securement points. WC19 also evaluates a wheelchair with regard to how well it accommodates (i.e., facilitates) proper lap/shoulder belt placement on passengers seated in the wheelchair by an attendant (i.e., someone other than the wheelchair user). The tests and performance ratings of WC19 are therefore not applicable to drivers seated in wheelchairs for which the wheelchair is necessarily secured by an auto-docking securement device and the driver is using a lap/shoulder belt with vehicle-anchored lap belt that is typically pre-buckled (i.e., a passive belt restraint) before the wheelchair user moves forward into the driver station.

The 2012 version of WC19 provides for crash testing of wheelchairs secured by an auto-docking system, but it does not require it. As a result, most wheelchair models, and especially most powered wheelchairs used by drivers, including those that comply with WC19, have not been crash tested in this securement mode. Many WTORS manufacturers provide wheelchair-securement adaptor hardware for the most popular wheelchair models so that they can be secured using their docking-securement system.

The most common type of auto-docking securement system uses a single securement bolt attached to a wheelchair securement adaptor that is permanetly attached to the wheelchair frame. The securement bolt is located close to the ground under the wheelchair frame and is oriented vertically with the head of the bolt toward the vehicle floor. When the driver moves his/her wheelchair forward into position, the securement bolt automatically engages with, and is locked into, a docking device mounted to the vehicle floor in a location that is intended to position the driver to most effectively operate the vehicle controls.

Recognizing that additional research was needed to address the unique situations faced by individuals who drive personal vehicles while seated in their wheelchairs, NHTSA recently funded a research program at the University of Michigan Transportation Research Institute (UMTRI) that was largely focused on improving occupant crash protection for drivers seated in wheelchairs [Schneider et al., 2016]. One of the key questions addressed in this research is the effectiveness of air bags in reducing and preventing injuries in frontal crashes versus the risk of air bag induced injuries for drivers seated in wheelchairs.

A key motivation behind this question is the "Make Inoperative Exemptions" from certain FMVSS provided in 49 Code of Federal Regulations Part 595 to accommodate people with disabilities [49 CFR 595]. This exemption allows vehicle modifiers to deactivate air bags in personal vehicles modified for use by people with disabilities, and particularly for people who drive a personal vehicle while seated in their wheelchair. As a result, if vehicle modifiers have concerns about clients being injured by a deploying air bag, they may also submit a request to NHTSA for approval to install an air bag on/off switch that can deactivate the air bags. In many cases, these concerns may be unfounded, in which case air bag deactivation unnecessarily removes the protective benefits of air bags for drivers in wheelchairs during frontal crashes.

Prior to investigating the tradeoffs between the protective benefits and injury risks for drivers in wheelchairs resulting from deployment of air bags in frontal crashes, a measurement/observation study of twenty-one people who drive a personal vehicle while sitting in their wheelchair was conducted [Schneider et al., 2016; van Roosmalen et al., 2013]. In addition to quantifying the position of drivers seated in wheelchairs relative to vehicle interior components, such as the steering wheel and knee bolster, the study demonstrated the importance of driver wheelchairs having arm supports that are cantilevered off of the back support posts so that they are open at the front and underneath. These arm supports allow drivers in wheelchairs to be provided with good seat belt positioning with the lap belt placed against the lower pelvic region, especially if used in a passive mode [Ritchie et al., 2009].

The investigation of air bag protective effects versus air bag induced injury risk involved conducting 48-km/h WC19 frontal impact sled tests with the 50th percentile male and 5th percentile female Hybrid III ATDs, and using the results of these tests to validate computational models of crash-test dummies representing wheelchair drivers configured in MADYMO. For both sled tests and computer simulations, the interior package geometry of a 2006 Chrysler Town and Country minivan was used since it is a vehicle that has been commonly modified for use by people who drive while seated in wheelchairs. Because the "smart" features of today's advanced air bags are typically bypassed in vehicles modified for use by drivers seated in wheelchairs, full deployments of advanced steering wheel air bags were used in both sled tests and computer simulations performed by UMTRI.

Parametric computer simulations of 48-km/h frontal-impacts using the validated MADYMO models were conducted with and without air bag deployments using midsize male and small female ATDs seated in wheelchairs at representative distances (based on the wheelchair driver measurement study) relative to the steering wheel and air bag module. Simulations were also conducted for angled crashes in which both the side-curtain and steering wheel air bags deployed, and for ATDs positioned in close proximity (i.e., out of position) to the air bag module at the time of deployment. The ATD response measures from these simulations were compared with current injury assessment reference values (IARVs) in FMVSS No. 208, "Occupant crash protection," [49 CFR 571.208].

