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Wheelchair Occupant Studies

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16. Abstract

The goal of this project was to improve transportation safety for occupants of motor vehicles seated in wheelchairs (i.e., to improve wheelchair transportation safety, or WTS), with an emphasis on drivers seated in wheelchairs. Investigation of crash and non-crash events involving one or more occupants in wheelchairs indicates that a primary reason occupants in wheelchairs sustain serious-to-fatal injuries is improper or incomplete use of lap/shoulder-belt restraints due, in large part, to interference by wheelchair arm supports with proper belt positioning. Efforts to improve frontal crash protection for drivers in wheelchairs resulted in a prototype seat-belt deployment system (SBDS) that provides components needed to complete the vehicle lap/shoulder belt for use in a passive mode while eliminating obstacles that interfere with maneuvering a wheelchair into the driver space. Sled-test evaluations and design improvements of a commercially available vehicle-anchored head-and-back restraint for rear-impact protection of drivers in wheelchairs led to several design and material changes that improved performance and that the manufacturer can use to improve the commercial system. Results of sled tests and computer simulations of drivers in wheelchairs with and without steering-wheel air-bag deployments during a 48-kph frontal crash indicate that there is little basis for concern that advanced steering-wheel air bags will cause serious injuries in frontal crashes. Rather, steering-wheel air bags almost always reduce the risk of head, neck, and chest injuries. Deactivating steering-wheel air bags should only be considered when the driver in a wheelchair is positioned with his/her chest or chin 200 cm or less from the air-bag module during normal operation of the vehicle. Using a fixed upper shoulder-belt anchor point instead of the OEM seat-belt retractor will reduce driver movement toward the airbag module during pre-impact braking and may enhance safety for many drivers in wheelchairs by providing greater torso stability in their optimal posture. Safety Tip Sheets and a *DriveSafe* brochure have been developed to provide vehicle modifiers and other key stakeholder with information on how to provide safer transportation for occupants seated in wheelchairs. These are being made available on a new UMTRI website that provides a wide range of educational materials on WTS, including lists of wheelchairs, wheelchair tiedown and occupant restraint systems (WTORS), and wheelchair seating systems that comply with WTS industry standards. Additional work is needed to implement the SBDS into a commercial product and to continue efforts to educate key stakeholder groups with regard to best practice in WTS and their role in improving transportation safety for passengers and drivers seated in wheelchairs.

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EXECUTIVE SUMMARY

Much of the improvement in motor-vehicle safety for drivers and passengers over the past thirty to forty years has been achieved through improved vehicle crashworthiness and restraint-system technologies that are, in large part, due to improvements in safety regulations and restraint-system performance requirements set forth by the NHTSA in federal motor vehicle safety standards (FMVSS). In addition, significant contributions to reductions in occupant injury risks have also been achieved through the implementation of seatbelt laws by states and by federal education campaigns, such as "Click-It-or-Ticket," that have resulted in significant increases in seatbelt use by adults and in the use of safety seats and booster seats by children.

However, during the same time that injury risks for people using vehicle manufacturer' seats and occupant-protection systems have been dramatically reduced, increasing numbers of people with physical and/or cognitive disabilities have been traveling in motor vehicles while seated in wheelchairs, and available evidence suggests that these travelers are at significant greater risk of serious-to-fatal injuries in crash and even non-crash events. For this population of vehicle occupants, safe transportation and effective occupant crash protection depends on the ability to use and effectively secure crashworthy wheelchairs, and the ability to properly use complete belt-restraint systems consisting of both upper and lower torso belts, all or part of which are aftermarket products installed by vehicle modifiers.

Upon recognizing the transportation safety problem for travelers seated in wheelchairs and the fact that federal motor vehicle safety standards generally do not apply to the aftermarket restraint systems required by most occupants seated in wheelchairs, or to wheelchairs and wheelchair securement systems, national and international industry standards have been developed for these products relative to their use in motor vehicles. While these voluntary industry standards are critical to improving transportation safety for travelers seated in wheelchairs, it is equally important to make sure that vehicle modifiers and other key stakeholders are aware of these standards so that compliant products are made available and used. It is also important that all parties involved in the transportation of occupants seated in wheelchairs (i.e., in wheelchair transportation safety, or WTS) are knowledgeable about "best practice" in transporting people in wheelchairs safely.

In this project, work was conducted on five Subtasks with the goal of improving transportation safety for occupants of motor vehicles seated in wheelchairs. While the project addressed transportation safety for both passengers and drivers seated in wheelchairs, a primary focus of the project was on drivers who operate personal vehicles (primarily vans and minivans) while seated in their wheelchair.

In Subtask 1, results of investigations and analyses of crash and non-crash events involving one or more occupants seated in wheelchairs indicate that a primary reason for these occupants sustaining serious-to-fatal injuries, even in minor to moderate crashes and non-crash events such as sudden braking, is a lack of use and/or proper positioning of a crashworthy lap/shoulder-belt restraint system. Although statistical analyses of injury factors for people seated in wheelchairs during frontal crashes in the UMTRI wheelchair-occupant crash injury database are currently limited by the relatively small sample size (n = 74 wheelchair occupants), the results suggest that current belt restraints are not as effective in preventing serious-to-fatal injuries for this population of travelers as they are for people seated in vehicle seats. This may be because drivers and passengers seated in wheelchairs have lower injury tolerance than the average vehicle occupant using vehicle seats.

However, it is also known that vehicle occupants who remain seated in their wheelchairs when traveling in motor vehicles often have difficulty achieving proper or optimal positioning of lap/shoulder belt restraints due to interference by wheelchair arm supports with proper positioning of vehicle-anchored lap belts by wheelchair components, and especially interference of lap-belt positioning in contact with the lower pelvis. In addition, positioning of occupants in wheelchairs further from the side of the vehicle compared to outboard occupants using vehicle seats often causes the shoulder belt to be position off the side of the shoulder rather than near the center of the shoulder, thereby reducing the effectiveness of shoulder belts in reducing chest and head excursions in frontal crashes.

A study of twenty-one people who drive a personal vehicle while seated in their wheelchairs confirmed that these drivers are often using poorly positioned and/or incomplete lap/shoulder belt restraints that would offer relatively little protection in frontal crashes, and would be more likely to cause abdominal and chest injuries than a properly positioned lap/shoulder belt. In many cases, this is because the driver requires a pre-buckled (i.e., passive) lap/shoulder belt due to the lack of manual dexterity required to buckle and unbuckle a standard seat belt, combined with a wheelchair having closed-front arm supports that prevent the proper placement of a passive lap belt low on the pelvis and in contact with the body when the driver moves forward into the driving position.

In Subtask 2, an effort to improve seat-belt restraint systems for frontal crash protection of drivers seated in wheelchairs evaluated several design approaches and prototype systems. The most promising system is referred to as the seat-belt deployment system, or SBDS. This design provides add-on vehicle components that allow drivers seated in wheelchairs to use the vehicle manufacturer's (OEM) lap/shoulder belt restraint in a nearly passive mode (pre-buckled seat belt activated by an accessible button), while eliminating obstacles on the vehicle floor that can interfere with maneuvering a wheelchair into the driver space. A prototype SBDS has been successfully evaluated in a static minivan laboratory buck and in several 48-kph, 20-*g* frontal-impact sled tests.

Efforts to improve rear-impact protection for drivers seated in wheelchairs include the development and successful sled-impact testing of a deployable head-and-back restraint system developed by a Biomedical Engineering (BME) senior design team under the supervision of UMTRI faculty and staff. However, the primary focus was on the evaluation and improvement of a commercially available vehicle-anchored head-and-back restraint system that the driver deploys behind his/her wheelchair or moves into the stored position against the side of the vehicle by means of an accessible button. Several changes to the design and performance of the head-and-back restraint system received from the inventor were made by UMTRI based on sled-test results, and have been conveyed to the manufacturer so that improvements to the commercially available equipment can also be made.

The goal of Subtask 3 was to determine the potential benefits of steering-wheel air bags for drivers seated in wheelchairs versus the risks of being seriously injured by deploying air bags. Forty-eight kph frontal sled tests and MADYMO computer simulations of small-female and midsize-male drivers (i.e., crash-test dummies) seated in wheelchairs in the driver space were conducted with and without deployment of an advanced steering-wheel airbag. All sled tests and simulations used a range of seat-belt configurations, including good and poor (loose) seat-belt positioning, as well as no belt restraint. The computer models were validated using results from frontal sled-impact tests with steering-wheel air bag deployments, and the validated models were used in simulation matrices to investigate the protective benefits and injury risks associated with allowing steering-wheel airbags to deploy or deactivating the steering-wheelchair airbag in 48-kph frontal crashes. Simulation matrices included angled frontal crashes at 15- and 30-degrees to 12 o'clock, midsize-male and small-female drivers in wheelchairs positioned in close proximity (125 mm and 25 mm) to the air-bag module at the onset of frontal-crash deceleration, and small-female drivers seated in a surrogate wheelchair versus a minivan driver seat.

The results of these tests and simulations show little basis for concern that the energy of deploying "advanced" steering-wheel air bags in today's vehicles will cause serious-to-fatal injuries to drivers seated in wheelchairs. Rather, the steering-wheel air bag almost always reduces the risk of head, neck, and chest injuries due to contact with the steering wheel that can occur when the air bag is deactivated. Also, in angled frontal impact, deployment of the side curtain airbag offers additional protection to drivers in wheelchairs. The results of this study therefore indicate that steering-wheel air bags will generally offer tangible safety and crash-protection benefits for a wide range of drivers seated in wheelchairs just as they do for drivers in vehicles seats, and should only be deactivated on rare occasions. The only situation when consideration should be given to deactivating a steering-wheel air bag for a driver seated in a wheelchair is when the driver is positioned with their chest or chin located 8 inches or less from the air-bag module during normal operation of the vehicle, which is the same as the recommendation for when to deactivate airbags for short drivers in vehicle seats.

In this regard, using a lap/shoulder belt with a fixed B-pillar anchor point rather than a retractor-based anchorage may offer several potential benefits to drivers seated in wheelchairs. In addition to providing for greater torso stability in the driver's optimal posture for operating the vehicle, and removing seat-belt retractor forces that can pull drivers away from their preferred driving posture, a properly adjusted seat belt with a fixed shoulder-belt anchor point would prevent the wheelchair driver's head and torso from moving closer to the airbag module during pre-impact braking and prior to airbag deployment during a frontal crash. Implementing fixed shoulder-belt anchor points on B-pillars should, however, be done in a manner that does not compromise seat-belt load limiters and/or seat-belt pre-tensioners.

If efforts toward improving transportation safety for occupants seated in wheelchairs such as those performed in this study and through development of voluntary wheelchair transportation safety standards, are to have to have a meaningful impact in the real world, there is a need to inform and educate key stakeholders regarding the existence of products that comply with voluntary industry standards and of best practice in providing safe transportation to travelers seated in wheelchairs. Toward this end, "Safety Tip Sheets" targeted to vehicle modifiers and other key stakeholder groups have been developed in Subtask 4, and a *DriveSafe* brochure is nearly ready for printing and distribution. The latter provides key steps to safe transportation and optimal crash protection for drivers who remain seated in wheelchairs, and is similar to the widely distributed and successful *RideSafe* brochure that is targeted primarily for passengers seated in wheelchairs.

In Subtask 5, a new Wheelchair Transportation Safety (WTS) website was developed that provides a wide range of educational materials for vehicle modifiers and other key WTS stakeholders. The website includes articles on WTS written for various consumer magazines over the past decade, downloadable sled-test videos that show the potential negative consequences of several wheelchair-tiedown and occupant-restraint misuse scenarios, answers to many frequently asked questions regarding wheelchair transportation safety, and summaries of the latest WTS standards for wheelchairs, WTORS, and wheelchair seating systems. The website provides access to the *RideSafe* brochure and will soon include access to the *DriveSafe* brochure as well as to several sets of Safety Tip Sheets for different stakeholder groups. An important aspect of the website is frequently updated lists of products that comply with WTS standards so that clinicians and consumers can find compliant products in one location.

While significant progress has been made during this project toward improving transportation safety and crash protection for occupants seated in wheelchairs, and particularly for drivers of personal vehicles who remain seated in their wheelchairs, there is a need for additional work. To a large extent, this involves implementing the results of the work completed to date, such as commercialization of the seat-belt deployment device. There is also a critical need to continue efforts to educate vehicle modifiers, their clients, and other key stakeholder groups with regard to implementing best practice in wheelchair transportation safety, and to prescribing and using products that have been tested to, and that fully comply with, WTS standards.

It would also be beneficial to continue to investigate, analyze, and document, crash and non-crash events involving drivers and passengers seated in wheelchairs to increase the sample size of cases available for statistical analyses to clarify the reasons why "optimal" restraint use and occupant age were not found to be significant predictors of injury for occupants in wheelchairs and to determine comparative injury risk and risk factors for occupants in wheelchairs who are involved in side impacts, rear impacts, and rollover crashes. Finally, there are many questions that continue to be posed by professionals who work with wheelchair users and who train people with disabilities to drive for which there are currently no clear evidence-based answers. To answer these questions, additional research and testing are required.

INTRODUCTION

Much of the improvement in motor-vehicle safety for drivers and passengers over the past forty years has been achieved through improved vehicle crashworthiness and restraint-system technologies developed in response to improvements in safety regulations and restraint-system performance requirements by the National Highway Traffic Safety Administration (NHTSA). However, significant reductions in occupant injury risks have also been achieved through the implementation of seat belt laws by states and by federal education campaigns, such as "Click-It-or-Ticket," that have resulted in significant increases in seat belt use by adults (Dinh-Zarr et al, 2001; NHTSA, 2005) and increased use of child safety seats and booster seats by infants and children (Zaza et al., 2001; Winston et al., 2007).

During the same time that injury risk for people using vehicle manufacturer' seats and occupant protection systems has been dramatically reduced, improved access to transportation by people with disabilities has increased the numbers of people traveling in motor vehicles while seated in wheelchairs (Bureau of Transportation Statistics, 2002; The Education of All Handicapped Children Act, 1973; Americans with Disability Act, 1990; Individuals with Disability Education Act, 1997; Kaye et al., 2000). Accurate data are not available on the proportion of the nearly two-million wheelchair users in the U.S. who remain seated in their wheelchairs when traveling in motor vehicles, but there can be little doubt that tens of thousands of children and adults remain seated in their wheelchairs everyday when traveling in private vans and minivans, school buses, paratransit vans, and city buses.

In a study by the University of Michigan's Health System, 87% of 107 wheelchair users surveyed had access to a privately owned vehicle, with 55% using only this method of transportation (Brinkey et al., 2009). The NHTSA's National Center for Statistics and Analysis (NCSA) examined data from the Consumer Product Safety Commission's National Electronic Injury Surveillance System (NEISS) database, which is a representative sample of emergency department visits. The NCSA's analysis estimated that between 1991 and 1995 about 2,294 injuries/deaths occurred to wheelchair-seated occupants as a result of "improper securement" (NHTSA, 1997). Typically, improper securement implies not attaching four tiedown straps of a four-point, strap-type wheelchair tiedown system to structural components of a wheelchair or seating-system frame. However, it is believed that use of the term "improper securement" in this study also covers improper or incomplete use of seat-belt restraints.

In a survey of 596 wheelchair users in 45 states conducted by researchers at the University of Pittsburgh, it was found that 26% 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, 2005; Fitzgerald and Songer, 2007). Also, in a sample of vehicle crashes involving one or more occupants seated in wheelchairs reported by Schneider et al. (2010), of 42 occupants seated in wheelchairs, 14 were drivers of personal vehicles and 10 of these, or nearly 25%, died from crash-related injuries or from medical complications related to injuries sustained in the crash. Many of these crashes were minor to moderate in severity and most likely would not have resulted in serious or fatal injuries to occupants using the vehicle manufacturer's seat and restraint systems.

For these reasons, it is generally recommended that people who use wheelchairs for improved mobility should transfer to the vehicle seat whenever this is feasible and safe to do. There are, however, potentially hundreds of thousands of wheelchair users for whom transfer is not feasible or safe because of their degree and type of disability, strength limitations, and/or their need for special support provided by their wheelchair seating system and associated postural support devices (PSDs). For this population of vehicle occupants, safe transportation and effective occupant crash protection depends on the ability to effectively secure crashworthy wheelchairs and the ability to effectively and properly use belt restraint systems consisting of both upper and lower torso belts.

Upon recognizing the transportation safety problem for travelers seated in wheelchairs and that the dynamic crash performance requirements of Federal Motor Vehicle Safety Standards (FMVSS) may not apply to aftermarket restraint systems installed by vehicle modifiers for use by occupants seated in wheelchairs or to wheelchairs and wheelchair securement systems, national (Society of Automotive Engineers, 1999; ANSI/RESNA 2000 and 2012) and international (ISO 7176-19:2008; ISO 10542-1:2012) industry standards have been developed for these products (Schneider et al., 2008). The latest versions of U.S. voluntary standards are contained in Volume 4 of ANSI/RESNA wheelchair standards: *Wheelchairs and Transportation* (ANSI/RESNA, 2012). Volume 4 currently includes:

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

While voluntary industry standards are critical to improving transportation safety for travelers seated in wheelchairs, it is equally important to make sure that key stakeholders are aware of these standards and of “best practice” in transporting people in wheelchairs safely. There is also a need to collect and analyze data on real-world crashes and non-crash incidents involving occupants seated in wheelchairs to determine injury scenarios that are unique to this population of vehicle occupants. This information is essential to developing and improving industry safety standards and educational materials, and to designing and evaluating equipment that will improve transportation safety, usability, and independence for travelers in motor vehicles who remain seated in their wheelchairs. To date, the primary focus on research and voluntary industry standards has been on people who travel as passengers in motor vehicles. New efforts are therefore needed to address the unique situations faced by people who drive a private vehicle, such as a minivan or van, while seated in their wheelchair.

PURPOSE AND SCOPE

The purpose of this project has been to conduct research, testing, development, and information dissemination activities that support the continued improvement of transportation safety, usability, and independence for people who remain seated in their when traveling in motor vehicles. While the project addressed transportation safety issues for both passengers and drivers seated in wheelchairs in all types of motor vehicles, a particular focus of the effort has been on drivers seated in wheelchairs operating personal vans and minivans.

To accomplish these objectives, the project involved the following five Subtasks.

Subtask 1: Investigate and perform biomechanical analyses of crashes and moving-vehicle non-crash incidents involving occupants seated in wheelchairs
Subtask 2: Design, develop, and evaluate improved occupant-protection systems for drivers seated in wheelchairs
Subtask 3: Investigate safety issues and provide recommendations regarding the use and/or deactivation of frontal-impact air bags for drivers seated in wheelchairs
Subtask 4: Develop and disseminate educational materials for vehicle modifiers and their clients, and for other key stakeholder groups
Subtask 5: Develop and maintain an UMTRI website on wheelchair transportation safety (WTS)

TECHNICAL SUBTASKS

1 Subtask 1: Investigate and perform biomechanical analyses of crashes and moving-vehicle non-crash incidents involving occupants seated in wheelchairs

1.1 Background and Objectives

The objective of this Subtask was to collect, compile, and analyze data on real-world crashes and moving-vehicle incidents, such as sudden braking or turning, involving occupants seated in wheelchairs. A primary goal was to gain a better understanding of injury scenarios that are unique to occupants seated in wheelchairs. It was also desired to gain a better understanding of real-world usage and performance of occupant-protection systems available to drivers and passengers seated in wheelchairs when traveling in personal licensed vehicles, paratransit vans and minivans, school buses, and public transit buses. The results have been used to guide the development and improvement of voluntary industry standards for wheelchair tiedown and occupant restraint systems (WTORS), and for wheelchairs and wheelchair seating systems used during travel in motor vehicles. They have also been used to guide the development of improved occupant-protections systems (Subtask 2) and to develop educational materials targeted to different stakeholder groups (Subtask 4).

1.2 Methods

Notifications of potentially relevant events were received from investigators in the National Automotive Sampling System Crashworthiness Data System (NASS CDS)[1], law enforcement agencies, emergency medical services, seating clinics, wheelchair user groups, vehicle modifiers, and manufacturers of tiedown/restraint equipment. They were also obtained from local news outlets and internet searches by UMTRI personnel. If a preliminary investigation indicated that the conditions of the case met the study criteria, which meant that one or more vehicle occupants was seated in a wheelchair during a crash or non-crash moving-vehicle incident (e.g., sudden braking or turning), an effort was made to obtain more detailed information about the event.

If a case was investigated by UMTRI because detailed information was not available from another source, such as a NASS investigation, the involved wheelchair user and/or their responsible caregiver was contacted by an UMTRI crash investigator.[2] After receiving verbal consent by the participant, the UMTRI investigator conducted a phone interview to obtain additional details about the event and injuries to the occupant, or occupants, seated in a wheelchair. If the information collected during the interview indicated that a full investigation was warranted, an effort was made to inspect, measure, and photograph the crash scene and the involved vehicles. One of the primary objectives of the vehicle inspection was to determine and document the specific type (e.g., front, side) and magnitude of the crash or non-crash event

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[1] The NASS CDS is a nationwide in-depth crash data-collection program sponsored by the U.S. Department of Transportation and operated by the National Center for Statistics and Analysis (NCSA) of the National Highway Traffic Safety Administration (NHTSA).

[2] The procedures and protocol used for investigations conducted by UMTRI were approved by a properly constituted University of Michigan (UM) Institutional Review Board (IRB) and all participants or their legal representative signed an informed consent form that was also approved by the UM IRB.

experienced by occupants seated in wheelchairs, and to determine the use or non-use of belt restraints. Together, this information was used to determine the direction and extent of occupant movements and potential occupant contacts with the vehicle interior, other occupants, or, in the case of ejection, objects outside of the vehicle.

With the exception of vehicle rollovers, whenever possible, measurements of the crush profile along the damaged plane and data on vehicle stiffness and mass were used in validated crash-reconstruction computer programs such as *WinSmash* (Sharma et al., 2007) to estimate the severity of the impact event for the case vehicle. Crash severity is typically reported as the change in speed of a vehicle during an impact and is commonly referred to as the vehicle's "Delta V." However, in some cases, where it was not possible to estimate the vehicle's Delta V from physical measurements of the crush profile, the Delta V was estimated from photos showing the extent and location of vehicle damage based on the expertise of UMTRI crash investigators with extensive experience in crash reconstruction.

Also, whenever possible, inspection and measurement of the vehicle interior were performed to determine the availability of wheelchair tiedowns and belt restraints, to document intrusions into the occupant space of vehicle interior components such as door panels, knee bolsters, and steering wheels, and to document occupant contacts with vehicle interior components, which often correspond to injuries. For example, scuffmarks on, or dents in, a knee bolster following a frontal crash indicate occupant knee contact with the knee bolster, which often corresponds with knee, femur, or hip fractures. Similarly, deformation of the steering-wheel rim in frontal crashes without air-bag deployment often corresponds to loading of, and injury to, the abdomen or chest, and star-patterned cracks in the windshield often indicate hand or head contact corresponding to bone fractures and/or brain injury.

One of the most important factors to determine from vehicle inspections is seat-belt use. In moderate-to-severe frontal crashes, seat-belt use can usually be confirmed by belt webbing imprints on the plastic cover of the D-ring attached to the upper sidewall or B-pillar of a vehicle and/or by webbing imprints on the plastic loop of the latch plate of the seat-belt buckle. In some cases, there is also evidence of webbing elongation/deformation or marks from the plastic D-ring cover on the seat-belt webbing. In addition, firing of a seat-belt pretensioner usually indicates that an occupant was using the seat belt.

However, in side impacts and rollovers, the seat belt is often not loaded sufficiently to produce webbing imprints on plastic components. In these cases, the best indicators of seat-belt use are a seat-belt retractor that is locked after the crash with the belt webbing pulled out from a fully retracted or stored position, the belt webbing being cut by rescue personnel with the latch plate in the buckle receptacle after the crash, and/or blood on an extended portion of the belt webbing from an occupant's external wound.

For occupants seated in wheelchairs, it is also important to determine, to the extent possible, how and if an available belt restraint system was used. In particular, it is important to attempt to understand how the lap belt was routed relative to wheelchair components and where it was positioned on the wheelchair occupant. For example, was the lap belt positioned over or in front of wheelchair arm supports or was it routed so that it was positioned low on the occupant's pelvis near the thigh-pelvis junctions? Since the shoulder belt of after-market belt restraints often allow for manually disconnecting the shoulder belt from the lap belt, it is important to know if a shoulder belt was used and, if so, how was it routed and positioned on the wheelchair occupant.

Many of the variables used in previous UMTRI in-depth crash investigations, which are comparable to those used by NASS-CDS investigations, were used to document information obtained for each case included in the study. However, additional variables were added to the standard dataset to document information that is unique to occupants seated in wheelchairs. These include information on:

- the location and orientation of the wheelchair occupant within the vehicle, including the longitudinal (seating row) and lateral (left, middle, right) positions,
- the method and location of access to the vehicle for occupants in wheelchairs (e.g., side-entry ramp, rear-entry power lift),
- the wheelchair type (e.g., power, manual, stroller, scooter) and whether it complies with the voluntary wheelchair transportation safety standard, WC19,
- the type of wheelchair seating system,
- the type of wheelchair tiedown/securement system that was available and whether it was properly used,
- the available restraint systems and whether and how they were used,
- the types of vehicle controls installed for drivers seated in wheelchairs,
- the availability and use of wheelchair-anchored postural supports and belts, including rear head supports,
- the availability and use of vehicle-anchored head-and-back restraints, and
- the post-crash conditions and damage to any of the above components.

For each occupant seated in a wheelchair for which sufficient data were obtained to constitute a complete case, a written summary report was also completed. Each report includes:

- a description of the crash or non-crash scenario with a scene drawing, if applicable,
- a description of exterior damage to the case vehicle with photos when available and the estimated crash severity and direction,
- a description of the wheelchair and how it was secured in the vehicle with photos of the vehicle interior when available,
- a description of the occupant seated in the wheelchair and, when known, whether and how they were restrained,
- a description of occupant kinematics during the crash or non-crash event,
- and occupant injuries with the suspected source and/or cause.

The final section of each report documents the key findings and "lessons learned" from a biomechanical analysis of the case data.

1.3 Results

1.3.1 Summary of key variables and observations/findings

Data on 69 crash and non-crash events involving 74 occupants seated in wheelchairs have been collected. Because these cases are based on notifications from the sources described above rather than on a statistical sampling of rear-world events, the dataset is considered a "convenience" sample rather than a representative sample or even a weighted representative sample, as is the case with NASS CDS.

Figure 1.1 provides pie-chart distributions of key variables for cases in the UMTRI wheelchair crash/injury database. Note that, although there are 69 crash and non-crash events, the sample size for all pie charts is 74 since each occupant is considered to be a separate case, even though some occupants were involved in the same crash. An Excel file with the data on the key variables for the 74 cases (one case per occupant in a wheelchair) is available on the UMTRI *Wheelchair Transportation Safety* website (see Subtask 5 in Section 5). Appendix A provides a summary of the variables and descriptive lists of possible outcomes for these variables.

Over half of the occupants in wheelchairs were involved in frontal crashes, but seven were in rollovers, eight were in side impacts, two were in rear impacts, and eight were involved in non-crash events (e.g., sudden vehicle braking or turning). Thirteen of the crash events were classified as severe, 21 were classified as moderate, and 31 were considered minor. Twenty-two of the 74 occupants in wheelchairs were driving a private vehicle and all others were passengers, primarily in private and paratransit vans and minivans, with two of these seated in the front row (i.e., right-front passenger position).

Forty of the vehicles were equipped with four-point, strap-type tiedowns and 22 were equipped with docking-securement devices. Fifty-eight (58) or 78% of the wheelchairs were properly secured, 22 by a docking-securement device and 36 by a four-point, strap-type tiedown. In contrast, only 28 or 38% of the occupants seated in wheelchairs were properly restrained, where proper restraint for a passenger means that they were using a three-point lap/shoulder belt restraint and, for a driver or front-row passenger, that they were using a three-point belt and had an air bag that deployed if a frontal crash of sufficient magnitude occurred. Corresponding to this low percentage of properly restrained occupants in wheelchairs, 14 occupants died from injuries sustained in the crash or non-crash event, 10 sustained serious injuries, 11 sustained moderate injuries, and 39 sustained minor or no injuries. Stated another way, 33% of the occupants in the UMTRI wheelchair crash/injury database sustained serious to fatal life-threatening injuries. This is clearly a high proportion of all the 74 drivers and passengers seated in wheelchairs, especially given the distribution of crash severities, more than half of which were minor or non-crash events.

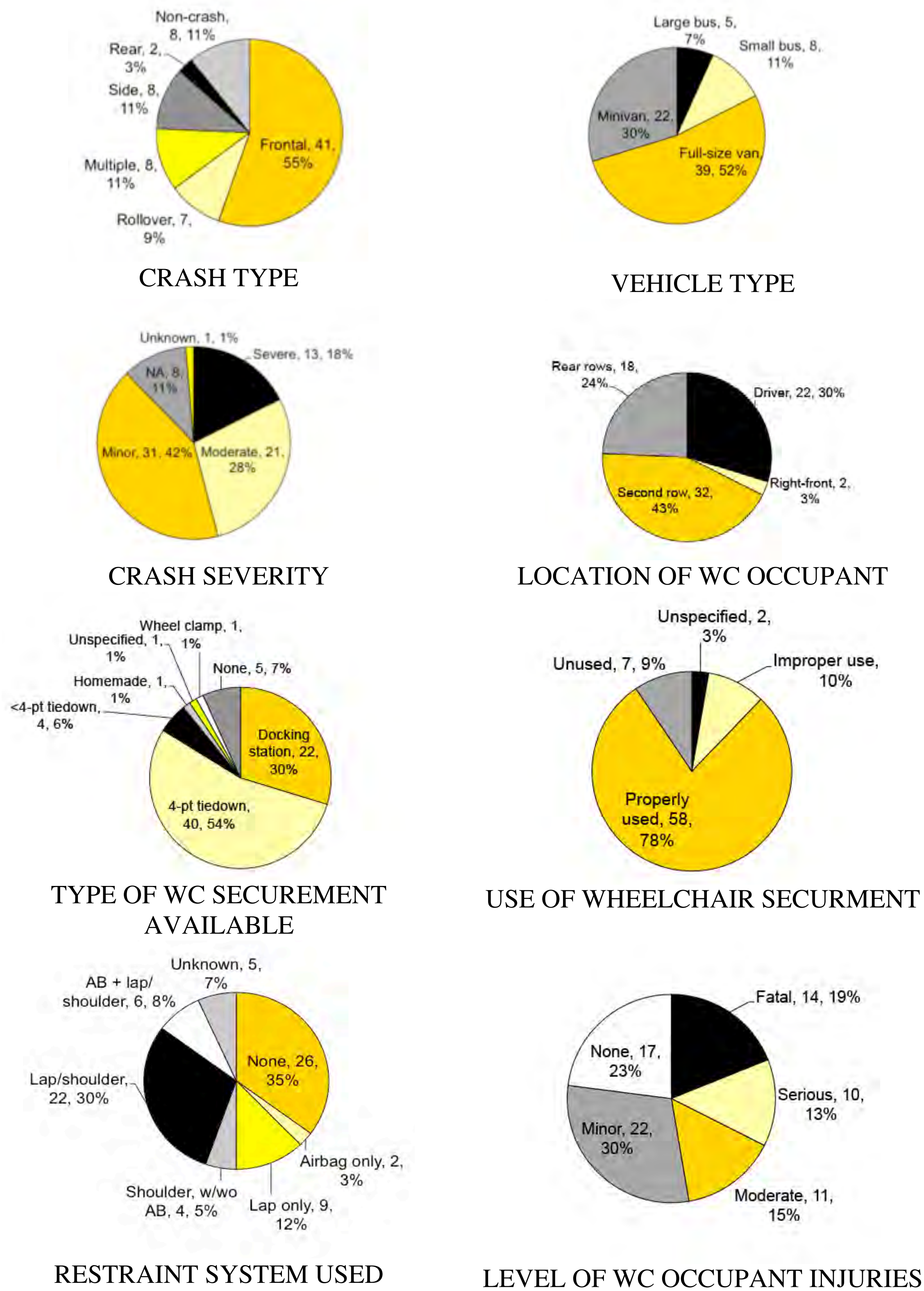


Figure 1.1 - Distributions of selected variables in UMTRI's wheelchair-occupant crash/injury database

1.3.2 Example cases

Appendix B provides three examples of case summary reports that illustrate the level of detail for a majority of the investigations, and that also illustrate some key points that have been learned from these case studies. Summaries of all 74 cases will be available on the UMTRI WTS website described in Section 5 of this report.

The first case is for a driver of a full-size van seated in a power wheelchair secured by a docking device during a severe frontal crash with a pickup truck. The second case involves a frontal impact of a full-size van with the side of a dump truck and a second-row young-adult male passenger seated in a power crashworthy wheelchair that was secured by a four-point, strap-type tiedown. The third case involves ejection during a four quarter-turn rollover of a male passenger restrained by a lap/shoulder in properly secured manual wheelchair at the back of a van.

Severe frontal crash resulting in fatal injuries to a driver seated in a power wheelchair

In the first case, a 32-year-old male driver of a 1992 Ford Econoline van seated in a power wheelchair sustained fatal chest and abdomen injuries when his van collided head on with a 1992 Chevrolet K-1500 pickup truck after the van crossed the median of a two-lane road following blowout of the left-front tire. Figure 1.2 shows post-crash exterior and interior photos of the van, including the driver's wheelchair, the docking-securement device, the steering wheel, and the belt restraint. The docking-securement device deformed considerably during the severe 60-kph (36 mph) full-frontal collision but did not release the wheelchair. The vehicle was not equipped with a steering-wheel air bag and there was a tri-pin assistive steering device attached to the rim of the steering wheel. The driver was also using only a two-point shoulder belt that had been modified with safety pins, presumably to help with passive belt positioning and/or comfort.

Although this was a severe frontal crash, there was no evidence of driver contact with the steering wheel or assistive steering device. It is therefore believed that the fatal chest and abdominal injuries, including lung lacerations and contusions plus liver lacerations, were caused primarily by chest and abdomen loading by the loosely worn two-point shoulder belt. Injury to the spleen may also have been caused by contact with the tri-pin steering assist device even though there was no evidence of contact with the tri-pin. The lack of a frontal-impact air bag, significant deformation of the docking-securement device, and use of only a user-modified loosely worn shoulder belt rater than a properly fitted lap/shoulder belt, are likely contributors to the fatal chest and abdominal injuries to this driver.

Figure 1.2 - Exterior and interior photos of a full-size van operated by a driver seated in a power wheelchair who sustained fatal chest and abdomen injuries in a severe frontal crash

Vehicle rollover with ejection of a passenger seated in a manual wheelchair

The second case involves a paratransit van that was traveling on a four-lane roadway. The sole passenger of the van was an adult male seated in a manual wheelchair at the very back of the van. Figure **1.3** shows exterior and interior photos of an exemplar paratransit van, including reconstruction of the wheelchair securement and positioning of the lap/shoulder belt restraint on an individual of the same gender and similar size as the male passenger. The manual wheelchair was secured by a four-point, strap-type tiedown attached to the frame of the wheelchair and the female driver reported that she positioned the available aftermarket lap/shoulder belt on the passenger.

The vehicle was struck from behind which caused the driver to lose control, such that the vehicle rotated counterclockwise, causing the vehicle to enter into a four quarter-turn rollover with the passenger side leading. During the rollover, the passenger in the wheelchair was completely ejected through a rear side window of the van and he sustained multiple bilateral lower-extremity fractures. Following the rollover, the wheelchair was still effectively secured to the floor of the vehicle.

Upon reconstructing securement of the wheelchair and restraint of an adult male seated in the wheelchair in an exemplar van using the same tiedown/restraint equipment that was used in the vehicle rollover, it was determined that there was no mechanism for adjusting the length of the lap belt and thus the position of the buckle, and that the end-release button on the seat-belt buckle would have been located just below the metal rim of the large right wheel of the wheelchair. It was therefore concluded that ejection of the wheelchair passenger was the result of the buckle release button being contacted and depressed by the inside metal wheel rim of the large right wheel as the wheelchair shifted from side to side during the rollover. The key lesson from this case is the importance of providing adjustability in the length of vehicle-anchored lap belts so that seat-belt buckles can be positioned against the wheelchair occupant's body and away from hard structures on the wheelchair that can contact and depress the buckle release button during a crash or non-crash event.

Figure 1.3 - Paratransit van similar to a van from which a lap/shoulder-belt restraint male passenger seated in a properly secured manual wheelchair was ejected during a four quarter-turn rollover due to contact of the buckle release button by the rim of the wheelchair wheel.

Moderate frontal impact to a full-size van with a passenger seated in a wheelchair

In the third case, a 1998 Ford Econoline van with a 28-year-old male C6/C7 quadriplegic passenger seated in a power wheelchair in the center of the second row was involved in a frontal collision with the cab and box of a Chevy dump truck. The crash occurred at a four-leg intersection and the estimated crash severity for the Econoline van was 33 kph (20 mph). Figure 1.4 shows exterior and interior post-crash photos of the van, including the power wheelchair with postural belts and the four-point, strap-type tiedown. The power wheelchair used by the passenger had four successfully crash-tested securement-point brackets attached to the base frame and was effectively secured in the collision by a four-point, strap-type tiedown. However, the passenger in the wheelchair was only using postural lap and chest belts that were attached to the wheelchair by means of screws through metal grommets in the belt webbing.

During the frontal collision, one side of the postural lap belt and one side of the postural chest belt tore free from the wheelchair (grommets tore through webbing), which allowed the passenger to come out of the wheelchair near the end of the frontal-crash deceleration. He sustained a laceration to the back of his head, a contusion to the spleen, a fracture to the second finger on his right hand, and lost consciousness for less than an hour.

After the crash, an aftermarket lap/shoulder belt restraint system was found hanging on the side of the vehicle. The driver and the wheelchair passenger reported that they thought that the postural belts provided a sufficient vehicle restraint system and therefore they did not think it was necessary to use the available vehicle-anchored seat belt. Although this passenger in a wheelchair was not seriously injured, in part because he was using a crash-tested power wheelchair that was properly and effectively secured during this moderate frontal collision, it is likely that he would have been much more seriously injured had the crash been more severe.

Figure 1.4 - Exterior and interior photos of a van driven by a male driver seated in a power wheelchair that was involved in a frontal crash into the side of the cab and box of a dump truck at a four-leg intersection

1.3.3 Statistical comparison of injury risk factors in frontal crashes for occupants in wheelchairs and in vehicle seats

<u>Methods</u>

To better understand the factors contributing to serious and fatal injuries to occupants in wheelchairs, multivariate logistic regression analysis was conducted using cases in UMTRI's wheelchair crash/injury database for which the primary event was a frontal crash (i.e., the primary or most significant damage was to the frontal plane of the vehicle). In addition, a comparative logistic-regression analysis of frontal crashes in the NASS-CDS database was conducted to estimate the relative effectiveness of occupant-protection system for people seated in wheelchairs compared to people seated in vehicle manufacturer' seats who are able to use the vehicle manufacturer' restraint systems that must comply with Federal Motor Vehicle Safety Standards (FMVSS).

At the time the analyses were conducted, the UMTRI wheelchair-occupant crash-injury database contained information for 62 vehicle occupants seated in wheelchairs who were involved in 56 crash and non-crash events. To be included in the wheelchair-occupant dataset, information on wheelchair securement, occupant restraint usage, and an estimate of the frontal crash severity based on vehicle crush measurements or photos of vehicle damage were needed. This resulted in a dataset of 35 case occupants involved in frontal crashes for use in the analysis.

To conduct the logistic-regression analyses, occupant injury was converted to a binary outcome as either "acceptable" or "adverse" based on the Abbreviated Injury Scale (AIS). Injury outcome was coded as "acceptable" if the occupant was not injured or their most severe injury was minor (AIS 1) or moderate (AIS 2). Injury outcome was coded as "adverse" if the occupant sustained a serious or more severe injury, including fatal injuries (AIS 3+).

Factors considered as potential predictors of injury outcome included:

- crash severity classified as minor, moderate, or severe based on the estimated Delta V,
- tiedown type (4-point strap tiedown or docking-securement device),
- tiedown/securement system use (proper, improper, none),
- occupant restraint condition (optimal, suboptimal, none),
- occupant seating position (front or rear rows),
- vehicle type (minivan, van, small bus, large bus),
- occupant age from 8 years and up, and
- occupant gender.

"Optimal" restraint was considered to be a lap/shoulder belt restraint with or without air-bag deployment and without "known" misuse, such as improper positioning of the lap and/or shoulder belt. "Suboptimal" restraint included using only a lap belt, using only a shoulder belt, no seat belts with or without air-bag deployment, or any type of belt restraint with known misuse, including improper positioning of the lap and/or shoulder belts on the occupant. Occupants using only postural belts (i.e., belts attached to the wheelchair that help the person seated in the wheelchair maintain a more stable and upright posture during normal wheelchair use but that are not intended to effectively restrain an occupant in a crash when traveling in motor vehicles) were classified as unrestrained because postural belts are not designed and tested to provide effective occupant restraint during vehicle crashes.

For analyses of NASS CDS, frontal crashes investigated from 2000 through 2010 in which the occupant was traveling in a minivan, full-size van, SUV, small bus, or large bus were considered. Occupant age was restricted to 8 years and older, which corresponds to the same age range in UMTRI's wheelchair-occupant crash/injury dataset and is the population where vehicle-mounted three-point lap/shoulder belts can be expected to offer effective crash protection without use of a child safety seat or booster seat.

Multivariate logistic regression was performed on each dataset to identify significant predictors of injury. Odds ratios of factors contributing to injury risk were calculated, as well as 95% confidence intervals – i.e., 95% statistical certainty that the true odds ratio lies within the 95% confidence interval. Estimates of injury risk were not calculated for the wheelchair-occupant dataset because the crashes do not represent a random distribution of crashes. However, this dataset can still be used to identify odds ratios for factors contributing to injury.

Results
summarizes the sources of the most serious injuries for the 25 wheelchair occupants who sustained an injury according to injury outcome and restraint condition. For the 7 unrestrained injured occupants, the cause of the most serious injury was the seatback of the driver's seat in 3 cases, the floor or knee bolster in 2 cases, and the wheelchair or adaptive equipment in 2 cases. For 11 occupants with suboptimal restraint, 7 sustained an injury and the most severe injury was attributed to the vehicle seatbelt or postural belt in 8 cases. Seven of these were attributed to the seatbelt and included 4 fatal injuries, 1 severe injury, 1 moderate injury, and 1 minor injury. One of these was a minor injury that was attributed to a postural harness attached to the wheelchair.

For 7 cases with optimal restraint, all of which were involved in minor frontal crashes, the seatbelt was the source of the most serious injury in 3 cases, with 2 of these injuries being minor and 1 being moderate. Other sources of injuries for occupants who were considered to have optimal restraint are the wheelchair or adaptive equipment (1 serious injury), the airbag (1 serious injury), and the floor or knee bolster (2 serious injuries).

Table **1**.**1** compares odds ratios for factors contributing to occupant injury outcome for the occupant population seated in wheelchairs and the general population. As previously noted, models for both datasets used crash severity, occupant age, and occupant restraint as predictors. As indicated by the low P-value ($P < .05$) and 95% confidence interval that does not cross 1.0, crash severity (i.e., Delta V) is the only significant injury predictor for occupants seated in wheelchairs. For the other comparisons, high p-values and 95% confidence intervals that cross zero indicate that the null hypotheses that injury risks are the same for optimal restraint versus unrestrained, for suboptimal restraint versus unrestrained, and for differences in occupant age cannot be rejected for occupants seated in wheelchairs.

In contrast, crash severity, optimal restraint, and age are significant predictors of injury for the general population, and suboptimal restraint is marginally significant. In particular, the odds ratio of 0.249 with a low p-value and a 95% confidence interval (0.145, 0.427) for optimal restraint versus unrestrained in the general population indicates that the likelihood of optimally restrained occupants sustaining a serious-to-fatal injury is one-fourth that of occupants without any restraint.