The results of both the UMTRI sled tests and computer simulations showed little basis for concern that fully deployed advanced steering wheel air bags will cause serious injury to drivers seated in wheelchairs for the test conditions examined. In almost all of the conditions studied, the steering wheel air bags reduced the risk of head, neck, and chest injuries that can occur from contact with the steering wheel and other vehicle components if the air bag is deactivated. In angled frontal impacts, the driver is provided with an extra measure of protection by deployment of the side curtain air bag when the driver's head is cushioned between the two air bags.

The results of the UMTRI wheelchair-driver air bag study therefore suggested that steering wheel air bags offer tangible safety benefits for a wide range of drivers seated in wheelchairs. The study recommended that air bags are only deactivated when the chest or chin of a driver seated in a wheelchair is less than 20 cm from the air bag module during normal driving. As with drivers using vehicle seats, for steering wheel air bags to provide maximum benefit in frontal crashes for drivers seated in wheelchairs, use of a properly positioned lap/shoulder belt restraint is important. In general, this requires that the wheelchair is equipped with cantilevered arm supports that allow the lap portion of the seat belt to slide under the arm supports into contact with the driver's lower pelvic region when he/she moves forward into the driving position.

OBJECTIVE

The primary objective of the current study was to further investigate the results of the UMTRI study with regard to the potential benefits or harm of steering wheel air bags for drivers seated in wheelchairs during frontal crashes. This was accomplished by conducting barrier crash tests of modified vehicles with crash test dummies seated in wheelchairs.

METHODS

Test Vehicles, Crash Severity, and ATDs

Two full-frontal vehicle crash tests into a rigid barrier were conducted using the FMVSS No. 208 test configuration. A new 2015 Dodge Caravan BraunAbility EVII Conversion Van, shown in Figure 1, was used in each test. The vehicles were adapted to accommodate a driver seated in a wheelchair and certified to all applicable Federal Motor Vehicle Safety Standards. Each vehicle was equipped with standard steering wheel and knee bolster air bags in addition to a retractor mounted seat belt pretensioner. However, driver hand-control linkages for braking and accelerating that would typically be used by a driver seated in a wheelchair were not installed in these vehicles. The rear seat and front passenger seats were removed prior to the crash tests for installation of cameras and data-acquisition equipment.

To be consistent with the UMTRI tests and simulations, both tests were conducted at 48-km/h instead of the regulatory impact velocity of 56-km/h. Also, both tests were conducted using the 50th percentile male Hybrid III ATD.

Figure 1. Dodge Caravan BraunAbility EVII Vehicle used in each test

Wheelchairs, Wheelchair Securement System, and Belt Restraints

In each test, an adult-size Q6 Edge 2.0 power wheelchair with Synergy seating system by Quantum, Inc. (shown in Figure 2) was secured by a QLK-150 docking securement system by Q'Straint, Inc. shown in Figure 3. The QLK-150 is compliant with WC18, formerly SAE Recommended Practice J2249 [Q'Straint website, SAE, 1999 and UMTRI *Wheelchair Transportation Safety* website] and the Q6 Edge 2.0 wheelchair complies with WC19 [UMTRI *Wheelchair Transportation Safety* website]. However, while Q'Straint provides QLK-150 wheelchair securement adaptor hardware for the Q6 Edge 2.0 wheelchair, this wheelchair model had not been previously crash tested when secured by this docking device per a discussion with a Q'Straint representative.

The ATD was positioned in the Synergy seating system on a 50 mm thick seat cushion with the buttock and back of the upper torso against the wheelchair back support. In both tests, a postural lap belt attached to the Quantum wheelchair seating system was then placed around the ATD's pelvic region. After the wheelchair and ATD were positioned in the driver station as described below, the ATD was restrained by the vehicle lap/shoulder belt for which the inboard anchorage of the belt assembly was anchored to the vehicle floor (instead of to the vehicle seat as the vehicle was originally equipped) by the vehicle modifier using an adjustable length of belt webbing material (see Figure 7b). Both wheelchairs were equipped with cantilevered arm supports to facilitate proper positioning of the lap/shoulder belt restraint on the ATD with the lap belt in contact with the lower pelvic region and the shoulder belt across the chest and over the outboard shoulder, thereby isolating the contributions of the air bags to crash protection or air bag induced injury in these tests.

Figure 2. Quantum Q6 Edge 2.0 power wheelchair with cantilevered arm supports

Figure 3. Q'straint QLK-150 docking-securement device

Figure 4 shows the QLK-150 docking device installed on the floor in one of the vehicles. In addition to the docking-securement device, the system includes a front stabilizing bracket into which a forked steel bar attached to the front of the securement adaptor is engaged to prevent lateral rotation of the wheelchair about the single-point securement bolt during normal vehicle travel. This stabilizing bracket can help resist forward pitching and rearward rotation of the wheelchair during frontal crashes.

Figure 4. Docking-securement device installed on the vehicle floor along with front stabilizing bracket (to the right of the docking device)

As shown in Figure 5, the lower portion of each wheelchair was fitted with a Q'straint QLK-150 securement adaptor with the securement bolt that engages, and locks into, the docking device mounted to the vehicle floor.

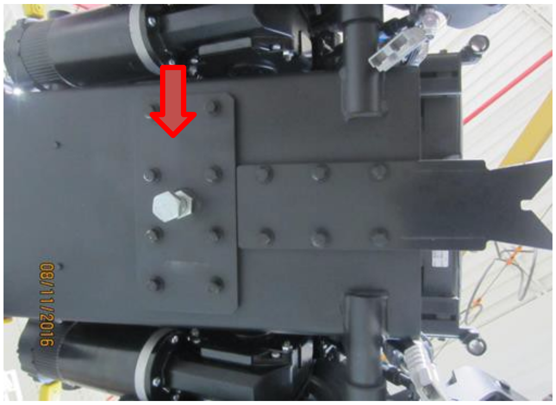

Figure 5. Bottom view of a Q6 Edge wheelchair showing the Q'Straint securement adaptor with securement bolt and forked steel bar (on right) that engages with the front stabilizing bracket

Positioning ATD Relative to Vehicle Interior Components

The docking securement device and stabilizing bracket were located in each vehicle so as to replicate the average distances of midsize-male drivers from vehicle interior components from UMTRI's driver-measurement study and illustrated in Figure 6. Table 1 lists these recommended distances of the ATD to the steering wheel and knee bolster, which were also used in the UMTRI sled tests and computer simulations.

To properly locate the docking device, the ATD was seated in in the wheelchair with the securement bolt locked in the uninstalled docking device. The wheelchair was then positioned to achieve the desired ATD to steering wheel and knee bolster distances, to the extent possible. The vehicle floor was then marked for bolting the Q'Straint docking device in the desired location.

Figures 7a and 7b show outboard and inboard views of the pre-test position and posture of the ATD. While it was not possible to achieve the exact distances recommended by UMTRI because of differences in vehicle package geometry and other factors, an effort was made to achieve the closest match for ATD-to-steering wheel distances. When this was done, the left knee of the ATD was 257 mm from the knee bolster and the right knee was 246 mm from the knee bolster. Thus, the distances from the anterior aspect of the ATD's knees to the knee bolster were about 100 mm greater than the distance of 155 mm recommended by UMTRI, while distances of the ATD to the steering wheel were very close to those listed in Table 1.

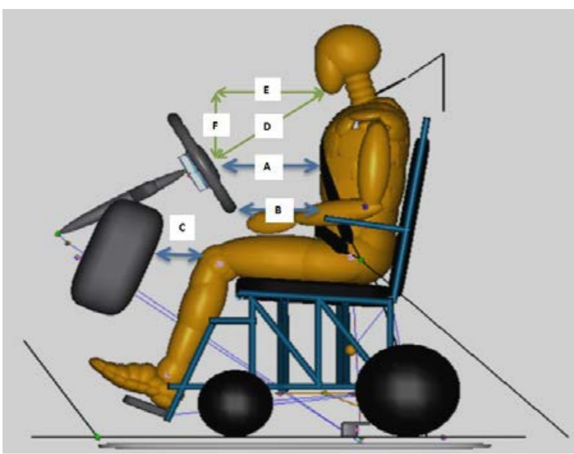

Figure 6. ATD pre-test position relative to the steering wheel and knee bolster

Table 1. UMTRI Recommendation for ATD Pre-Test Distances to Vehicle Components

Measurement	Distance (mm)
Between the center of the steering wheel and the ATD's chest (A)	330
Between the bottom of the steering wheel rim and the ATD's abdomen (B)	195
Between the front of the ATD's knees and the un-deployed knee restraint (C)	155
Diagonal distance from center of steering wheel to ATD's chin (D)	380
Horizontal distance of center of steering wheel to ATD's chin (E)	320
Vertical distance from center of steering wheel to ATD's chin (F)	210

Figure 7a. Outboard view of ATD and wheelchair in pre-test positions and posture

Figure 7b. Inboard view of ATD and wheelchair in pre-test positions and posture showing lap belt anchored to the vehicle floor

RESULTS

Wheelchair and ATD Kinematics, Contacts, and Performance

Figure 8 shows the crash deceleration pulses for the two tests. The peak deceleration of approximately 25 *g* occurred at 50 ms in both tests. Based on review of the high-speed videos, it was determined that the steering wheel air bag deployed at approximately 12-to-14 ms following the onset of vehicle deceleration, which is consistent with the air bag deployment time of 12 ms used in the sled tests and computer simulations conducted by UMTRI. Also, in both tests, the retractor mounted seat belt pretensioners deployed at approximately the same time as the air bag. In each test, the postural pelvic belt remained in place around the ATD's pelvis and attachments to the wheelchair frame without any signs of damage.