The distribution of cases by crash severity, occupant restraint condition, and injury outcome for the wheelchair-occupant dataset is shown in Figure 1.5. For this plot, crash severity was categorized into three levels of low, moderate, and severe based on Delta Vs of less than 25 kph, between 25 and 42 kph, and greater than 42 kph, respectively. Six of seven combinations of crash severity and restraint condition resulted in an adverse injury outcome, which includes serious-to-fatal injuries. Of the five occupants involved in severe frontal crashes, none were considered to have had optimal restraint, and four of these occupants sustained serious-to-fatal injury outcomes. Three of these serious-to-fatally injured occupants were documented as having suboptimal restraint and one was not using any restraint system. The fifth occupant seated in a wheelchair was a passenger involved in a severe frontal crash who was also not using any belt restraints but sustained only minor facial injuries.

In the 13 moderate frontal crashes, none of the occupants were considered to have had optimal restraint and 6 of these 13 occupants sustained serious-to-fatal (i.e., adverse) injuries. In the 17 low-severity crashes, four occupants sustained serious-to-fatal injuries. Two of these were among the 9 occupants considered to have had optimal restraint, while two others were among five occupants for which the restraint condition was classified as suboptimal.

Table **1.2** summarizes the sources of the most serious injuries for the 25 wheelchair occupants who sustained an injury according to injury outcome and restraint condition. For the 7 unrestrained injured occupants, the cause of the most serious injury was the seatback of the driver's seat in 3 cases, the floor or knee bolster in 2 cases, and the wheelchair or adaptive equipment in 2 cases. For 11 occupants with suboptimal restraint, 7 sustained an injury and the most severe injury was attributed to the vehicle seatbelt or postural belt in 8 cases. Seven of these were attributed to the seatbelt and included 4 fatal injuries, 1 severe injury, 1 moderate injury, and 1 minor injury. One of these was a minor injury that was attributed to a postural harness attached to the wheelchair.

For 7 cases with optimal restraint, all of which were involved in minor frontal crashes, the seatbelt was the source of the most serious injury in 3 cases, with 2 of these injuries being minor and 1 being moderate. Other sources of injuries for occupants who were considered to have optimal restraint are the wheelchair or adaptive equipment (1 serious injury), the airbag (1 serious injury), and the floor or knee bolster (2 serious injuries).

Table 1.1 - Logistic regression model parameters and odds ratios predicting injury for occupants seated in wheelchairs and the general population in vehicle seats

Population	Parameter	Coefficient	Wald χ^2	P-value	Odds ratio	95% CI
Occupants in Wheelchairs	Delta V	0.1887	5.1742	0.0229	1.208	1.036-1.408
	Optimal vs. unrestrained	1.4419	1.0324	0.3096	4.229	0.262-68.252
	Suboptimal vs. unrestrained	1.1727	1.0059	0.3159	3.231	0.327-31.957
	Age	0.0405	1.9028	0.1678	1.041	0.983-1.103
General Occupant Population	Delta V	0.1508	131.5833	<0.0001	1.163	1.133-1.193
	Optimal vs. unrestrained	-1.4432	10.8079	0.0010	0.249	0.145-0.427
	Suboptimal vs. unrestrained	1.4958	2.8051	0.0940	4.703	0.318-69.628
	Age	0.0265	8.6085	0.0033	1.027	1.009-1.045

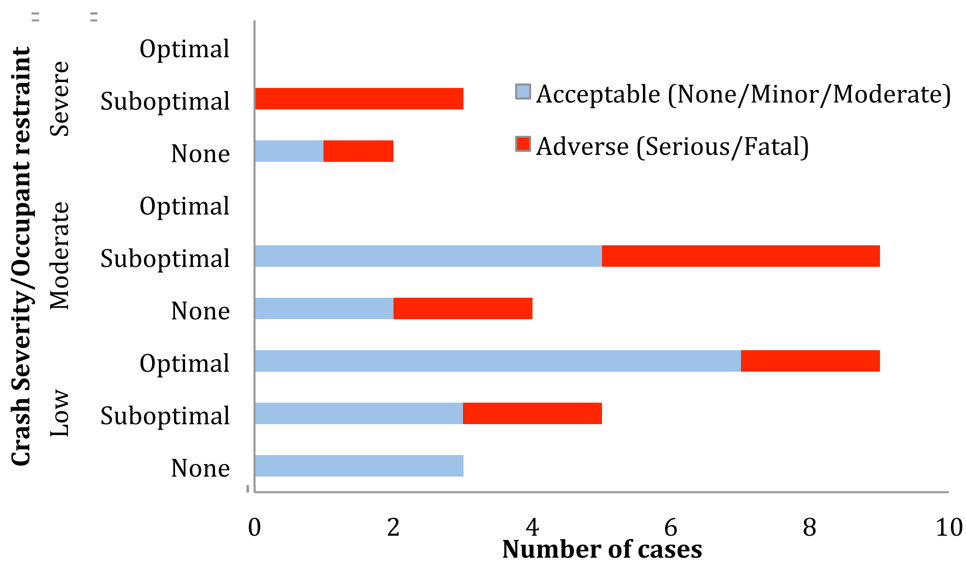


Figure 1.5 - Distribution of wheelchair-occupant cases by crash severity, occupant restraint, and injury outcome

Table 1.2 - Sources of most serious injury by injury outcome and occupant-restraint condition for occupants seated in wheelchairs

Injury outcome	Restraint type	Vehicle or postural belts	Wheelchair or adaptive equipment	Driver seatback	Air bag	Floor/ knee bolster	Roof
Minor	None		1	1			
	Suboptimal	2					
	Optimal	2					
Moderate	None		1			1	
	Suboptimal	1					
	Optimal	1					
Severe	None					1	
	Suboptimal	1	1				1
	Optimal		1		1	2	
Fatal	None			2			
	Suboptimal	4			1		

Discussion

The results of these statistical analyses suggest that occupants seated in wheelchairs are more likely to sustain serious-to-fatal injuries in frontal motor-vehicle crashes than the general population who are seated in vehicle seats. Unlike the general population, where the odds of injury are four times higher for unrestrained occupants compared to those using a lap/shoulder belt, belt restraint use by occupants seated in wheelchairs does not appear to have a significant effect on injury outcome.

Several reasons are hypothesized to explain why belt restraints do not appear to offer significant protection for occupants seated in wheelchairs during frontal crashes. The first is that occupants seated in wheelchairs have lower tolerance to injury than the population of people who use vehicle seats. The second is that some, or perhaps many, of the positioning of lap/shoulder belts categorized as "optimal" for occupants in wheelchairs were not positioned as properly as the lap/shoulder belts used by occupants seated in vehicle seats. Wheelchair components, and particularly arm supports, often interfere with achieving proper fit of the lap belt low on the pelvis. Also, positioning of occupants seated in wheelchairs further from the side of the vehicle because of the width of their wheelchair, and often in the center of the vehicle, will generally not allow for the shoulder belt to cross over the middle of the shoulder and chest and connect with the lap belt near the occupant's inboard hip (see results for the study of drivers seated in wheelchairs in Section 2.3). Thus, unlike occupants seated in vehicle seats, it is often difficult to determine with certainty how lap and/or shoulder belts were positioned on occupants seated in wheelchairs during investigations of crash and non-crash events, even when the wheelchair and restraint system are inspected and the driver and/or wheelchair occupant are interviewed.

Another factor that may contribute to the non-optimal positioning of lap/shoulder belts on occupants seated in wheelchairs is that the seated posture of occupants in wheelchairs is often not as upright as occupants in vehicle seats. In addition, the low seat angles of wheelchairs compared to vehicle seats, which are often 4 degrees to the horizontal or less, the use of thick and soft seat cushions that are used to reduce the incidence of pressure sores, and the lack of support offered by wheelchair seats during frontal-impact loading by the occupant will all tend to increase the risk of lap-belt submarining in frontal crashes, and thereby reduce the effectiveness of lap/shoulder belts in offering frontal crash protection.

While the results of these analyses are limited by the relatively small number of occupants seated in wheelchairs during frontal-crashes in the UMTRI wheelchair-occupant injury dataset as well as by other factors described above, they suggest a need to further improve the design of belt-restraints used by occupants seated in wheelchairs. The results also suggest a need to improve the positioning of belt restraints on occupants in wheelchairs by: 1) designing wheelchairs so that they better facilitate the proper positioning of vehicle-anchored belt restraints, 2) improving education and training regarding the proper installation of aftermarket wheelchair tiedown and occupant-restraint equipment, 3) expanding and improving education and training of caregivers and drivers of transit and paratransit vehicles on the proper routing and positioning of belt restraints on occupants seated in different types of wheelchairs, and 3) increasing the availability and use of crash-tested wheelchairs as well as the use of crashworthy wheelchair-anchored lap belts that comply with industry standards referenced in the Introduction to this report (i.e., with Section 19 of RESNA WC-4:2012 – *Wheelchairs Used as Seats in Motor Vehicles*).

2 Subtask 2: Design, develop, and evaluate improved occupant-protection systems for drivers seated in wheelchairs

2.1 Background

The results in the sample of real-world crash and non-crash events involving occupants seated in wheelchairs in Subtask 1, and especially the statistical analyses, suggest that people seated in wheelchairs during frontal crashes are not being provided with complete and properly positioned belt restraints and that they may not benefit from seat belts to the same degree that occupants who are using the vehicle manufacturer' seats. From the experience of UMTRI researchers who have been involved in efforts to improve transportation safety for travelers seated in wheelchairs for nearly four decades, it is believed that there are three primary reasons for the improper, incomplete, and/or total lack of using a lap/shoulder restraint system. As previously noted, these include:

1. lack of training by drivers of public and paratransit vehicles and caregivers operating personal vehicles on how to properly position belt restraints on people seated in wheelchairs,
2. interference by wheelchair components, and especially wheelchair arm supports, with the proper positioning of lap-belt restraints, and
3. improper or incomplete installation of after-market crash-tested lap/shoulder belt restraints or restraint system components to complement the vehicle manufacturer' lap/shoulder belt restraint after removal of the vehicle seat and seat-belt buckle receptacle.

As noted in the Introduction section of this report, voluntary industry standards have been developed both nationally (SAE and RESNA) and internationally (ISO) in efforts to improve transportation safety for people who travel in motor vehicles while seated in their wheelchairs. In the U.S., Section 19 of ANSI/RESNA Wheelchair Standards/Volume 1 was the first industry standard that established design and frontal-impact performance requirements for wheelchairs used as seats by passengers in motor vehicles (ANSI/RESNA, 2000).

In addition to requiring wheelchairs to demonstrate crashworthiness integrity in a 48-kph, 20-*g* (30-mph, 20-*g*) frontal-impact sled test when secured by a four-point, strap-type tiedown system, this standard required evaluation of wheelchairs with regard to accommodation of vehicle-anchored lap/shoulder belt restraints (Annex E of WC19). Using the procedures of WC19 Annex E, wheelchairs were rated on factors related to the ease of using and positioning lap/shoulder belt restraints in an optimal location relative to the occupant and wheelchair components. However, in this initial version of WC19, it was only required that wheelchairs be tested for their accommodation of vehicle-anchored three-point lap/shoulder-belt restraints, and that the ratings be disclosed in the manufacturer' presale literature. It was therefore possible for a wheelchair to be rated "poor" with regard to proper positioning of vehicle-anchored lap/shoulder belt restraints and still comply with the standard. For this reason, it can be very difficult for a driver of a public or paratransit vehicle or a caregiver of a private vehicle to properly position a vehicle-anchored lap/shoulder belt and especially a vehicle-anchored lap belt low on the wheelchair passenger's pelvis near the thigh-pelvis junctions, even if a person is using a wheelchair that fully complies with the 2000 version of WC19.

Because of the importance of wheelchair design to achieving proper seat-belt use and positioning on people who remain seated in their wheelchairs, the requirement to measure and disclose the rating of how well a wheelchair accommodates the easy and proper use of vehicle-anchored lap/shoulder belts was changed to a pass/fail requirement in the latest (ANSI/RESNA 2012) version of WC19. In this most recent version of the standard, a wheelchair must achieve a minimum rating of "acceptable" for 1) the "ease of properly positioning a lap/shoulder belt" on an appropriate size anthropomorphic test device (ATD), or crash-test dummy, and 2) "the degree to which proper positioning" is achieved.

However, both the 2000 and 2012 versions of WC19 test a wheelchair with regard to its accommodation of proper seat-belt placement by an attendant (i.e., someone other than the wheelchair user). The test and ratings are therefore not directly applicable to rating seat-belt accommodation for drivers seated in wheelchairs, and particularly drivers who require a passive, or nearly passive, belt restraint system (i.e., seat belts that require little or no action by the occupant). In these situations, the seat belt is usually pre-buckled before a wheelchair user moves forward into the driver station, and the lap belt typically ends up being routed in front of the wheelchair arm supports, in which case it is located a substantial distance in front of the driver's body, or over the wheelchair arm supports, which locates the lap belt over the soft abdomen rather than low on the pelvis near the driver's thigh/pelvis junctions. In such cases, belt restraints will not be as effective in moderate-to-severe frontal collisions, and there is a greater risk of serious and even fatal injuries being caused by seat-belt loading.

In addition to the seat-belt issues described above, WC19 requires only frontal sled-impact testing of wheelchairs when they are secured by a four-point, strap-type tiedown system since this is the "universal" method for securing a wide range of types and sizes of wheelchairs occupied by passengers in all types of motor vehicles. It also only evaluates the dynamic strength of wheelchair back supports during ATD rebound loading in the frontal-impact test. In contrast, drivers seated in wheelchairs must use an auto-docking wheelchair securement device that allows for independent use of their vehicle. It has also been demonstrated in sled tests conducted at UMTRI (Manary et al., 2007) that wheelchair back supports that are strong enough to hold up under ATD frontal-impact rebound loading will often catastrophically fail in moderate (e.g., 25-kph Delta V, > 14-*g*) rear-impact tests.

The most common type of auto-docking device uses a single securement bolt attached to the lower portion of the wheelchair frame by a docking-securement adaptor. The securement bolt is oriented vertically with the head of the bolt toward the ground or vehicle floor. When the wheelchair is rolled forward into position, a docking-securement device mounted to the vehicle floor in the driver space captures the bolt head and locks the wheelchair in a position that allows the driver to most effectively operate the vehicle controls. In most cases, a forked bar extends forward from the wheelchair-securement adaptor and engages with a front stabilizing bracket mounted to the vehicle floor forward of the docking-securement device. The stabilizing bracket helps keep the wheelchair from rotating left and right when the vehicle is moving but have been shown in testing conducted at the Transportation Research Center (TRC) in Ohio (Sword, 2007) to have little to no effect on reducing forward pitching of the wheelchair (i.e., downward movement of the front of the wheelchair) during frontal crashes due to bending of the forked bar that engages with the stabilizing bracket (see 2.4.3.1).

While WC19 allows for testing wheelchairs secured by commercially available docking-securement devices, and the latest version of the standard contains wording that more strongly encourages wheelchairs to be tested when secured by methods other than four-point, strap-type tiedowns, the standard does not currently require wheelchairs to be crash tested for this securement mode. Therefore very few wheelchairs have been crash tested for docking securement and it is generally the manufacturers of docking-securement devices (e.g., EZ-Lock, Q'Straint-Sure-Lok), rather than the wheelchair manufacturers, who have made efforts to test different models of power wheelchairs secured by their docking-securement devices.

2.2 Objectives

The overall objective of Subtask 2 was to design, develop, and/or evaluate restraint systems that offer improved crash protection for drivers seated in wheelchairs during frontal and rear impacts. However, the initial phase involved a study of people who drive personal vehicles while sitting in their wheelchairs, with the goals of better defining the current state of occupant-protection systems for this population of drivers, identifying the primary impediments to providing effective occupant protection in crashes, and quantifying the positioning of drivers seated in wheelchairs relative to the vehicle interior components and restraint systems.[3] This was accomplished by observing individuals using their own vehicles and by taking measurements to quantify the spatial relationships between belt restraints, drivers in wheelchairs, and vehicle interior components. It also involved rating the drivers' use of belt restraints with regard to the ease of seat-belt use and the degree of proper belt positioning, and asking the drivers about the ease of using their vehicle and their perception of their level of safety.

2.3 Study of drivers seated in wheelchairs using their personal vehicle

2.3.1 Methods

Twenty-one drivers were observed and measured in their private vehicles while seated in their wheelchairs. Table **2.1** lists the vehicle year and model, the wheelchair model and type, and whether the driver's wheelchair was secured by a docking-securement device. Of the 21 drivers, two did not have their wheelchair secured and 19 used a docking-securement device.

Each participant was observed entering their vehicle and the driver space, securing their wheelchair, and using the available belt restraint. With the driver ready for travel, the measurements illustrated in Figure 2.1 and Figure 2.2, and listed in Table **2.1** and Table **2.2** were taken to quantify the position of the wheelchair and occupant relative to vehicle-interior components (e.g., the steering wheel, air bag, knee bolster, driver controls, belt restraints), and

[3] The procedures and protocol used in this study were approved by a properly constituted University of Michigan (UM) Institutional Review Board (IRB) and all participants signed an informed consent form that was also approved by the UM IRB.

the position of the wheelchair securement system and occupant restraints relative to the occupant and vehicle interior, respectively. Measurements were taken using both manual and digital techniques, with the latter taken using a Faro Arm as shown in Figure 2.3. The photo in Figure 2.4 shows the horizontal and vertical distances of a driver's chin and abdomen relative to different locations on the steering wheel and the photo in Figure 2.5 shows the location of a driver's left knee relative to the knee bolster and hand-control linkages.

Table 2.1 - Vehicles and wheelchairs used by drivers of personal vehicles

Vehicle New (N)/pre-owned (P), year, manufacturer and model		**Wheelchair** Manufacturer, model, power-assisted manual (PA)/powered (P), docking securement (D)/no securement (-)	
N	2007 Chevrolet Uplander	Quickie 2 with power assist	PA / D
N	2005 Plymouth Montana	Invacare Storm TDX3	P / D
P	2002 Dodge Grand Caravan Sport	TiLite Evo w. Emotion power assist	PA / D
N	2005 Chrysler Town & Country (Entervan)	Invacare Arrow	P / D
N	2002 Ford Econoline E150	Quickie P-220	P / D
P	1998 Unknown	Quickie V-521	P / D
N	2007 Chrysler Town & Country (Entervan)	Permobil C500	P / D
P	2002 Chrysler Town & Country (Entervan)	Invacare Power 9000 Storm	P / D
N	2000 Ford E150	TiLite Evo, 2005 w. Emotion power assist	PA / D
N	2004 Dodge Caravan (Entervan)	Permobile C300	P / D
N	1997 GMC Pickup Truck	Quickie GP with Xtender power assist	PA / -
N	2006 Toyota Sienna	Permobil C500 Stander	P / D
N	2005 Toyota Sienna	Invacare Action Arrow Storm, 1999	P / D
N	1996 Ford Winstar	Invacare Action 300SD (3G)	P / D
N	2007 Dodge Grand Caravan	Invacare Torque	P / D
N	2005 Dodge Caravan SXT	Invacare Torque SP, 2005	P / D
N	2004 Toyota Sienna XLE	Invacare Arrow, 2004	P / D
N	2001 Ford Econoline	Permobil Chairman, 2001	P / D
N	2006 Toyota Sienna	Invacare Ranger 2, 2000	P / D
N	2005 Toyota Sienna	C500 Permobil	P / -
N	Ford Club Wagon	Quickie P200	P / D

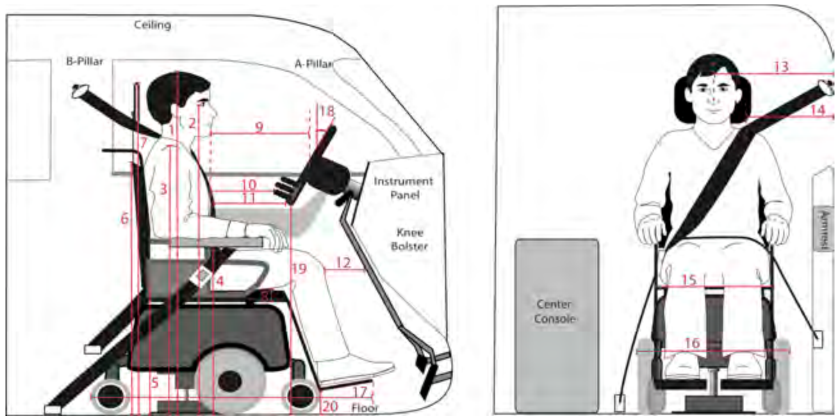


Figure 2.1 -Illustration of measurements of the wheelchair and driver relative to the vehicle interior

Table 2.2 -Measurements of the wheelchair and driver relative to the vehicle interior

1	Height of top of head from vehicle floor
2	Height of corner of eye from vehicle floor
3	Height of top of shoulder from vehicle floor
4	Height of thigh-abdominal junction from vehicle floor
5	Height of seat bight from vehicle floor
6	Height of top of wheelchair backrest from vehicle floor
7	Height of top of wheelchair headrest from vehicle floor
8	Seat cushion thickness
9	Fore-aft distance from center of steering wheel to chin
10	Fore-aft distance from other steering control device to chin
11	Fore-aft distance from lower steering-wheel rim to abdomen
12	Fore-aft distance from knee bolster/pedal extension hardware to knee (n=11 UM subjects)
13	Lateral distance from vehicle side-wall/B-pillar to centerline of subject
14	Lateral distance from vehicle side-wall/B-pillar to center of outboard shoulder
15	Wheelchair width at seat bite
16	Wheelchair width at widest point (drive-wheel)
17	Wheelchair length (footprint)
18	Steering-wheel angle with respect to vertical
19	Height of lower steering-wheel rim from vehicle floor
20	Height of footrest bottom from vehicle floor

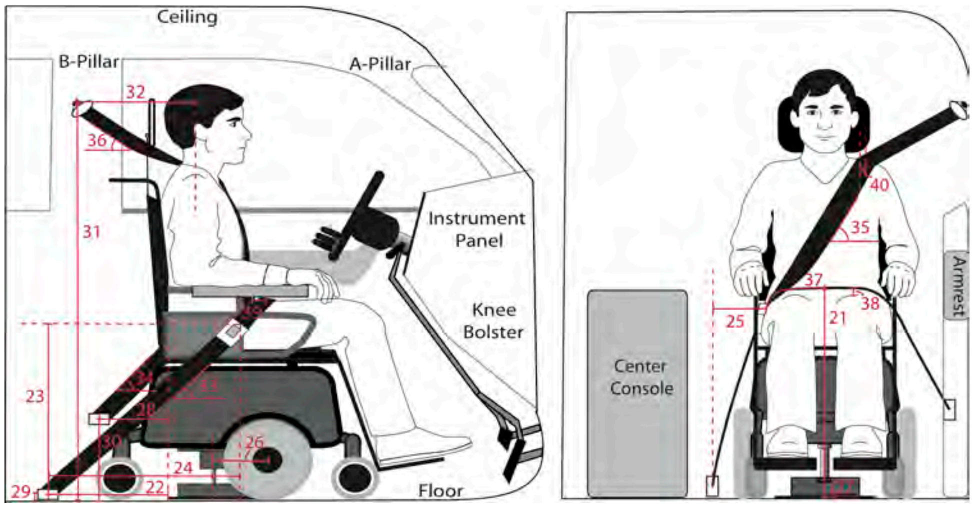


Figure 2.2 - Illustration of measurements of the wheelchair securement and occupant restraint system relative to the driver and vehicle interior space

Table 2.3 - Measurements of the wheelchair securement and occupant-restraint system relative to the occupant and vehicle interior space

21	Height of center of lap belt from vehicle floor at midline of driver
22	Fore/aft distance of inboard lap-belt anchor point from seat bite
23	Height of inboard lap-belt latch plate from stock anchor point
24	Fore/aft distance of inboard lap-belt latch plate from stock anchor point
25	Lateral distance from inboard lap-belt latch plate to stock anchor point
26	Fore/aft distance of docking securement bolt to center axle of wheelchair driving wheel
27	Height of docking securement bolt from vehicle floor
28	Fore/aft distance of outboard lap-belt anchor point from seat bite
29	Height of inboard lap-belt anchor point from vehicle floor
30	Height of outboard lap-belt anchor point from vehicle floor
31	Height of upper shoulder-belt anchor point from vehicle floor
32	Fore/aft distance from the upper shoulder-belt anchor point to the center of the driver's shoulder
33	Side-view angle of inboard lap belt with respect to horizontal
34	Side-view angle of outboard lap belt with respect to horizontal
35	Front-view angle of shoulder belt with respect to horizontal
36	Side-view angle of shoulder belt between shoulder and upper anchor point re horizontal
37	Distance along the lap belt from the occupant midline to the junction of the lap/shoulder belt if used as a three-point belt
38	Height of center of lap belt from thigh-abdominal junction
39	Smallest fore/aft distance from thigh-abdomen junction to center of lap belt at the midline (value is 0 if belt in contact with the driver)
40	Lateral distance from center of outboard shoulder to center of shoulder belt at top of shoulder

Figure 2.3 - UMTRI investigator taking measurements of a vehicle using the FARO Arm

Figure 2.4 – Photo showing horizontal and vertical distances measured between the driver and the steering wheel and the steering assist device

Figure 2.5 – Photo showing driver's knee position relative to the knee restraint and hand-control linkages

2.3.2 Measurement results

Table **2.4** lists the minimum, maximum, mean and standard deviations for each of the measurements taken of the position of the wheelchair and occupant relative to vehicle interior components for the drivers in the study. Table **2.5** lists the same data for measurements of the wheelchair securement and occupant-restraint system relative to the occupant and the vehicle interior components. It will be noted that, while the study included 21 drivers in their vehicles, the sample size for some measurements is less than 21 because not all measurements were applicable for all driver and vehicle situations.

During the interview portion of the study, six of the nineteen drivers who secured their wheelchair with a docking-securement device mentioned that they experienced problems with the low clearance of the docking hardware on the wheelchair (i.e., the vertical securement bolt that engages with the docking device) catching on entryway thresholds and rug edges during everyday use, and one of the drivers who did not use a docking device to secure her wheelchair had removed the docking-securement adaptor from her wheelchair for this reason. The photo in Figure 2.6 shows this low ground clearance on one wheelchair. The average height of the docking hardware above the ground shown in for the 19 drivers with docking-securement systems was 23.8 mm.

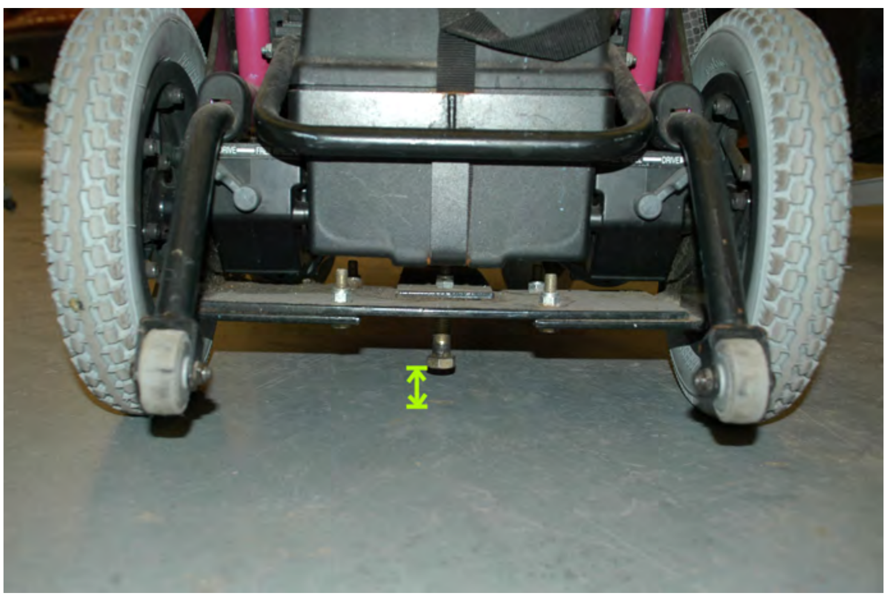


Figure 2.6 - Docking-securement adaptor on a wheelchair showing the low clearance of the securement bolt head to the ground

Table 2.4 - Measurements of the wheelchair and occupant relative to vehicle interior components for drivers seated in wheelchairs ready for travel in their personal vehicles

Measurement		Sample Size	Minimum (mm/deg)	Average (mm/deg)	Standard Deviation (mm/deg)	Maximum (mm/deg)
1	Height of top of head from vehicle floor	n=21	1223.6	1327.8	75.0	1559.9
2	Height of corner of eye from vehicle floor	n=21	1130.3	1219.4	72.7	1462.8
3	Height of top of shoulder from vehicle floor	n=21	967.7	1077.3	71.7	1292.3
4	Height of thigh-abdominal junction from vehicle floor	n=21	584.2	713.1	78.2	988.3
5	Height of seat bight from vehicle floor	n=21	406.4	558.1	81.3	812.5
6	Height of top of wheelchair backrest from vehicle floor	n=21	849.9	987.5	114.3	1373.8
7	Height of top of wheelchair headrest from vehicle floor	n=5	1203.1	1257.7	34.4	1282.7
8	Seat cushion thickness	n=21	30.4	76.4	23.6	101.6
9	Fore-aft distance from center of steering wheel to chin	n=21	115.6	313.6	83.2	508.0
9b	Diagonal distance from center of steering wheel to chin	n=11	173.1	352.5	69.2	446.1
10	Fore-aft distance from other steering control device to chin	n=21	34.4	200.3	93.9	372.6
11	Fore-aft distance from lower steering-wheel rim to abdomen	n=21	2.5	123.9	80.3	304.8
12	Fore-aft distance from knee bolster/pedal extension hardware to knee	n=11	0.0	147.0	95.6	303.0
13	Lateral distance from vehicle side-wall/B-pillar to centerline of subject	n=21	190.5	307.2	61.6	443.9
14	Lateral distance from vehicle side-wall/B-pillar to center of outboard shoulder	n=21	76.2	165.2	59.2	320.2
15	Wheelchair width at seat bite	n=19	262.3	433.6	78.3	584.2
16	Wheelchair width at widest point (drive-wheel)	n=21	515.1	637.4	46.0	736.1
17	Wheelchair length (footprint)	n=21	750.5	1091.3	117.9	1268.9
18	Steering-wheel angle with respect to vertical	n=11	18.6	31.3	6.2	40.4
19	Height of lower steering-wheel rim from vehicle floor	n=11	620.2	736.4	46.1	804.7
20	Height of footrest bottom from vehicle floor	n=9	52.1	116.7	41.8	168.6

Table 2.5 - Measurements of the wheelchair-securement and occupant-restraint system relative to the occupant and vehicle-interior components for drivers ready for travel in their personal vehicles

Measurement		Sample Size	Minimum (mm/deg)	Average (mm/deg)	Standard Deviation (mm/deg)	Maximum (mm/deg)
21	Height of center of lap belt at subject midline from vehicle floor	n=17	633.1	717.3	63.7	850.9
22	Fore/aft distance of inboard lap-belt anchor point from seat bite	n=18	-167.0	7.3	111.4	279.4
23	Height of inboard lap-belt latch plate from stock anchor point	n=17	130.2	510.1	175.7	777.5
24	Fore/aft distance of inboard lap-belt latch plate from stock anchor point	n=17	2.4	221.6	147.0	473.9
25	Lateral distance from inboard lap-belt latch plate to stock anchor point	n=17	-63.5	129.6	94.3	273.5
26	Fore/aft distance of docking securement bolt to center axle of wheelchair driving wheel	n=20	-128.9	34.6	94.7	228.6
27	Height of docking securement bolt from vehicle floor	n=10	12.5	23.8	10.7	42.8
28	Fore/aft distance of outboard lap-belt anchor point from seat bite	n=19	-284.1	-4.3	113.9	177.8
29	Height of inboard lap-belt anchor point from vehicle floor	n=19	0.0	171.8	189.0	546.1
30	Height of outboard lap-belt anchor point from vehicle floor	n=18	40.5	287.9	138.0	657.6
31	Height of upper shoulder-belt anchor point from vehicle floor	n=20	1005.8	1152.7	60.0	1269.7
32	Fore/aft distance from the upper shoulder-belt anchor point to the center of the subject's shoulder	n=20	0.0	144.4	68.7	278.3
33	Side-view angle of inboard lap belt with respect to horizontal	n=16	24.2	59.6	17.8	86.0
34	Side-view angle of outboard lap belt with respect to horizontal	n=17	5.3	54.4	20.0	80.0
35	Front-view angle of shoulder belt with respect to horizontal	n=19	16.0	39.1	12.2	63.0
36	Side-view angle of shoulder belt between shoulder and upper anchor point with respect to horizontal	n=19	7.9	30.5	15.8	68.0
37	Distance along the lap belt from the occupant midline to the junction of the lap/shoulder belt if used as a three-point belt	n=7	114.3	308.4	169.9	584.2
38	Height of center of lap belt from thigh-abdominal junction	n=16	0.0	41.8	47.5	152.4
39	Smallest fore/aft distance from thigh-abdomen junction to center of lap belt at the midline (value is 0 if belt in contact with subject)	n=16	0.0	15.9	47.2	177.8
40	Lateral distance from center of outboard shoulder to center of shoulder belt at top of shoulder	n=18	-50.8	95.0	85.9	220.8

2.3.3 Observations and results for seat belt use and positioning

Of the 21 drivers in the study, three did not use any seat-belt restraint and two did not secure their wheelchair. Of the 18 drivers who used some type of belt restraint, three used manual wheelchairs with power assist and 15 used power wheelchairs. One manual wheelchair did not have arm supports, 4 wheelchairs (2 manual and 2 powered) had arm supports that were characterized as "open-front," and 13 wheelchairs (all power) had arm supports that were "closed-front." Of the thirteen wheelchairs with a closed-front arm supports, 12 had a desk-type (or L-shaped) arm support and one had arm supports that connected to the wheelchair in the front and back by arc-shaped components. Figure **2.7** shows several different types of wheelchair arms supports.

wheelchair with open-front arms supports

wheelchair with open-front arm supports

power wheelchair with closed desk-type arm supports

manual wheelchair with closed-front arm supports

Figure 2.7 -Different types of wheelchair arm supports – top row: open front arm supports cantilevered from the wheelchair back support; bottom row: closed desk-type arm support on the left and closed-front standard arm supports on the right

Figure **2.8** shows different types of seat belts and seat-belt configurations used by drivers in the study. Of the eighteen drivers using some type of belt restraint, 13 used the original equipment manufacturer (OEM) lap/shoulder belt system with an after-market inboard buckle receptacle attached to a cable stalk or a length of webbing anchored to the vehicle floor. Two drivers used a complete after-market lap/shoulder-belt restraint system, and one used a wheelchair-anchored lap belt. This lap belt was used in conjunction with a separate vehicle-anchored shoulder belt used in the passive mode. Two of the drivers used only a passive shoulder-belt restraint and no lap belt.

OEM seat belt being used in the active mode

After-market seat belt being used in the active mode

OEM seat belt used in the passive mode

After-market seat belt used in the passive mode

Figure 2.8 - Different types of driver seat belts used by subjects in the study

Five of the 18 drivers using some type of belt restraint routed the lap belt around the front of the forward-most vertical structural member of the closed-front arm supports on both sides of the wheelchair, while two drivers routed the lap belt around the front of the arm support on the outboard side of the wheelchair and over top of the wheelchair arm support on the inboard side. Two drivers routed the lap belt over the top of both wheelchair arm supports and one driver routed the lap belt around the front of the arm support on the outboard side of the wheelchair and around the back-support post on the inboard side of the wheelchair. This latter configuration was considered to be a gross misuse of the belt restraint.

Routing of any portion of the lap belt over the top of the arm supports resulted in the lap belt being positioned high on the driver's abdomen and not in contact with the pelvis near the thigh-pelvic junctions, unlike the proper seat-belt positioning illustrated in Figure **2.9**. Figure 2.10 shows examples of common positioning of lap belts on drivers due to interference by wheelchair arm supports. The average height of the center of the lap belt above the driver's thigh-pelvic junction was 41.8 mm (± 47.5 mm) and, on average, the lap belt was 15.9 mm (± 47.2 mm) forward of the thigh abdominal junction.

Figure 2.9 - Illustration of proper positioning of the lap/pelvic belt of a three-point seat belt

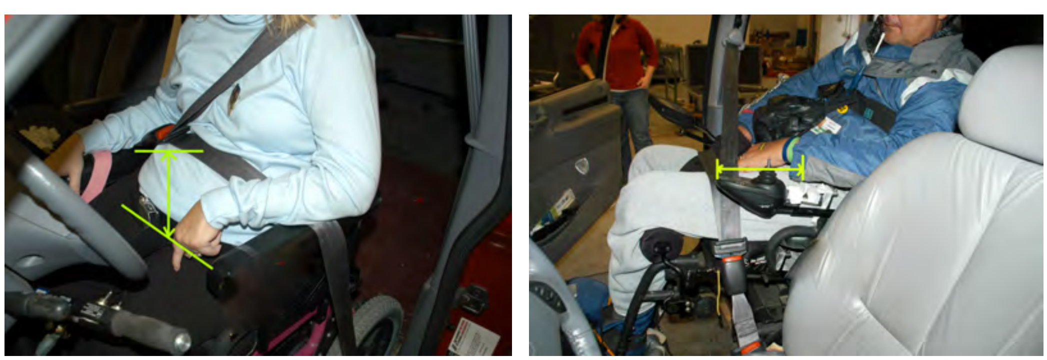


Figure 2.10 - Photos showing lap-belt locations over the arm supports and on the abdomen (left) and forward of the thigh-pelvis junctions (right)

Seventeen of the drivers who used some type of belt restraint were rated by the investigator with regard to the "ease-of-seat-belt-use" in the manner that the driver typically used the belt restraint. The rating for ease-of-belt use for one subject was not included because of the gross misuse of the seat belt previously described (i.e., wrapping the belt around the wheelchair back-support cane).

Figure 2.11 compares these ratings for the two different wheelchair arm-support configurations (i.e., close-front and open-front). All 5 subjects with open-front arm supports were assigned a rating of "good" for ease-of-use. Of the 12 subjects with closed-front arm supports, 11 received a "good" rating for ease-of-use and one received an "acceptable" rating due to the effort required to place the belt into narrow spaces between components of the arm supports. A Chi-Squared test showed that the ratings for "ease-of-use" are not statistically different for the two categories of wheelchair arm supports (p=0.51).

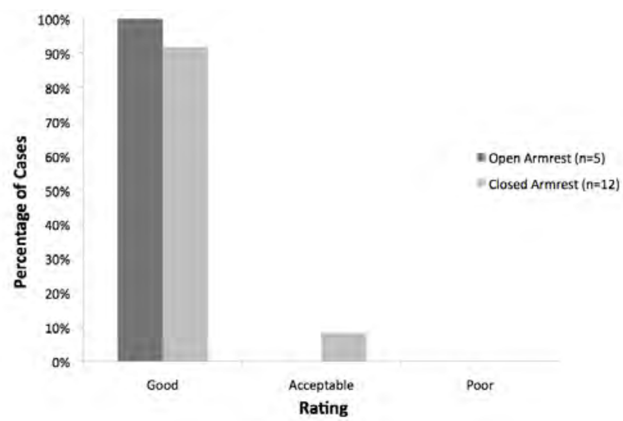


Figure 2.11 - Ratings for ease-of-belt-restraint use by drivers seated in wheelchairs with open-front and closed-front arm supports

Positioning of the lap belt on drivers who used a lap belt was also rated by the investigator. These ratings were assigned to ten drivers with closed-front arm supports and five drivers with open-front arm supports. Figure 2.12 compares the ratings for positioning of the lap belt for the two wheelchair arm-support configurations. For all five wheelchairs with open-front arm supports a rating of "good" was assigned. For the ten drivers whose wheelchairs had closed-front arm supports, pelvic-belt contact was rated "good" in 4 cases, "acceptable" in 2 cases, and "poor" in 4 cases. However, a Chi-Squared test for ratings of closed-front and open-front arm supports revealed that these differences are not statistical significant (p = 0.082).

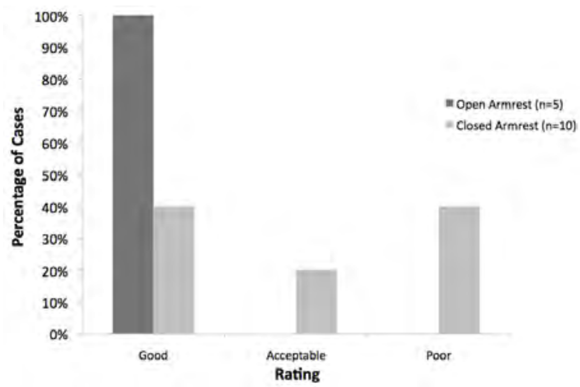


Figure 2.12 - Ratings for lap-belt positioning on drivers with wheelchairs having closed-front and open-front arm supports

When a shoulder belt was used, it was often routed off of the edge of the driver's outboard shoulder and/or had a lot of slack as shown for two drivers in Figure 2.13. Several drivers mentioned that the shoulder belt did not provide enough upper-torso support so that they often felt unstable while maneuvering the vehicle around turns. Other drivers commented that a shoulder belt with a retractor was too tight such that it pushed their torso sideways when they were in position to drive the vehicle.

Poor positioning of the shoulder belt was often the result of the wheelchair's width, which caused the driver to be shifted more inboard than a driver using the OEM vehicle seat. The average lateral distance from the center of the driver's shoulder belt (measured at the height of the top of the shoulder) to the center of the subject's shoulder (measured at the acromion) was 95.0 mm (± 85.9 mm).

Figure 2.13 - Photos showing typical positioning of the shoulder belt nearly off (left) or completely off (right) the driver's outboard shoulder

2.3.4 Driver perception of safety versus actual safety

Although drivers in this study were often using improperly/poorly positioned or incomplete seat belts, most reported that they felt safe when driving their vehicle. There was therefore a significant disconnect between the perception of safety by drivers seated in wheelchairs and the reality of effective crash protection available to this sample population. This is probably due to a willingness to ignore safety because of the desire for independence in using their personal motor vehicle. It is also likely due to a lack of understanding of what is required for effective occupant protection and transportation safety. However, many drivers also reported that they believed that the safety of their vehicle could be improved, although there were few suggestions as to how improvement in their safety could be achieved.

2.3.5 Summary and discussion

The results of this initial phase of Subtask 2 confirmed the lack of effective occupant-protection systems for a significant proportion of drivers seated in wheelchairs and indicated several reasons for this. Lap belts of three-point belt restraints, particularly when used in a passive mode, which is a frequent need of a large percentage of people who remain in a power wheelchair when they drive a personal vehicle, are necessarily placed over, or in front of, wheelchair arm supports or other wheelchair components, thereby resulting in poor belt fit (i.e., lap belts over the soft abdomen and belts being held away from the driver's body). Also, a couple of wheelchair users mistakenly assumed that the postural belt on their wheelchair, such as that shown around the occupants chest on the right side of Figure 2.13, is a crashworthy belt restraint and therefore chose not to use the vehicle seat belt. Most drivers did not understand the safety need for, and benefits of, properly positioning a crashworthy lap/shoulder belt.

When interpreting the results of the ratings for ease of seat-belt use and proper seat-belt positioning, it is important to appreciate that the ratings were assigned by the investigator based on observation of the wheelchair user's positioning the belt restraints in their usual manner, and not on the ease for achieving optimal or proper belt fit. All but one driver with closed-front arm supports were assigned a rating of "good" for ease-of-use, indicating that drivers will generally do what is easiest in using the belt restraint, regardless of whether this results in proper belt positioning.

The contact location of the pelvic belt on the wheelchair drivers was also evaluated by the investigator and, although the differences for ratings of lap-belt location for closed-front and open-front arm supports were not found to be statistically significant, this is most likely due to the small sample size of drivers in this study. On average, the center of the lap belt was positioned 41.8 mm above and 15.9 mm forward of the thigh-abdominal junction of drivers due to interference of wheelchair arm supports with the lap belt, so that proper pelvic belt fit was often not achieved. Also, on average, shoulder belts were positioned 95.0 mm outboard of the centers of drivers' shoulders, so that proper shoulder-belt contact with the middle of the shoulder was not achieved for a larger percentage of drivers in the study.