High-speed videos from several views and angles of each test were reviewed to examine wheelchair and ATD kinematics and contacts of the ATD with vehicle components during each test. The wheelchairs were effectively secured by the QLK-150 docking devices in both tests with very little forward movement of the wheelchair base. As shown in Figure 9, there was no observable deformation of the docking device after the tests. In addition, the forked bracket bar from the wheelchair securement adaptor remained engaged with the stabilizing bracket throughout each test, with little observable bending, so there was very little forward or rearward rotation of the wheelchair base.

However, in each test, the wheelchair back support deflected forward and stayed in contact with the back of the ATD's torso that was restrained by the lap/shoulder belt system during frontal impact loading. This forward deflection of the back support resulted in complete failure of the back-support posts where they connect to the wheelchair base, as shown in Figure 10. A review of the high-speed videos shows that the posts failed just over 100 ms after the onset of vehicle deceleration when the back-support posts are at, or near, their maximum forward deflection. Following this, complete separation of the posts occurred at the points of failure as the back support began to rebound and rotate rearward.

As a result of these failures, the back supports completely detached from the wheelchair base and were on the floor behind the wheelchairs at the end of both tests, as shown in Figure 11. However, as also shown in Figure 11, the ATD's torso remained in an upright posture at the end of each test.

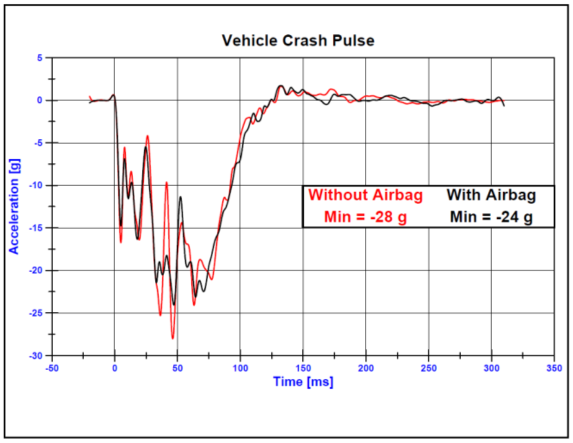

Figure 8. Vehicle deceleration pulses

Figure 9. Post-crash photo of the docking securement device from the crash test with air bag deployment

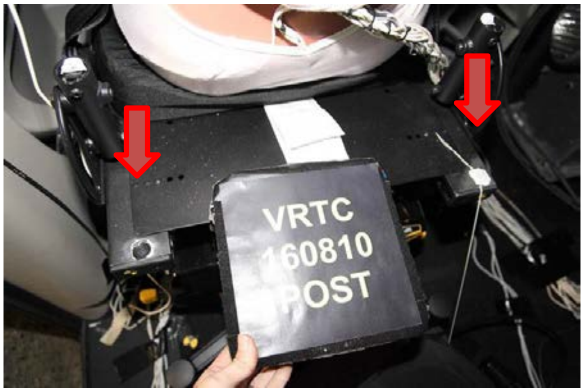

Figure 10. Photo of back of wheelchair base showing failure points of back support posts

Figure 11. Post-test photo showing wheelchair back support on the vehicle floor behind the wheelchair with the ATD torso upright

ATD head excursions were measured by photogrammetry. The head trajectories for the two tests are shown and compared in Figure 12. For both tests, the maximum forward excursion (from the pre-test position) of the head center of gravity (CG) was measured. The maximum excursion was 429 mm in the test without air bags and 368 mm in the test with air bags. Thus, in the test with air bag deployment, the maximum excursion of the head's CG was 61 mm, or 14 percent, lower than in the test without air bag deployment.

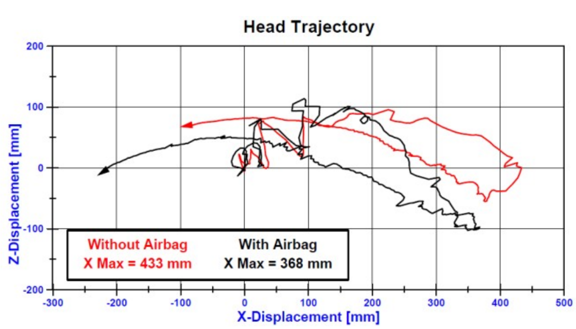

Figure 12. Trajectories of head CG with and without air bag deployment

Figures 13 and 14 show the ATD's chest contacting and bending the steering wheel and the head striking the top of the instrument panel (IP) and upper part of the steering wheel rim in the test without the air bag. Figure 15 shows the resulting contact marks on the upper steering wheel rim and upper IP evidenced by transfer of chalk on the ATD's head and face in the test without air bag deployment. Figure 16 shows where the ATD's abdomen contacted the lower steering wheel rim evidenced by transfer of chalk on the lower rim to the ATD clothing.

As shown in Figures 17 and 18, in the test with air bag deployments, the steering wheel air bag prevented direct contact of the ATD's chest and abdomen with the steering wheel and the ATD's head/face with the upper steering wheel rim and upper IP.

Figure 13. ATD in forward-most position in test without air bag deployment

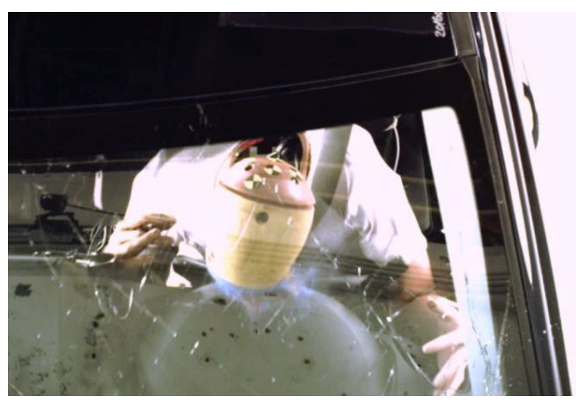

Figure 14. ATD head contacting the upper IP in test without air bag deployment

Figure 15. Chalk on upper steering wheel rim and upper IP indicating ATD head and face contact in the test without air bag deployment

Figure 16. Chalk mark on ATD clothing showing where the abdomen contacted the lower steering wheel rim in the test without air bag deployment

Figure 17. ATD forward-most position in the test with air bag deployment

Figure 18. ATD head contact with the steering wheel air bag

IAVs With and Without Air Bag Deployment

Table 2 presents the injury assessment values (IAVs) measured by ATD instrumentation in the two crash tests, as well as the IARVs from FMVSS No. 208. Almost all IAVs measured in the test where the air bags deployed are 18 to 72 percent lower than for the test where air bag deployment was suppressed. Specifically, HIC15 is 72 percent lower and BrIC is 31 percent lower when the driver's air bag deployed, thereby indicating a reduced risk of serious head/brain injury. Chest deceleration and chest deflection are 24 and 18 percent lower, respectively, with air bag deployment due to the lack of contact with the steering wheel and upper IP.

The sole exception to a lower IAV with air bag deployment is peak axial load in the right femur, which, as shown in Figure 19, is almost 60 percent higher in the test with air bag deployment. In both tests the peak loads for the left femur are very similar. For the test with the air bags suppressed, the peak left femur load was 3,931 N while it was 3,868 N in the test with air bag deployment. It can also be noted, that the peak load in the right femur without air bag deployment is 5,846 N, which is higher than the peak left-femur loads in both tests.

Table 2. ATD Injury Assessment Values

IAV	IARV	NHTSA Test No. 10029 without Air Bags	NHTSA Test No. 10030 w/ Air Bags	% Change
HIC15	700	368	101	- 72 %
BrIC*	1.0	0.80	0.55	- 31 %
Nij	1.0	0.37	0.37	--
Chest *g* (3ms clip)	60	58.4	44.2	- 24 %
Chest Deflection (mm)	63	47.5	38.9	- 18 %
Max Femur Load (N)	10,000	5,845	9,265	+ 58 %