Most drivers in this study used after-market grip-enhancing assistive-steering devices attached to the steering-wheel rim. These devices, and particularly tri-pin devices, are typically very rigid and protrude rearward toward the driver, thereby posing an additional risk of injury to drivers seated in wheelchairs in crash events. However, it has been shown in static air-bag deployment tests that driver-assist devices attached to the steering-wheel rim do not to interfere with deployment of steering-wheel air bags (Dalrymple, 1996 and Dalrymple and Ragland, 1998).

Therefore, leaving the air bag activated is one of the best ways to prevent, or at least reduce, injurious interaction of drivers with these steering-assist devices during frontal crashes.

Finally, none of the drivers in this study had a vehicle-anchored head-and-back restraint for rear-impact protection. It is, of course, strongly recommended that vehicle-anchored head restraints for drivers in wheelchairs not be installed without a vehicle-anchored back restraint because failure of a non-crashworthy wheelchair back support in a rear impact would likely result in severe neck injuries if the head is effectively restrained. However, at least two of the drivers in the study did have a vehicle-anchored head restraint installed in their vehicles without a vehicle-anchored back restraint. In one of these cases, the head restraint had been moved out of the way because it interfered with the driver's head movement and/or vision.

With regard to rear-impact protection of drivers and passengers seated in wheelchairs, sled-impact tests of wheelchairs conducted at UMTRI, including those that comply with WC19 (and therefore have shown good back restraint during crash-dummy rebound loading), have shown that wheelchair back supports are likely to significantly deform rearward, and even catastrophically fail, in moderate rear-impact collisions (Manary et al., 2007). The UMTRI wheelchair-occupant crash/injury database only includes two cases involving rear impacts and these were relatively minor events that did not result in back-support failures. Nevertheless, the results of UMTRI rear-impact wheelchair sled tests suggest that drivers (and passengers) seated in wheelchairs traveling in personal-licensed vehicles are at significantly greater risk of sustaining serious-to-fatal head/neck injuries in rear-impact collisions than are occupants seated in the vehicle manufacturers' seats.

2.4 Design and evaluation of improved occupant-protection systems for front and rear crash protection

2.4.1 Introduction

To address the concerns and problems of belt-restraint systems for drivers seated in wheelchairs described in the driver measurement study, efforts were focused on developing and evaluating prototype restraint systems for frontal-impact protection, and on developing and/or evaluating prototype or commercial vehicle-anchored head-and-back restraint systems. In addition, one of the key observations in the study of drivers seated in wheelchairs using their personal vehicles is the importance of wheelchairs having open-front arm supports to achieve proper belt restraint, especially for drivers who need to use a passive lap/shoulder belt restraint. Clinicians who prescribe wheelchairs rarely consider the possibility that a power wheelchair user may choose to drive a personal vehicle while seated in their wheelchair. Therefore, they rarely consider the need for the wheelchair to easily accommodate the proper use and positioning of a passive lap/shoulder belt restraint system. For this reason, wheelchairs used by people who decide that they would like to drive a personal vehicle without transferring from their wheelchair to the vehicle seat often have a wheelchair that is equipped with closed-front arm supports. Because of this, an effort to retrofit a wheelchair with closed-front arm supports to one having open-front arm supports was undertaken to demonstrate the feasibility of making this type of wheelchair retrofit. Section 2.4.3.6 describes this arm-support retrofit activity.

2.4.2 Scope and general approach to designing and evaluating improved occupant-protection systems for drivers seated in wheelchairs

In efforts to improve front and rear crash protection for drivers seated in wheelchairs, several design concepts were explored and evaluated. For frontal crash protection, this involved two biomedical engineering (BME) senior design projects (WEAR, 2008; Intrinsic, 2009) that were supervised by UMTRI faculty, and two restraint-system design concepts developed by UMTRI researchers.

For rear-impact protection, a deployable head-and-back restraint system was developed and evaluated by one of the BME senior design teams that also developed a prototype restraint system for frontal crash protection (Intrinsic, 2009). However, efforts were subsequently turned toward evaluating a commercially available deployable head-and-back restraint system, and working to with the manufacturer to improve the system's effectiveness in providing occupant restraint in rear impacts.

Evaluation of prototype designs involved two approaches. One was to install a prototype of the design in a laboratory minivan buck obtained from the Transportation Research Center (TRC) in Ohio, and that had been reinforced for use in their wheelchair-driver sled-test program described in Section 2.4.3.1 (Sword, 2007). When the buck was brought to UMTRI, it was set up in the high-bay laboratory and modified to include side-entry and rear-entry ramps so that wheelchair users could access the driver space and provide comments regarding prototype restraint-system designs. Figure 2.14 shows the minivan buck in one of UMTRI's high-bay laboratories for this purpose, while Figure 2.15 shows the driver space inside the minivan buck.

Figure 2.14 -Minivan buck in UMTRI high-bay laboratory with rear-entry and side-entry ramps used for wheelchair driver ingress and egress to evaluate prototype restraint-system designs

Figure 2.15 – Forward view of driver area inside the minivan laboratory buck

The second method used for prototype evaluations was to conduct sled-impact tests of prototype systems. Frontal-impact tests were conducted using a 48-kph (30-mph) Delta V impact with a deceleration pulse similar to that shown in Figure 2.16. Rear-impact tests were conducted using a 25-kph (15-mph) Delta V impact with a deceleration pulse that falls within the corridor shown in Figure 2.59.

All tests were conducted using the Hybrid III midsize male anthropomorphic test device (ATD), or crash-test dummy, seated in a new or refurbished commercial power wheelchair or seated in the surrogate wheelchair frame (SWCF) shown in Figure 2.17. The latter was designed to evaluate the crashworthiness of commercial wheelchair seating systems independent of the different commercial wheelchair frames on which they may be installed. It includes back-support posts connected to the base frame by means of replaceable deformable rods and front caster wheels mounted to the frame by means of deformable aluminum bars. In this way, the SWCF provides a surrogate wheelchair that mimics the kinematics and key deformability features of typical commercial wheelchairs.

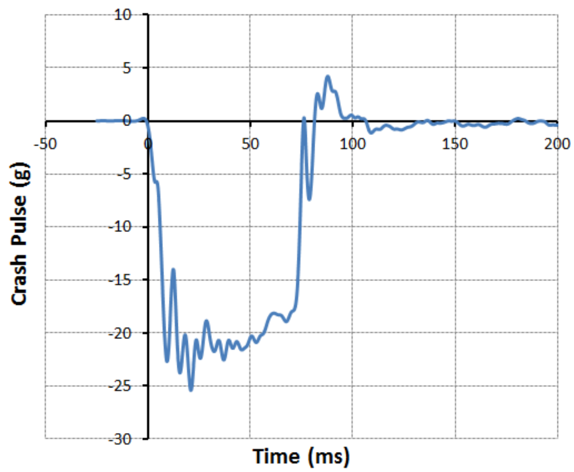


Figure 2.16 - Typical 48-kph, 20-*g* sled deceleration pulse used for all frontal-impact sled tests of prototype restraint systems

Figure 2.17 - Surrogate wheelchair frame (SWCF) used in tests to evaluate front- and rear-impact restraint systems to evaluate restraint systems in both front and rear impacts

2.4.3 Restraint systems for frontal-crash protection

2.4.3.1 Wheelchair-driver sled testing at the Transportation Research Center (TRC)

Prior to UMTRI's efforts to develop and evaluate improved frontal crash protection systems, several sled impact tests were conducted by the NHTSA at TRC in Ohio (Sword, 2007). The tests were conducted using a structurally reinforced occupant compartment from a modified 2003 Dodge Caravan (Braun Entervan), which is a vehicle commonly used by drivers seated in wheelchairs. For each test, a new commercial single-point (i.e., vertical bolt under wheelchair) docking-securement device with front stabilizing bracket was installed in the driver space of the modified van. All tests were conducted using the Hybrid III midsize-male ATD and either a Pronto or TDX3 Invacare power wheelchair.

A total of eight 48-kph, 20-*g* frontal-impact sled tests were conducted with the ATD restrained by a variety of different seat-belt configurations, but none of the tests included deployment of steering-wheel air bags. Several of these tests used an OEM lap/shoulder belt with an emergency locking retractor (ELR)[4] that was completed by means of a seat-belt buckle mounted to a cable stalk attached to the floor anchorage track on the inboard side of the wheelchair. For two of these tests, the lap belt was placed over the wheelchair arm supports. One test used a modified shoulder belt with a separate vehicle-anchored lap belt, in another test the ATD was restrained by only a shoulder belt (i.e., no lap belt), and in two tests the ATD was restrained by lap/shoulder belt with the lap belt anchored to the wheelchair base frame or seat frame.

Figure 2.18 shows two of the pre-test setups, one with the inboard half of the lap belt anchored to the floor by means of the cable stalk, and the other with the inboard half of the lap belt anchored to low at the back of the wheelchair frame near the docking-securement adaptor. It can be noted in both photos that the steering-wheel rim is deformed from previous sled tests since the steering wheel was not replaced between tests.

Figure 2.18 - Photos of pretest setups for two TRC sled tests – the photo on the left shows the inboard buckle of the OEM seat belt anchored to the vehicle floor by means of a cable stalk, and photo on the right shows an aftermarket lap/shoulder belt with the lap belt anchored to the back of the wheelchair near the docking-securement adaptor

[4] An Emergency locking retractor is a seat-belt retractor incorporating a mechanism that is activated to lock up the seat belt to withstand restraint forces by vehicle accelerations and decelerations, webbing movement relative to the vehicle, or other automatic action during an emergency.

These TRC sled tests resulted in a range of wheelchair and ATD kinematics, none of which demonstrated good restraint or effective frontal-crash protection. In all tests with the OEM lap/shoulder belt, there was considerable spool-out of the shoulder-belt webbing from the ELR retractor, resulting in contact of the ATD with the steering wheel and instrument panel. Figure 2.19 shows typical post-test positions of the ATD, and demonstrates that the ATD also demonstrated considerable submarining-type kinematics in many of the tests due to the positioning of the lap belt over the wheelchair arm supports, forward pitching (i.e., rotation) of the wheelchair, or a combination of both.

As previously noted, because the forked bar connecting the wheelchair securement adaptor to the front stabilizing bracket bends too easily, it did little to reduce or prevent this forward wheelchair rotation. Thus, the commercial front stabilizing bracket available at the time of these tests offered little benefit to wheelchair kinematics during frontal crashes and its primary benefit is therefore to prevent left/right rotation of the wheelchair during normal vehicle operation.

In this regard, one observation from these sled tests was that locating the single securement bolt more rearward under the wheelchair reduces forward pitching of the wheelchair and therefore helps to reduce ATD submarining. This is especially the case when the lap belt is anchored to the back of the wheelchair rather than to the vehicle floor. However, while locating the securement bolt more rearward may be beneficial in frontal crashes, it has a potentially negative effect in rear impacts where the wheelchair will tend to rotate rearward such that the front of the wheelchair rises up off the floor.

Figure 2.19 - Typical post-test positions of the ATD following TRC wheelchair-driver sled tests

Other observations from these tests are:

- The lap belt was sometimes cut by wheelchair components, resulting in ATD submarining.
- Placing the lap belt over the arm supports often caused the belt to “cut into” the upper abdomen of the ATD.
- The cable-stalk anchoring the inboard portion of the lap/shoulder belt occasionally failed or partially failed.
- There was significant extension of the ATD’s neck when the ATD loaded the wheelchair back support during rebound.
- The ATD often separated from (i.e., came out of) the wheelchair seat.
- When used, wheelchair postural belts failed during these frontal-impact tests.

Overall, it was concluded from these sled tests that "the unique and custom application of driving from the wheelchair presents many challenges for effective occupant restraint."

2.4.3.2 Overview of UMTRI restraint-system design approaches for frontal-crash protection

Following sled testing at TRC, four different frontal-impact restraint system concepts were explored at UMTRI. These include:

1) a user friendly wheelchair-anchored lap/shoulder-belt restraint system with connection for an aftermarket shoulder belt,
2) a passive lap/shoulder belt restraint with the lap belt anchored to the floor by means of pivoting bars,
3) a close proximity knee restraint with a passive two-point shoulder belt, and
4) a seat-belt deployment device (SBDS) to enable use of the vehicle lap/shoulder belt in a passive mode

Each of these is described briefly below. Because the results of the driver study reported in Section 2.3 demonstrated the importance of open-front wheelchair arm-supports to allow proper positioning of a passive vehicle lap belt low on the pelvis of drivers seated in wheelchairs, evaluations were typically conducted with these types of arm supports or, in some cases, with no arm supports.

2.4.3.3 Lap/shoulder belt restraint with wheelchair-anchored lap belt

Figure 2.20 shows pre-test photos of a sled-test setup of a prototype lap/shoulder belt restraint with wheelchair-anchored lap belt designed by a team of Biomedical Engineering (BME) senior-design students (WEAR, 2008). The lap belt is installed on a commercial Invacare TDX3 wheelchair and uses standard belt webbing material sewn to metal anchorages bolted to a steel bar that was welded to the lower frame at the back of the wheelchair. The add-on docking securement bolt was moved rearward from its more typical central location on the frame of the wheelchair, which, as noted above, was demonstrated in the tests conducted by the NHTSA at TRC to reduce undesirable forward rotation (i.e., pitching) of the wheelchair in frontal crashes. The lap belt webbing is threaded up through "pockets" placed on both sides of the wheelchair to allow the buckle halves to be readily available to the wheelchair user. To increase usability of the buckle for quadriplegics who do not have full function of their hands and fingers, the design used an aircraft-type buckle in which the buckle is released by pulling up on a metal lever. A similar buckle was used to connect a shoulder belt with a fixed upper anchor point to the wheelchair-anchored lap belt.

This restraint system was tested twice in 48-kph, 20-*g* frontal impacts on the UMTRI sled using the deceleration pulse in Figure 2.16. As shown in Figure 2.20e, the securement bolt on the TDX3 wheelchair was captured in a commercial docking-securement device and a front stabilizer bracket was used in both tests, as shown in Figure 2.20f.

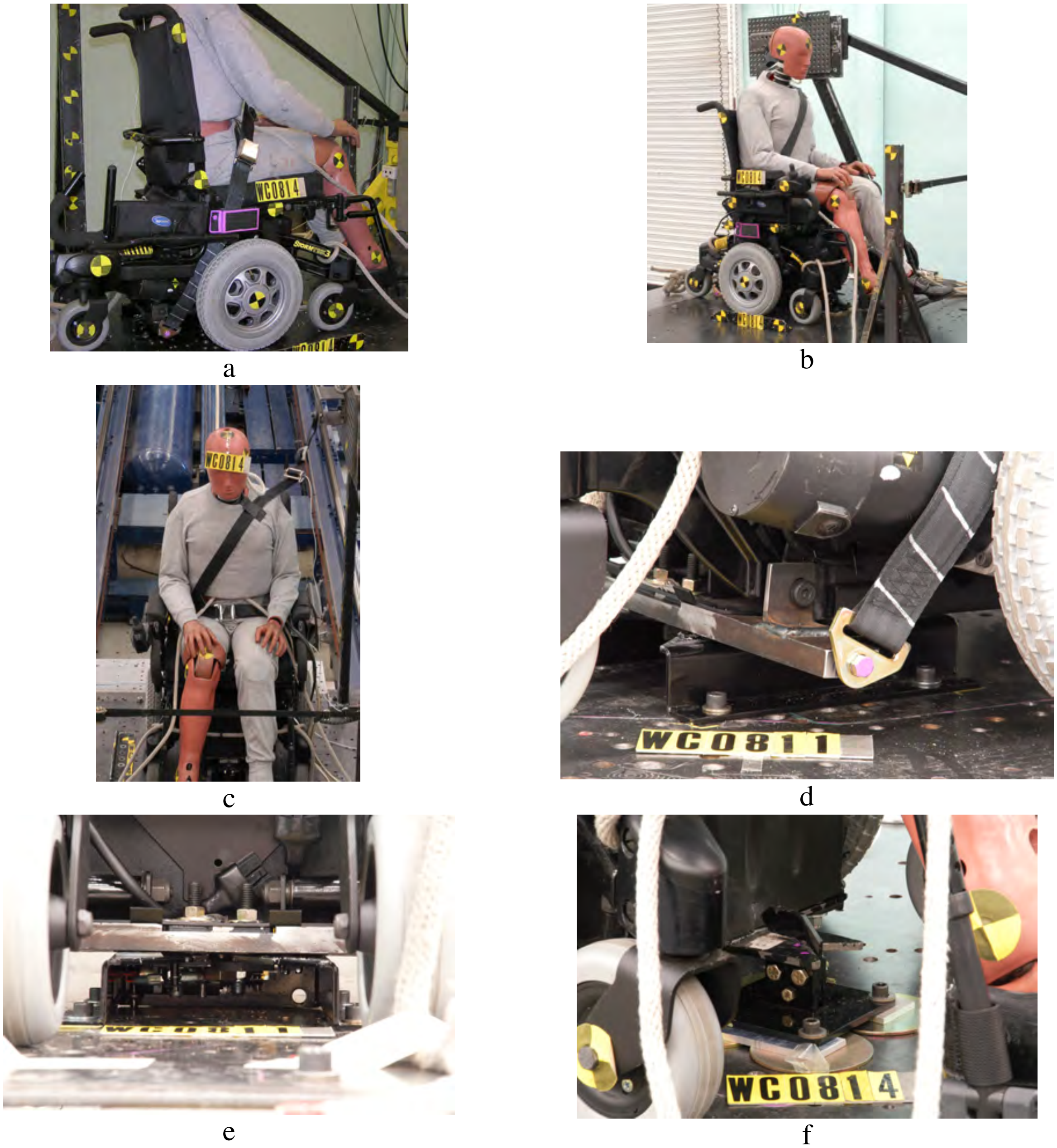


Figure 2.20 - Prototype driver belt-restraint system with accessible wheelchair-anchored lap belt from a BME student design project

In the first test, stitching in the seat belt failed, which allowed excessive forward excursion of the ATD. In the second test, for which a time-sequence frames[5] from the high-speed side-view digital video are shown in Figure 2.21, there were no failures in the restraint system and the ATD was effectively restrained from forward movement. Figure 2.22 shows post-test photos of the wheelchair and midsize-male ATD. As shown in Figure 2.22c, there was some deformation of the upper retaining plate of the docking-securement device.

[5] For all time-sequence frames from high-speed videos in this report, time starts at the top of the left column, proceeds to the bottom of that column, then goes to top of the right column, and proceeds to the last time frame at the bottom of the second column.

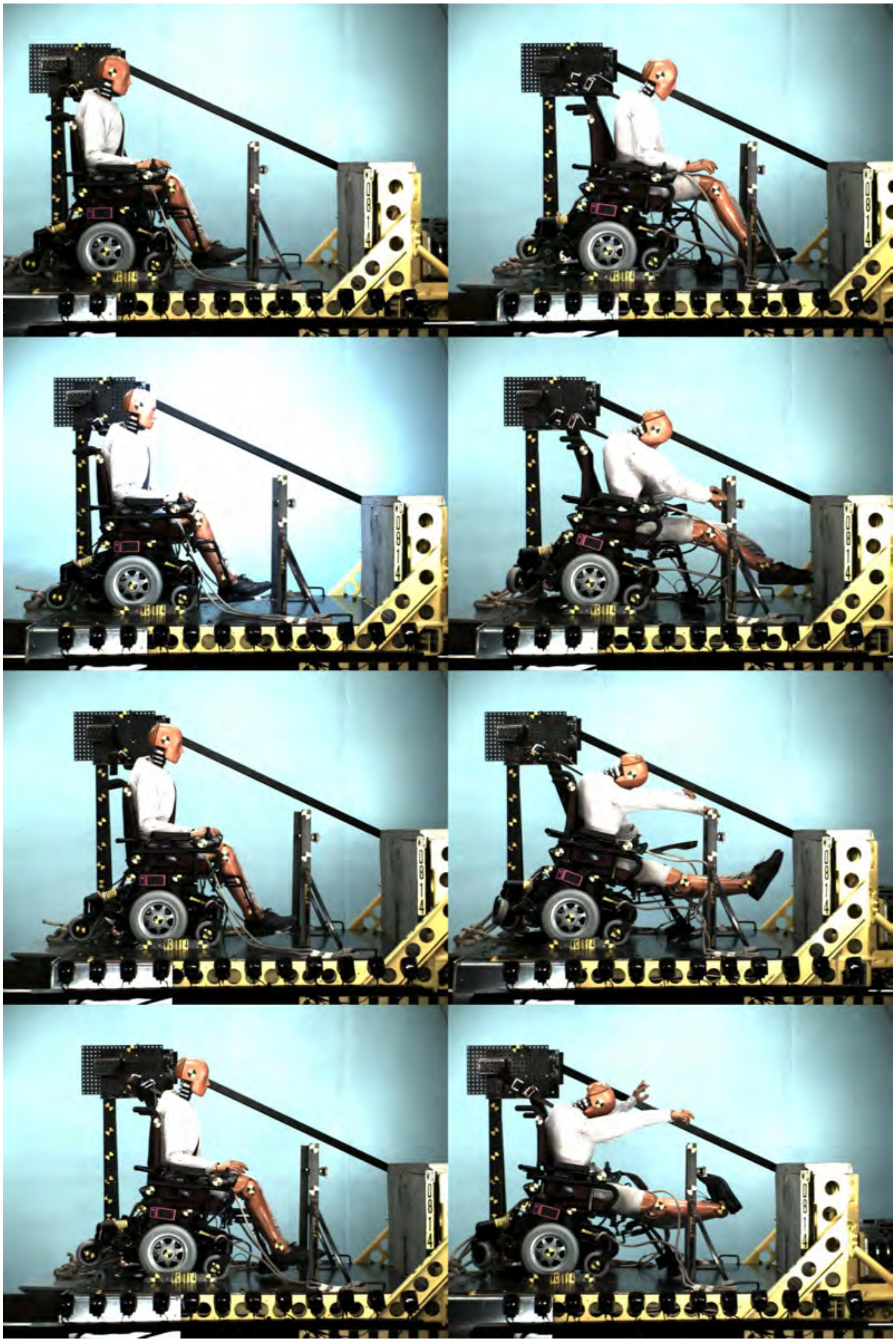
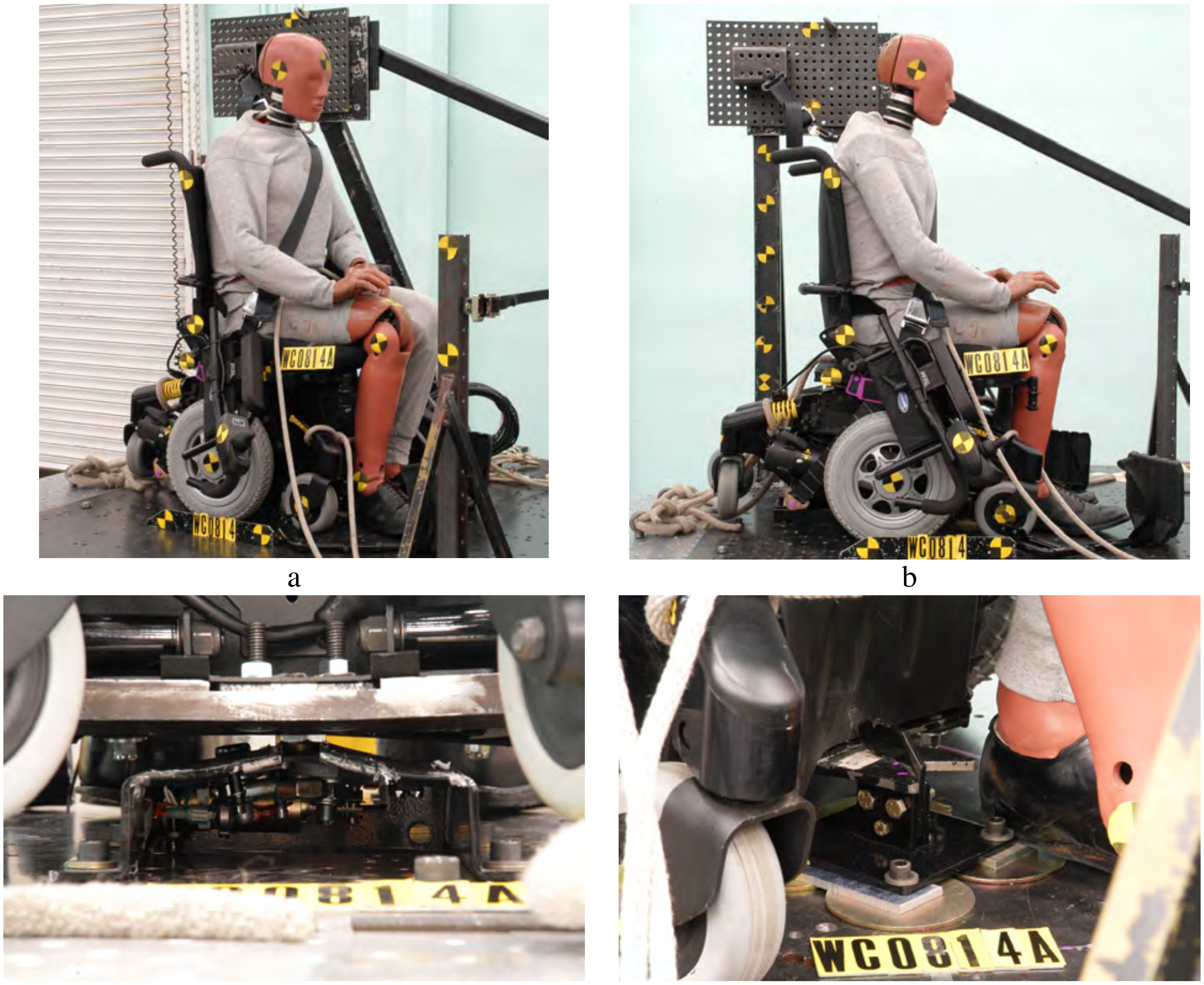


Figure 2.21 - Side-view time-sequence photos from the side-view high-speed digital video of the second test of a BME-student prototype lap/shoulder belt restraint system with wheelchair-anchored lap belt



a b c d

Figure 2.22 - Post-test photos of TDX3 wheelchair secured by commercial docking-securement device with front stabilizing bracket and midsize-male crash-test dummy restrained by a BME-student prototype lap/shoulder belt with accessible wheelchair-anchored lap belt

2.4.3.4 Vehicle-anchored lap/shoulder belt with floor-anchored pivoting bars

A second BME senior design team used a different approach to providing improved occupant protection for drivers seated in wheelchairs. This student team designed and evaluated prototypes for both a vehicle-anchored lap/shoulder belt restraint for frontal crash protection as well as a deployable vehicle-anchored head-and-back restraint for rear-impact protection. The lap/shoulder belt restraint system, which is referred to as the pivoting-bar system, can be used in either a passive or active mode and is described in this section, while the deployable head-and-back restraint system is described in the Section 2.4.4 on "Rear-Impact Protection."

The photos in Figure 2.23 and Figure 2.24 show photos of a prototype of the pivoting-bar lap/shoulder belt restraint system mocked up in the minivan buck, and the photos in Figure 2.25 show the system being evaluated by two students seated in power wheelchairs. In this prototype, an OEM lap/shoulder belt with an ELR retractor mounted to the floor of the minivan buck near the bottom of the B-pillar was used. The key feature of the system is two spring-loaded pivoting bars that are anchored to the vehicle floor on the inboard and outboard sides of the wheelchair-driver space. Gimbaled D-rings are attached to the tops of both pivoting bars. After the shoulder belt portion of the OEM seat belt is pulled diagonally down and across the driver space from an upper shoulder-belt D-ring on the B-pillar, the seat-belt latch plate is inserted through a pivoting D-ring mounted to the top of the inboard pivoting bar. The buckle receptacle of the OEM seat belt is fastened to the outer (left) side of the outboard pivoting bar below a pivoting D-ring mounted to the top of this bar.

When used in the passive mode, the seat belt is buckled so that the lap belt is suspended horizontally across the driver space between the two pivoting bars. When the driver with a wheelchair having open-front arm supports moves his/her wheelchair forward into position, the lap belt rides over the driver's thighs and into contact with the lower pelvis near the thigh-pelvis junctions. As the driver continues to move further forward into the driving position until the wheelchair is secured by the docking-securement device, the pivoting bars rotate forward to form angles of about 45 degrees or greater to the horizontal.

a b

Figure 2.23 – Photos of a prototype of the pivoting-bar lap/shoulder belt restraint system installed in the static minivan buck

a

b

c

d

Figure 2.24 – Additional photos of a prototype of the pivoting-bar lap/shoulder belt restraint system installed in the static minivan buck

a

b

c

d

Figure 2.25 - Photos of BME students in power wheelchairs without arm supports evaluating the pivoting-bar lap/shoulder-belt restraint system used in the passive mode in the static minivan buck

In addition to evaluating a prototype of the pivoting-bar restraint system in the minivan buck, prototypes of the restraint system were fabricated for frontal-impact sled testing. The initial runs were conducted with the surrogate wheelchair frame (SWCF) previously described and shown in Figure 2.17. For these tests, the SWCF was fitted with an aluminum seat and fabric back support, loaded with a midsize-male Hybrid III ATD, and secured by a commercial docking-securement device. In the initial test, the inboard buckle of the restraint system failed due to contact with the aluminum seat of the SWCF caused by inward movement of the pivoting bars during frontal-impact loading. In a subsequent test, the shoulder belt webbing failed due to interaction with the D-ring.

These failures led to modifications of the restraint design, which was successfully tested using an Invacare Pronto power wheelchair. These modifications involved mounting the buckle receptacle further down on the outboard pivoting bar on the side facing away from the wheelchair, so that it would not contact rigid wheelchair components when the bar moves inward during frontal-impact loading on the belt restraints.

Figure 2.26 shows pre-test photos of the third and final frontal-impact sled test of the modified pivoting-bar belt-restraint system with the midsize-male Hybrid III test dummy. In this design, the upper shoulder belt anchor point was fixed on the simulated B-pillar structure mounted to the sled platform. Figure 2.27 shows time-sequence frames from the side-view high-speed video and Figure 2.28 shows post-test photos from this test. No failures of any components were noted during or after the test and the lap/shoulder belt restrained the ATD within the forward-excursion criteria in Section 18 of ANSI/RESNA Volume 4 (ANSI/RESNA, 2012). Table **2.6** lists the maximum ATD response values, also known as injury assessment reference values or IARVs, allowed by FMVSS 208 "Occupant Crash Protection" for front outboard seating positions (49 CFR Part 571.208). Table **2.7** summarizes peak values for the ATD response measures for the third and final sled test (WC0912) of the pivoting-bar restraint system from which it can be seen that all values are below the IARVs in Table **2.6**.

Table 2.6 - Summary of NHTSA injury assessment reference values (IARVs) for the Hybrid III midsize male and small-female ATDs

Injury Criteria (units)	Midsize Male	Small Female
Head: HIC 15	700	700
Neck: Nij	1.0	1.0
Critical Intercepts		
Tension/Compression (N)	4500	3370
Flexion (Nm)	310	155
Extension (Nm)	125	62
Thorax:		
Chest deflection (mm)	63	52
3-md chest acceleration (*g*)	60	60
Femur: Peak force (kN)	10	6.8

Table 2.7 - ATD responses measures from the final test of the pivoting-bar restraint system (Test #WC0912)

Injury Criteria (units)	**Value**
Head: HIC 15	226
Neck: Nij	0.56 (Ntf)
Critical Intercepts	
Tension/Compression (N)	+2030/-116
Flexion (Nm)	87
Extension (Nm)	-35
Thorax:	
Chest deflection (mm)	47
3-ms chest acceleration (*g*)	53
Femur: Peak force (kN)	not measured

Ntf = Nij in tension/flexion

Figure 2.26 -Photos of the prototype pivoting-bar lap/shoulder belt restraint system prior to conducting the third and final 48-kph, 20-*g* frontal sled-impact test

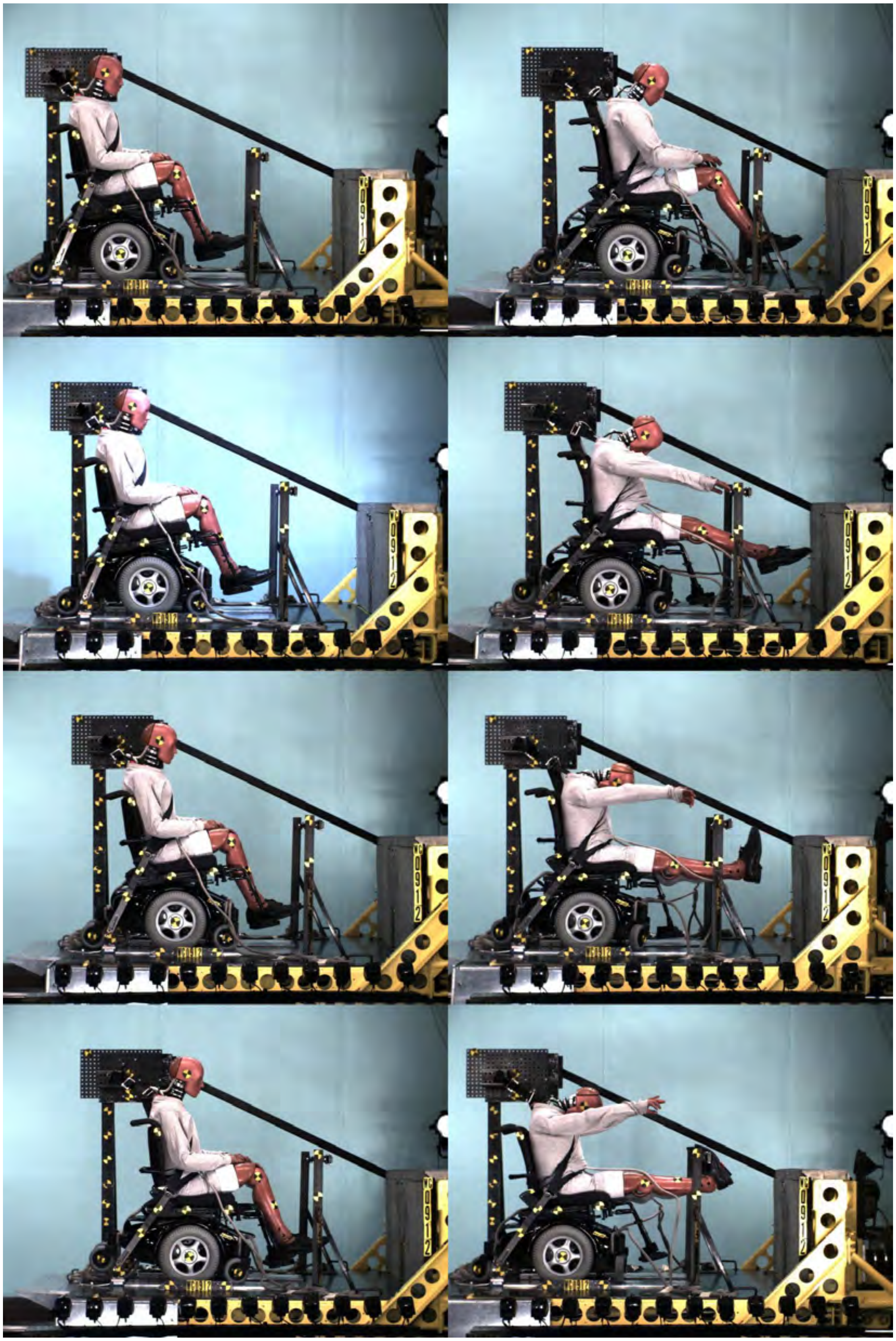


Figure 2.27 – Time-sequence frames from the side-view high-speed digital video for the third 48-kph, 20-*g* sled test of the pivoting-bar lap/shoulder belt restraint system

Figure 2.28 - Photos of the wheelchair and ATD following the third 48-kph, 20-*g* frontal-impact test of the prototype pivoting-bar lap/shoulder belt restraint system

2.4.3.5 Close-proximity knee restraint

<u>Design approach</u>
As noted above, closed-front wheelchair arm supports are one of the primary obstacles to achieving proper positioning of vehicle-anchored lap belts low on the pelvis and in good contact with the pelvic region of drivers seated in wheelchairs, especially when the driver needs to use a passive belt restraint. Also, few, if any, commercial wheelchairs have been designed and tested for use with a crashworthy wheelchair-anchored lap belt that are compatible with the vehicle-manufacturer's shoulder belt.

For these reasons, consideration was given to completely eliminating the lap belt as the lower-torso restraint by replacing it with a knee restraint that is in very close proximity to the driver's knees and legs when the driver's wheelchair is secured and the driver is operating the vehicle. This is a possible alternative approach to lower torso-restraint for drivers seated in wheelchairs because these drivers use hand controls and do not move their legs and feet to operate brake and accelerator pedals when driving. This restraint concept is similar to the approach to passive restraint systems used by Volkswagen and other manufacturers in the late 1980s and early 1990s, whereby a door-mounted, or power-actuated, two-point shoulder belt was used to provide a passive upper-torso restraint and an energy absorbing knee bolster would provide for lower-torso restraint, usually in conjunction with a lap belt that required buckling by the driver or right-front passenger (Chi and Reinfurt, 1981; Evans, 1981; Huelke and Sherman, 1988).

While it was recognized that the strengths of bones in the lower extremities of drivers who cannot transfer out of their wheelchair are generally lower than for ambulatory people due to lack of use and weight-bearing, it was hypothesized that the lower bone strength would be compensated by lower forces applied to the knees during frontal crashes. These lower forces would result from the knees being in contact with, or nearly in contact with, the energy absorbing knee restraint during normal driving, thereby reducing the pre-contact velocity between the knees and the knee restraint during a frontal crash to essentially zero. By reducing the knee-to-knee-bolster impact velocity, the forces applied to the knees during a frontal crash are also reduced. In addition, it was thought that the close-proximity knee restraint could be made of a relatively soft material with significantly more energy absorbing depth than standard OEM knee restraints. A final advantage of using a close-proximity knee bolster for lower-torso restraint is that it could offer improved stability for the driver during normal operation of the vehicle.

Figure 2.29 illustrates one possible way to implement a close-proximity knee restraint. In this design, the energy-absorbing portion of the restraint is attached to a rigid structure mounted to the vehicle floor. This approach was subsequently abandoned in favor of attaching an add-on knee restraint to the OEM driver knee bolster because of concerns that the rigid floor-mounted structures could interfere with wheelchair access to the driver space and present potential injury hazards near the driver's lower extremities. Also, by adding the close-proximity knee restraint to the OEM knee bolster, the energy absorbing properties of the OEM knee restraint could also be utilized.

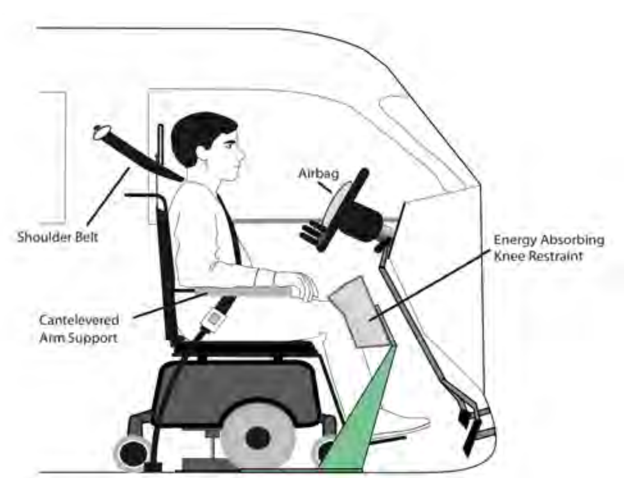


Figure 2.29 - Design concept for a passive driver restraint system for frontal crash protection using a two-point passive shoulder belt, a close-proximity energy absorbing knee restraint, and a steering-wheel air bag

Evaluation in minivan buck

Figure 2.30 shows a mockup of a close-proximity knee restraint attached to the OEM knee bolster in the static minivan buck and Figure 2.31 and Figure 2.32 shows a person in a wheelchair positioned in the driver space with his knees in very close proximity to the add-on knee restraint. This add-on knee restraint was custom designed to provide a close and contoured fit to the knees of a member of the project design team when he was seated in a power wheelchair. Commercial hardware for a set of vehicle hand controls was implemented in the minivan prior to installing the add-on knee restraint so that a realistic idea of the additional constraints and problems imposed by this hardware could be addressed during knee-bolster installation.

In this particular mockup, a prototype four-point upper-torso harness restraint was developed and installed in the minivan-buck. The restraint harness consists of two lengths of webbing that are anchored to the vehicle roof and floor and are connected together by two straps across the chest. The design allows the wheelchair driver to maneuver into the driver space and use the harness in a passive mode without the need to buckle the webbing.

Figure 2.30 – Photo of a prototype close-proximity knee restraint installed in the static minivan buck

Figure 2.31 - Position of the right knee relative to a prototype contoured close-proximity knee restraint in the static minivan buck

Figure 2.32 - A member of the UMTRI design team evaluating a prototype close-proximity knee restraint in the static minivan buck with a passive shoulder harness to provide upper-torso restraint

Computer simulations to evaluate potential reductions in forces on the knees

To investigate the potential reductions in knee-thigh-hip forces using a close-proximity knee restraint, computer simulations were conducted. The MADYMO computer model was used to configure a Hybrid III midsize-male ATD seated in a surrogate wheelchair (SWC) secured by a docking-securement device. The model was previously validated against 48-kph, 20-*g* frontal-impact sled tests with lap/shoulder belt restraint and air-bag deployments (See 3.3 in Subtask 3).

Figure 2.33 shows pre-impact and a peak-of-action frames for the baseline model configured to simulate a 48-kph, 20-*g* frontal crash with a typical production knee bolster located 100 mm from the anterior aspects of the ATD's flexed knees and with the driver restraint system consisting only of a steering-wheel air bag (i.e., no belt restraints). Based on data collected in a study of human cadaveric knee-thigh-hip impact tests performed by Rupp et al. (2008), the OEM knee bolster was modeled with a constant stiffness of a 100 N/mm and maximum deflection of 100 mm before bottoming out. The peak femur forces from the simulation were approximately 6,450 N.

Figure 2.34 and

Figure 2.35 show pre-impact and peak-of-action frames from simulations in which a 100-mm deep close-proximity knee restraint was added between the production knee bolster and the ATD's knees for the ATD restrained only by a steering-wheel air bag and for the ATD restrained by a steering-wheel air bag plus a passive shoulder-belt restraint. For both of these simulations, when the stiffness of the add-on close-proximity knee restraint was set to 50 N/mm (half that of the production knee bolster), the peak femur force was approximately 3,336 N, which is about half the peak force generated in the simulation using a production knee bolster with a knee-to-knee-bolster pre-crash distance of 100 mm.

Pre-impact | Peak-of-Action

Figure 2.33 - Baseline MADYMO simulations of a 48-kph, 20-*g* frontal impact for an unbelted midsize-male ATD seated in a simulated wheelchair and restrained by a steering-wheel air bag and a typical production knee-bolster with a stiffness of 100 N/mm

Pre-impact | Peak-of-Action

Figure 2.34 - MADYMO simulation for an unbelted midsize-male ATD restrained by a steering-wheel air bag and a 100-mm deep, 50 N/mm close-proximity knee restraint added to the production knee restraint

Pre-impact | Peak-of-Action

Figure 2.35 - MADYMO simulation for an unbelted midsize-male ATD restrained by a two-point shoulder belt, a steering-wheel air bag, and a 100-mm deep, 50 N/mm close-proximity knee restraint added to the production knee restraint

Sled-impact tests of close-proximity knee restraint

To further evaluate the concept of using an add-on driver-specific close-proximity knee restraint for passive lower-extremity restraint for drivers seated in wheelchairs during frontal crashes, two sled-impact tests were conducted without airbag deployments - one with no belt restraint and one with a two-point shoulder belt. Although the computer simulations previously described included airbag deployments, it has been shown that airbags have no effect on injuries to the lower extremities in frontal crashes and it can therefore be expected that they have essentially no effect on the forces applied to the knees (Kuppa and Fessahaie, 2003).