*Brain Injury Criteria - Not in FMVSS No. 208

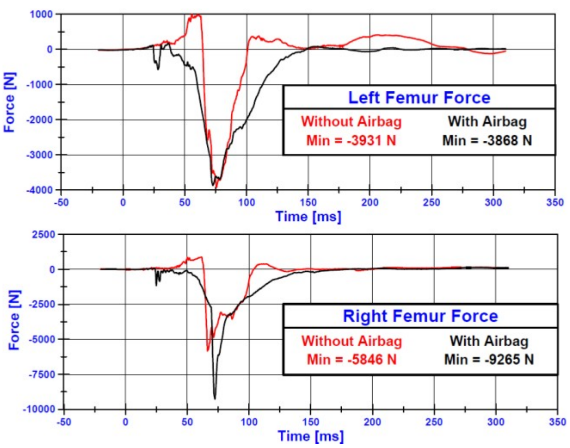

Figure 19. ATD axial femur loads versus time

DISCUSSION

Steering Wheel Air Bags and Reduction of Injury Risk to the Upper Body

Results of the two vehicle crash tests with and without air bag deployment show that a steering wheel air bag in conjunction with effective wheelchair securement and a properly positioned lap/shoulder belt restraint reduces the risk of upper-body injuries for a 50th percentile male ATD seated in a wheelchair compared to driver ATD with a deactivated air bag. The deployed steering wheel air bag controlled ATD kinematics, reduced the amount of forward head excursion, and prevented head and chest contact with the steering wheel and upper IP, thereby reducing the head, neck, and chest IAVs and thus the risks of head, neck, and upper torso injury in frontal crashes. As was found in the UMTRI study, there was no indication in the test with air bag deployment that a 50th percentile male driver seated in a wheelchair who is properly using a lap/shoulder belt will sustain any serious harm from full deployment of advanced steering wheel air bags in today's vehicles.

Results from the vehicle test in which the air bags deployed also compare reasonably well with the results from the 56-km/h New Car Assessment Program (NCAP) crash test of a sister 2012 Chrysler Town and Country van that was also equipped with a knee bolster air bag [NHTSA Test No. 7460] and tested with a 50th percentile male Hybrid III ATD in the driver position. In the NCAP test, the driver HIC15 was 236, Nij was 0.36, peak chest displacement was 23 mm, and chest resultant acceleration was 38 *g*.

High Femur Loads for Drivers in Wheelchairs

Of some concern in the modified-van test where both the steering wheel and knee bolster air bags deployed is the very high peak force in the right femur. Although the ATD's interaction with the steering wheel air bag showed positive results with regard to reduced injury risk for the upper body, the right femur IAV almost exceeded the 10,000 N IARV of FMVSS No. 208 in the test with the deploying knee bolster air bag.

In an effort to understand the reason for the high right femur load in the test with knee bolster air bag deployment, the structural components behind the knee bolster trim and air bag of both modified vehicles were inspected after the crash tests. The contact locations on the IP structure behind the knee bolster for the two vehicles are shown by the round high-contrast targets in Figures 20 and 21.

In both tests, the ATD's right knee loaded a structural element behind the trim, and, in the test with air bag deployments, behind and through the deployed knee bolster air bag. However, the locations of the loaded components are slightly different in the two tests. In the test in which the knee bolster air bag deployed, the right knee loaded a stiff bracket that did not deform after bottoming out the air bag. In contrast, the right knee struck just to the left of this stiff bracket in the test without air bag deployment, resulting in some deformation and energy absorption, and thus a lower peak femur force.

Figure 20. Right knee contact location with structures behind the knee bolster indicated by round contrast marker for the test with knee bolster air bag deployment

Figure 21. Right knee contact location with structures behind the knee bolster indicated by round contrast marker for the test without air bag deployment

In addition to the high peak force in the right-femur in the test with knee bolster air bag deployment, the IAVs for the right femur are greater for both 48-km/h modified-vehicle tests than in the 56-km/h NCAP test of a 2012 Chrysler Town and Country noted above. In the NCAP test the right peak femur loads were 3,450 and 3,479 N, respectively. By comparison the right peak femur loads were 5,848 N and 9,265 N for the tests without and with air bag deployment, respectively. Interestingly, the peak left femur loads for the modified vehicle tests are comparable to those in the NCAP test, with values of 3,931 N and 3,868 N, respectively, without and with air bag deployment. The reason for the lower peak loads in the left femurs of the modified vehicle tests compared to the right femurs is not clear but is likely due to differences in underlying structural members in the areas struck by the left and right knees.

High Lower-Torso and Knee Excursions for Drivers in Wheelchairs

As noted in the methods section, it was not possible to achieve all of the ATD-to-vehicle-component distances recommended by UMTRI, given the different vehicle interiors and other factors of the modified vehicle used in these tests compared to the different personal vehicles in UMTRI's driver measurement study. As a result, a decision was made to achieve ATD-to-steering wheel distances as close as possible to UMTRI's recommended distances, which resulted in significantly larger (about 100 mm) distances between the ATD's knees and the lower IP or knee bolster. In spite of these larger knee-to-knee bolster pre-crash distances, the ATD's knees made forceful contact with the knee bolster or knee bolster air bag and, in fact, caused bottoming out of the latter.

These high lower-torso/knee excursions for an ATD seated in a wheelchair are of some concern and are possibly due to several factors. One is that wheelchairs have much lower (nearly horizontal) seat-pan angles than original equipment driver seats, thereby providing less resistance to forward movement of the lower torso and knees. Another is that the power wheelchairs used in these tests have a spring suspension system that may increase forward movement of the wheelchair seat during frontal-impact loading.