Figure 2.36 shows the test set up in which a mid-sized male Hybrid III ATD was seated in an Invacare TDX3 power wheelchair secured by an UMTRI-designed surrogate docking-securement device (see 2.4.3.6). The driver instrument panel and steering wheel from a 2006 Dodge Caravan were installed on the UMTRI sled to represent a typical wheelchair driver station.

The close-proximity knee restraint was constructed of 4-inch thick closed-cell polyolefin foam (MicroCell 2900) that was mounted to the production OEM driver knee bolster. Additional pieces of the same material were added to create a concave surface that was essentially in contact with the anterior aspects of the ATD's flexed knees. As in the MADYMO simulations, the foam for the close-proximity knee restraint was selected to be approximately 50 N/mm and this stiffness was confirmed with quasi-static testing on an Instron machine using a ATD knee indenter. The contoured surface of the add-on knee restraint was covered with neoprene wetsuit material to create a non-abrasive surface for contact with driver knees.

The ATD was positioned relative to the steering wheel and instrument panel based on the mean observed position of drivers who participated in the driver study described in Section 2.3. The test was conducted using a 48-kph, 20-*g* crash pulse with a surrogate passive two-point vehicle-anchored shoulder belt to provide upper-torso restraint.

Figure 2.36 - Photos of the setup for frontal-impact sled test of the close-proximity knee restraint with no airbag and a two-point vehicle-anchored shoulder belt

Figure 2.37 shows time-sequence frames from the high-speed digital video recorded during the test. As indicated, the ATD moved forward into the close-proximity knee restraint but the knees went under the knee restraint, resulting in severe submarining kinematics. The recorded femur loads reached approximately two-thirds of the expected peak levels based on the simulations with the MADYMO model.

After the test, it was determined that the adhesive used to hold sections of the add-on knee restraint to the OEM knee bolster failed. This failure, along with forward "kick" of the feet and legs of the ATD due to the lack of foot contact with a toepan and/or pedals and downward movement of the front of the wheelchair (i.e., forward pitching of the wheelchair) were all considered to have contributed to the submarining kinematics of the ATD.

After evaluating the results of the first sled-impact test of a prototype close-proximity knee restraint, modifications to the design were made and two additional sled tests were conducted. The goal was to reduce the submarining kinematics of the crash-test dummy observed in the first test. These additional tests were conducted using the SWCF equipped with a generic planar seating system to represent a typical power wheelchair while avoiding the problems associated with failure of the wheelchair seating system that occurred in the first test using a commercial power wheelchair. Also, an early prototype of an UMTRI-designed surrogate docking-securement device was used to secure the SWCF in a manner similar to the single-point commercial docking-securement devices.

Figure 2.38 shows a pre-test photo for the first additional test in which:

- the standard aluminum mounting bars for attaching the front wheels to the SWCF were replaced by steel bars to limit downward movement at the front of the SWCF,
- the shape, mounting orientation, and stiffness of the close-proximity knee-restraint were modified to better contact, capture, and control the movement of the ATD's lower torso and lower extremities,
- a toepan was added to the test setup to limit and control forward movement of the ATD's feet and legs, and
- a different adhesive was used to attach the close-proximity knee restraint to the production knee restraint and for attaching layers of knee-restraint material with different stiffness values.

Figure 2.39 and Figure 2.40 show time-sequence frames from the side-view and close-up (to knee restraint) rear-oblique high-speed videos of this test. The ATD kinematics are improved over those in the first test with good upper and lower body restraint and little evidence of ATD submarining. However, the ATD's right foot slipped behind the SWCF foot support during sled acceleration to pre-impact speed and therefore did not move forward as expected during the frontal impact. Also, the lower portion of the shoulder belt did not stay near the ATD's hip but moved up on the ATD's torso to load the upper-right portion of the abdomen and chest. The peak femur loads of 3782 N (left) and 4417 N (right) measured during the test are somewhat higher than those predicted by the MADYMO simulations.

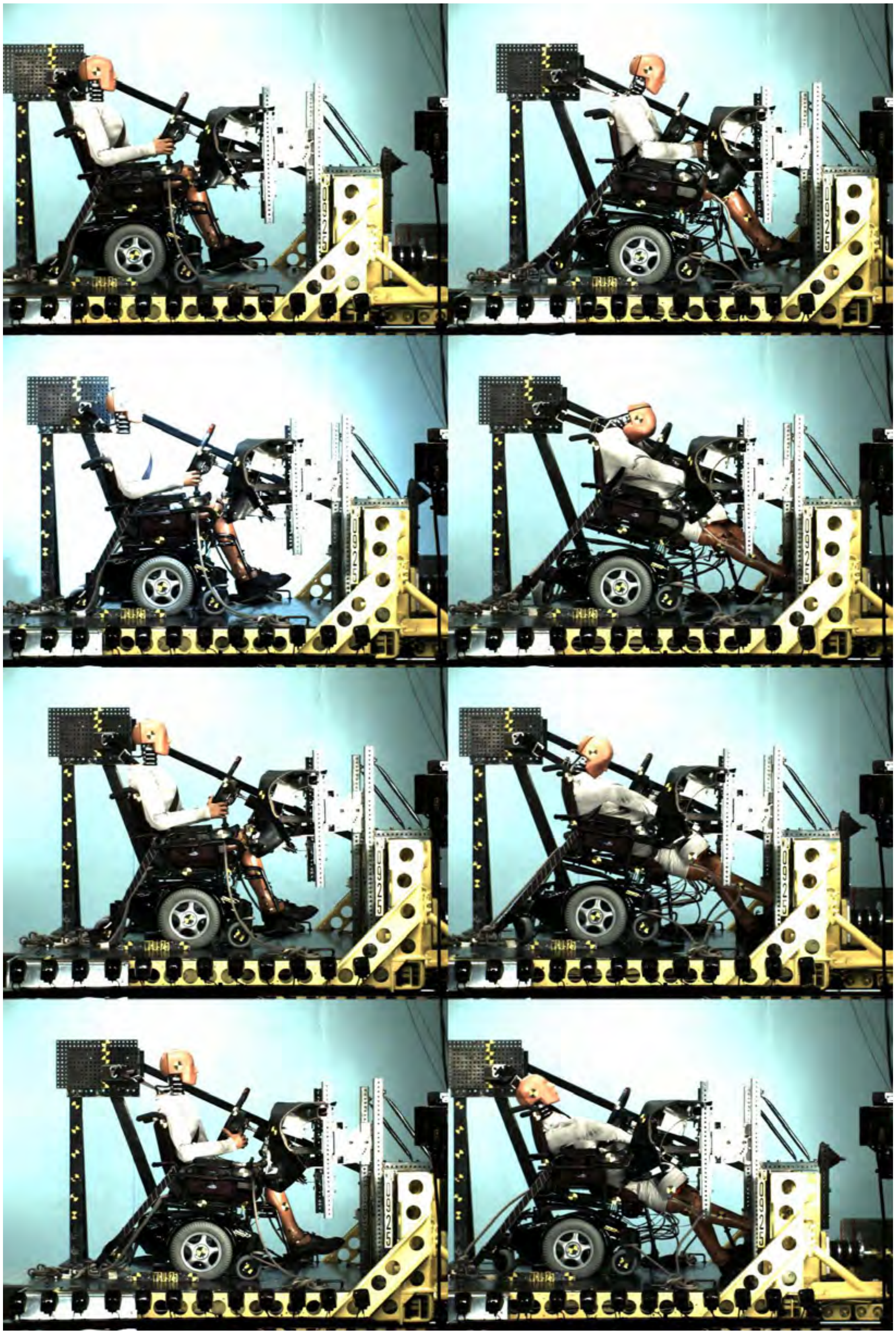


Figure 2.37 – Time-sequence frames of the lateral-view high-speed video showing submarining ATD kinematics during a 48-kph, 20-*g* frontal-impact sled test with the ATD restrained by a prototype close-proximity knee restraint and a two-point shoulder belt

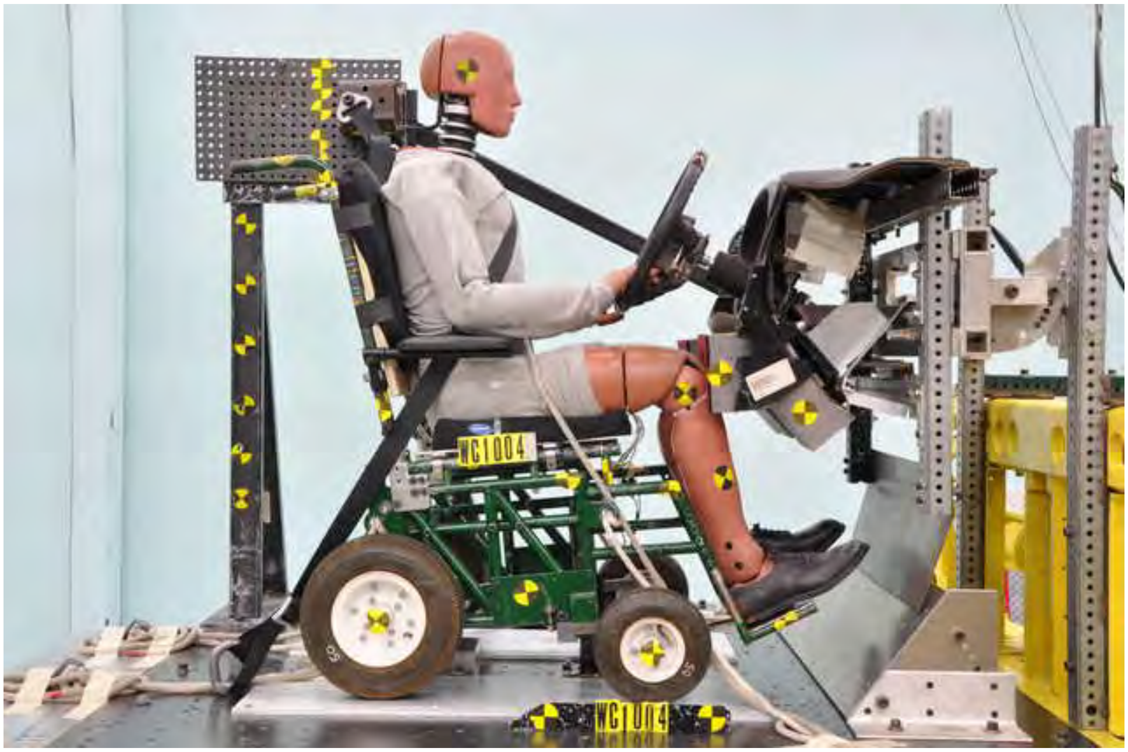


Figure 2.38 - Pre-test side view photo prior to the second test of the close-proximity knee restraint plus two-point shoulder belt

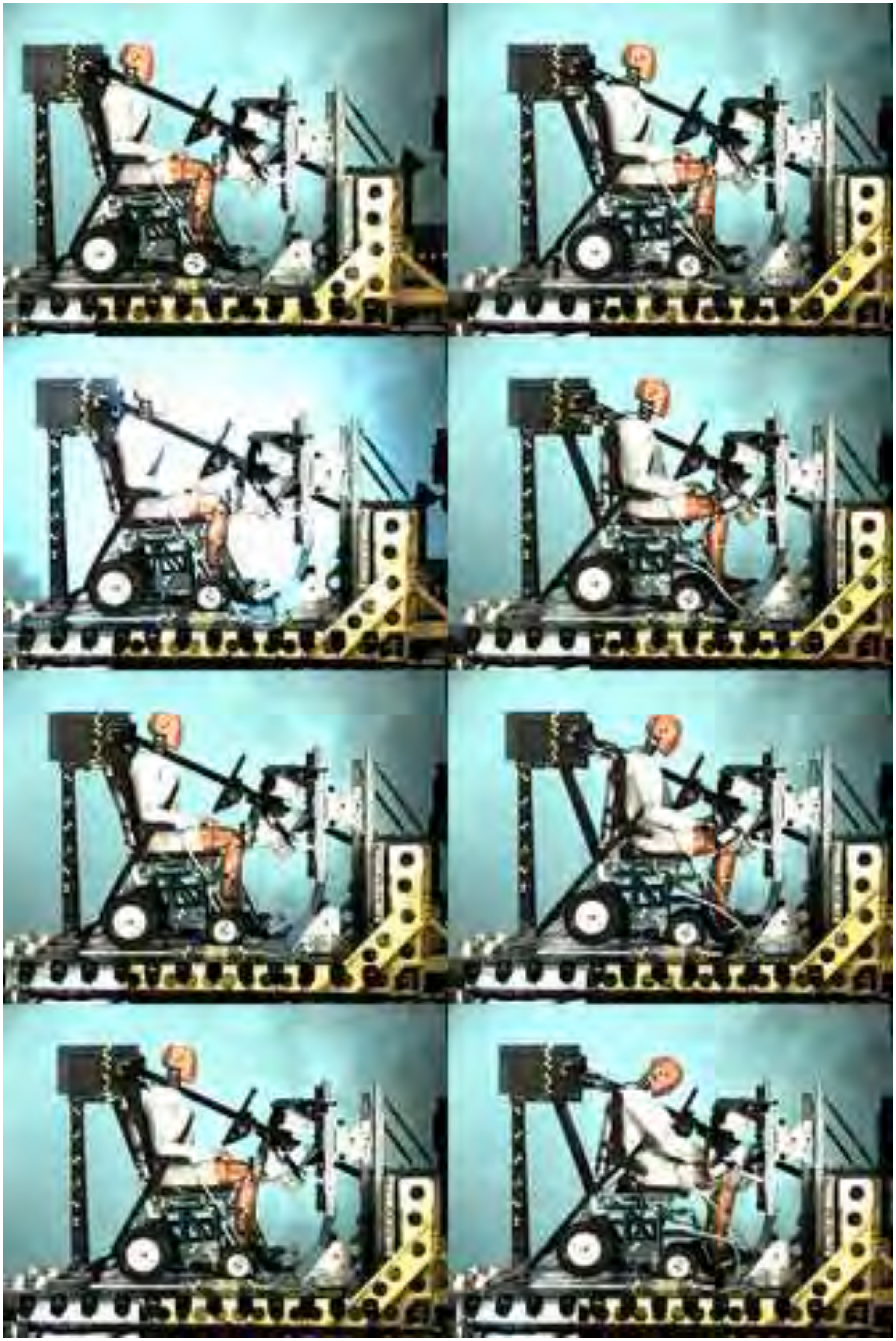


Figure 2.39 - Time-sequence frames of the side-view high-speed video during a 48-kph, 20-*g* frontal-impact sled test with the ATD restrained by a modified close-proximity knee restraint and a two-point vehicle-anchored shoulder belt

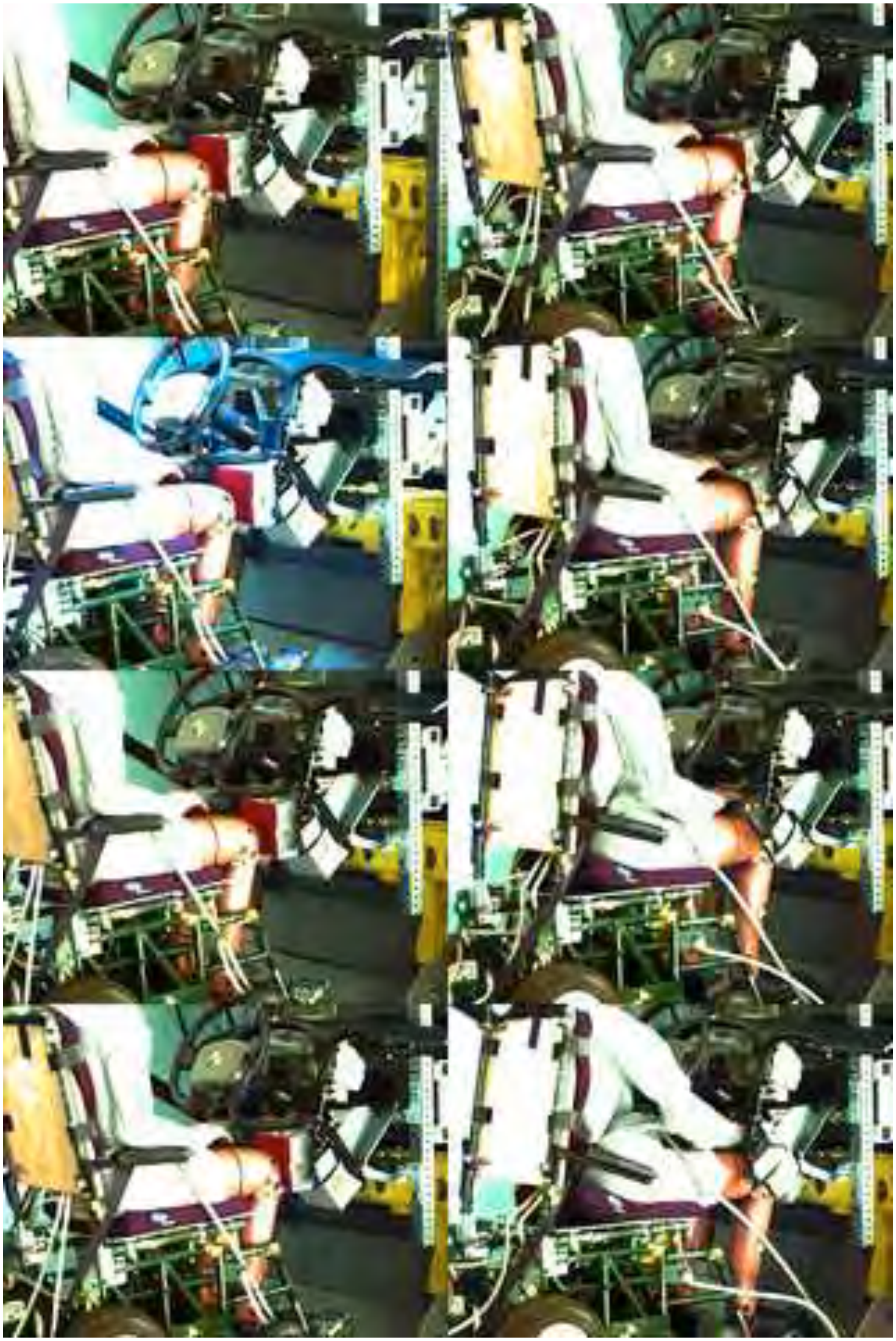


Figure 2.40 – Time-sequence frames from a close-up high-speed video showing interaction of the ATD’s knees with the improved prototype close-proximity knee restraint

The third and final sled test of the close-proximity knee-restraint was conducted with linkages of adaptive hand controls placed between the close-proximity knee restraint and the production knee bolster. In this test, it was also desired to evaluate a modified version of the two-point shoulder belt that included a length of webbing sewn to the shoulder belt near the ATD's right hip and attached to the sled platform just to the right of the SWCF's right-front wheel. This was added in an attempt to keep the shoulder belt from riding up on the ATD's torso and thereby reduce shoulder-belt loading of the upper-right region of the abdomen, which has been shown to increase the risk of liver injuries to drivers using two-point shoulder belts (Augenstein et al., 1995; Jolly and Grebing, 2997).

Figure 2.41 is a pre-test side-view photo that shows the ATD and the length of webbing added to the shoulder belt. Figure 2.42 shows the side-view time-sequence frames from the side-view high-speed video of this test. Unfortunately, the length of webbing connecting the shoulder belt to the sled platform did not perform as intended in keeping the shoulder belt from moving up and loading the upper-right region of the abdomen. Also, the left side of the add-on close-proximity knee restraint came free of the production knee bolster and the ATD femur loads were 5056 N (left) and 6637 N (right), which are significantly higher than those predicted by the MADYMO simulations.

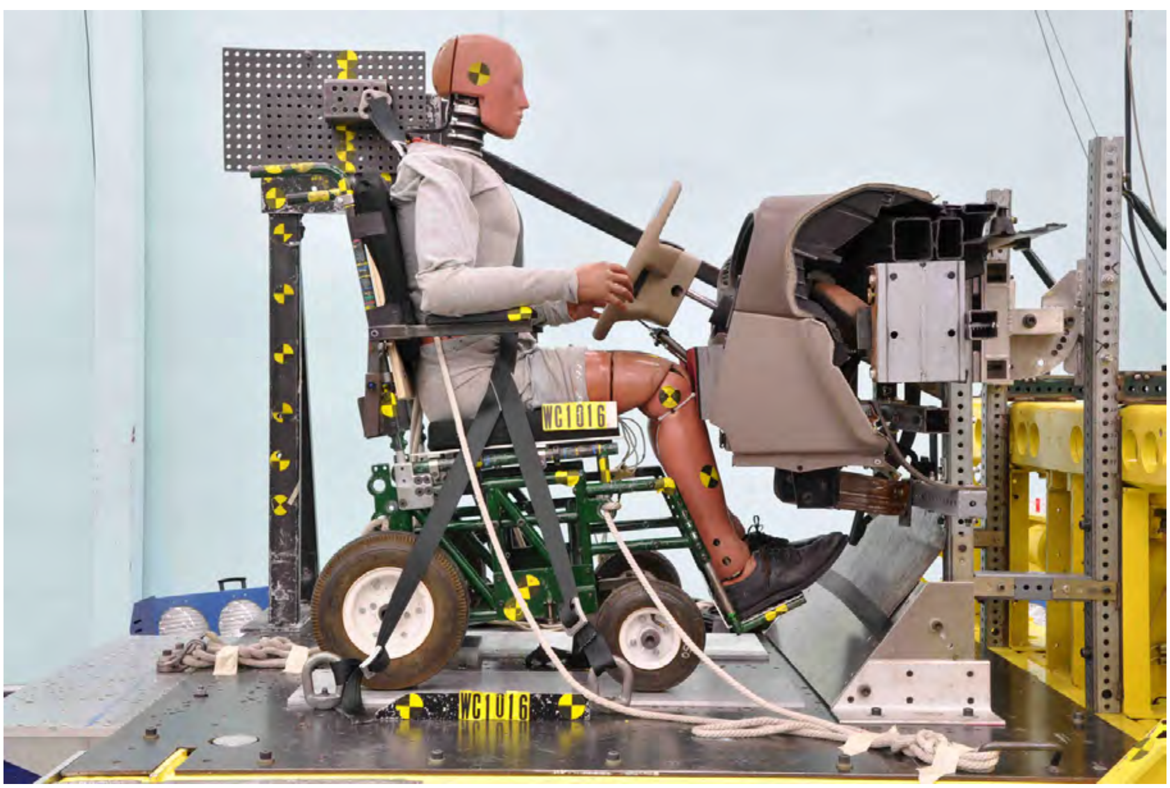


Figure 2.41 - Pre-test photo of setup for the third frontal-impact sled test of the close-proximity knee-restraint with a modified two-point shoulder belt

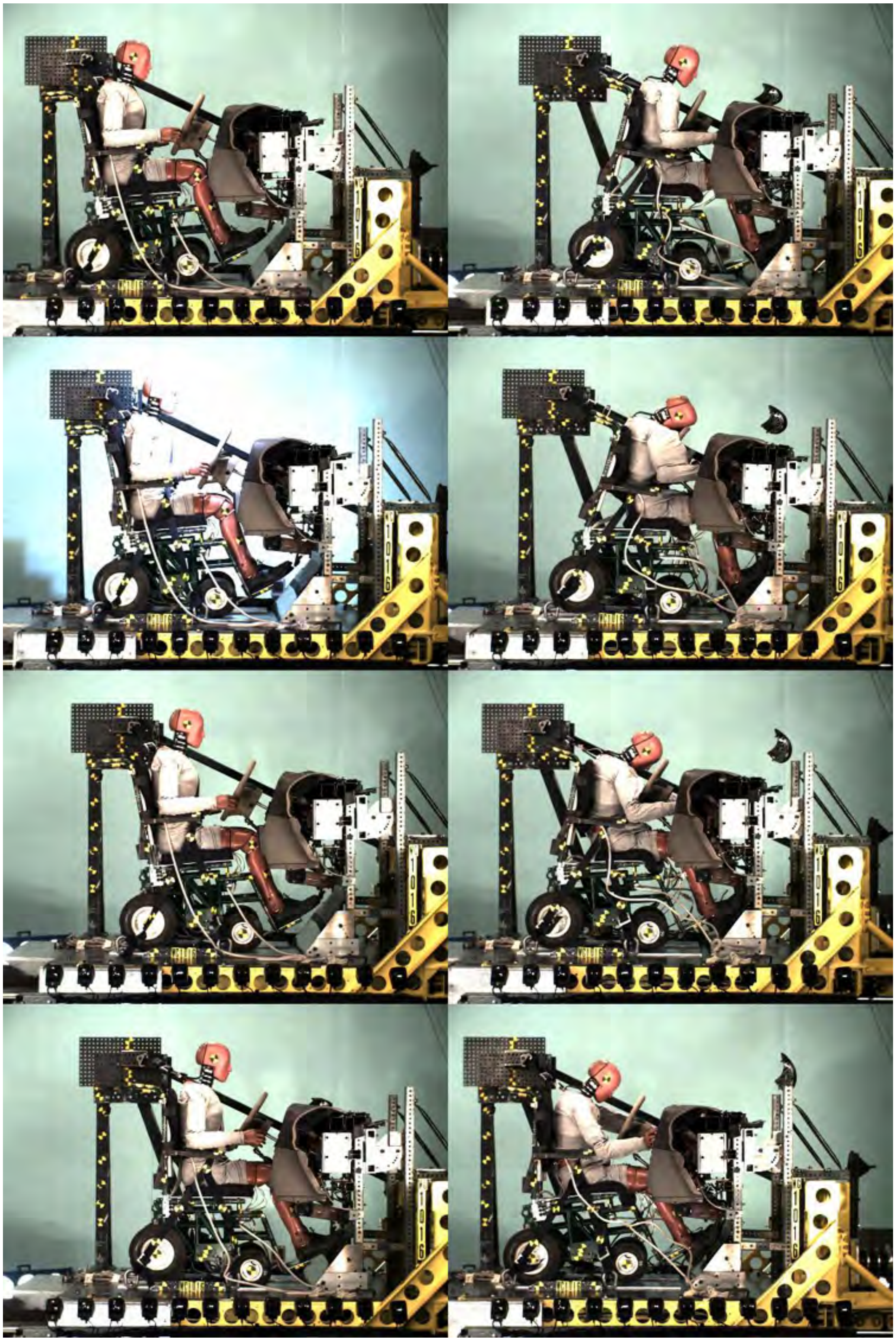


Figure 2.42 –Time-sequence frames from the side-view high-speed video of the third frontal-impact sled test of the close-proximity knee restraint plus modified shoulder belt

Discussion of close-proximity knee restraint concept

The results of the minivan mockup, computer simulations, and frontal-impact sled tests showed some potential for the close-proximity knee restraint concept as an alternative to a lap belt for providing lower-torso restraint of drivers seated in wheelchairs with closed-front arm supports during frontal crashes when used with some type of passive belt restraint for the upper torso. However, there were also several concerns and problems that led to a decision to abandon this approach. These include:

- the challenge and cost of customizing each add-on knee restraint to each driver's position and geometry and the geometry of each vehicle's instrument panel, knee restraint, and hand controls,
- problems with fastening the add-on knee restraint to the OEM knee restraint in a manner that would hold it in position during knee loading in moderate-to-severe frontal crashes while not interfering with the movement of hand control linkages, and allowing for removal of the add-on knee restraint when the vehicle is used by other drivers,
- concerns about contact between the driver's legs and the surface of a close-proximity knee restraint that could cause skin ulcers and sores due to vehicle movement and vibration during normal driving,
- the inability to achieve consistently low peak forces on the ATD's knees in sled tests with prototype close-proximity knee restraints due to variations in lower-extremity kinematics and interaction with the ATD's knees with the close-proximity knee restraint, and
- reduced restraint effectiveness and increased risk of driver ejection from the vehicle during vehicle rollovers compared to drivers using lap/shoulder-belt restraints.

Table **2.8** provides a summary of the peak femur loads from the three sled-impact tests and other ATD response measures. As indicated by bold font in shaded cells, the only response variables that exceed IARVs are HIC-15 and Nij values in the first test. A review of the high-speed video for this test indicates that these high values are likely due to the ATD's chin striking the chest due to "submarining" kinematics, and are not due to head contact with the steering wheel. Although the ATD's head contacted the upper steering-wheel rim in the third test because of the lack of airbag deployment, this did not result in a HIC-15 value that exceeds the IARV.

Table 2.8 - ATD Responses of Hybrid III midsize-male ATD from three 48-kph, 20-*g* frontal-impact sled tests of the close-proximity knee restraint with two-point shoulder belt and no air bag deployment
(values in bold exceed the IARV levels of Table 2.6)

ATD Response Measure	WC0925	WC1004	WC1016
Head: HIC 15	**860**	352	441
Neck: Nij	**1.05** (Nte)	0.55 (Ntf)	0.55 (Ntf)
Critical Intercepts			
Tension/Compression (N)	3605/-273	2377/-2	2497/-43
Flexion (Nm)	140	88	51
Extension (Nm)	-100	-44	-49
Thorax:			
Chest deflection (mm)	24	32	24
3-ms chest acceleration (*g*)	41	39	49
Femur: Peak force (kN)	L: 2409 R: 3987	L: 3782 R: 4417	L: 5056 R: 6637

Nte = Nij for tension/extension; Ntf = Nij for tension/flexion

2.4.3.6 Development and validation of a surrogate wheelchair docking-securement system

Need for a surrogate docking-securement device

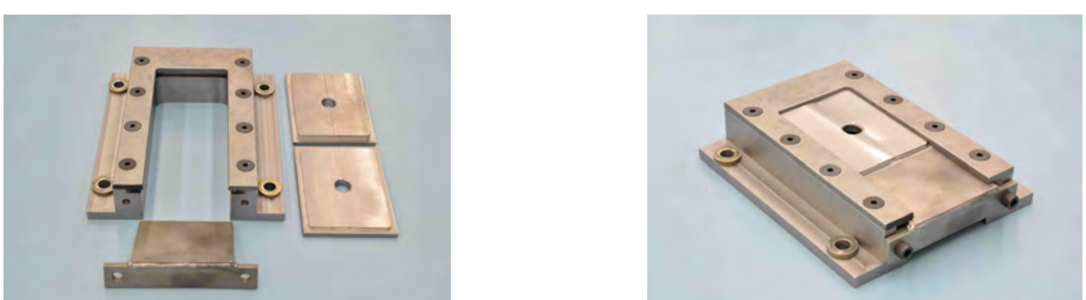
For the last two sled-impact tests of the close-proximity knee restraint reference was made to securing the surrogate wheelchair frame using an early version of a surrogate docking device. This device was developed in anticipation of the need to conduct several additional sled-impact tests during the remainder of Subtask 2 and for Subtask 3 (wheelchair driver interactions with deploying air bags). UMTRI therefore set out to design and validate a surrogate docking-securement device (SDSD) that could be used repeatedly in sled-impact tests but that would mimic the performance of commercial docking-securement devices, thereby avoiding the cost of purchasing a new commercial docking-securement system for each sled test.

Design concept

Since the most common docking securement system used by drivers seated in wheelchairs uses a single securement bolt suspended upside down under the wheelchair that is captured by a docking mechanism on the vehicle floor, this design concept was also used for the surrogate docking-securement device. In developing the SDSD, it was desired to achieve a balance among the following design and performance criteria:

a) be reusable except for a low-cost replaceable component that would permanently deform during loading by the securement bolt in a manner similar to deformations observed for commercial docking-securement devices,
b) produce forces on the docking-securement device and wheelchair, and wheelchair kinematics, that are representative of forces and wheelchair kinematics produced by commercial docking-securement devices, and
c) be user friendly when securing and removing wheelchairs from the device before and after a sled-impact test.

To achieve the desired balance in these design and performance criteria, several design iterations were examined and tested before arriving at the design shown in the photos of Figure 2.43. A key feature of the design is the upper plate with a clearance hole into which the docking-securement bolt on the wheelchair is placed. This plate is the only deformable and replaceable part and must be relatively easy to insert into the U-shaped docking-securement block before a test and relatively easy to remove and replace when deformed after a test. It must also be effectively retained in place throughout each test.



a b

Figure 2.43 - Photos of the final design of the surrogate docking-securement device: a) disassembled with two thicknesses of deformable/replaceable plates; b) assembled

Testing and validation

In developing and finalizing the final design of the SDSD, nine sled-impact tests were conducted using different versions of the surrogate docking-securement device when used to secure an 87-kg surrogate wheelchair (SWC) loaded with the midsize-male Hybrid III ATD restrained by a surrogate three-point lap/shoulder belt restraint system with the lap belt anchored to the SWC. Tests were also conducted with commercial docking securement adaptors installed on the SWC and without a front stabilizer bracket.

The primary differences across the nine tests were the thickness and hardness of the deformable steel inserts in which the docking securement bolt was secured. These conditions included plate thicknesses of 6.35 mm (1/4"), 7.94 mm (5/16"), and 9.53 mm (3/8") and both hot-rolled and cold-rolled steel. In addition, tests were conducted with and without a 44.5 mm (1-¾") diameter steel washer placed on the head of the securement bolt to distribute force more evenly over the deformable plate.

For all tests, the SDSD or commercial docking device was bolted to the sled platform with a set of triaxial load cells between the device and the platform so that all forces on the docking-securement device could be measured during testing. Peak forces on the securement device in the vertical (up) and fore/aft (longitudinal) directions, and peak SWC and ATD excursions were compared for tests using the SDSD and the commercial docking-securement device.

Figure 2.44 shows photos of a typical test setup and Figure 2.45 shows post-test photos for this tests and the 7.94-mm (5/16") thick hot-rolled steel plate of the SDSD after removal from the SDSD. By comparison, Figure 2.46 shows post-test photos of a test in which a 6.35-mm (1/4") thick hot-rolled steel plate was used. While the replaceable retaining plates deformed in both cases, the plastic deformation of the 6.35-mm (1/4") thick hot-rolled plate is substantially greater than for the 7.94-mm (5/16") thick hot-rolled plate. Although the 6.35-mm (1/4") thick plate resulted in greater peak excursions of the SWC and ATD that were closer to those of the excursions with the commercial docking-securement devices, this extensive deformation made removal of the plate extremely difficult upon completion of a test.

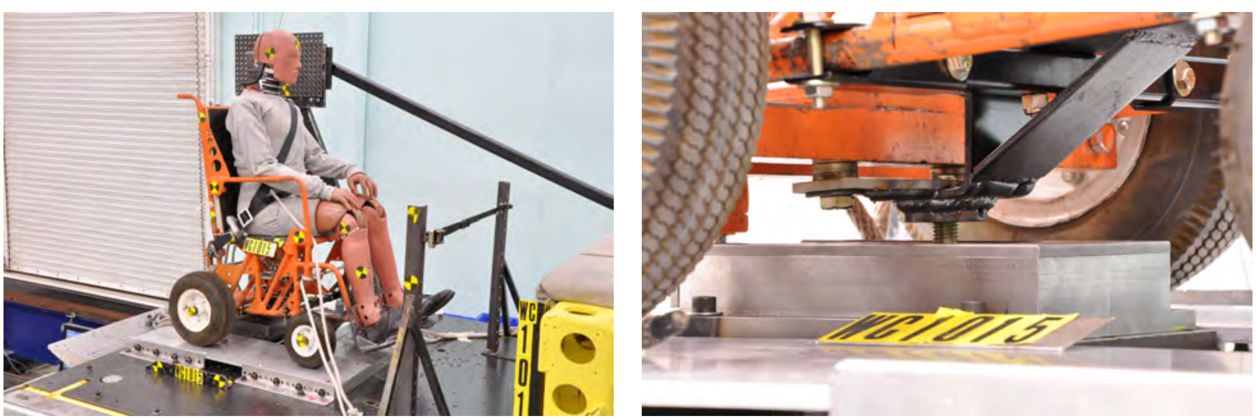


Figure 2.44 - Setup photos for a test of the surrogate docking-securement device (SDSD) with a 7.94-mm (5/16") thick hot-rolled steel plate used to secure the surrogate wheelchair (SWC) loaded with the midsize-male Hybrid III ATD restrained by a surrogate lap/shoulder belt and SWC-anchored lap belt

Figure 2.45 - Post-test photos for the sled test of Figure 2.44 showing the degree of plastic deformation of the 7.94-mm (5/16”) thick hot-rolled steel plate on the right

Figure 2.46 - Post-test photos showing plastic deformation of a 6.35-mm (1/4”) thick hot-rolled steel plate still installed in the SDSD (left) and after removal from the SDSD (right)

<u>Discussion</u>

Upon reviewing the results for all the tests, it was determined that a 7.94-mm (5/16”) thick hot-rolled steel deformable plate with a 44.5-mm (1-¾”) diameter steel washer at the head of the securement bolt provided results that were a best match to all the design and performance criteria listed above. Table **2.9** compares average values of key measurement variables from two sled tests of the SDSD with the 7.94-mm (5/16”) thick hot-rolled steel plate and washer to results for the Q’Straint-Sure-Lok QLK commercial docking device. In general there is very good agreement in the measurement variables although the peak excursions of the ATD and SWC are somewhat higher for the commercial docking-securement device than for the SDSD. Because the 7.94-mm thick plate makes the SDSD much easier to use in terms of removing the deformed plate from the docking device after a test, this plate thickness was selected as the preferred replaceable insert for most tests. However, if it is desired to conduct a sled that produces higher SWC and ATD excursions, the 6.35-mm thick hot-rolled steel plate is used to achieve the desired results.

Table 2.9 - Comparison of measurement variables for sled tests with a commercial docking-securement device with average results for two tests using the surrogate docking-securement device (SDSD) using a 7.94-mm (5/16") thick hot-rolled steel deformable plate insert and a 44.5-mm (1-3/4") diameter washer on the securement bolt

Measurement Variable	Commercial docking-securement device	Average of two tests with the surrogate docking-securement device
Sled Delta V (mph)	29.7	29.9
Sled Average Deceleration (*g*)	20.4	20.1
Total Longitudinal Peak Force (N)*	46,638	50,908
Total Vertical Peak Force (N)**	43,181	41,866
Resultant Head Acceleration (g)	55.0	49.8
HIC (15)	281	206
3-ms clipped chest acceleration (g)	50.4	45.7
Peak Resultant Pelvic acceleration (g)	62.7	68.6
Peak Resultant Force at Upper Neck (N)	2293	2,122.0
Peak Resultant Force at Lower Neck (N)	2843	2,897.5
Peak Lap-Belt Load (N)	13,503	12,798.0
Peak Shoulder-Belt Load (N)	11,255	11,086.0
Peak SWCF Point-P Excursion (mm)	117.1	93.9
Max Forward Head Excursion (mm)	420.3	292.8
Max Forward Knee Excursion (mm)	290.4	249.5

- The total longitudinal peak force is the peak value of the sum of the force-time curves measured in the direction of sled travel from all triaxial load cells used to attach the docking device to the sled platform.

** The total vertical peak force is the peak value of the sum of the force-time curves measured in the vertical direction from all triaxial load cells used to attach the docking device to the sled platform.

2.4.3.7 Seat belt deployment system (SBDS)

<u>Design and evaluation in minivan buck</u>

Following development and evaluation of the belt-restraint systems and close-proximity knee restraint described above, it was determined that a modification of the pivoting-bar seat-belt system described in Section 2.4.3.4 offered the most promising solution for a passive lap/shoulder belt with the potential to improve both the ease of use as well as frontal-crash protection for drivers seated in wheelchairs. As with the pivoting-bar system, this design makes use of the vehicle-manufacturer's (i.e., OEM) lap/shoulder-belt restraint system and, perhaps more importantly, it eliminates obstacles to maneuvering a wheelchair into the driver space.

The latter was determined to be a significant negative feature of the pivoting-bar restraint system during evaluations in the static minivan buck. Also, in the driver study described in Section 2.3, components mounted to the vehicle floor, such as the inboard floor-mounted cable stalk, were found to be a particular problem for many drivers seated in wheelchairs most of whom enter their vehicle from the passenger-side door. In this study of drivers using their personal vehicles, drivers frequently had difficulty maneuvering into the driver space. Drivers often required several trials of back-and-forth movements of their wheelchair to maneuver around the inboard lap-belt anchorage and align their wheelchair with the docking-securement device.

The photos in Figure 2.47 show an early prototype of the new seat-belt design installed in the minivan buck. The system is referred to as the seat-belt-deployment system, or SBDS, since it deploys a passive (pre-buckled) lap/shoulder belt into position on a driver seated in a wheelchair after the driver has moved his/her wheelchair into the driving and locked-down position.

The key feature of the SBDS is a DC pivoting arm, or bar, driven by a DC motor mounted to the vehicle floor near the center instrument panel on the right side of the driver space. The end of the bar is fitted with an anchorage pin (Figure 2.47b) that engages with a solenoid-activated anchorage mechanism recessed into the vehicle floor (Figure 2.47c) at a location that is behind and to the right of where the driver's wheelchair will be positioned when it is secured for driving.

A webbing-sensitive emergency locking retractor (ELR) is attached near the end of the pivoting bar on the side opposite the anchorage pin (Figure 2.47b). The end of the webbing from this retractor is fitted with a seat-belt buckle receptacle that is compatible with the latch plate on the OEM lap/shoulder belt. The seat belt is buckled with the pivoting bar in the up or stored position and a break-away seat-belt retainer (Figure 2.47d) is attached to the shoulder-belt behind the upper D-ring and tethered to the D-ring anchorage so that the seat belt remains in an extended mode with the buckle located close to the end of the pivoting bar when not in use. To keep the belt webbing from hanging down on the floor, the belt is draped over a steering assist device, such as a spinner knob or tri pin, when not in use (Figure 2.47a).

As shown in the sequence of photos in
Figure 2.48 taken in the static minivan buck, after the driver moves his/her wheelchair into the driver station and secures their wheelchair in a docking-securement device, he/she activates the SBDS by depressing an accessible switch or button. This causes the top of the pivoting arm to rotate rearward and down until the pivoting bar is lying horizontal on the floor with the anchorage pin captured in the recessed anchorage mechanism. As the pivoting bar moves down, the webbing on the ELR retractor spools out and the driver lifts the belt webbing off the steering wheel and guides the lap belt into contact with his/her lower pelvis.

As shown in
Figure 2.48C, with the pivoting arm in the down and locked position, the seat belt provides an excellent fit to the occupant with the lap belt low on the pelvis and/or upper thighs, and with a lap-belt angle of about 45 degrees to the horizontal. In the demonstration shown in the photos, the wheelchair is equipped with cantilevered open-front arm supports, which greatly facilitate proper positioning of a passive belt restraint on a driver seated in a wheelchair.

Figure 2.47 - Early version of the seat-belt deployment system (SBDS) installed in the minivan buck

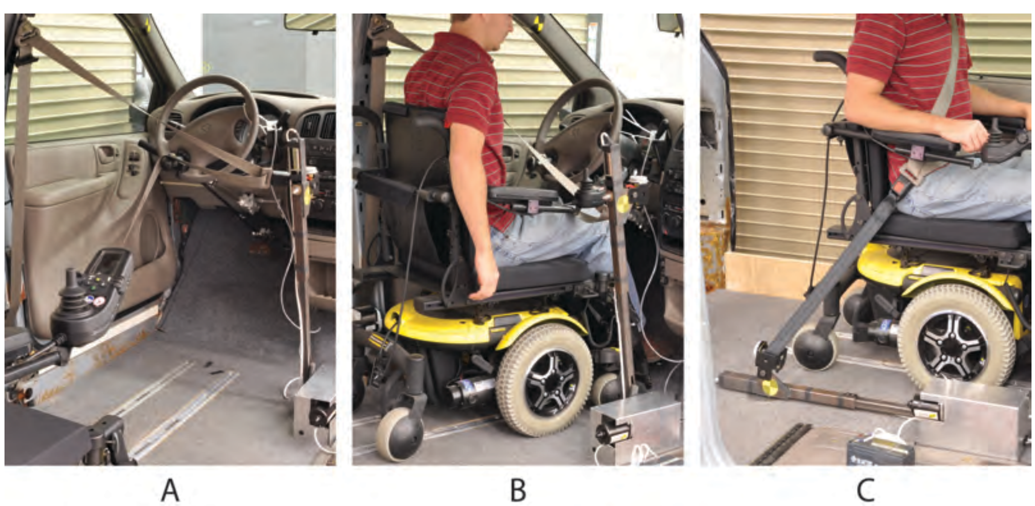


Figure 2.48 - Sequence of photos of the seat-belt deployment system (SBDS) with the pivoting arm in the up or stored position (A), with a wheelchair-seated driver after maneuvering into the driving position (B), and with the pivoting arm in the down and locked position (C).

Following development and evaluation of the first SBDS prototype in the minivan buck, several improvements were made. These include:

- reducing the size and footprint of the motor and motor housing so that it does not intrude into the right-front passenger space,
- adding a force-limiting sensor to the pivoting-arm drive mechanism to stop the bar from moving if it encounters a resistance, thereby reducing injury risk,
- adding circuitry and an algorithm to sequence through the steps of activating the solenoid to unlock the floor anchorage and retract the arm to the stored position, and
- improving the robustness of the floor anchorage mechanism.

Figure 2.49 shows a set of photos of an improved version of the SBDS in which the size of the gear drive motor and its housing have been significantly reduced.

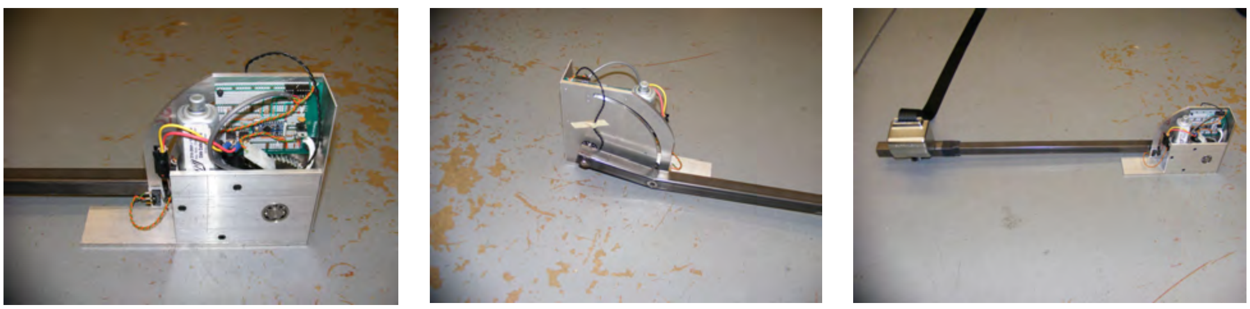


Figure 2.49 - Improved prototype of the SBDS components with smaller motor and housing, and programmable electronics to control arm movement and sequence disengagement of the floor anchorage and retraction of the pivoting arm into the stored position

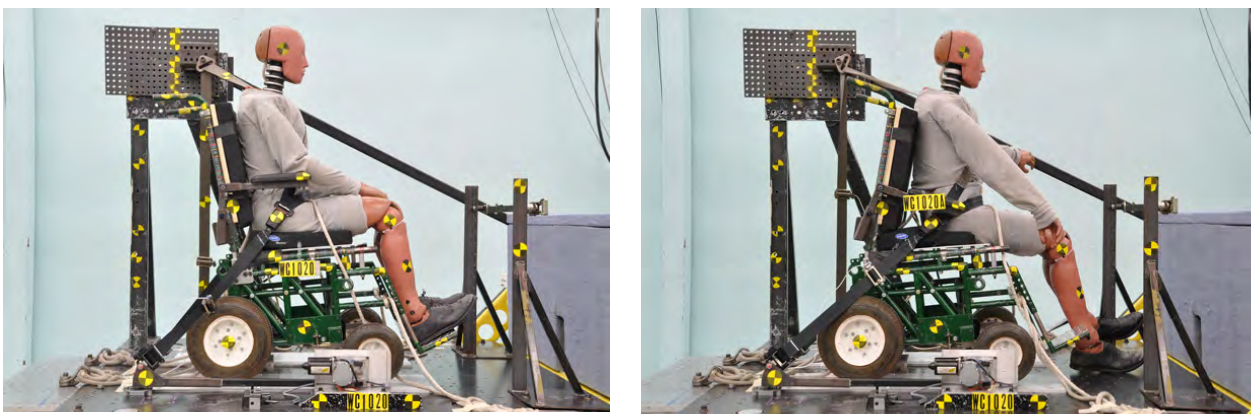
<u>Sled-test evaluation of the SBDS</u>

Several 48-kph, 20-*g* frontal sled-impact tests of different versions of the SBDS with OEM, aftermarket, and surrogate lap/shoulder belt restraints were conducted. All these tests were conducted using the surrogate wheelchair frame loaded with a midsize-male Hybrid III ATD and with a deformable back support. Figure 2.50 and Figure 2.51 show pre-test and post-test photos for the sled test of the SBDS used with a surrogate three-point belt restraint having a fixed upper shoulder-belt anchor point, and for the sled test of the SBDS used with the OEM minivan lap/shoulder belt obtained from TRC for which there is a shoulder-belt ELR retractor mounted near the sled platform below the shoulder-belt D-ring. Figure 2.52 and Figure 2.53 show time-sequence frames from the side-view high-speed videos for these two sled tests.

The SBDS performed well in all tests and none of the components failed. However, with the OEM lap/shoulder belts obtained from TRC, there was considerable spool out of the shoulder-belt retractor, which allowed higher forward movements of the ATD. As noted in Section 2.4.3.1, this high degree of retractor spool-out occurred in most, if not all, of the tests conducted at TRC (Sword, 2007). However, the reasons for this excessive spool-out remain unknown.

pre-test post-test

Figure 2.50 - Pre-test and post-test side-view photos for the 48-kph, 20-*g* frontal sled test of the SBDS used with a surrogate lap/shoulder belt with fixed upper-shoulder-belt anchor point



pre-test post-test

Figure 2.51 - Pre-test and post-test side-view photos for the 48-kph, 20-*g* frontal sled test of the SBDS used with an OEM minivan lap/shoulder belt with ELR shoulder-belt retractor

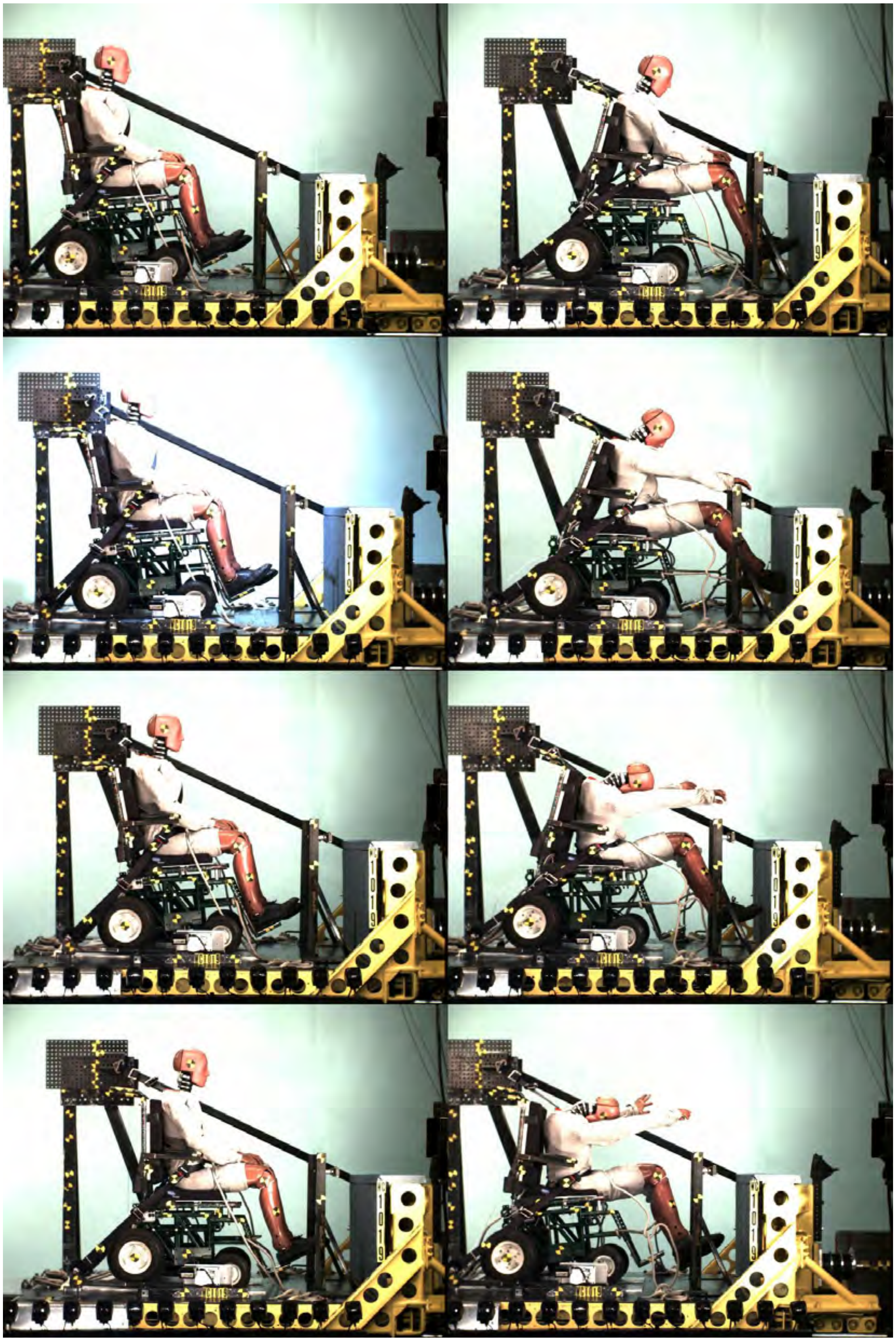


Figure 2.52 - Time-sequence frames from the side-view high-speed video of a 48-kph, 20-*g* frontal-impact sled test of the SBDS with a surrogate three-point lap/shoulder belt and fixed upper shoulder-belt anchor point

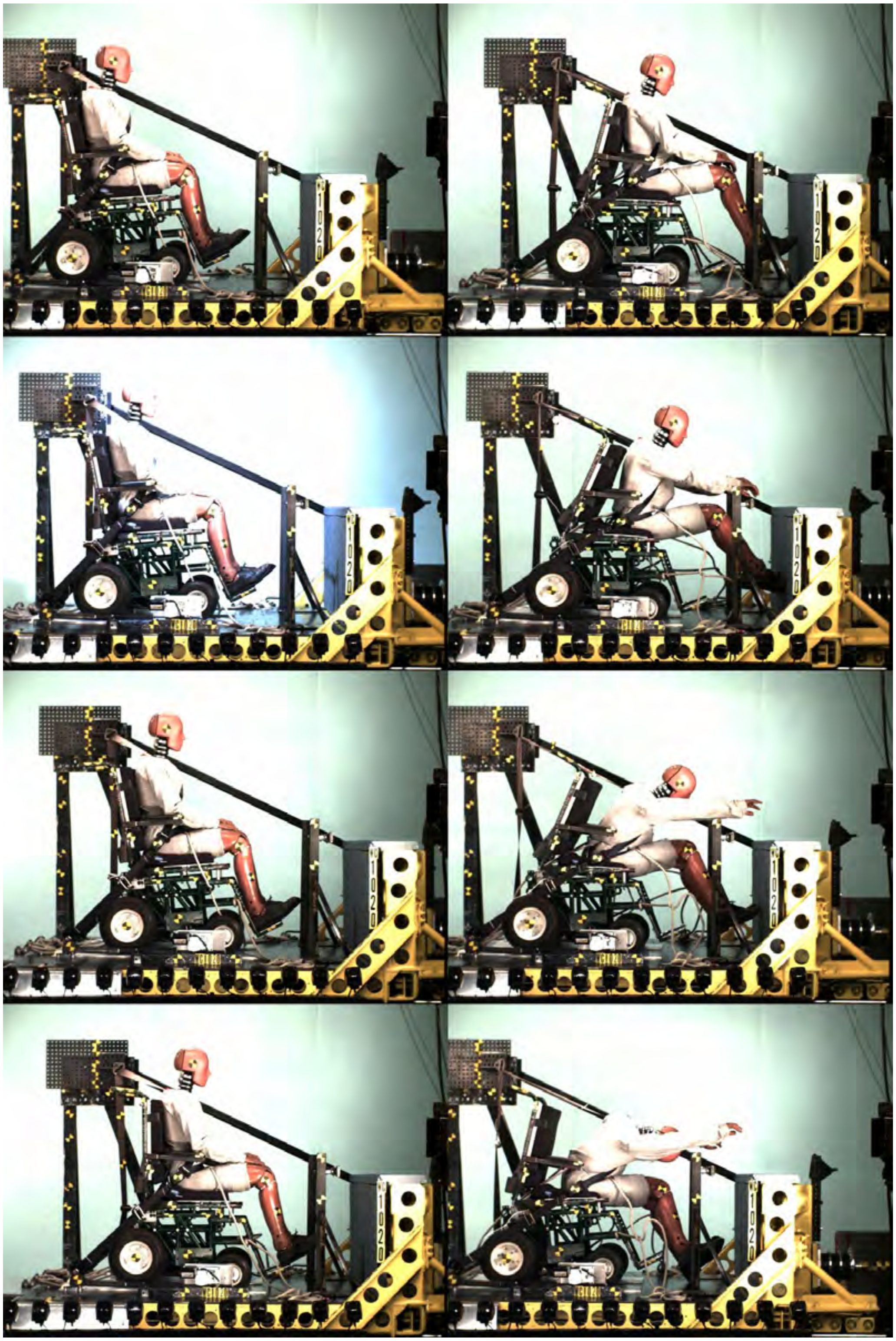


Figure 2.53 – Time-sequence frames from the side-view high-speed video of a 48-kph, 20-*g* frontal-impact sled test of the SBDS with an OEM lap/shoulder belt and upper-shoulder belt D-ring and ELR retractor

2.4.3.8 Retrofitting a power wheelchair with open-front cantilevered arm supports

As previously noted, it is most often the case that wheelchairs are prescribed by clinicians with little concern about whether or when the client will want or need to operate a personal vehicle while seated in their wheelchair. To help address this problem, educational materials (e.g., safety tip sheets and *RideSafe* and *DriveSafe* brochures described in Subtask 4) have been developed to inform and educate key stakeholders regarding their roles in providing safer transportation for people who must remain in their wheelchairs when traveling in motor vehicles. However, it is also important to be able to deal with the situation that currently exists – namely that a large percentage of wheelchair users seeking to drive a personal vehicle while seated in their wheelchair have already purchased an expensive wheelchair with closed-front arm supports. Since closed-front arm supports are a primary deterrent to attaining proper and positioning of passive lap/shoulder-belt restraint on drivers seated in wheelchairs, an activity was undertaken to determine the feasibility of retrofitting power wheelchairs that have closed-front arm supports to be equipped with open-front arm supports, thereby improving seat-belt fit during driving.

The opportunity came when one of the participants in the wheelchair-driver measurement study obtained a previously owned power wheelchair that was equipped with closed-front arm supports. Figure 2.54 shows the individual in their power wheelchair equipped with these arm supports and the resulting poor positioning of the lap belt over their abdomen when ready to drive in their personal vehicle. Figure 2.55 shows the same wheelchair retrofitted with open-front cantilevered arm supports and the improved fit of the lap belt in the minivan buck when using a vehicle lap/shoulder belt and the seat belt deployment system.

Retrofitting the arm supports on this wheelchair was performed by National Seating, Inc. and was reportedly a relatively simple matter of disconnecting the closed-front arm supports from the wheelchair and replacing them with a used pair of cantilevered arm supports that attached to the back-support posts. The joystick controller and related components were removed from the right-side closed-front arm support and attached to the right-side cantilevered arm support. According to an engineering technician at National Seating, such retrofits can be performed relatively easily on about 75% of all power wheelchairs.

a b

Figure 2.54 – Closed-front arm supports on power wheelchair (a) and poor positioning of passive lap belt over closed-front arm supports and on the abdomen (b) with the driver ready for travel in his personal vehicle

a b

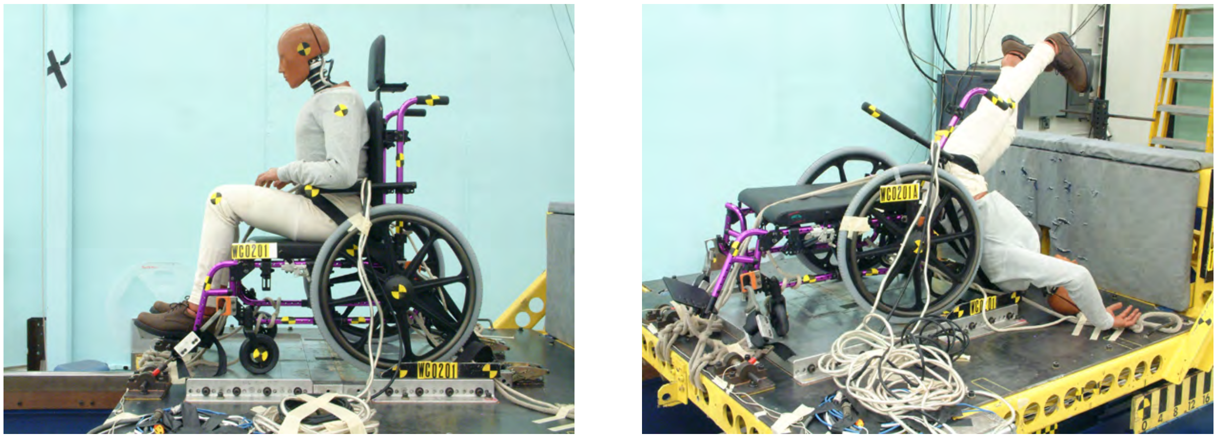
Figure 2.55 - Power wheelchair retrofitted with open-front cantilevered arm supports (a) and driver using a passive lap/shoulder belt with the seat-belt deployment system showing good fit of the lap belt low and in contact with the pelvis (b)

2.4.4 Rear-impact protection

2.4.4.1 Introduction

As has been previously noted, and as illustrated in the pre-test and post-test photos in Figure 2.56, rear-impact sled tests of wheelchairs conducted at UMTRI indicate that today's wheelchairs, and even those that have been designed and successfully frontal-crash tested to WC19, will generally not provide effective restraint for their occupants, even in moderate rear-impact collisions (Manary et al., 2007). While vehicle seat performance is important to occupant protection in frontal impact crashes, it is even more critical in rear-impact crashes where the seat back provides the primary restraint for the occupant. For this reason, WC19 and its comparable international wheelchair transportation safety (WTS) standard (ISO 7176-19) are being expanding to include procedures for evaluating wheelchairs in a rear-impact sled test using a crash pulse with a Delta V of 25-kph and a peak deceleration of 14 *g* or greater.

Because the initial implementation of this test to wheelchair transportation standards will be "informative" rather than "normative," wheelchairs that comply with WTS standards will not need to pass this rear-impact test for several years. In addition, even if every wheelchair manufacturer were to design their wheelchairs to comply with the proposed rear-impact test, it would be many years before wheelchairs that offer effective restraint for their occupants in rear impacts have penetrated the marketplace and the fleet of wheelchairs used by people who travel seated in their wheelchairs. Also, the wheelchair design features needed to comply with the proposed rear-impact criteria, such as higher and stronger back supports, may conflict with the activities of daily living for many people who use wheelchairs.



pretest posttest

Figure 2.56 - Photos of a manual WC19-compliant wheelchair and midsized male ATD before and after a 25-kph, 14-*g* rear-impact sled test

For these reasons, there is a need to address the concern of rear-impact protection for occupants traveling facing forward in motor vehicles by means of vehicle-mounted head-and-back restraint systems. This is particularly true for occupants seated in wheelchairs traveling in personal vehicles, such as minivans and full-size vans, where the likelihood of being involved in a rear-impact collision of significant magnitude is greatest because of the lower vehicle mass. In addition, for people who drive a personal vehicle while seated in their wheelchair, the driver must be able to activate movement of a vehicle-mounted head-and-back restraint system in and out of position behind their wheelchair so that it does not interfere with the driver moving into and out of the driver space.

2.4.4.2 Design and evaluation of a prototype deployable vehicle-mounted driver head-and-back restraint system

The initial effort to develop and evaluate a deployable vehicle-mounted head and back restraint for use by drivers seated in wheelchairs was made by the same BME student design team that developed the pivoting-bar vehicle-anchored lap/shoulder belt restraint system previously described for frontal crash protection. As with the pivoting-bar restraint system, this student design effort was conducted with the close oversight, supervision, and assistance of UMTRI faculty and staff.

Figure **2.57** shows photos of an early prototype of the deployable vehicle-mounted head-and-back restraint system installed in the minivan buck, and Figure 2.58 shows the head-and-back restraint deployed behind a student sitting in a wheelchair. The design uses a back-restraint frame constructed of welded steel tubing that is attached to, and pivots on, two hinges anchored to the driver-side B-pillar. A steel bar connected to the lower portion of the back-restraint frame by means of a rod-end bearing and clevis joint connects at the other end by means of another rod-end bearing to a block that slides on linear bearings in a Unistrut channel mounted to the vehicle's C-pillar on the driver side of the vehicle. In the stored position against the side interior of the vehicle, the end of the steel-bar linkage in the channel on the C-pillar is in the raised position. When the driver depresses an accessible button after his/her wheelchair is secured in the driver space, a linear actuator (not implemented in the prototype) would move the C-pillar end of the linkage downward, causing the back-and-head restraint to rotate into position behind the driver and their wheelchair. When the driver is ready to exit the vehicle, another accessible button would be depressed and the linear actuator would move the end of the bar linkage on the C-pillar upward, causing the back-and-head restraint to rotate back into the stored position against the side of the vehicle.

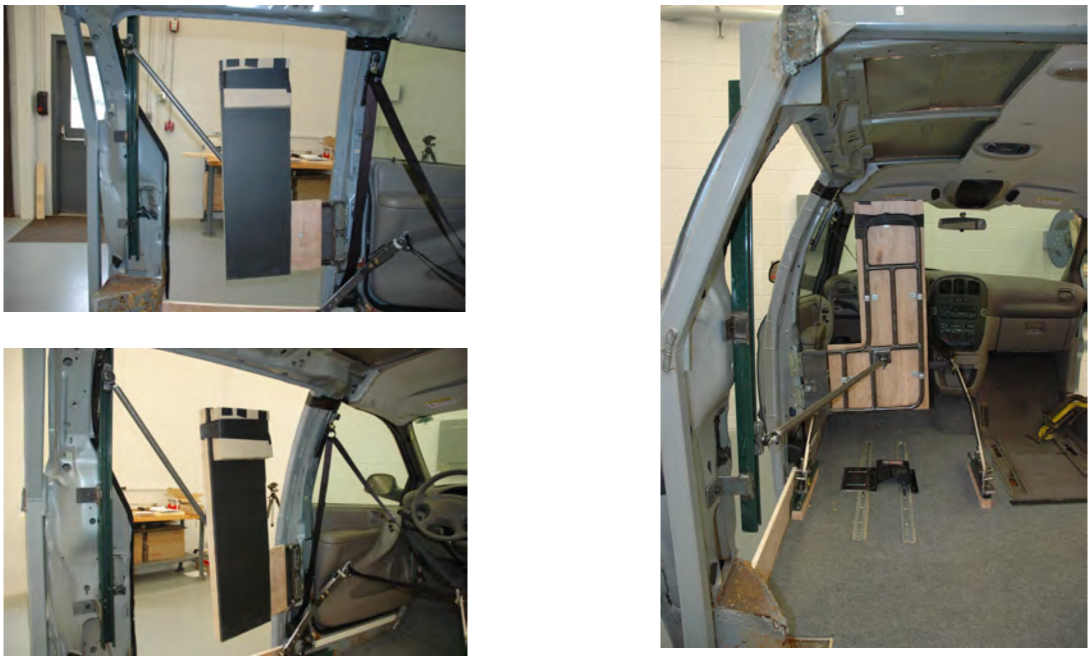


Figure 2.57 - Photos of a BME student-designed deployable vehicle-mounted head-and-back restraint system installed in the static minivan buck – the photos on the left show the head-and-back restraint in the stored position while the photo on the right shows the head-and-back restraint in the deployed position

Figure 2.58 – Early prototype of the BME student-designed deployable vehicle-mounted head-and-back restraint in the deployed position behind a student seated in a wheelchair

In addition to evaluating the prototype head-and-back restraint in the minivan buck, two rear-impact sled tests of the prototype design were conducted using a 25-kph, 14-*g* crash pulse that falls within the deceleration corridor shown in Figure 2.59. This crash-pulse acceleration corridor is representative of a moderate-severity rear impact for a passenger vehicle, and was selected to represent the crash severities used to verify that OEM vehicle seat backs have sufficient strength and integrity to restrain an occupant from rearward ejection during moderate-to-severe rear-ed collisions. As with WC19 frontal-impact sled testing, the rear-impact sled test is primarily a dynamic strength test for the wheelchair, and particular the wheelchair back support, under this loading mode. Thus, the proposed performance criteria are focused on the structural integrity of the wheelchair and wheelchair back support with regard to providing a safe and supportive seating position for the wheelchair occupant throughout the rear-impact event.

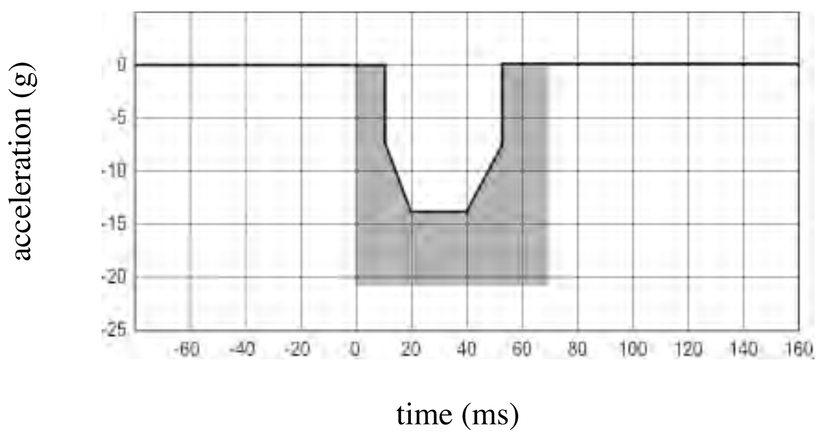


Figure 2.59 - Deceleration corridor (shaded area) for proposed rear-impact testing of wheelchairs in WTS standards now under development

Figure 2.60 shows photos of the test setup for the second of the two tests. Both tests were conducted using a new or renovated commercial Invacare Pronto power wheelchair that was secured to the sled platform using a commercial single-point docking-securement system. The wheelchair was loaded with the midsize-male Hybrid III ATD that was held in the wheelchair by a belt placed around the ATD's chest and wheelchair back support and a second belt placed over the upper part of the ATD's thighs and anchored to the sled platform. The steel bar between the back-restraint frame and the vehicle C-pillar was connected by a rod-end bearing to a simulated C-pillar mounted to the front of the sled.

In the first test, this rod-end connection at the C-pillar failed, allowing the back-and-head restraint to rotate freely about the hinges attached to the simulated B-pillar, resulting in unacceptably high ATD excursions. This weak point was fixed for the second test in which the prototype head-and-back restraint provided effective restraint for the ATD's torso and head.

Figure 2.61 shows post-test photos from the second test and Figure 2.62 and Figure 2.63 show side-view and top-view time-sequence frames from the side and overhead high-speed videos, respectively. As indicated, all components of the system remained intact and the prototype head-and-back restraint provided effective restraint for the ATD's head and back. Table **2.10** lists the values for the injury criteria from this test.

Table 2.10 - Hybrid III midsize-male response measures from the second rear-impact test (WC0914) of the vehicle-mounted head-and-back restraint

ATD Response (units)	Value
Head: HIC 15	101
Neck: Nij	0.18 (Ntf)
Critical Intercepts	
Tension/Compression (N)	1029/-171
Flexion (Nm)	16
Extension (Nm)	-14
Thorax:	
Chest deflection (mm)	Not measured
3-ms chest acceleration (*g*)	24
Femur: Peak force (kN)	Not measured

Figure 2.60 - Pre-test photos for the second rear-impact sled test of a BME student-designed vehicle-mounted head-and-back restraint

Figure 2.61 - Post-test photos of the second rear-impact sled test of a BME student-designed vehicle-mounted head-and-back restraint

Figure 2.62 – Time-sequence frames from the side-view high-speed digital video of the second rear-impact sled test of the BME student-designed vehicle-mounted head-and-back restraint

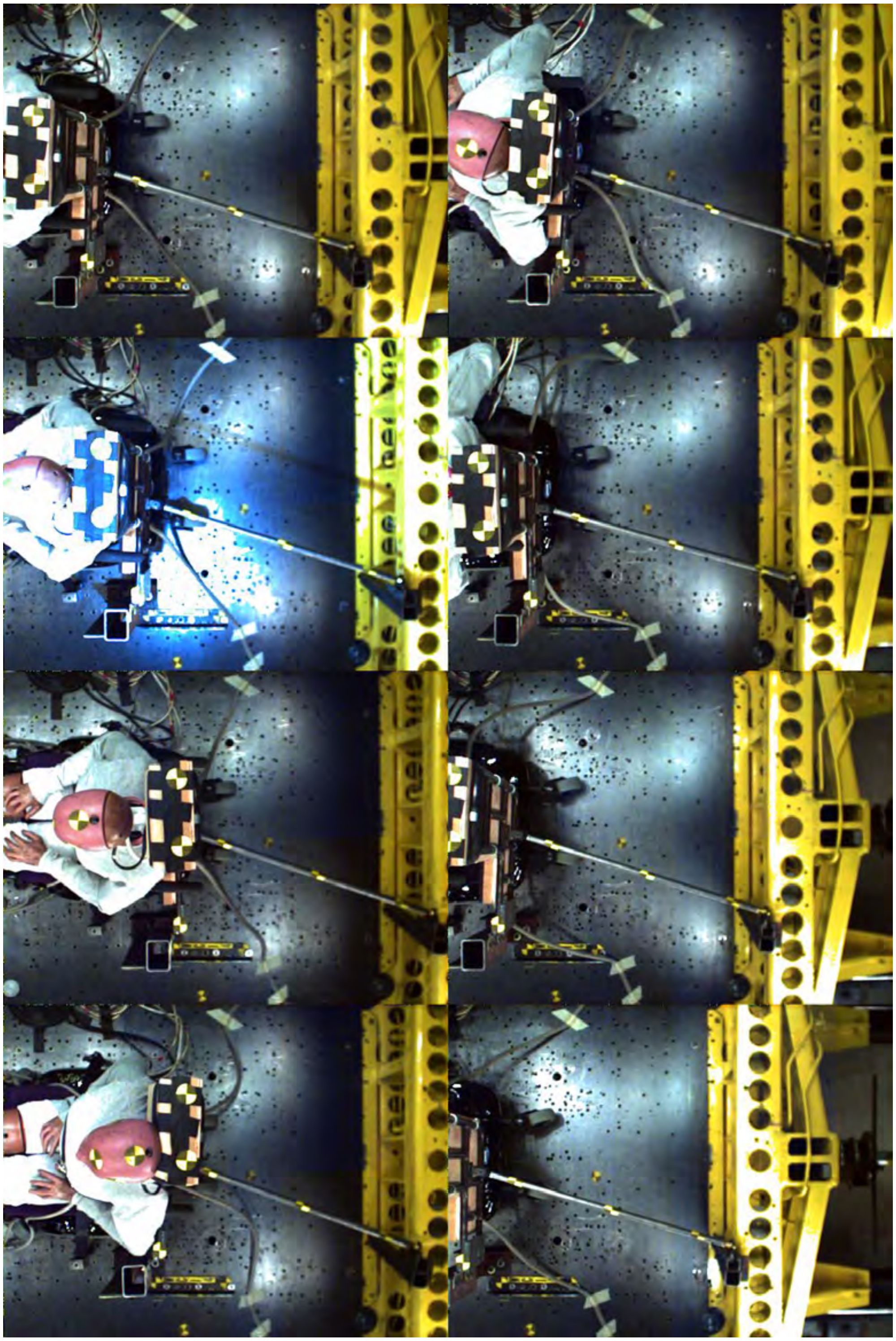


Figure 2.63 – Time-sequence frames from the overhead high-speed digital video of the second rear-impact sled test of the BME student-designed vehicle-mounted head-and-back restraint

2.4.4.3 Sled-test evaluations of a commercially available deployable vehicle-mounted driver head-and-back restraint

Although the student-designed vehicle-mounted deployable head-and-back restraint for drivers in wheelchairs was successfully tested on UMTRI's sled, it was subsequently learned during a visit to manufacturer' exhibits at the National Mobility Equipment Dealers Association (NMEDA) conference that a vehicle-mounted head-and-back restraint system that is deployed by a powered linear screw actuator contained inside a post mounted to the B-pillar was commercially available for drivers from a small company in Sweden. At the same time, a survey of several participants from the measurement study of people who drive their private vehicle while seated in a wheelchair described in Section 2.3 indicated that blocking use of the driver-side passenger door of their minivan by the linkage between the back restraint and the vehicle C-pillar was a negative aspect of the student's design for solving the rear-impact protection problem. As a result, it was decided that the best approach going forward was to conduct rear-impact sled tests of the head-and-back restraint system and, if necessary, work with the designer/manufacturer to improve the system's performance.

Upon receiving one of the Swedish head-and-back restraint systems from its inventor, the system was setup on the UMTRI impact sled for a rear-impact test using the same 25-kph, > 14-*g* sled pulse used for the tests of the student's prototype. Figure 2.64 shows photos of the setup for the first sled test. The main functional part of the Swedish system is a vertical post consisting of a fixed lower section and a rotating upper section of smaller diameter than the bottom section. The bottom section of the vertical post is mounted to the vehicle floor by means of a fixed circular base plate with curved grooves for the anchorage bolts that allow for adjusting the angular position of the unit relative to the vehicle interior. The upper rotating section of the vertical post is connected to the vehicle B-Pillar by means of a rectangular anchorage plate. The upper section of the post is allowed to rotate in this upper anchorage plate by a means of a bolt through a bearing sleeve at the top of the upper section of the post.

The padded head-and-back restraint is a single fixed assembly that does not allow for adjusting the fore-aft location of the head restraint relative to the back restraint. The assembly is connected to the upper rotating section of the vertical post by means of a manually adjustable horizontal linkage consisting of a length of round steel tubing that fits inside another length of round steel tubing. The outer horizontal tube is attached to the upper rotating section of the vertical post by means of a circular pinch clamp that is tightened around the tube by Allen bolts. A tab on the inside of the clamp engages with a vertical keyway on the tube to provide for vertical adjustment of the head-and-back restraint and prevent rotation of the clamp on the tube during impact loading. When deployed, the position of the head-and-back restraint can be adjusted laterally behind to a driver in a wheelchair by sliding the inner horizontal tube relative to the outer tube. Once adjusted, the head-and-back restraint assembly is secured in position by a bolt placed through holes in both the inner and outer horizontal steel tubes.

A linear screw actuator powered by a DC motor is located inside the bottom section of the vertical post and includes a reaction pin that is inserted through a hole in the translating end of the actuator. The reaction pin travels in a spiral slot in the upper rotating portion of the vertical post causing the head-and-back restraint to rotate into the deployed or stored position when the driver pushes an accessible switch that activates the screw actuator to move up (deployed) or down (stored).

For each test, the bottom plate of the head-and-back restraint system was bolted to the sled platform and the top of the post was attached to a simulated rigid B-Pillar structure mounted to the sled platform. The tests were conducted using the surrogate wheelchair frame (SWCF) with a surrogate seating system consisting of a planar metal seat covered with a commercially available seat cushion and a separate commercially available contoured back support with overlying cushion. The back-support posts were attached to the SWCF using highly deformable aluminum rods so that the ATD and SWCF back support would rotate to nearly horizontal orientations, or below, during impact loading in the absence of a vehicle-anchored head-and-back restraint.

The SWCF was secured facing rearward on the sled platform by the UMTRI-designed surrogate-docking device described above. A front stabilizing bracket was also used and was modified in an effort to keep the forked bar engaged with the sled-mounted stabilizing bracket throughout the test so that the head-and-back restraint would be loaded only by the ATD's torso and head and not by the complete mass of the SWCF due to rearward rotation of the SWCF frame. As will be noted below, the first attempts to achieve this were unsuccessful so that the complete SWCF rotated rearward in the first two tests (see Figure 2.66 and Figure 2.68).

For each test, the SWCF was loaded with the Hybrid III midsize-male ATD that was restrained by an SWCF-anchored lap belt and a chest belt wrapped around the SWCF back support to keep the ATD in position during sled acceleration to pre-impact speed. The motorized linear actuator inside the post was activated by a 12-volt battery to rotate the head-and-back restraint into the deployed position so that it was in contact with the SWCF back support. The posture and neck angle of the ATD were adjusted to minimize the distance between the front of the head restraint and the back of the ATD's head, but the pre-test distance was still significantly greater than the current back-set requirement of 50 mm or less specified in FMVSS 202a *Head Restraints* (49 CFR Part 571.202a) because of a lack of independent adjustment in the fore-aft positions of the back restraint and the head restraint.

Figure 2.64 - Photos showing the setup of SWCF and midsize-male ATD for the first rear-impact sled test of the deployable Swedish head-and-back restraint system

As indicated by the post-test photos in Figure 2.65 and the time-sequence photos from the high-speed digital videos in Figure 2.66 and Figure 2.67, there was considerable rotation of the head-and-back restraint in the first test due to several factors. This resulted in a high rearward head displacement of 598 mm, which is well in excess of the rearward head-excursion limit of 450 mm allowed during ATD rebound in WC19. The factors that contributed to the rearward rotation of the head-and-back restraint and therefore the high rearward head excursion include deformation (i.e. bending) of the inner tube connecting the head-and-back restraint to the vertical post, and rotation of the reaction pin within the vertical post due to deformation (i.e., dimpling) of the inner steel tubing at one end of the spiral slot in which the reaction pin travels. It can also be noted that the method for securing the forked bar to the front stabilizing bracket was not effective so that the whole SWCF rotated rearward in this test.

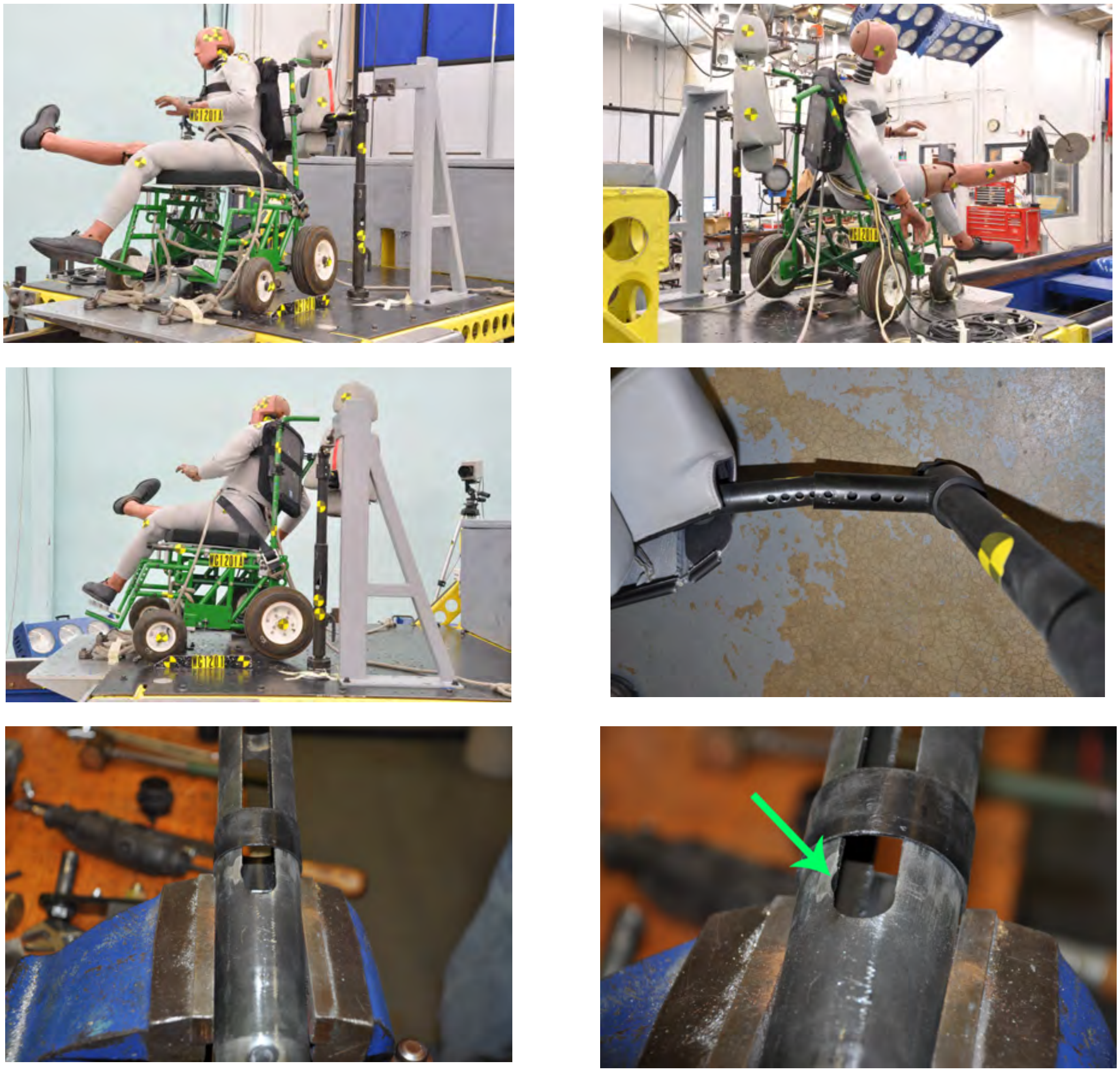


Figure 2.65 - Post-test photos of the SWCF, ATD, and head-and-back restraint components following the first rear-impact sled test of the deployable Swedish vehicle-anchored head-and-back restraint system

Figure 2.66 – Time-sequence photos from the side-view high-speed digital video of the first rear-impact sled test of the deployable Swedish vehicle-anchored head-and-back restraint system – note the rearward rotation of the SWCF

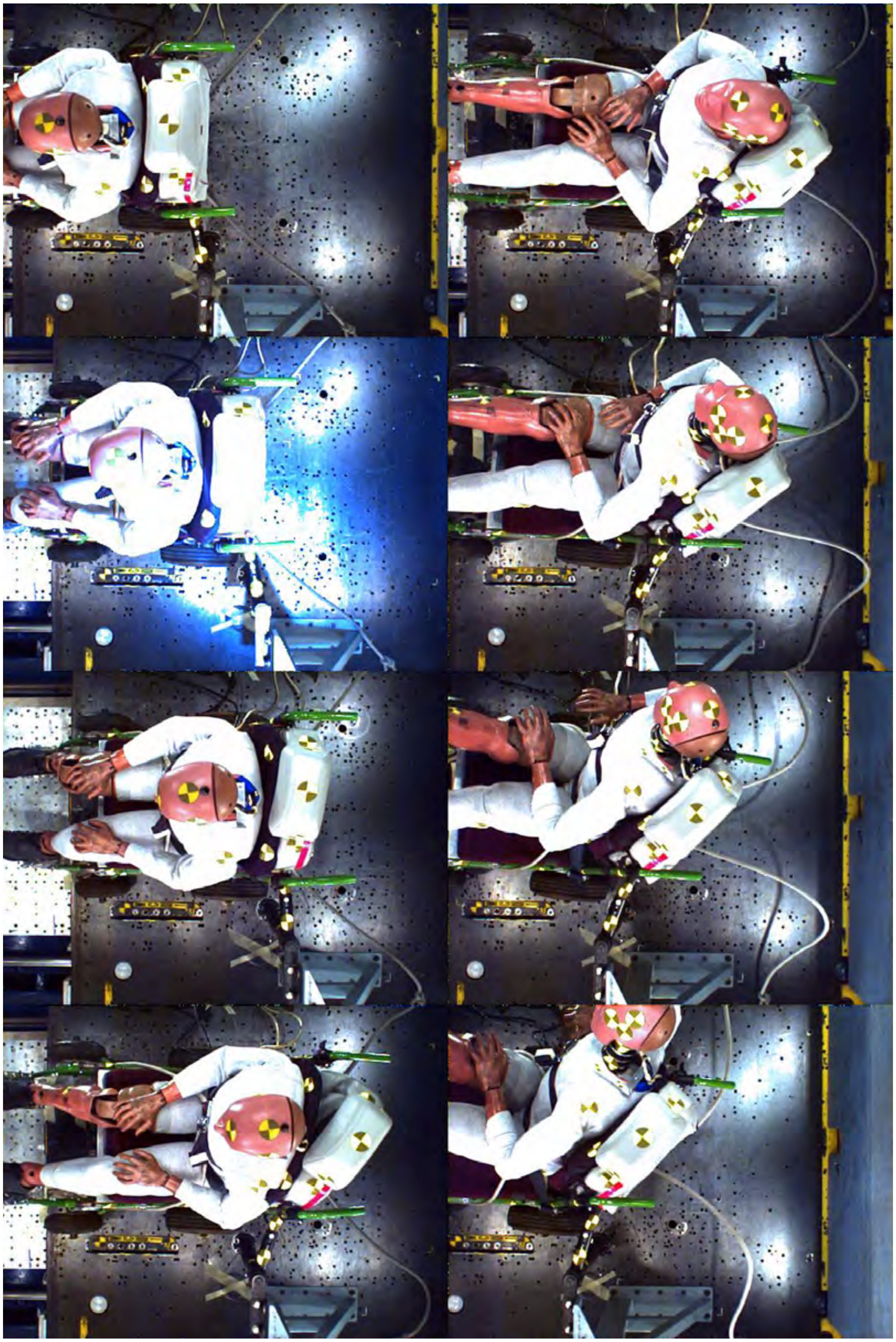


Figure 2.67 – Time-sequence frames from the overhead high-speed digital video of the first rear-impact sled test of the deployable Swedish vehicle-anchored head-and-back restraint system

In an effort to reduce bending of the inner horizontal steel tube connecting the head-and-back restraint to the vertical post, a solid steel round bar was inserted inside the inner steel tube. Also, the length of the inner tube was increased to provide greater overlap and therefore load bearing within the outer tube. However, as shown in the time-sequence photos of Figure 2.68 and Figure 2.69 for a second rear-impact test of this system, there was still excessive rotation of the head-and-back restraint and the peak rearward excursion of the ATD's head was 673 mm, which is even greater than in the first sled test. While there was no bending of the inner steel tube connecting the head-and-back restraint to the post in this test, the reaction pin rotated within the vertical post due to dimpling or mushrooming of the steel material in the spiral slot of the inner tube in which a horizontal reaction pin travels. However, as shown in Figure 2.70, more significant contributors to the rearward rotation of the head-and-back restraint were: 1) rotation of the base plate due to sliding of the anchorage bolts in curved slots and 2) failure of a plastic lead-screw drive nut on the screw actuator, which allowed the reaction pin to rotate even further.