A third factor is that the lap belts in the modified vehicles are longer than a standard lap belt since wheelchairs have significantly higher seat-to-floor distances (than vehicle seats) and the inboard portion of the lap belt is anchored to the vehicle floor rather than the seat base (see Figure 7b). The longer seat belt will have a greater amount of stretch during frontal-impact loading and thereby be less effective in limiting lower-torso restraint. Finally, the pre-test angle of the lap belt on the inboard side of the wheelchair in these tests was quite steep in the modified-vehicle tests (> 70 degrees to the horizontal as shown in Figure 7b), thereby reducing lap-belt effectiveness in reducing forward movement of the pelvis.

These high forward knee excursions combined with greater pre-impact knee-to-knee-bolster distances in the modified vehicle tests may result in higher velocities of impact of the ATD's knees with the knee bolster, the knee bolster air bag, and structural components behind the air bag and lower IP trim. These high knee excursions are therefore another likely reason for the high peak right femur forces in both tests of the modified vehicles and the reason that the peak forces for the left femur are comparable in magnitude to peak forces for the left femur in the NCAP test even though the modified vehicles were tested at a lower impact speed than the NCAP test (48-km/h versus 56-km/h).

Back-Support Failure

The other concern from the wheelchair-driver tests of modified vehicles is the complete failure and detachment of the wheelchair back supports in both tests. As previously noted, the back support rotated forward in both tests so that it remained in contact with the back of the ATD as the torso rotated forward during frontal-impact loading. Failure of the back-support posts where they connect to the wheelchair base occurred at, or near, peak forward back-support deflection. It is therefore possible that the mass of the back supports could have increased the forward excursions of the ATD's torso and head and thereby increased the IAVs somewhat, although all upper-body IAVs are well below the IARVs in both tests. Also, the effects of back-support forward deflection and failures would have been similar in both tests and the failed back-support posts are therefore thought to not have had an effect on the directionality of the IAVs (i.e., lower values with air bag deployment).

The reason for the complete failures of the back supports in these tests when the same Synergy back support did not fail in several UMTRI WC19 sled tests of the Q6 Edge 2.0 wheelchair is not clear. However, securing the wheelchair using a docking device in the vehicle tests compared to securing wheelchair using a four-point, strap-type tiedown in the WC19 sled tests may be a contributing factor. In particular, the docking securement device may result in a higher peak deceleration of the wheelchair base, thereby placing higher forces on the back-support posts where they connect to the base.

Another factor contributing to the back-support failures in the vehicle tests may be the difference in arm supports. In UMTRI's WC19 sled tests, the wheelchairs were not equipped with arm supports that are attached to, and cantilevered off of, the back-support posts. Rather, the arm supports in the UMTRI tests were attached to the side frame of the wheelchair base. In addition to the cantilevered arm supports adding mass to the back supports and thus inreasing the force causing forward deflection during frontal-impact loading, the arm supports attached to the wheelchair base in the UMTRI tests may have provided some interference and resistance to forward deflection of the back supports in the WC19 sled tests, thereby preventing failure of the back-support posts.

The primary concern of back-support failure for real-world occupants in wheelchairs is the potential for driver injury during rebound from frontal-impact loading if the back support completely detaches from the base, or even if it rotates significantly rearward. While the ATD remained upright in the wheelchairs at the end of the two modified-vehicle tests, in real-world crashes, detachment of the back support increases the likelihood of the occupant moving rearward out of the back of the wheelchair during rebound or in a subsequent collision event, resulting in the potential for serious head and/or neck injury.

Comparison of Results to UMTRI Data

Overall, the results of the crash test where the steering wheel air bag deployed are consistent with the sled tests and simulations conducted by UMTRI [Schneider et al., 2016]. Table 3 provides a summary of the ATD IAVs in the crash tests, sled tests, and computer simulations. With the exception of peak femur loads, IAVs for the modified vehicle tests with and without airbag deployments are generally directionally consistent with IAVs from UMTRI sled tests and computer simulations with and without steering wheel air bag deployment. Specifically, for head injury, the deployment of the steering wheel air bag reduced the risk of serious head/brain injury. Although head forward excursion was not reported in the UMTRI study, ATD kinematics from screen shots of the computer simulations, such as that shown in Figure 22, and the time-sequence photos from the sled tests contained in the UMTRI report are also consistent with those in the two vehicle crash tests. That is, the upper torso and head are constrained better in the air bag deployment sled tests and simulations, thereby reducing peak forward head excursion and ATD contact with the steering wheel and upper IP.