In the final two tests, a new motorized linear actuator with a brass lead-screw drive nut was installed in the assembly. The solid steel bar was again placed within the inner horizontal tube connected to the head-and-back restraint and the base plate was positioned such that the anchorage bolts could not slide in the curved slots during rear-impact loading. Finally, the inner tube of the post assembly was replaced with a tube having a wall thickness of 6.35 mm (0.25") inches instead of the 3.68 mm (0.145") wall thickness of the original system. Since the latter would provide more surface area for loading by the reaction pin, it was thought that it would help to reduce rotation of the head-and-back restraint due to dimpling of the inner tube when loaded by the reaction pin during impact loading.

As shown in the post-test photo of Figure 2.71 and Figure 2.72, and in the time-sequence frames in Figure 2.73 through Figure 2.76, there was considerable improvement in performance during the last two tests, although the peak rearward head excursions of the test dummy were 452 and 470 mm, respectively, which are just slightly greater than the proposed excursion limit of 450 mm. Note also, that there is no rearward rotation of the SWCF in these last two tests due to improvements made in locking the forked bar to the front stabilizing bracket.

Figure 2.68 – Time-sequence frames from the side-view high-speed digital video of the second rear-impact sled test of the Swedish deployable vehicle-anchored head-and-back restraint system – note the rearward rotation of the SWCF

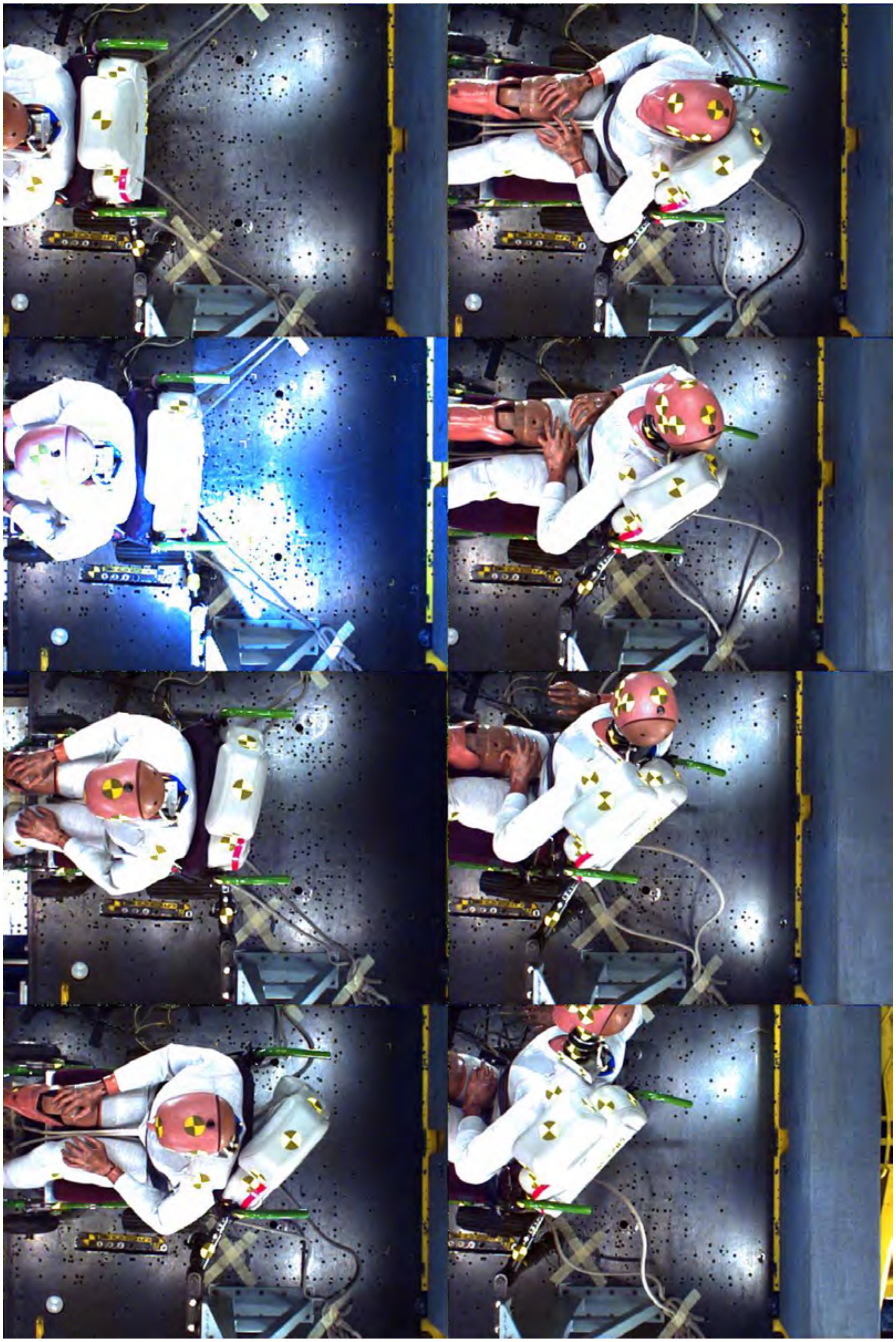


Figure 2.69 – Time-sequence frames from overhead the high-speed digital video of the second rear-impact sled test of the Swedish deployable vehicle-anchored head-and-back restraint system

Figure 2.70 - Broken plastic drive nut (upper part of photo on left) on screw-motor actuator and slippage in curved slots at the base of the Swedish head-and-back restraint post (right) that were significant contributors to the poor performance of the Swedish deployable vehicle-anchored head-and-back restraint system in the second sled test

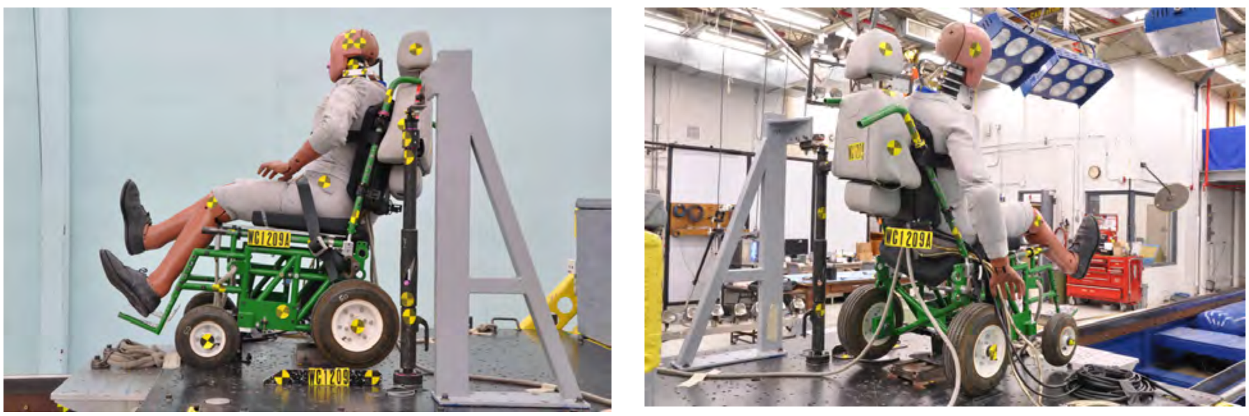


Figure 2.71 - Post-test photos from the third rear-impact test of the modified Swedish deployable vehicle-anchored head-and-back restraint system

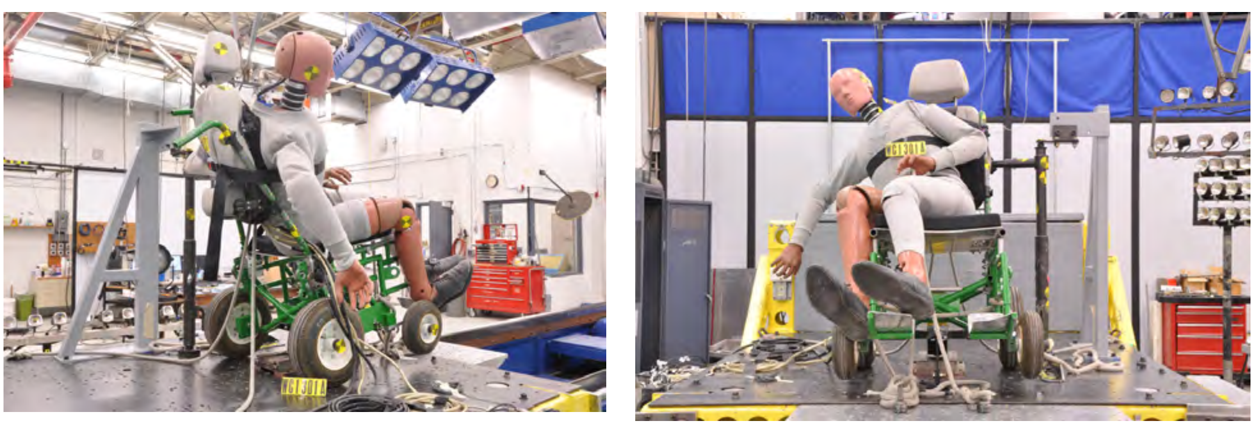


Figure 2.72 - Post-test photos from the fourth rear-impact test of the modified Swedish deployable vehicle-anchored head-and-back restraint system

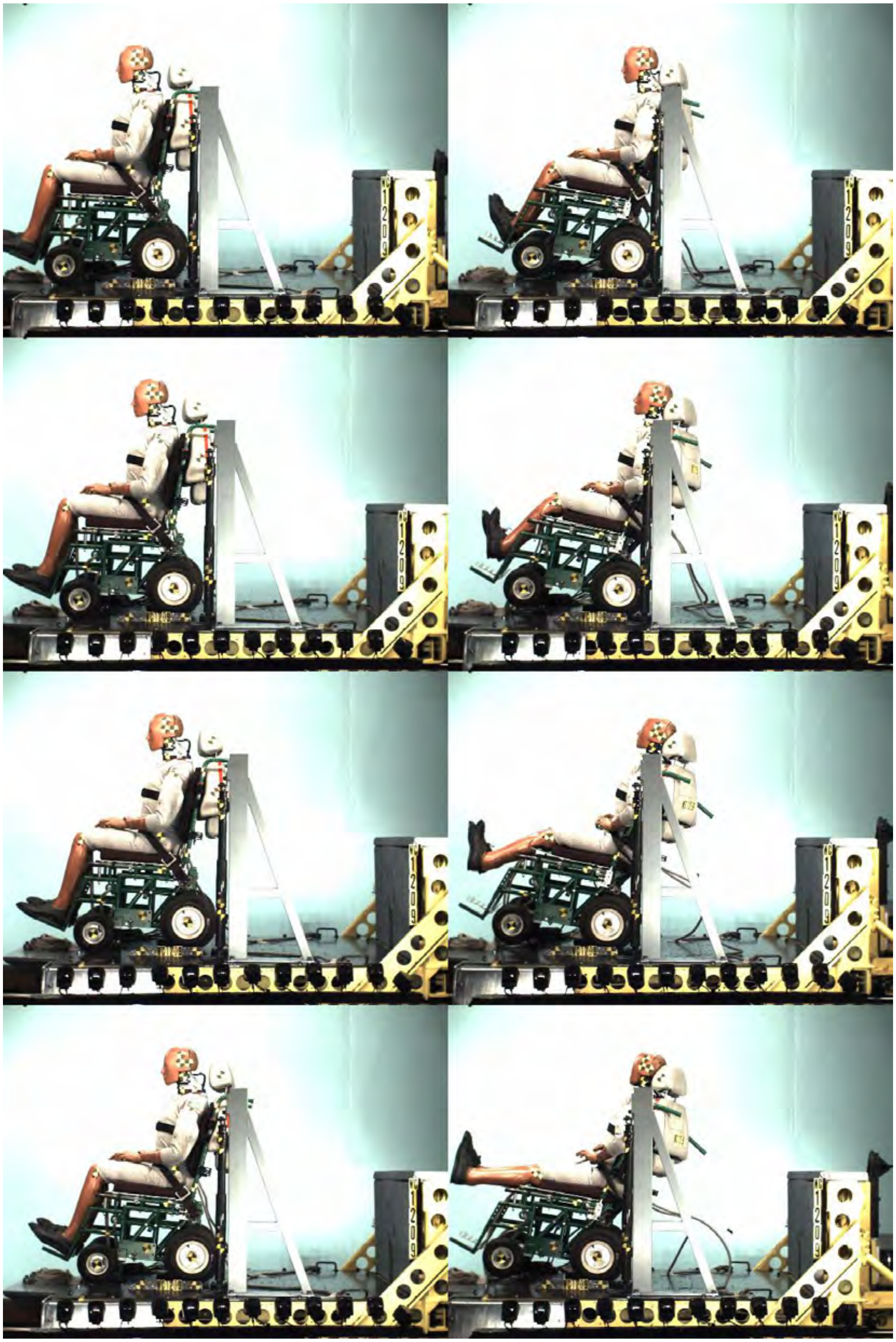


Figure 2.73 – Time-sequence frames from the side-view high-speed digital video of the third rear-impact sled test of the Swedish deployable vehicle-anchored head-and-back restraint system – note that there is no rearward rotation of the SWCF

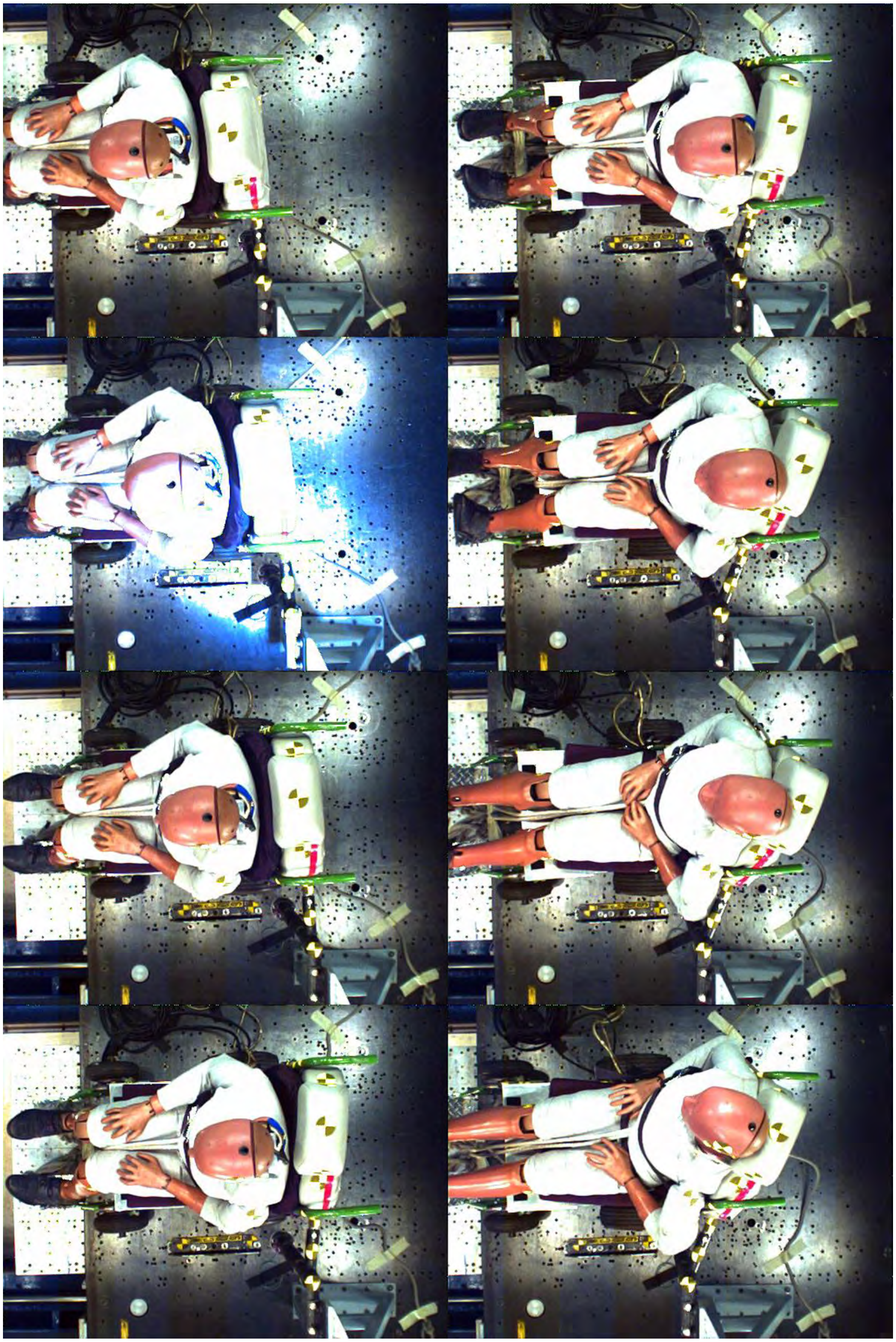


Figure 2.74 – Time-sequence frames from the overhead high-speed digital video of the third rear-impact sled test of the Swedish deployable vehicle-anchored head-and-back restraint system

Figure 2.75 – Time-sequence frames from the side-view high-speed digital video of the fourth rear-impact sled test of the Swedish deployable vehicle-anchored head-and-back restraint system – note that there is no rearward rotation of the SWCF

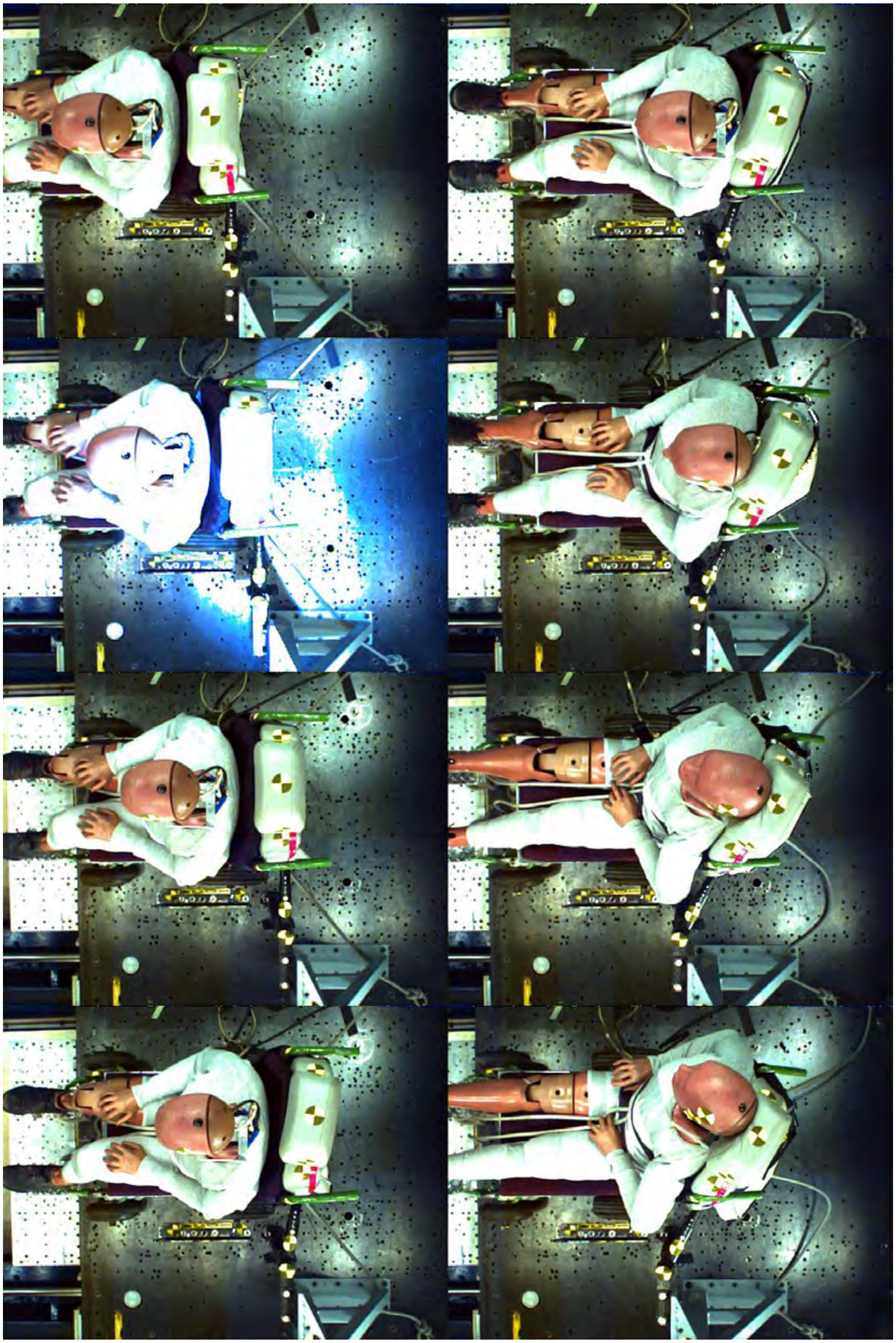


Figure 2.76 – Time-sequence frames from the overhead high-speed video of the fourth rear-impact sled test of the Swedish head-and-back restraint

Table **2.11** summarizes the test conditions and injury measures for the four rear-impact tests with the values for maximum rearward head excursion that exceed 450 mm in bold font and shaded cells. Modifications made by UMTRI to improve system performance in the last two tests were communicated to the manufacturer of the system and a new version of the head-and-back restraint system that was modified by the manufacturer to address the weaknesses in the previous system was tested. Unfortunately, the new system performed worse than the UMTRI modified versions of the original design. Figure 2.77 shows pre-test photos of the modified system ready for rear-impact testing on the UMTRI sled, while Figure 2.78 and Figure 2.79 show post-test photos and side and overhead time-sequence frames from the high-speed videos, respectively. Components of the system responsible for the poor performance were shipped to the manufacturer so that further improvements can be made.

Table 2.11 - Summary of test results from four rear-impact sled tests of the Swedish head-and-back restraint system

Test Variable and ATD Response Measure	Units	WC1201	WC1205	WC1209	WC1301
Sled Velocity change (Delta V)	kph	26.5	27.5	25.8	27.7
Average Sled Acceleration	*g*	16.1	16.0	16.9	16.9
Peak Result Head Acceleration	*g*	16	22	25	33
HIC (15 ms)		13	26	41	66
Peak Result Upper Neck Load	N	327	384	1023	2126
Peak Result Upper Neck Moment	Nm	26	27	27	41
Peak Result Lower Neck Load	N	820	799	1139	452
Peak Result Lower Neck Moment	Nm	90	85	122	109
Peak Result Chest Acceleration	g	79	77	25	32
Peak rearward head rotation	deg	56	49	35	36
Peak rearward chest rotation	deg	13	13	13	14
Max rearward head excursion	mm	**598**	**673**	**452**	**470**
Max rearward hip excursion	mm	377	443	295	280
Max head-to-torso angle	deg	45	36	24	22
Max P-point excursion	mm	195	202	103	102
Peak dynamic average back support angle	deg	41	44	36	37
Peak rearward rotation of the head-and-back restraint from the pre-test position	deg	50	58	36	34

Figure 2.77 - Pre-test photos of the manufacturer' revised design of the Swedish deployable vehicle-anchored head-and-back restraint system

Figure 2.78 - Post-test photos of the Swedish manufacturer's modified design of the deployable vehicle-anchored head-and-back restraint system

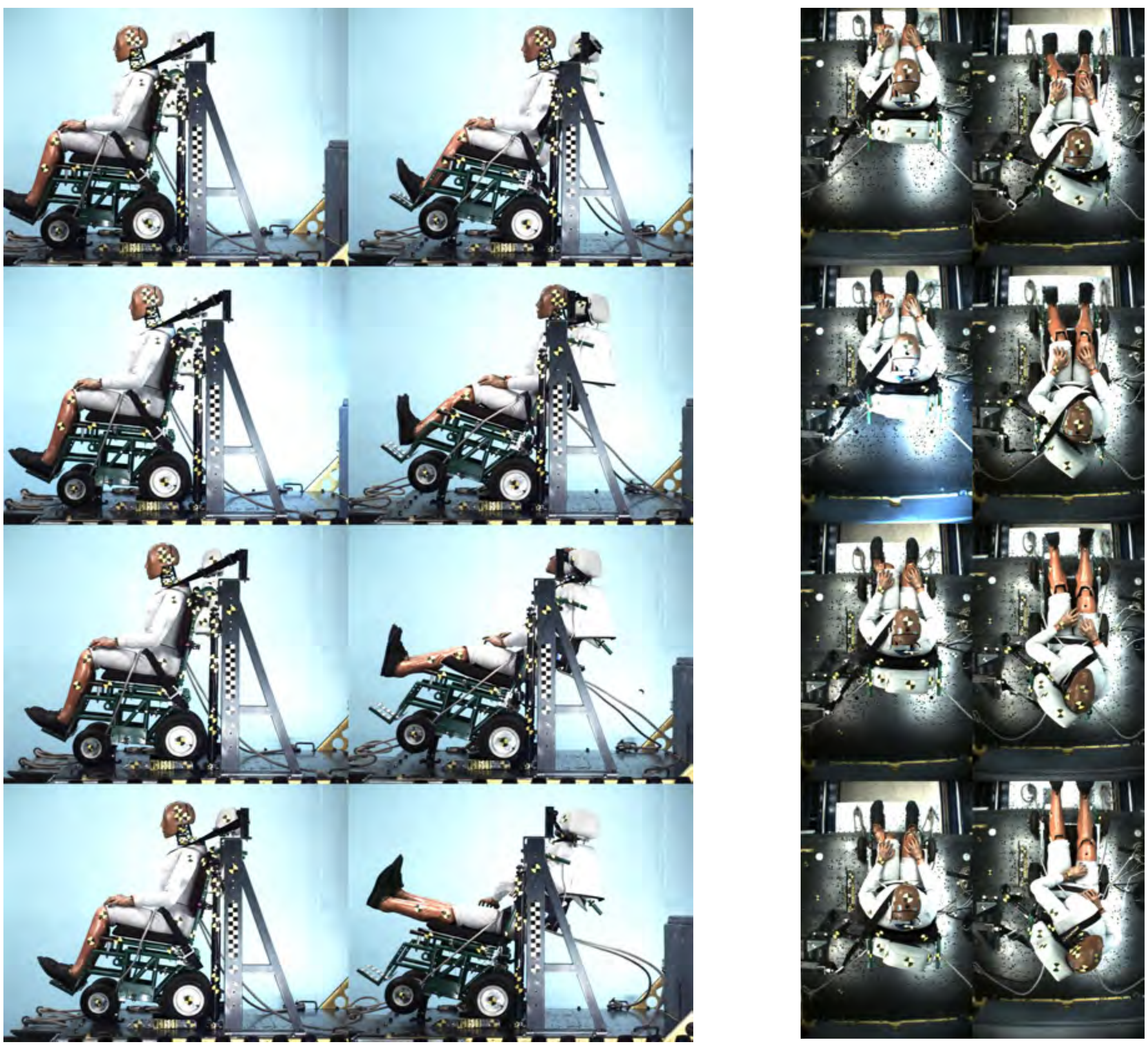


Figure 2.79 - Side-view (left) and overhead (right) time-sequence frames from high-speed videos for the rear-impact sled test of the Swedish manufacturer's modified design of the deployable vehicle-anchored head-and-back restraint system

2.4.4.4 Summary of design and testing of vehicle-anchored head-and-back restraints

In this part of Subtask 2, a prototype of a deployable vehicle-anchored head-and-back restraint was fabricated and evaluated in the static minivan buck and in two sled-impact tests. Although the design had potential for offering improved rear-impact protection for drivers seated in wheelchairs, the linkage used to move the head-and-back restraint between the deployed and stored positions used a significant amount of space behind the driver station and blocked access to the vehicle through the driver-side sliding door. While it would have been possible to design the system in a manner that allowed for manually disconnecting the linkage to the vehicle C-pillar when the vehicle was not being operated by a driver seated in a wheelchair, this linkage was considered a negative factor in the design by many of the drivers who participated in the wheelchair-driver measurement study described in Section 2.3 of this report.

For this reason, attention was turned toward conducting rear-impact sled-test evaluations of a commercially available and, depending on results, working to improve, a commercially available deployable vehicle-anchored head-and-back restraint system for which the complete deployment mechanism is contained with a vertical post that attaches to the vehicle floor and the B-pillar. Initial rear-impact sled tests of a system obtained from the inventor of this head-and-back restraint resulted in excessive rearward head excursion of the ATD due to a combination of factors. Modifications to several parts of the head-and-back system were made by UMTRI, resulting in considerable improvement in system performance. However, peak rearward head excursions still exceeded the rearward head excursion limit allowed by current standards for wheelchairs used as seats in motor vehicle during rebound of the midsize-male ATD in 48-kph, 20-*g* frontal-impact testing, which is also the rearward head-excursion limit being proposed for wheelchair rear-impact standards now under development.

Results of the four rear-impact tests of the Swedish head-and-back restraint system were communicated to the manufacturer along with information on the modifications made by UMTRI to improve performance. While modification made by the manufacturer to some components showed improved performance, other changes made by the manufacturer resulted in worse performance than the original system received and tested prior to the modifications and improvements made by UMTRI. These weak points in the revised system were communicated to the manufacturer and the tested components were returned so the design and performance can be improved and verified in future tests by the manufacturer.

3 Subtask 3: Investigate safety issues and provide recommendations regarding the use and/or deactivation of frontal-impact air bags for drivers seated in wheelchairs

3.1 Background, objectives, and general approach

Frontal-impact air bags installed in steering wheels on the driver side and in the dashboard on the passenger side are effective supplemental occupant restraint systems that enhance frontal crash protection for driers and right-front passengers. In particular, they offer significant protection for the head, neck, chest, and abdomen of front-row occupants and are most effective if the driver or right-front passenger is also properly using a lap/shoulder belt restraint (Ferguson and Schneider, 2008).

The "Make Inoperative Exemptions" from certain federal motor vehicle safety standards provided in 49 CFR PART 571.595 allow 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. Vehicle modifiers may permanently deactivate frontal-impact air bags or install an on/off switch when they have concern, which may be unfounded, about clients being injured by the energy of deploying air bags. As a result, steering-wheel air bags may be unnecessarily deactivated by a vehicle modifier or turned off by the driver seated in a wheelchair when, in fact, they would offer protective benefits in frontal crashes.

There is therefore a need for more definitive information on the potential benefits versus injury risks of frontal-impact air bags for people driving personal vehicles while seated in wheelchairs. The goal of Subtask 3 was to conduct research that will help clarify the conditions for which the potential of advanced[6] steering-wheel air bags to cause serious injury outweighs the potential safety benefits of these air bags for drivers of late-model minivans seated in wheelchairs, thereby justifying the decision to deactivate steering-wheel air bags. This effort involved four interrelated activities, including:

1) contacting vehicle modifiers to determine how they deal with advanced air-bag features when the driver seat is removed so the vehicle can be operated by a driver seated in a wheelchair,
2) conducting frontal sled tests with midsize-male and small-female Hybrid III ATDs using various seat belt conditions (good belt fit, poor belt fit, and no seat belt) and air-bag/seat-belt-pretensioner deployment times,
3) using the results of the sled tests in (2) to validate a wheelchair-driver MADYMO models, and
4) conducting parametric computer simulations with the validated MADYMO models to explore interactions of wheelchair-seated drivers with deploying and deployed advanced air bags, and thus injury potential as well as protective benefits of advanced airbags for a range of potential real-world conditions.

[6] Advanced airbags must comply with FMVSS 208 "Occupant Crash Protection" (49 CFR Part 571.208)

From the first activity, it was confirmed with several vehicle modifiers that the “smart” features of advanced air bags, including dual-stage deployment features, are typically bypassed in vehicles modified for use by drivers seated in wheelchairs. As a result, the air bag either does not deploy because the severity of the frontal crash is below the threshold for air-bag deployment, or the air bag fully deploys. However, a full deployment of an advanced air bag in today’s vehicles are much less aggressive, and are therefore much less likely to cause serious injuries to out-of-position (OOP) drivers who are very close to, or in contact with, the air-bag module at the time of deployment than first-generation air bags installed in vehicles during the early to mid-1990s.

In the sled tests and simulations of activities 2 through 4 above, full deployments of advanced steering-wheel air bags were used or simulated by computer models to represent worst-case air-bag-deployment loading/injury scenarios. Using driver-positioning data from the driver measurement study described in Section 2.3, these activities investigated interactions of ATDs seated in wheelchairs and vehicle seats with deploying and deployed airbags, and thus investigated airbag-induced injury potential as well as potential for protective benefits for midsize-male and small-female drivers (i.e., ATDs) seated in wheelchairs. The seat belt conditions investigated included ATDs:

- restrained a lap/shoulder belt with good lap-belt positioning,
- restrained a lap/shoulder belt with a poorly positioned lap belt, typically routed in front of closed-front arm supports, and
- not restrained by seatbelt.

As described in greater detail below, computer simulations were conducted to examine the potential benefits and injury concerns of steering-wheel air bags in several different situations for the range of seat-belt conditions listed above. These include simulations with and without deployment of the steering-wheel air bag for:

- midsize-male and small-female drivers(i.e., ATDs) seated in wheelchairs at representative distances relative to the steering wheel and air-bag module during a 48-kph, 20-*g* frontal crash,

- small-female drivers seated in wheelchairs compared to small females seated in vehicle seats during a 48-kph, 20-*g* frontal crashes,

- midsize-male and small-female drivers seated in wheelchair during angled frontal crashes, and

- midsize-male and small-female drivers positioned very close to the steering wheel (i.e., out of position or OOP) at the time of airbag deployment in 48-kph, 20-*g* frontal crashes.

For all of these simulations, ATD response measures were compared with current injury assessment reference values (IARVs) for the different size ATDs.

3.2 Sled-impact tests with ATDs seated in a surrogate wheelchair frame

3.2.1 Methods

Five 48-kph, 20-*g* frontal-impact sled tests were conducted to explore the effects of seat-belt fit, air-bag deployment timing, and occupant size on wheelchair driver interactions with deploying and deployed steering-wheel air bags. These tests were conducted to create a validation dataset for MADYMO models of wheelchair-seated drivers as well as to obtain a preliminary assessment of the possible injury outcomes for midsize-male and small-female drivers seated in wheelchairs for a range of belt-restraint conditions.

The 2006 Chrysler Town and Country minivan was selected as the nominal vehicle test environment because it is a vehicle commonly modified for use by people who drive while seated in wheelchairs. It is also the vehicle used in the previous sled tests of belt-restraint systems at TRC using the midsize-male Hybrid III ATD seated in commercial power wheelchairs in the driver position (Sword, 2007). Several tiedown/restraint components and power wheelchairs from the TRC test program were available for use in sled tests conducted at UMTRI.

The test setups included a driver instrument panel with steering column/steering-wheel/air-bag module assembly from a 2006 Town and Country minivan. Although the air bag used met the advanced air bag requirements of FMVSS No. 208, these features were not maintained for the tests. Rather, the air bag module was fully deployed as, as indicated previously from communications with vehicle modifiers, is typically the situation for air bags in vehicles modified for drivers seated in wheelchairs following removal of the driver seat. That is, the wiring of the airbag is shunted so that it is fully deployed if the threshold for deployment is reached in the crash pulse. Thus, if the original air bag included two stages of deployment, with the second stage deploying only in more severe crashes, both stages were deployed in the sled tests. This was appropriate, however, since the 48-kph, 20-*g* deceleration pulse represents a relatively severe frontal crash. Even so, full deployments of advanced airbags, and even so-called depowered airbags that preceded advanced airbags, are much less aggressive, and therefore much less likely to cause serious injuries to OOP drivers, than are deployments of first-generation airbags installed in vehicles in the early to mid 1990s (Ferguson and Schneider, 2008).

Data from the study of wheelchair drivers using their own vehicles described in Section 2.3 were used to position the midsize-male and small-female ATDs relative to the steering-wheel air-bag module and instrument panel for these tests. As illustrated in Figure 3.1, the horizontal distances between the steering-wheel center and lower rim and the ATD's abdomen and chest, along with the horizontal distance between the anterior aspect of the ATD's knees and the lower instrument panel, or knee restraint, were set, to the extent possible, to values for similar-sized drivers in the measurement study. In particular, the horizontal distances between the center of the steering wheel and the ATDs were set to 210 mm (8.3") for the small female and 330 mm (13.0") for the midsize male. Also, the horizontal distances between the bottom of the steering-wheel rim and the ATD were set to 135 mm (5.3") for the small female and 195 mm (7.7") for the midsize male ATD, and the horizontal distances between the anterior aspect of the ATDs knees and the knee restraint were set to 115 mm (4.5") for the small female and 155 mm (6.1") for the midsize male.

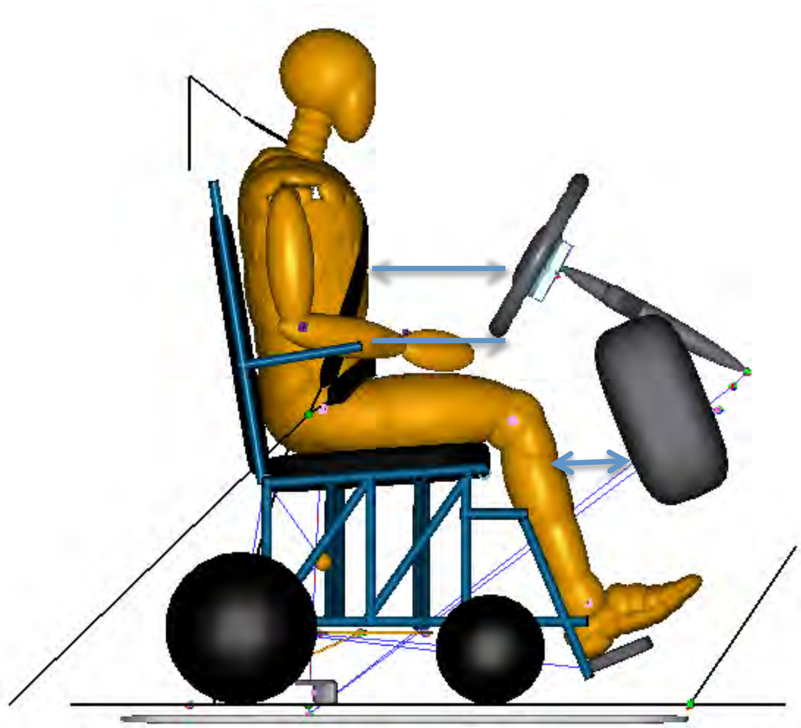


Figure 3.1 -Illustration of measurements used to position the midsize-male and small-female ATDs relative to the steering-wheel air-bag module and the knee restraint on the UMTRI sled

For these sled tests, the surrogate wheelchair frame (SWCF) described in 2.4.2 and shown in Figure 2.17 was fitted with a generic planar wheelchair seat and used to represent a typical driver wheelchair. As previously noted, the deformable bars and rods are used to connect the front casters and back-support posts to the base frame to replicate nominal wheelchair frame deformations during a 48-kph, 20-*g* frontal crash, and these deformable components are replaced after each test. The SWCF also allows for easy set up of open-front and closed-front arm-support conditions that were shown in the driver measurement study to have a significant influence on position of the lap belt on the driver's lower pelvis near the junctions with the upper thighs. For this test series, the SWCF was secured to the sled platform using the UMTRI-designed surrogate-docking device described in Section 2.4.3.6.

All tests were conducted using a 48-kph, 20-*g* impact pulse similar to that used for the sled tests and shown again in Figure 3.2. The Hybrid III midsize-male and small-female ATDs were used to represent typical wheelchair-seated drivers and were instrumented with head, chest, and pelvic accelerometers; upper and lower neck six axis load cells; a chest potentiometer to measure peak chest deflection at the sternum; and femur load cells. In addition, seat-belt load cells were used to collect seat-belt force histories during each test.

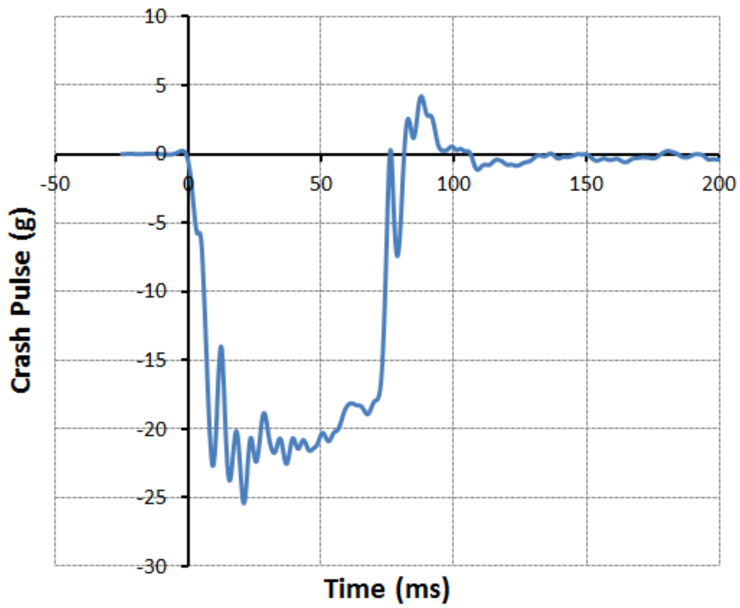


Figure 3.2 - Sled deceleration pulse used for frontal-impact sled tests with ATDs representing drivers seated in wheelchairs

For every test that included a belt restraint, the lap and shoulder portions, including the retractor with load-limiter and pre-tensioner, were OEM seat belts for the 2006 Chrysler Town and Country minivan. An inboard buckle receptacle that was compatible with the OEM seat-belt latch plate was either attached to a commercially available cable stalk that is commonly provided by van modifiers, or to the seat-belt deployment system (SBDS) described in Section 2.4.3.7.