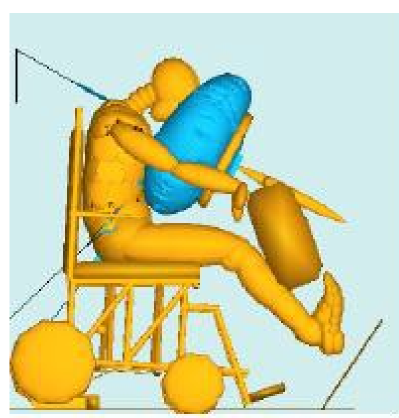

Figure 22. Screen shot from UMTRI computer simulation with properly seat belt restrained ATD and air bag deployment

Table 3. Summary of Test Results

IAV	Reference IARV	NHTSA Crash Test Without Air Bags	NHTSA Crash Test with Air Bags	UMTRI Sled Test with Air Bags Deployed at 12-ms	UMTRI Simulation Without Air Bag	UMTRI Simulation with Air Bag Deployed at 12-ms
HIC15	700	368	101	133	373	98
BrIC*	1	0.8	0.55	-	-	-
Nij	1	0.37	0.37	-	0.37	0.19
Chest g (3-ms clip)	60	58.4	44.2	-	-	-
Chest Deflection (mm)	63	47.5	38.9	41.2	33.2	36.2
Left Max Femur Load (N)	10,000	3,868	3,931	1,465	1,353	1,043
Right Max Femur Load (N)	10,000	5,845	9,265	3,325	1,109	762

*Brain Injury Criteria - Not in FMVSS No. 208

As in the vehicle crash test without deployment of the steering wheel air bag, UMTRI's computer simulations and sled tests illustrate the potential of the occupant impacting the steering wheel and making head contact with the upper IP.

A Real-World Case

Real-world data can also be used to evaluate and validate the safety of properly restrained drivers seated in wheelchairs and injury protection provided by steering wheel air bags. NHTSA's Special Crash Investigations division conducted an onsite crash investigation of a 2014 Toyota Sienna Braun Ability AEVIT conversion van adapted for a driver seated in a wheelchair [SCI, 2014]. The vehicle was involved in a multiple event, off-the-road sequence of crashes.

At the time of the crash, the vehicle was being operated by a 26-year-old male paraplegic driver who was seated in a power wheelchair of unknown make/model. The driver was restrained by a modified 3-point lap and shoulder belt restraint system, and the wheelchair was secured by a Q'Straint QLK-150 docking system.

After the driver made an avoidance maneuver in response to an animal in the roadway, the vehicle departed the road and impacted wooden beams of a flower bed. The vehicle proceeded to impact a wooden fence, then a detached garage, and finally struck a steel fire pit before coming to rest. In total, the vehicle traveled 67.4 meters from its initial contact with the flower bed.

Figure 23 shows the vehicle and front-end damage. According to data downloaded from the Event Data Recorder, the vehicle was traveling at 62-km/h when it impacted the wooden beams of the flower bed, resulting in a 13.5-km/h Delta V, or change in velocity. The primary frontal crash was with the wooden beams, which deployed the steering wheel air bag and both side curtain air bags, and activated the driver's seat belt pretensioner.

Figure 23. 2014 Toyota Sienna Braun Ability following multi-event off-road collisions

When the vehicle came to final rest, the driver released the wheelchair from the QLK-150 docking device using the available release button, and then deployed the side ingress/egress ramp. He operated the motorized wheelchair out of the vehicle and waited for emergency response personnel. The driver was later transported to a local hospital for evaluation where no injuries were found.

Even though the crash event that deployed the air bags in this real-world crash was of moderate severity, because the wheelchair was effectively secured and the driver was properly restrained by a lap/shoulder belt, injury to the driver was avoided during all subsequent collisions in the sequence of crash events.

CONCLUSIONS

Two 2015 Dodge Caravan BraunAbility EVII conversion vans, altered to accommodate drivers seated in wheelchairs, were crash tested by conducting 48-km/h full-width frontal barrier tests with a 50th percentile male ATD seated in powered wheelchairs that were secured by WC18-compliant QLK-150 docking devices. In the first crash test, the frontal air bags were suppressed, and in the second test, the air bags deployed. Power wheelchairs were selected that met the requirements of ANSI/RESNA WC-4: Section 19 and for which Q'Straint, Inc. provides a wheelchair securement adaptor for use with their QLK-150 auto-docking wheelchair-securement system. However, the wheelchairs had not been previously sled-impact tested when secured by this docking device.

The results of the crash tests were generally directionally consistent with the findings from the sled tests and computer simulations conducted by UMTRI. Moreover, all the upper-body IAVs from ATD measurements were lower in the test where the frontal air bags were deployed. The only IAV that did not improve was the peak force in the right femur. Furthermore, the kinematics of the ATD in the crash test where the steering wheel air bag deployed was more controlled, the forward excursion of the head was lower, and contact of the ATD's torso and head with the steering wheel and upper IP were prevented. Additionally, the deploying air bag did not induce harm as measured by the IAVs. This is also consistent with the UMTRI findings.

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