The sled test series included three levels of belt restraint fit. "Good" belt fit was achieved using open-front arm supports such that the lap and shoulder belt were positioned low on the pelvis and across the center of the torso and middle of the ATD's shoulder, respectively. For "poor" belt fit, the lap belt was routed in front of closed-front arm supports, thereby creating a gap between the lap belt and the ATD's pelvis similar to that observed for several of the drivers in the measurement study. In the "no-belt" condition, ATD forward movement was limited only by the air bag and knee restraint.

The air bags and belt pretensioners were either fired at 12 ms, which corresponds to a full-frontal crash, or at a delayed 42 ms, which is more typical in offset-frontal crashes. As previously noted, for all tests the air bag was always fully deployed (i.e., both stages deployed).

Table **3.1** summarizes the conditions for the test series and Figure 3.3 shows the pre-test setup on the UMTRI sled for two of the tests using the midsize-male ATD and good and poor positioning of the lap belt. Figure 3.4 provides time-sequence frames from the side-view high-speed digital video of the first test with good belt fit, and shows the ATD kinematics and interaction of the ATD with the belt restraint, deployed air bag, and knee restraint.

Table 3.1 – Matrix of conditions for five 48-kph, 20-*g* frontal-impact sled tests of midsize-male and small-female ATDs in the driver position of a simulated 2006 minivan

Test Variable	WC1022	WC1023	WC1106	WC1107	WC1109
ATD	50M	50M	50M	50M	5F
Lap/Shoulder Belt	OEM*	OEM*	OEM*	No Belt	OEM*
Buckle Anchorage	SBDS	Cable Stalk	Cable Stalk	None	Cable Stalk
Belt Fit	Good	Poor	Poor	NA	Poor
Arm Support	Open front	Closed front	Closed front	Closed front	Closed front
Air-bag Time (ms)	12	12	42	42	42

*OEM lap/shoulder belt is from a 2006 Town and Country minivan

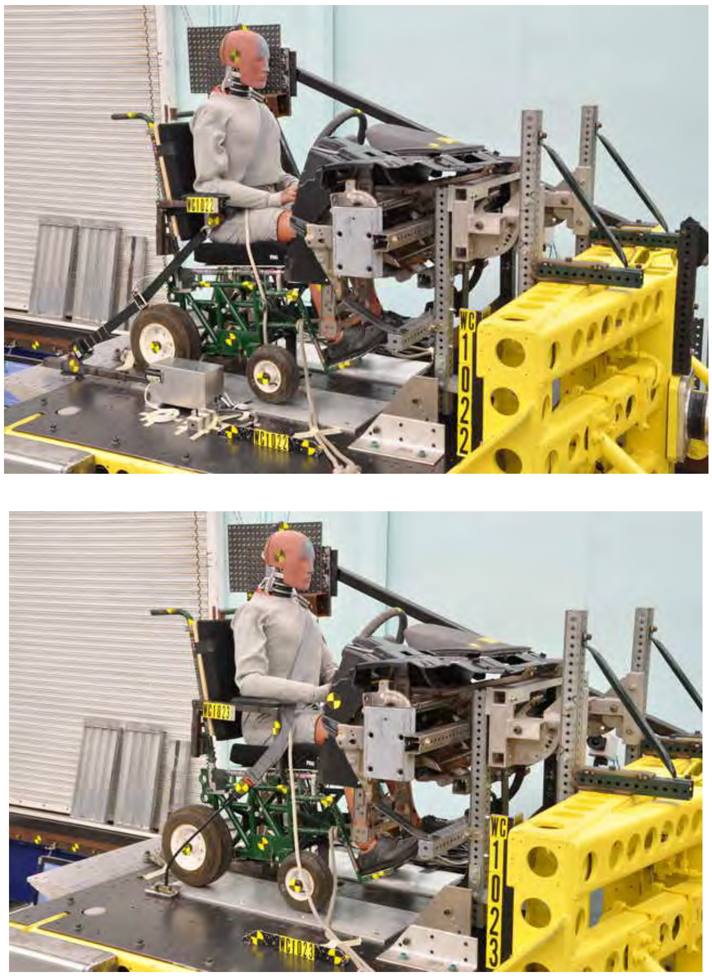


Figure 3.3 – Photos of the set up for two sled tests with the midsize-male ATD while seated in the SWCF and restrained by a 2006 Town and Country lap/shoulder belt with open-front arm supports and "good" lap/shoulder belt positioning using the SBDS (top) and with closed-front arm supports and poor belt positioning using a buckle stalk to complete the OEM lap/shoulder belt (bottom)

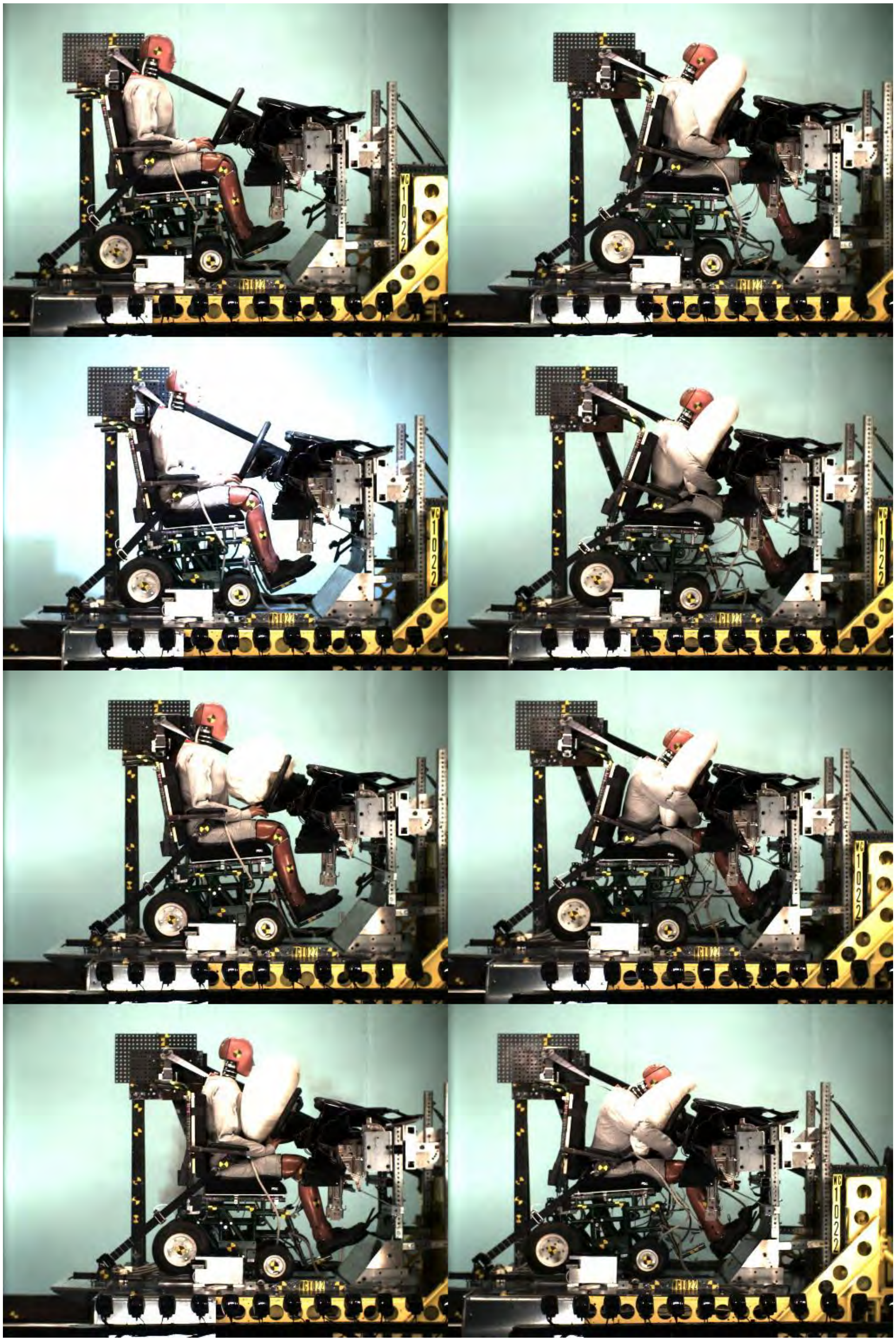


Figure 3.4 – Time-sequence frames from the side-view high-speed video from Test No. WC1022 with good belt fit and 12-ms air-bag deployment time, showing midsize-male ATD kinematics and interaction with the air bag

3.2.2 Results

Table 3.2 summarizes the key ATD injury response variables for the five sled tests described above. ATD response measures that exceed the FMVSS 208 "Occupant Crash Protection" (49 CFR Part 571.208) Injury Assessment Reference Values (IARVs) listed in Table **2.6** are in bold font and shaded cells. As expected, the best overall outcomes are associated with the test where the ATD had good belt-restraint fit and the air bag served as a supplementary restraint to prevent head and/or chest contact with the steering wheel. In the unbelted test, the midsize male ATD recorded a high left femur load that exceeds the 10 kN IARV due to contact with the knee restraint.

Table 3.2 - Summary of test conditions and ATD responses from frontal sled-impact tests with advanced steering-wheel air-bag deployment

Test Condition and Response Variable	WC1022	WC1023	WC1106	WC1107	WC1109
ATD	50M	50M	50M	50M	5F
Belt fit	Good	Poor	Poor	No Belt	Poor
Air bag deployment time	12 ms	12 ms	42 ms	42 ms	42 ms
HIC 15	133	227	384	137	691
Peak Resultant Upper Neck Force (N)	1771	2102	2987	2388	2832
Peak Chest D (mm)	41.2	58.8	61.1	62.7	**67.4**
Peak L Femur Load (N)	1465	5049	3789	5098	3313
Peak R Femur Load (N)	3325	2479	4426	**10,606**	2081

In the test with the small female ATD and poor belt fit, the high peak chest deflection of 67.4 mm, which exceeds the IARV of 52 mm, was determined from the high-speed video to be due primarily to chest loading by the loosely fitted shoulder belt when the retractor stopped spooling out, and not from loading by the deploying air bag. Similarly, the relatively high peak chest deflections for the midsize male in WC1106 with poor belt fit and in WC1107 (no seat belt) were determined from the high-speed videos to not have been caused by air-bag deployment loading. In fact, review of all the high-speed videos confirm that none of the ATD response data associated with interaction with the deploying steering-wheel air bag exceed, or are even close to, current IARVs.

For example, the relatively high HIC-15 value for the small female of 691 is very close to the IARV of 700. However, as shown by the time-sequence photos from the side-view high-speed video in Figure **3.5**, it clear that this high value of HIC was not caused by loading of the head by the deploying airbag and that it is also not due to pushing of the ATD's head though the deployed airbag into contact with the steering wheel. In fact, contact of the ATD's head with the airbag occurs when the head is still a significant distance from the steering wheel and when the airbag is at or near full inflation.

Figure **3.6** and Figure **3.7** show photos taken from the high-speed side-view videos for this sled test at the time of peak resultant head acceleration of 82.6 *g* and peak chest deflection of 67.4 mm, respectively, and include time histories for head acceleration and chest deflection. From the head-acceleration time histories, it is seen that the high head acceleration, and thus the high HIC-15, are due primarily to high head acceleration in the X (fore/aft) direction. It can also be noted that HIC-15 is calculated between 60.3 ms and 75.3 ms, that peak chest acceleration occurs at 65 ms, and that peak chest deflection occurs at 79 ms. It therefore appears that the high X-direction head accelerations and high HIC-15 are due to a combination of high chest deceleration just prior to peak chest deflection) caused by the loosely fitting shoulder belt and contact of the ATD's head/face with the inflated, or nearly inflated, air bag.

Figure 3.5 - Time-sequence frames from the side-view high-speed video of Test No. WC1109 with poor (loose) belt fit and 42-ms airbag deployment time, showing small-female ATD kinematics and interaction air bag

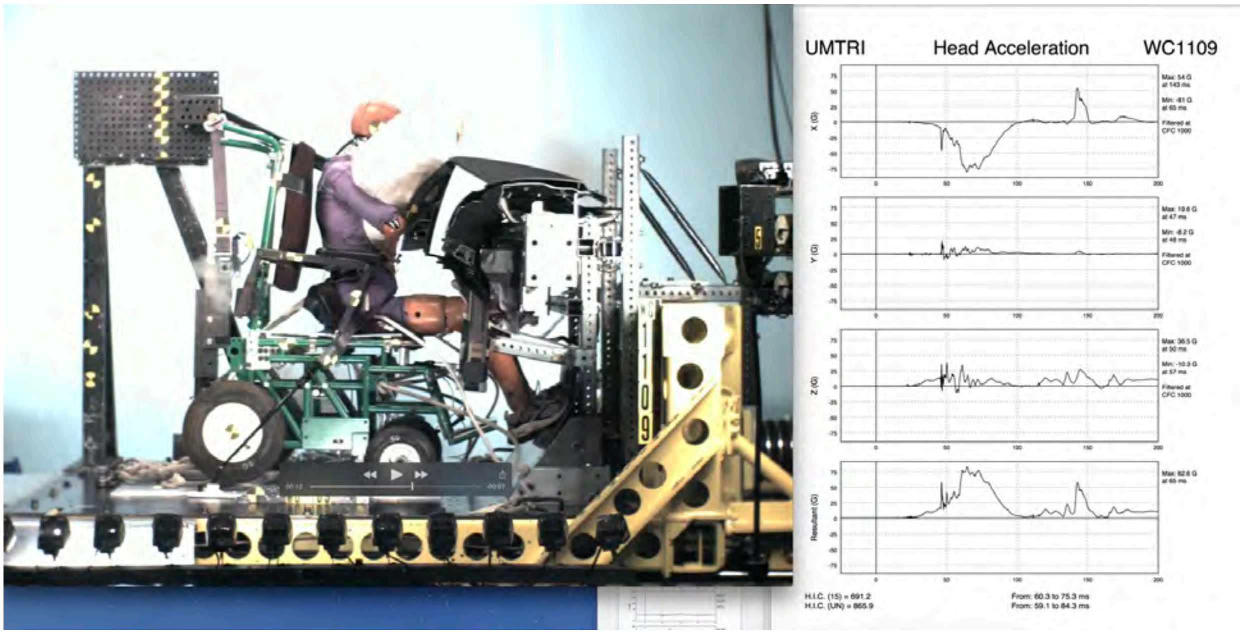


Figure 3.6 - Side-view photo at PEAK RESULTANT HEAD ACCELERATION from high-speed video for Test No. WC1109 with the small-female ATD restrained by a loosely fitting lap/shoulder belt and 42-ms an air-bag deployment time of 42 ms

Figure 3.7 - Side-view photo at PEAK CHEST DEFLECTION from high-speed video for Test No. WC1109 with the small-female ATD restrained by loosely fitting lap/shoulder belt and an air-bag deployment time of 42 ms

3.3 Development and validation of wheelchair-driver MADYMO models

Data from the set of five sled tests described in the previous section were used to develop, modify, and further validate MADYMO models of midsize-male and small-female ATDs representing drivers seated in a surrogate wheelchair (i.e., the surrogate wheelchair frame, or SWCF). The initial model simulated a midsize-male ATD in a 48-kph, 20-*g* frontal impact restrained by a three-point with fixed upper shoulder-belt anchor point. The instrument panel, air bag, and load-limiting features of the lap/shoulder belt restraint system used in the sled tests were added to the model and the simulation results were compared to the sled-test results for the different conditions. The modified and validated MADYMO models were then used to further explore wheelchair-driver interactions with steering-wheel air bags, steering wheels without air-bag deployment, and other vehicle components for different scenarios of belt-restraint condition, angled frontal crashes, and close-proximity pre-impact driver positions.

Comparisons of ATD and SWCF kinematics for two of the sled sleds tests and computer simulations with "good" and "poor" seat-belt fit are shown on the left and right halves of Figure 3.5, respectively. Good belt fit was achieved in the first test and simulation using the SBDS with an OEM belt restraint and open-front arm supports on the SWCF. Poor belt fit was achieved using a standard inboard floor-mounted buckle stalk and closed-front arm supports so that the lap belt was positioned in front of the arm supports and forward of the ATD's pelvis. As shown, the kinematics of the ATD and SWCF in the model match well to those in the sled tests for both conditions.

Table 3.3 compares the injury response measures from the sled test and MADYMO model for the three conditions noted in the top row. As indicated, the model produced similar HIC values and peak chest deflections as the tests, but somewhat lower upper-neck forces. The femur loads are also lower for the simulations than for the sled tests. The values for peak chest deflection for the small-female ATD with poor belt fit and 42 ms air-bag deployment time exceed the IARVs listed in Table **2.6** for both the test and the simulation. A review of the high-speed videos from the test as well as the simulation video indicates that this high chest deflection is not caused by chest loading by the deploying air bag, but rather is due to chest loading by the loosely fitting shoulder belt. The forward position of the lap belt increases the initial distance between the shoulder belt and the chest prior to crash-deceleration loading, thereby increasing forces on the chest. In addition, the submarining kinematics caused by the forward lap-belt position results in decreased shoulder belt loads on the shoulder and increased forces on the chest.

Table 3.3 - Comparison ATD responses for sled tests and MADYMO simulations

	MM, AB 12, good belt		**MM, AB 12, poor belt**		**SF, AB 42, poor belt**	
ATD Response Measure	**test**	**model**	**test**	**model**	**test**	**model**
HIC 15	133	129	227	215	691	544
Peak Upper Neck Force* (N)	1771	1117	2102	1737	2832	2442
Peak Chest Deflection (mm)	41.2	43.4	58.8	57.1	**67.4**	**63.6**
Peak Right Femur Load (N)	1465	839	5049	4269	3313	2977
Peak Left Femur Load (N)	3325	1627	2479	3858	2081	2725

*Resultant; MM = midsize male; SF = small female; AB 12/ AB 42 = air-bag deployment time of 12 or 42 ms; good belt/poor belt = good/poor belt fit or positioning

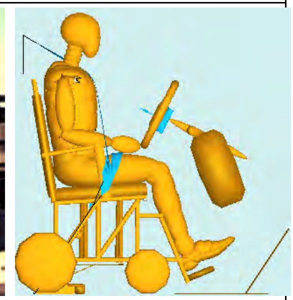
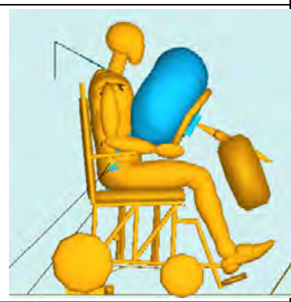
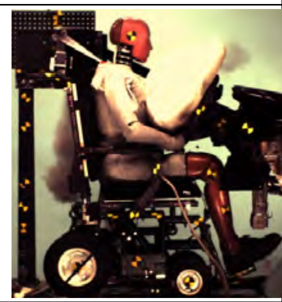
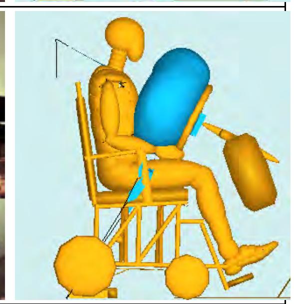
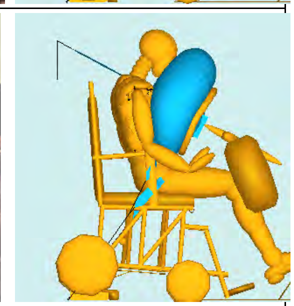
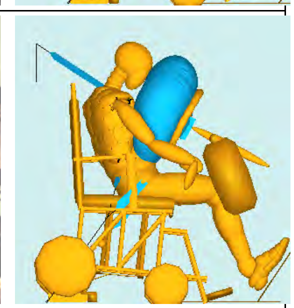
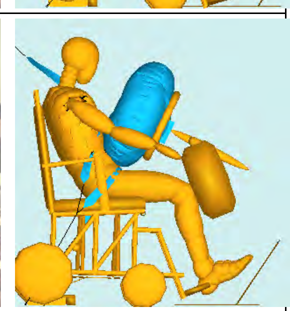
	ATD in SWCF with good belt fit		ATD in SWCF with poor belt fit	
Time (ms)	Test	Simulation	Test	Simulation
0				
30				
60				
90				
120				

Figure 3.8 - Comparison of SWCF and midsize-male ATD kinematics for sled tests and MADYMO simulations using good belt fit (left) and poor (loose) belt fit (right)

3.4 Parametric simulations of normally positioned midsize-male and small-female drivers seated in wheelchairs during 48-kph, 20-*g* frontal impacts

3.4.1 Methods

A parametric study of wheelchair driver interactions with seat belts and airbags was conducted using the validated MADYMO models described in the previous section. Two air-bag conditions (no air-bag deployment and deployment at 12 ms), and three seat-belt conditions (no seat belt, poor (loose) seat-belt fit, and good seat-belt fit) were used, resulting in a total of six restraint conditions.

The crash pulse used in the parametric study was the same as that used the validation sled tests and simulations. In all simulations, a seat-belt load limit of 3 kN was used based on information obtained from OEM manufacturers, and the seat-belt pretensioner fired at 12 ms for all simulations. The air-bag characteristics, seat-belt anchor-point locations, and the driver compartment geometry in simulations were based on the conditions used in the sled tests previously described. Based on information obtained from a vehicle manufacturer and prior UMTRI studies of knee, thigh, and hip injuries (Rupp et al., 2008), the stiffness of the steering-wheel rim was set to 50 N/mm, a 3-4 kN plateau was used for the steering-column stiffness, and the knee-bolster stiffness was set to 100 N/mm.

3.4.2 Results

Table **3.4** shows the injury response results for simulations of the midsize-male and small-female ATDs using three seat-belt conditions, with and without steering-wheel air-bag deployment. Lightly shaded rows indicate simulations without an air bag and the numbers in bold font in more darkly shaded cells indicate response values for the three simulations where values exceeded NHTSA's IARVs. Figure 3.9 shows frames from the output videos for these three simulations at 0 ms, 80 ms, and 120 ms.

For the midsize-male ATD, all HIC and all Nij values are lower with deployment of the air bag than for the comparable simulation without deployment of the air bag. High chest deflections exceeding the IARV of 63 mm occurred for the unbelted midsize male with and without deployment of the steering-wheel air bag. As indicated by the first two rows of simulation frames in Figure 3.9 (a and b), it is believed that these high chest deflections are due to loading of the ATD's chest by the steering wheel. For the simulation with air-bag deployment, the high chest compression appears to be due to the ATD overloading the air bag and thus contacting the steering wheel through the airbag. However, it is also noted that the peak chest deflection for this scenario is significantly less than for the scenario without air-bag deployment, in which case the ATDs chest is directly loaded by the steering wheel.

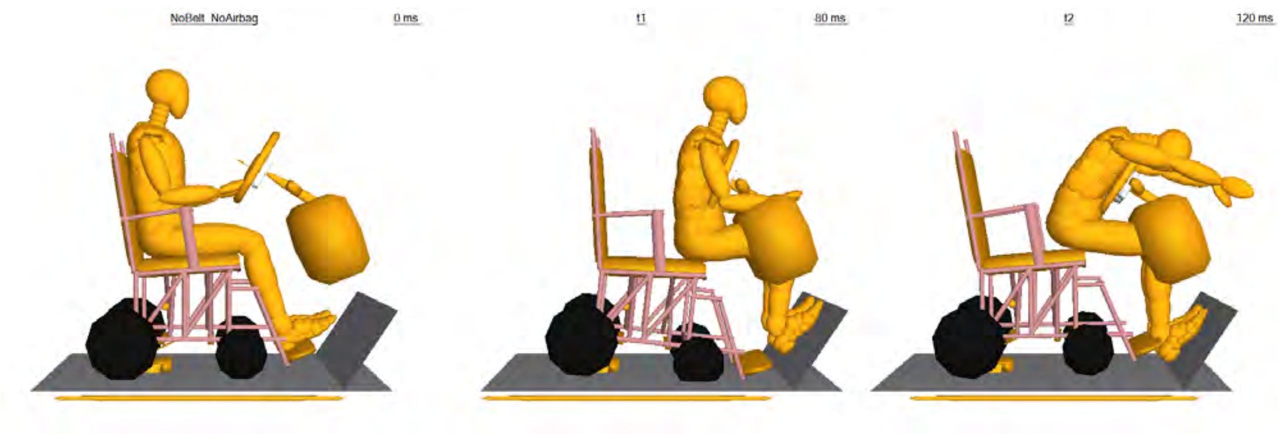
For the small female ATD, simulations with air-bag deployment again have lower HIC values than the comparable simulations without air-bag deployment. The only injury responses of the small-female ATD that are above the IARVs are for Nij and chest deflection and occur for the simulation of the unbelted ATD without air-bag deployment (i.e., for no restraints). Figure 3.9c shows the kinematics of the small-female ATD for this no-restraint condition, and shows the chest loading directly into the steering wheel and the neck contacting the upper rim of the steering wheel, followed by the head moving beyond the upper rim of the steering wheel. Thus, the high Nij value of 1.4 appears to be due to the manner in which the unrestrained ATD interacts with the steering-wheel rim, resulting in significant neck flexion as the head rotates over the upper portion of the steering-wheel rim. The high chest deflection measure results from direct loading of the center of the chest by the steering wheel. It can be also be expected that the HIC values for this simulation with an unbelted ATD, as well as other simulations of the small female ATD without air-bag deployment would have been even higher if an instrument panel and a windshield had been included in the model.

Table 3.4 - Results of parametric simulation study

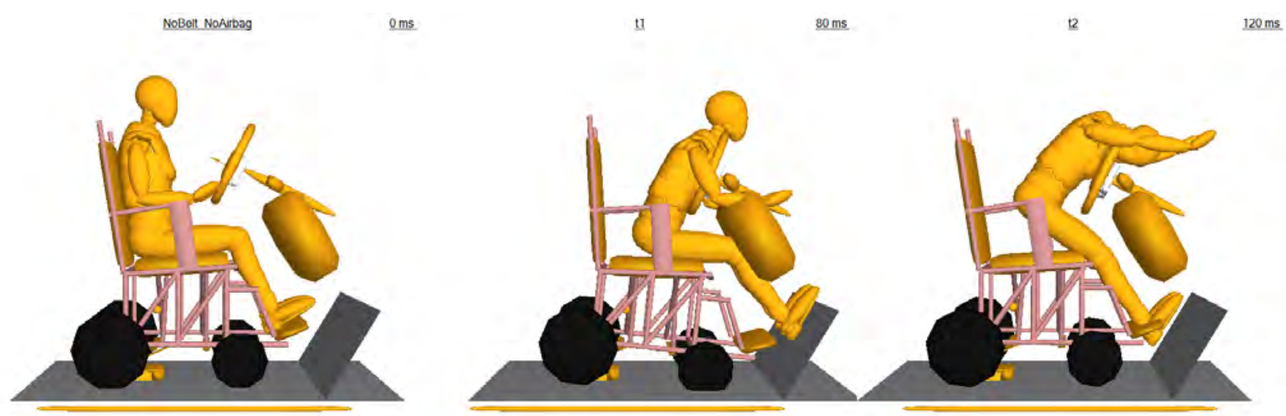
ATD	Belt fit	Air bag	HIC 15	Nij	Peak Chest Deflection (mm)	Peak Left Femur Load (N)	Peak Right Femur Load (N)
50M	Good	Yes	98	0.18	36.2	1043	762
50M	Poor	Yes	38	0.19	42.3	5538	5440
50M	No belt	Yes	38	0.14	**68.2**	5214	4742
50M	Good	No	373	0.37	33.2	1353	1109
50M	Poor	No	104	0.35	36.3	5759	5760
50M	No belt	No	281	0.64	**81.5**	5122	5147
5F	Good	Yes	124	0.37	43.0	1892	1893
5F	Poor	Yes	133	0.45	37.2	3200	3057
5F	No belt	Yes	29	0.26	37.9	4225	4210
5F	Good	No	381	0.41	33.5	1634	2693
5F	Poor	No	284	0.27	33.1	3457	3684
5F	No belt	No	240	**1.4**	**56.3**	4148	4090

Note: all air-bag deployments were initiated 12 ms after the onset of impact deceleration.

a – midsize-male no seat belt but with air-bag deployment



b – midsize-male ATD with no seat belt and no air bag



c – small-female ATD with no seat belt and no air bag

Figure 3.9 -Images from the simulation with an unbelted small-female ATD for which neck and chest response measures exceed IARVs

3.5 Comparison of air-bag interactions for small-female drivers seated in a simulated wheelchair (SWCF) and in a minivan seat

3.5.1 Methods

A second parametric study was conducted with the small-female ATD to compare results for small-female drivers seated in wheelchairs (i.e., the SWCF) with small-female drivers seated in a typical minivan driver seat. The purpose was to determine and compare the potential effects of wheelchair seating (e.g., low seat angle, more upright torso) on driver kinematics and interactions with deploying air bags and steering wheels with deactivated air bags.

Figure 3.10 compares the initial position of the small-female ATD relative to the instrument panel and steering wheel for the two seating conditions. In the simulations with vehicle-seated drivers, the vehicle seat angle was set to 18 degrees, the ATD H-point location was defined using UMTRI's driver seating-accommodation model (Reed et al., 2000, 2001), and the lap-belt anchor-point locations were defined based on measurements taken in a late-model Chrysler Town and Country minivan. For the ATD in the SWCF, three belt-restraint conditions were simulated, including good seat-belt fit, poor (loose) seat-belt fit, and no seat belt. In addition, the vehicle floor was lowered relative to the production vehicle floor to account for the higher seat height of wheelchairs compared to vehicle seats. Since there are no arm supports to cause poor belt fit for drivers in vehicles seats, only the good seat-belt and no seat-belt conditions were used for vehicle-seated simulations. All other values and conditions were the same as in the previous parametric simulation study with all airbag deployments occurring 12 ms after the onset of crash deceleration.

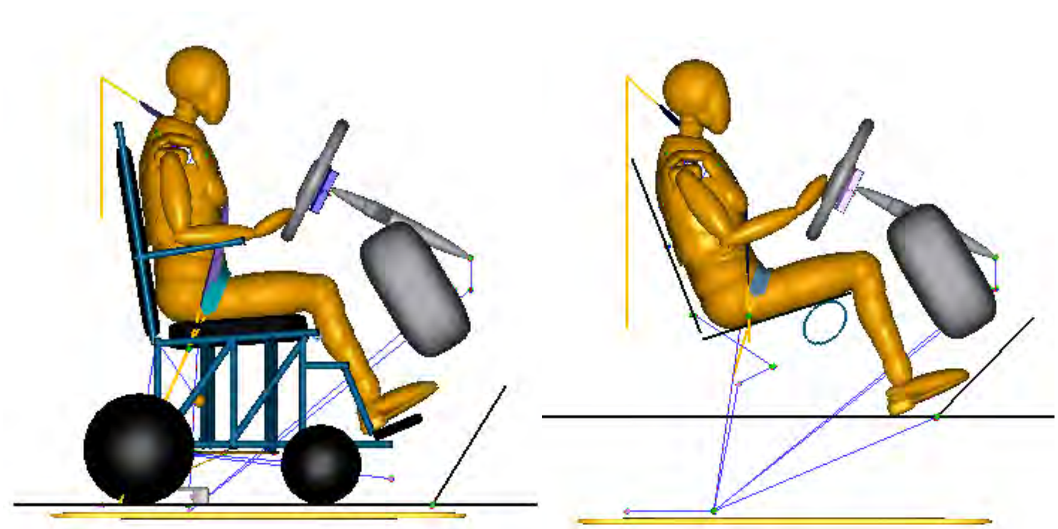


Figure 3.10 - Comparison of initial seated position relative to the steering wheel and knee restraint for a small-female ATD in the SWCF with lowered vehicle floor (left) and in an OEM minivan seat (right)

3.5.2 Results

Table **3.5** shows the ATD injury response measures for the small-female ATD seated in the surrogate wheelchair frame (WC in first column) and in the vehicle seat (OEM in the first column). Rows for results from simulations without air-bag deployment are lightly shaded. Three response values exceed the small-female IARVs and are indicated by bold font in darkly shaded cells. These all occurred for the no-seat-belt condition without air-bag deployment. Two of these values are Nij = 1.4 and peak chest deflection = 56.3, which occurred for the ATD seated in the SWCF. One value is Nij = 1.48, and occurred for the ATD in the OEM vehicle seat.

Table 3.5 - Results of parametric study for a small-female ATD seated in a wheelchair and in a vehicle seat for with and without air-bag deployment and different seat-belt conditions

Seat	Belt fit	Air bag	HIC15	Nij	Peak Chest Deflection (mm)	Peak Left Femur Load (N)	Peak Right Femur Load (N)
WC	Good	Yes	124	0.37	43.0	1892	1893
WC	Poor	Yes	133	0.45	37.2	3200	3057
WC	No belt	Yes	29	0.26	37.9	4225	4210
WC	Good	No	373	0.37	33.2	1353	1109
WC	Poor	No	284	0.27	33.1	3457	3684
WC	No belt	No	240	**1.4**	**56.3**	4148	4090
OEM	Good	Yes	110	0.31	37.0	2051	2179
OEM	No belt	Yes	70	0.37	11.3	2345	2337
OEM	Good	No	630	0.40	17.2	2173	2306
OEM	No belt	No	426	**1.48**	24.9	2436	2437

WC = wheelchair; OEM = vehicle seat
Note: all air-bag deployments were initiated 12 ms after the onset of crash deceleration.

It can also be noted that, while most HIC-15 values are well below the IARV of 700, HIC-15 values for all of the simulations without air-bag deployment are higher than those with air-bag deployment. The one HIC-15 value that is close to the IARV is for the ATD in the OEM vehicle seat without air-bag deployment but with good seat belt fit. While all peak chest deflections except the one noted above for the unrestrained ATD in the SWCF are well below the IARV, it can also be seen that peak chest deflections are generally lower for the ATD seated in the OEM vehicle seat compared to those with the ATD seated in the SWCF.

Figure 3.11 and Figure 3.12 show the positions of the ATD seated in the SWCF relative to the air bag, steering wheel, and knee restraint at 80 and 120 ms, respectively, for simulations of the three seat-belt conditions with and without air-bag deployment. Figure 3.13 and Figure 3.14 show the same relative positions of the ATD at 80 and 120 ms for the small-female ATD in the minivan seat for the two seat-belt conditions. From Figure 3.11and Figure 3.12, it can be seen that the cause of the high peak chest deflection for the unbelted ATD in the SWCF without air-bag deployment is loading of the chest by the steering wheel. It would also appear that the cause of the high Nij is flexion of the neck as the head goes over the upper rim of the steering wheel.

In contrast, it is seen from Figure 3.13 and Figure 3.14 that the high Nij for the unbelted ATD in the OEM seat without air-bag deployment is direct impact of the ATD head/face with the steering wheel. While this results in a high Nij and a somewhat high HIC, the chest is not loaded by the steering wheel in the same way as for the ATD in SWCF for these unrestrained conditions and the peak chest deflection is therefore much lower.

The differences in results between the ATD in the SWCF and in the OEM are most likely due the different initial sitting postures as well as the different seat angles that result in different interactions between the ATD and the deployed air bag, the steering wheel without air-bag deployment, and the knee restraint. However, the most important observation from these simulations is that, in no case, and even for the unbelted small-female ATD, is there any suggestion that the deploying air bag caused harm to the driver.

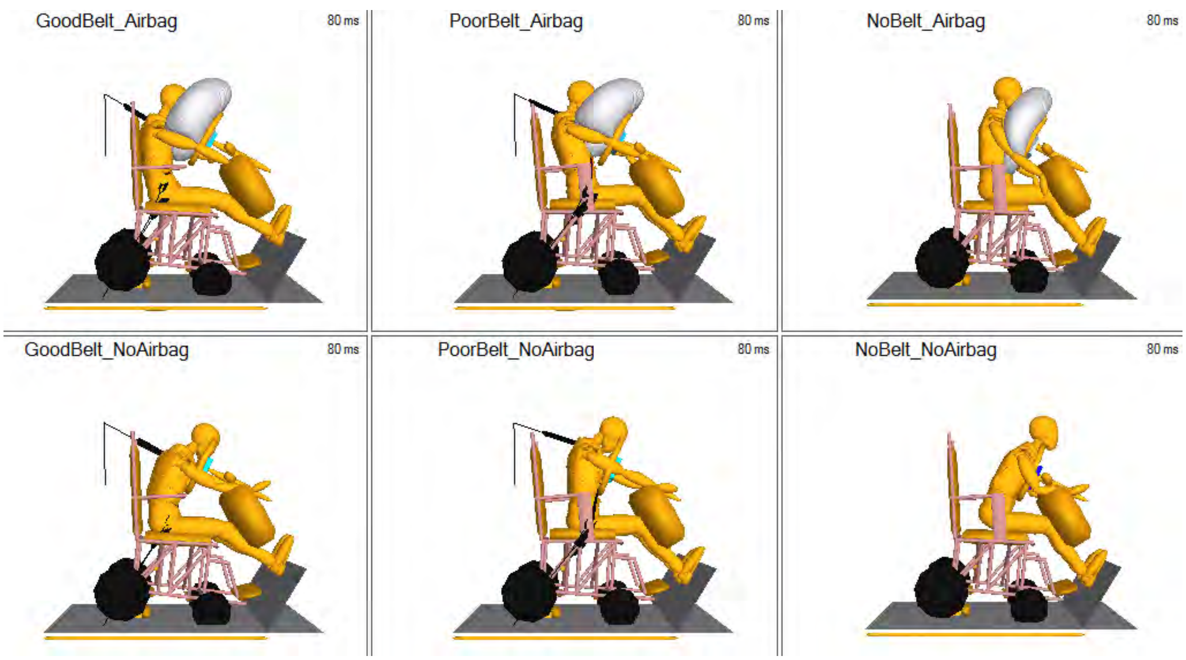


Figure 3.11 - Positions of the small-female ATD seated in the SWCF relative to the steering wheel, air bag, and knee bolster at 80 ms during a computer-simulated 48-kph, 20-*g* frontal impact – simulations are for good seat-belt fit (left), poor (loose) seat-belt fit (middle), and no seat belt (right) and for air-bag deployment at 12 ms (upper) and no air bag

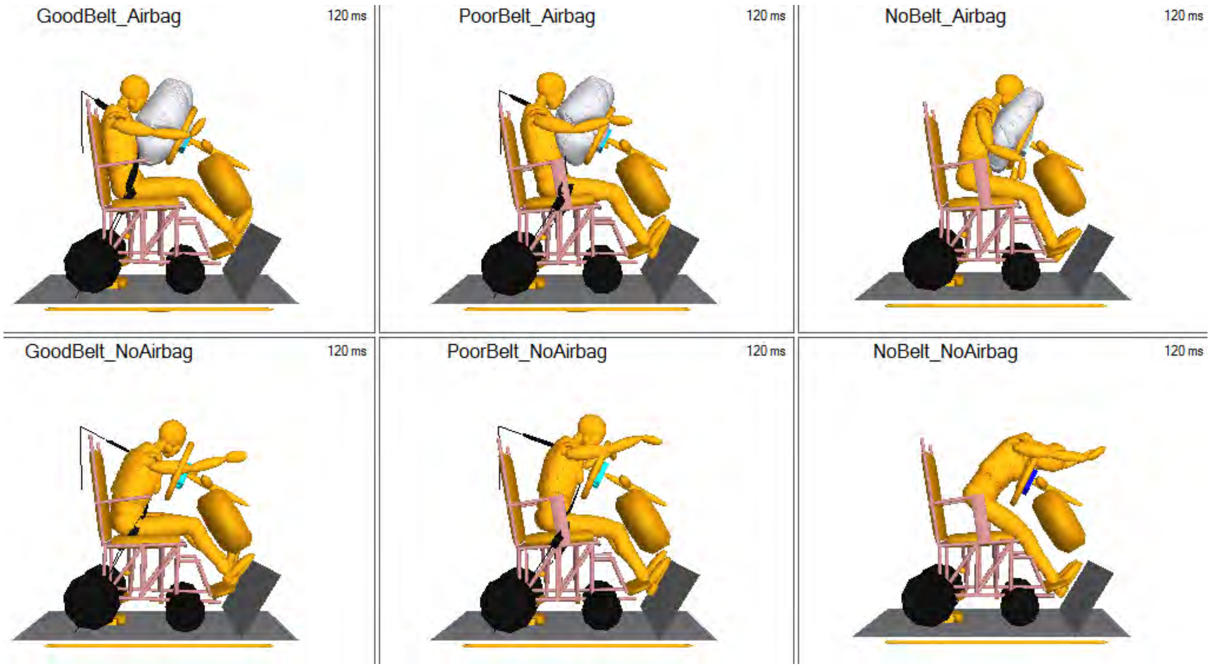


Figure 3.12 - Positions of the small-female ATD seated in the SWCF relative to the steering wheel, air bag, and knee bolster at 120 ms during a computer-simulated 48-kph, 20-*g* frontal impact – simulations are for good seat-belt fit (left), poor (loose) seat-belt fit (middle), and no seat belt (right) and for air-bag deployment at 12 ms (upper) and no air bag

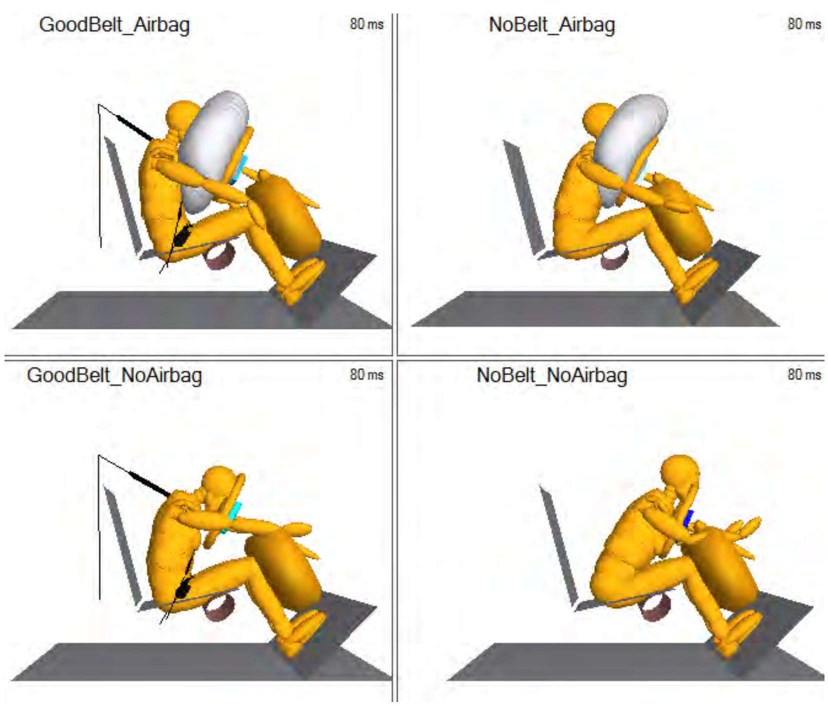


Figure 3.13 - Positions of the small-female ATD seated in an OEM minivan seat relative to the steering wheel, air bag, and knee bolster at 80 ms during a computer-simulated 48-kph, 20-*g* frontal impact – simulations are for good seat-belt fit (left) and no seat belt (right), and for air-bag deployment at 12 ms (upper) and no air bag

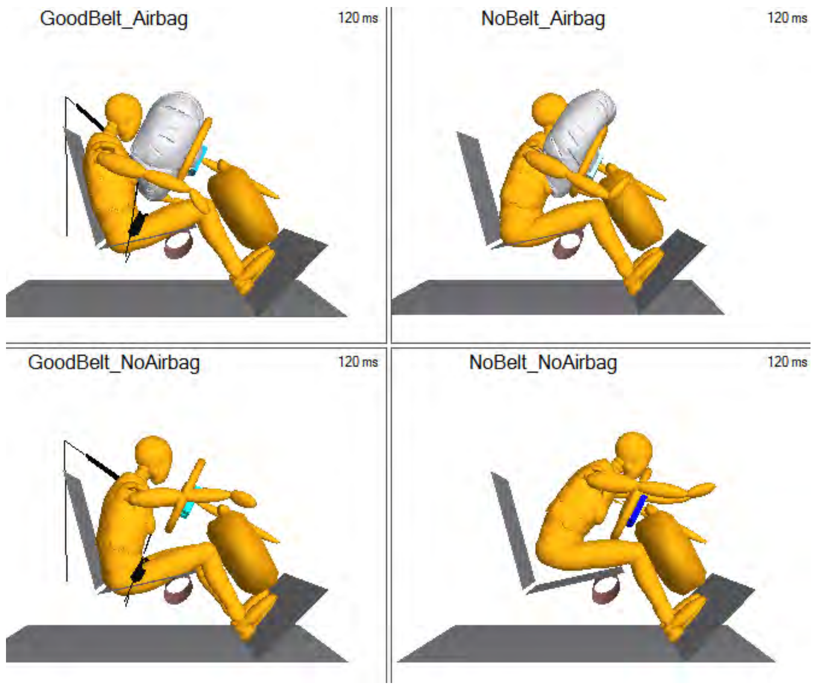


Figure 3.14 - Positions of the small-female ATD seated in an OEM minivan seat relative to the steering wheel, air bag, and knee bolster at 120 ms during a computer-simulated 48-kph, 20-*g* frontal impact – simulations are for good seat-belt fit (left) and no seat belt (right), and for air-bag deployment at 12 ms (upper) and no air bag

3.6 Computer Simulations of Drivers Seated in Wheelchairs During Angled Frontal Impacts

3.6.1 Methods

To examine responses of drives seated in wheelchair during angled frontal impacts, the previously validated model was used with the frontal crash pulse shown in Figure 3.2 but with the longitudinal axis of the vehicle oriented at either 15 or 30 degrees (about 11 and 10 o'clock) to the full-frontal orientation. Thus, for these simulations, the driver will move forward and to the left toward the A-pillar and the left side of the vehicle during the impact event.

The simulations were conducted using both the small-female and midsize-male ATD models with and without deployment of the steering-wheel air bag at 12 ms after the onset of the crash deceleration pulse, and with both good and poor belt fit as previously described. It was also determined from discussions with safety engineers at vehicle manufacturers, as well as from results of crash-tests conducted by the Insurance Institute for Highway Safety (http://www.autoblog.com/2015/02/20/2016-kia-sorento-iihs-top-safety-pick/) that side-curtain air bags will almost always deploy in today's vehicles during frontal crashes in which the direction of impact is anything other than head-on. For this reason, the side-curtain air bag was deployed in all angled simulations whether or not the steering-wheel air bag was deployed.

3.6.2 Results

Side-view and front-view still frames of the simulations at 0, 80, and 120 ms are presented in Figure **3.15** through Figure **3.22** and the key ATD response results of the simulations are summarized in Table 3.6. Lightly shaded rows in the table indicate runs without frontal air bag deployment, while values in bold font and darkly shaded cells (two HIC15 values and one Nij) show ATD responses that exceed the IARVs in Table **2.6**.

Table 3.6 - Results of angled frontal-crash simulations

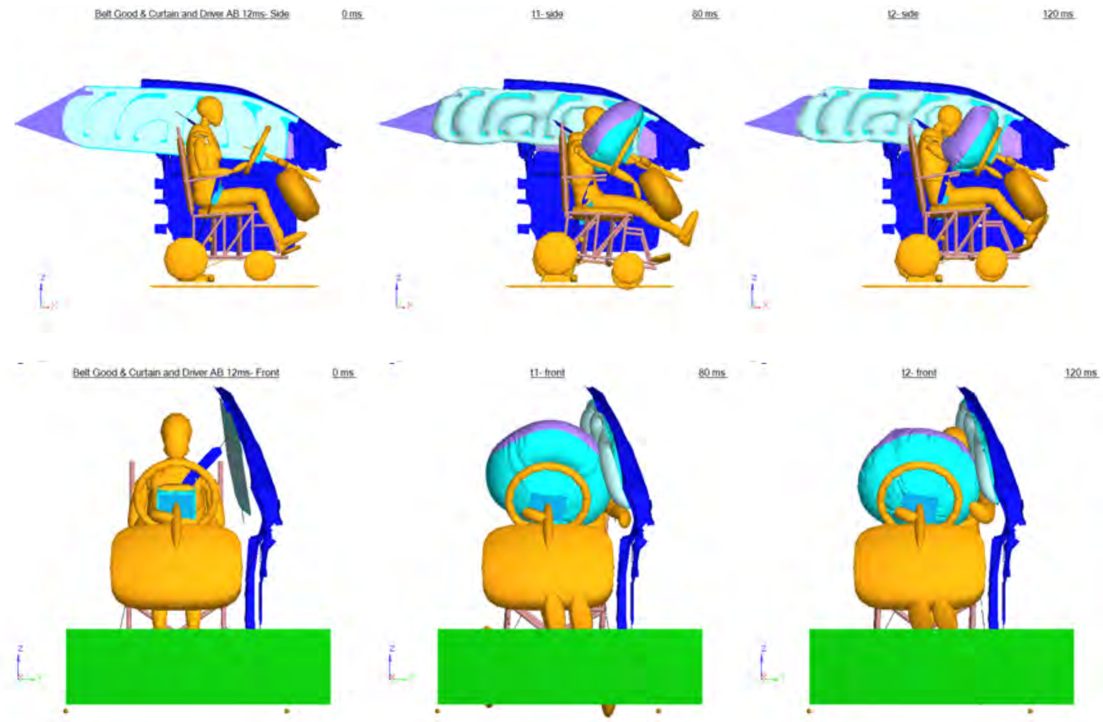
ATD	Angle (degrees)	Belt Fit	Steering-wheel Air bag	HIC 15	Nij	Peak Chest Deflection (mm)	Peak Left Femur Load (N)	Peak Right Femur Load (N)
5F	15	Good	Yes	143	0.44	43.4	2256	1140
5F	15	Good	No	421	0.41	34.4	1913	1618
5F	15	Poor	Yes	91	0.34	35.8	3958	2635
5F	15	Poor	No	205	0.43	34.7	4041	2894
5F	30	Good	Yes	104	0.38	41.6	1277	402
5F	30	Good	No	273	0.64	35.4	1164	582
5F	30	Poor	Yes	88	0.39	31.3	3495	2132
5F	30	Poor	No	111	0.45	21.0	3382	2331
50M	15	Good	Yes	92	0.22	44.3	2761	344
50M	15	Good	No	305	0.37	33.7	3062	434
50M	15	Poor	Yes	38	0.21	35.9	5366	4572
50M	15	Poor	No	113	0.45	28.9	5220	4793
50M	30	Good	Yes	222	0.70	40.0	1870	156
50M	30	Good	No	205	**1.21**	34.2	2130	543
50M	30	Poor	Yes	**975**	0.60	31.6	4788	3665
50M	30	Poor	No	**1336**	0.68	19.6	4545	4094

Note: all air-bag deployments were initiated 12 ms after the onset of crash deceleration.

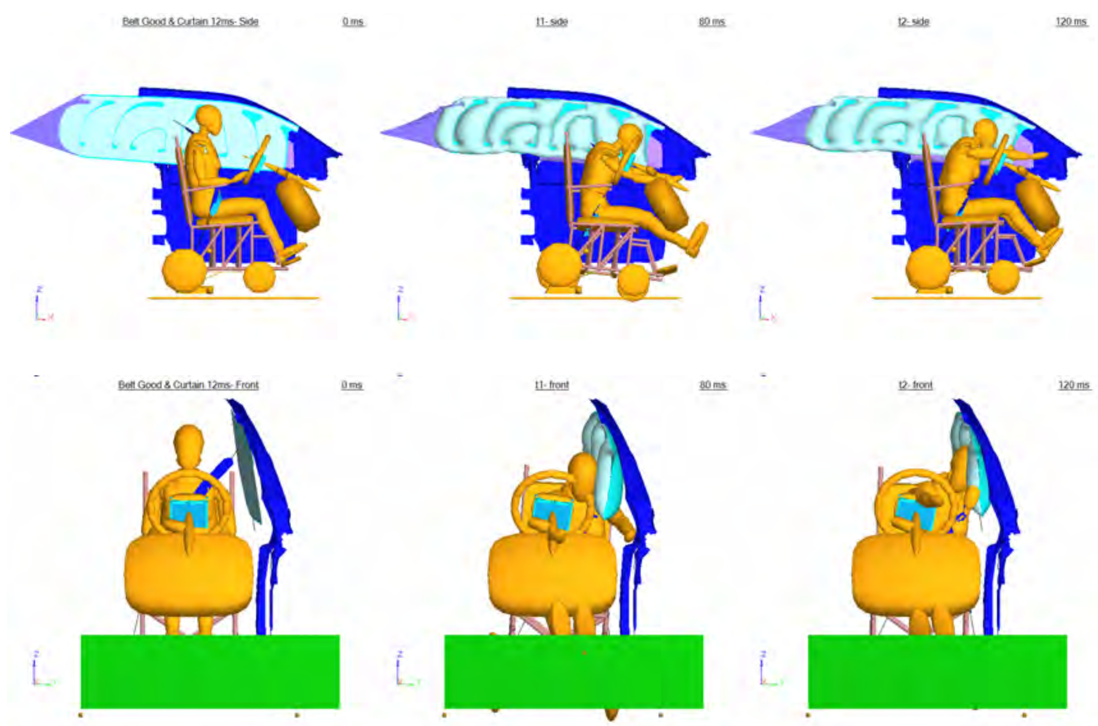
For both ATDs, it can be noted that all but two HIC15 values and all but one Nij value are well below the IARVs for these response measures. However, it can also be noted that HIC15 values are consistently higher for simulations without deployment of the steering-wheel air bag (i.e., the value in each shaded row is generally higher than value in the unshaded row above it). Many of these higher HIC values, especially for the 15-degree angled simulations, are due to head/face contact with the steering wheel, which occurs because the steering-wheel air bag was not deployed. However, in most of the 30-degree simulations, the head moves to the left of the steering-wheel when the steering-wheel air bag is not deployed, and the somewhat higher HIC values are due to head contact with the side-curtain air bag in the absence of prior contact with a steering-wheel air bag.

In this regard, the two HIC-15 values that exceed the IARV of 700 are for the midsize male ATD in the 30-degree angled impact with poor belt fit and with and without deployment of the steering-wheel air bag. However, the HIC-15 value is significantly higher without deployment of the steering-wheel air bag. From review of the simulation output videos, it appears that these high HIC values are due to head contact with the upper part of the curtain air bag. It is hypothesized that the air bag model may not be thick enough in this area to prevent the head from making contact with the roof side rail through the curtain air bag.

With regard to the one case with a high Nij value of 1.21, which occurs for the midsize-male ATD in a 30-degree angled impact with good belt fit and without deployment of the steering-wheel air bag, this value is not, as one might first expect, due to head contact with the steering wheel. Rather, the head misses the steering wheel to the left. It is thought that the high Nij may be due to neck forces generated when the ATD's left shoulder contacts the side of the vehicle under the curtain air bag, which produces a jerking action on the ATD's neck. If this is the case, curtain air bags that deploy lower than the one used in the model would help to prevent the high neck loads and moments that resulted in the high Nij.

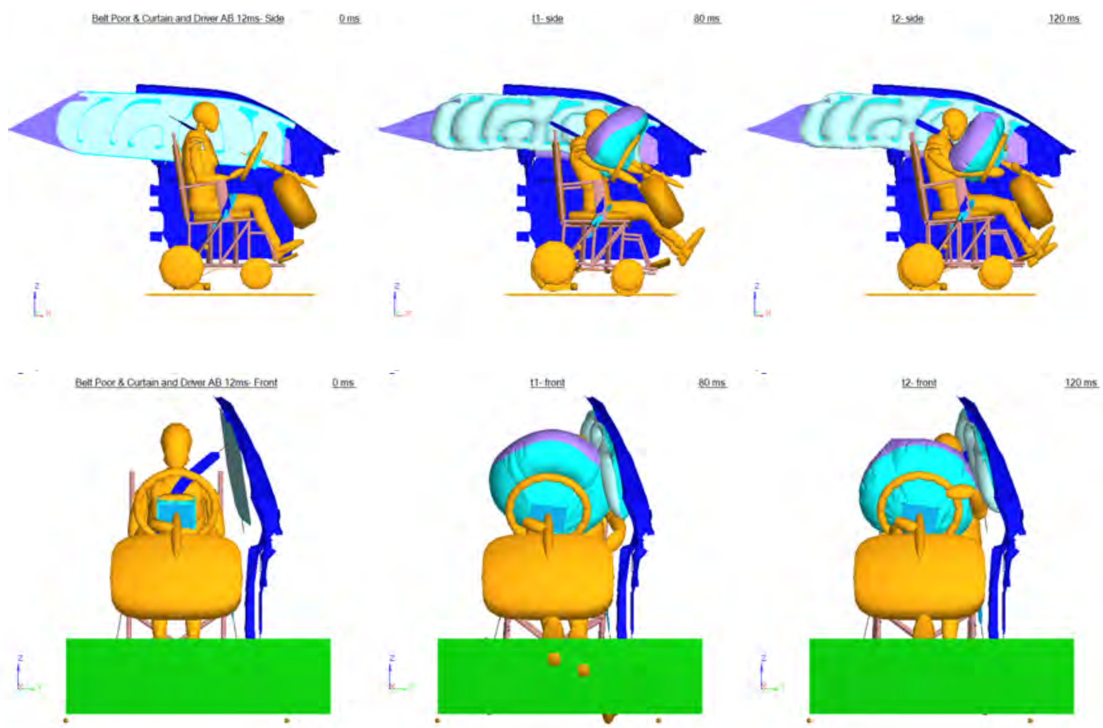


steering wheel and curtain air bags

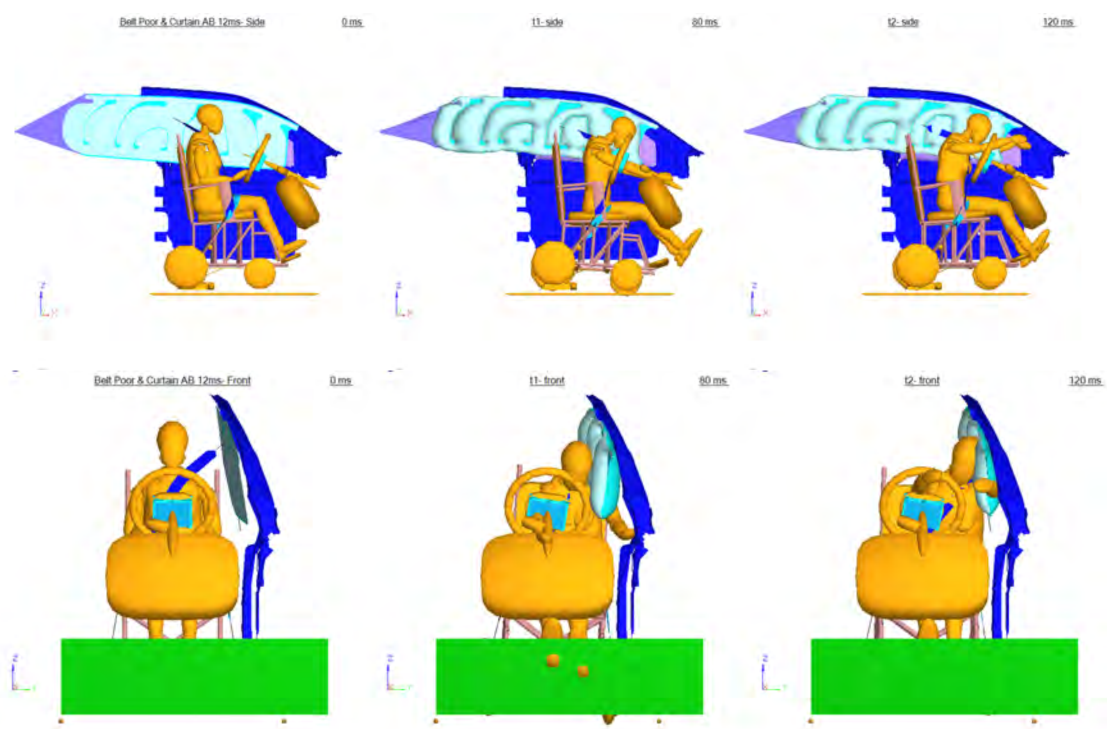


curtain air bag only

Figure 3.15 - Still frames at 0, 80, and 120 ms for 15-DEGREE angled frontal-impact computer simulations of the SMALL-FEMALE ATD with GOOD BELT FIT, with deployment of BOTH STEERING-WHEEL AND SIDE-CURTAIN AIRBAGS (upper) and with deployment of ONLY THE SIDE-CURTAIN AIRBAG (lower)

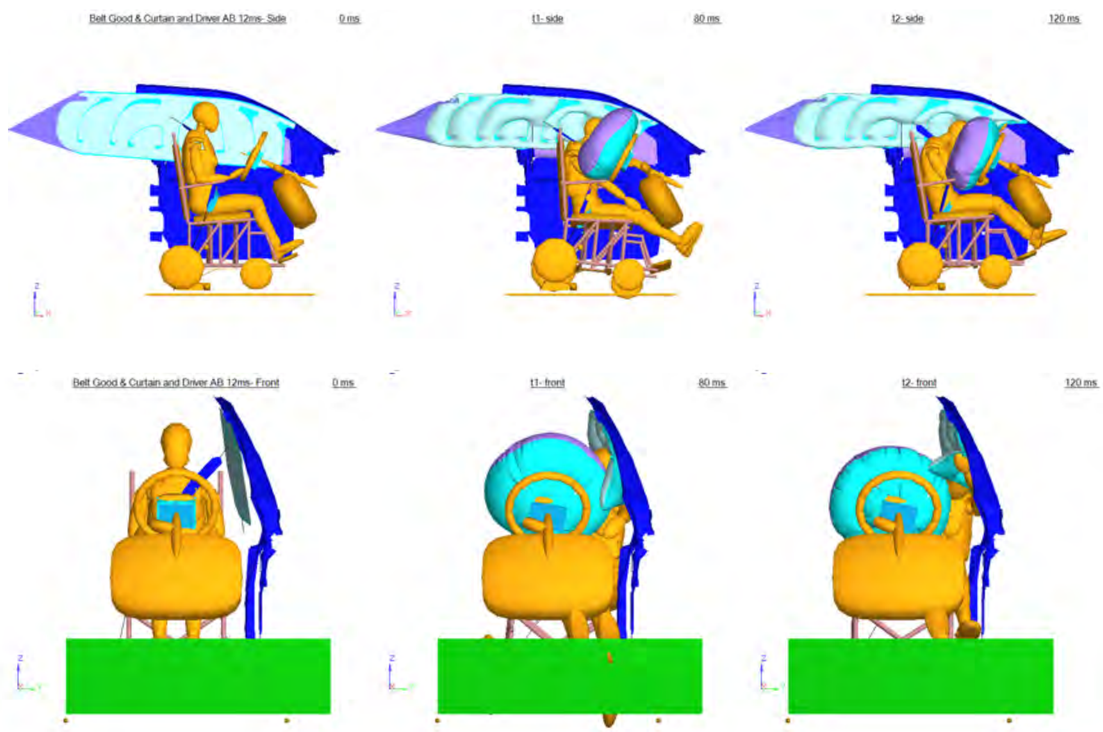


steering-wheel and side-curtain air bags

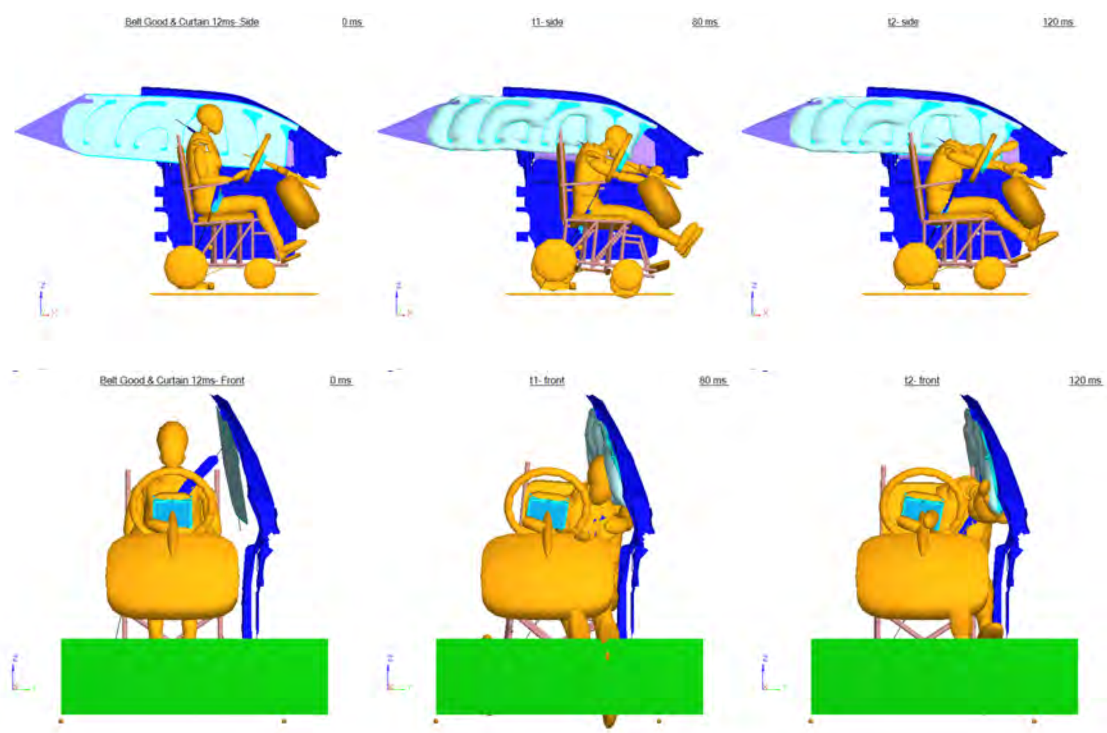


side-curtain air bag only

Figure 3.16 - Still frames at 0, 80, and 120 ms for 15-DEGREE angled frontal-impact computer simulations of the SMALL-FEMALE ATD with POOR BELT FIT, with deployment of BOTH STEERING-WHEEL AND SIDE-CURTAIN AIRBAGS (upper) and with deployment of ONLY THE SIDE-CURTAIN AIRBAG (lower)

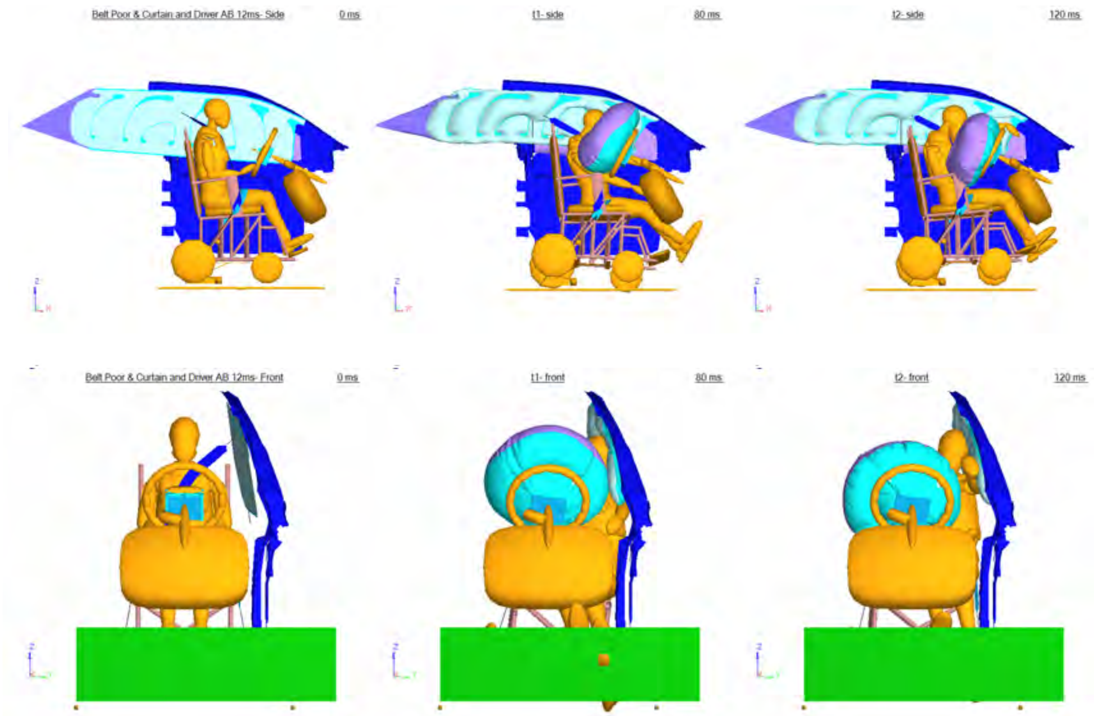


steering-wheel and side-curtain air bags

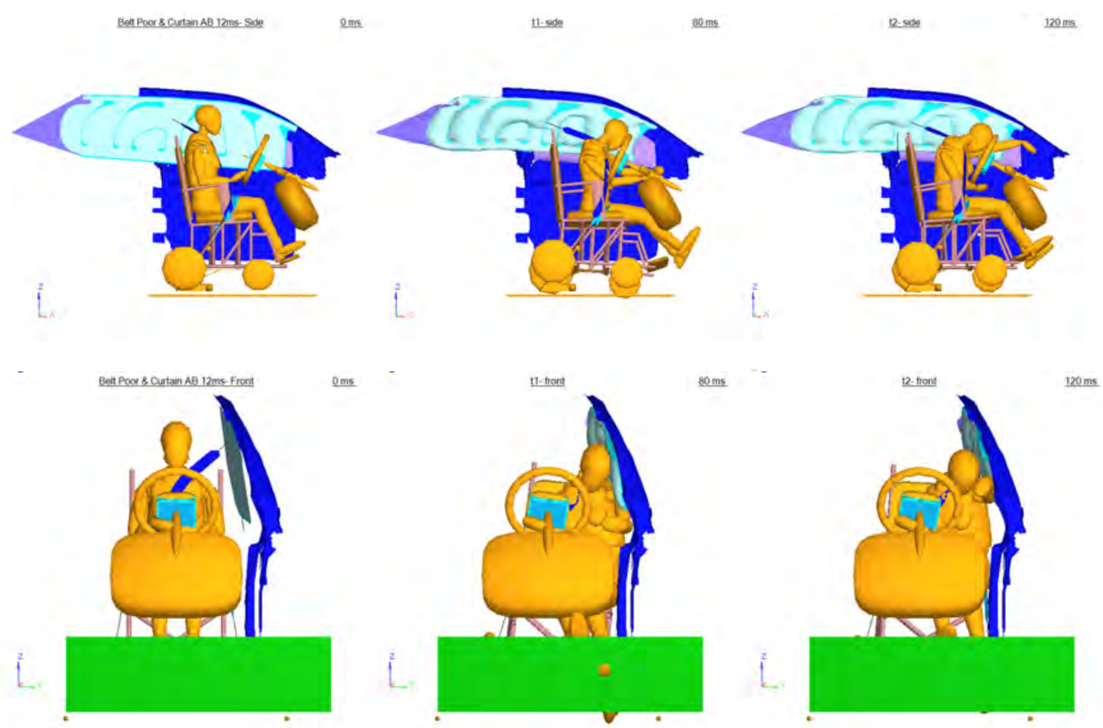


side-curtain air bag only

Figure 3.17 - Still frames at 0, 80, and 120 ms for 30-DEGREE angled frontal-impact computer simulations of the SMALL-FEMALE ATD with GOOD BELT FIT, with deployment of BOTH STEERING-WHEEL AND SIDE-CURTAIN AIRBAGS (upper) and with deployment of ONLY THE SIDE-CURTAIN AIRBAG (lower)

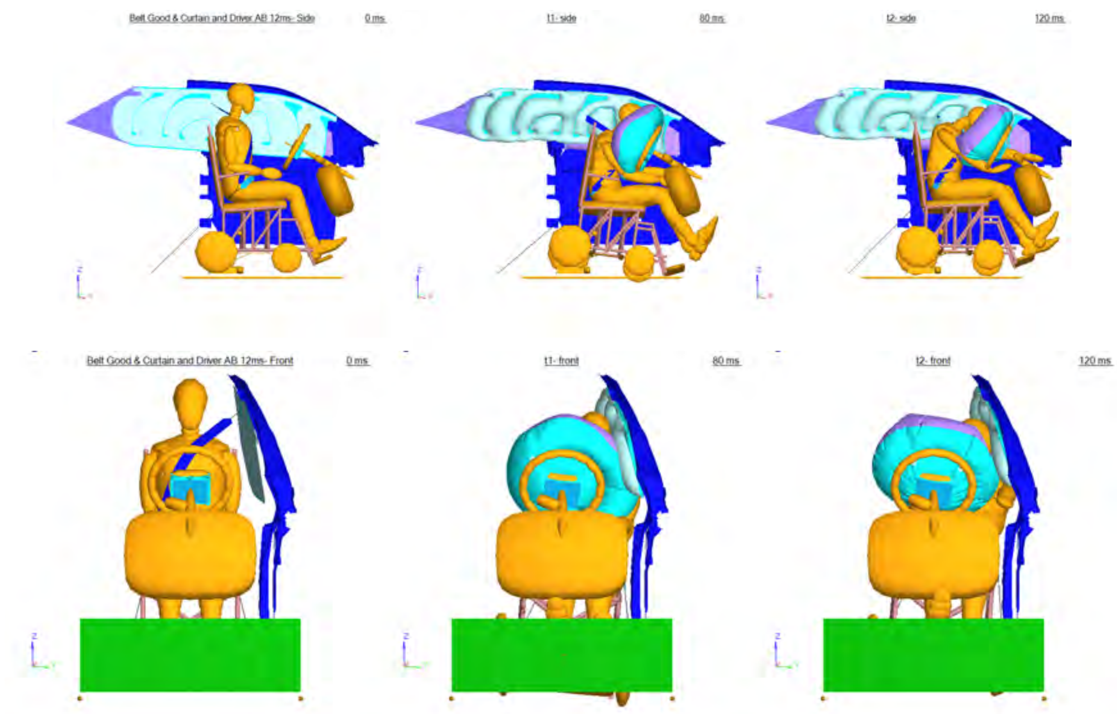


steering wheel and side-curtain air bags

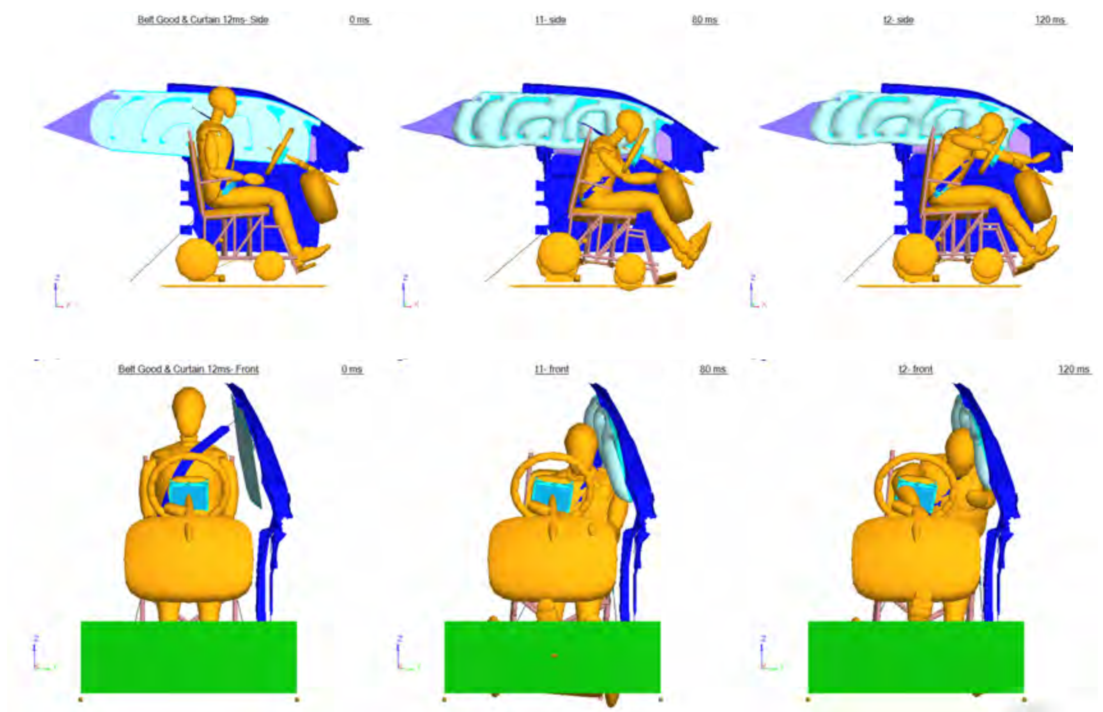


side-curtain air bag only

Figure 3.18 - Still frames at 0, 80, and 120 ms for 30-DEGREE angled frontal-impact computer simulations of the SMALL-FEMALE ATD with POOR BELT FIT, with deployment of BOTH STEERING-WHEEL AND SIDE-CURTAIN AIRBAGS (upper) and with deployment of ONLY THE SIDE-CURTAIN AIRBAG (lower)

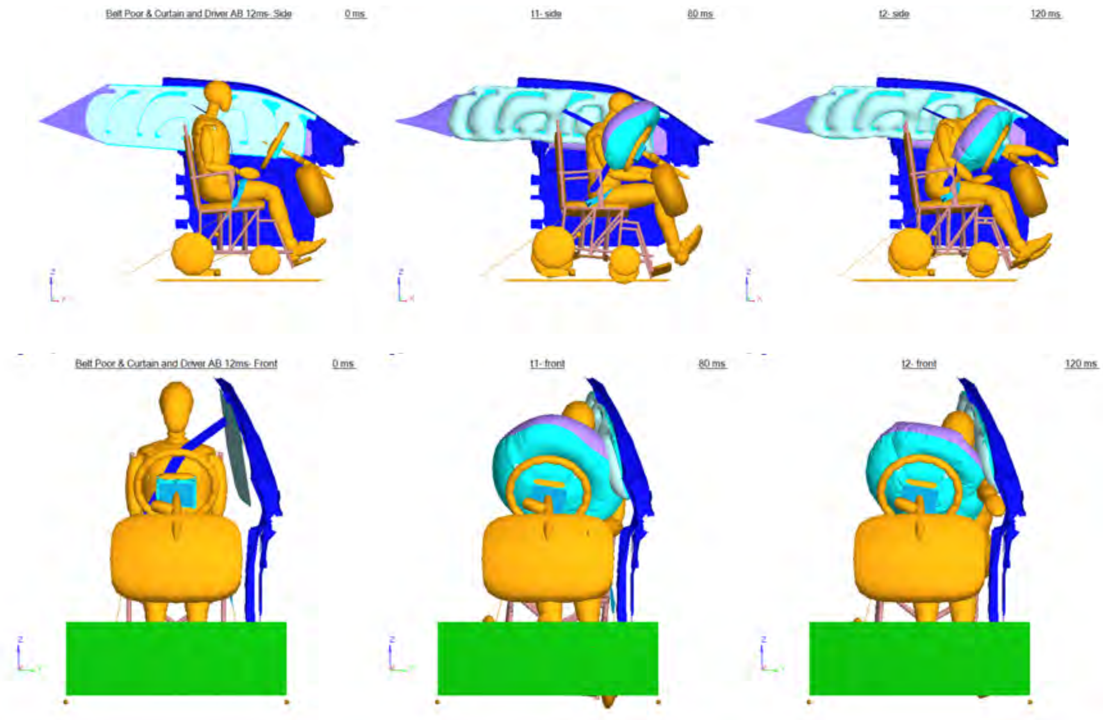


steering-wheel and side-curtain air bags

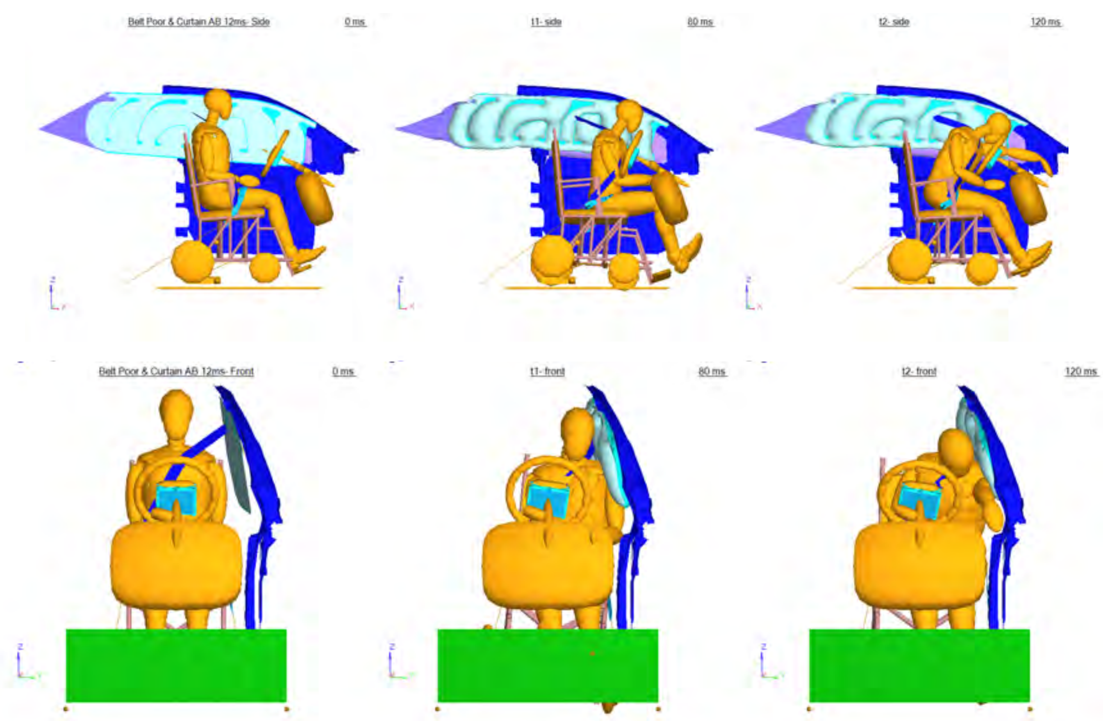


side-curtain air bag only

Figure 3.19 - Still frames at 0, 80, and 120 ms for 15-DEGREE angled frontal-impact computer simulations of the MIDSIZE-MALE ATD with GOOD BELT FIT, with deployment of BOTH STEERING-WHEEL AND SIDE-CURTAIN AIRBAGS (upper) and with deployment of ONLY THE SIDE-CURTAIN AIRBAG (lower)

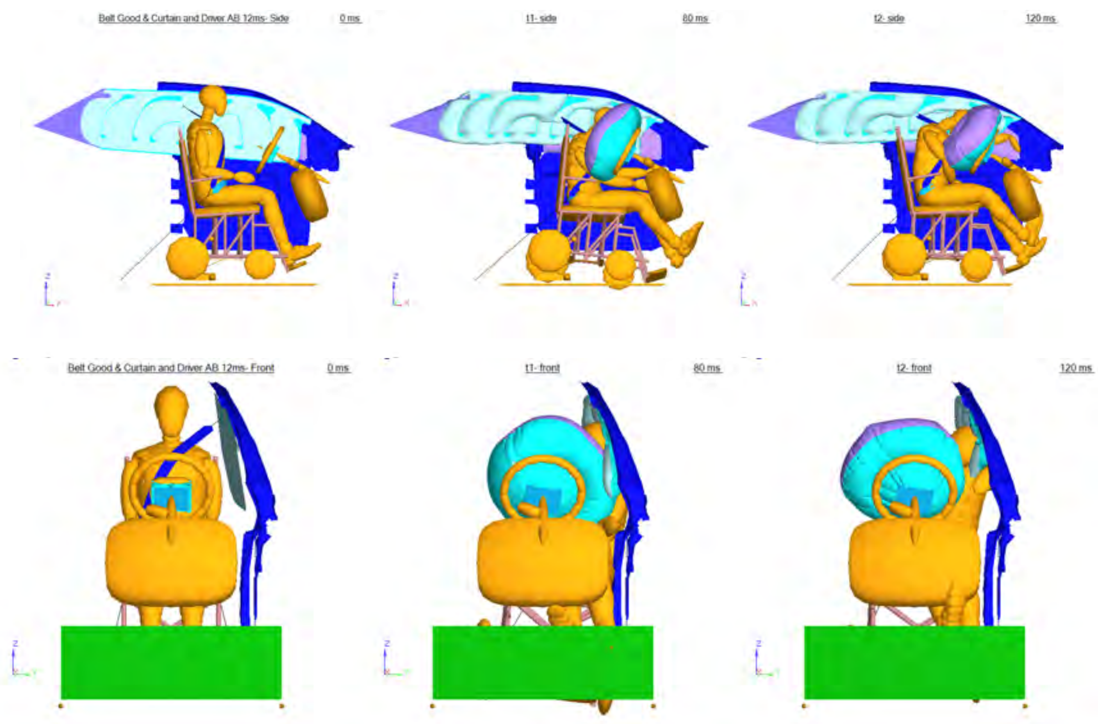


steering-wheel and side-curtain air bags

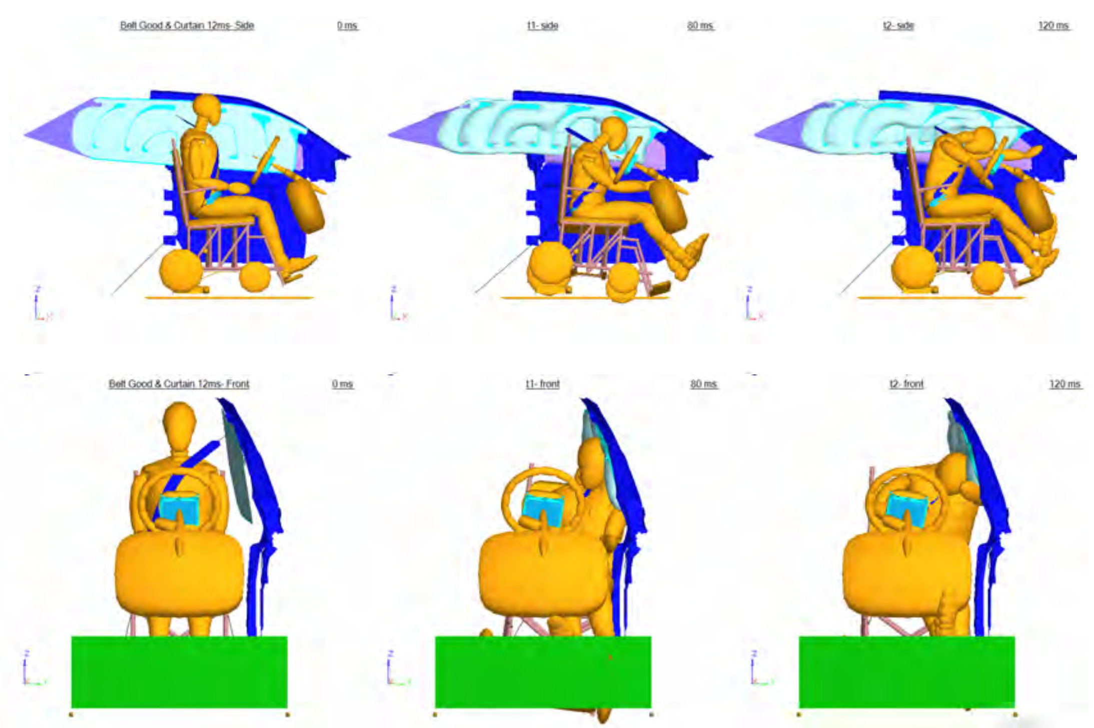


side-curtain air bag only

Figure 3.20 - Still frames at 0, 80, and 120 ms for 15-DEGREE angled frontal-impact computer simulations of the MIDSIZE-MALE ATD with POOR BELT FIT, with deployment of BOTH STEERING-WHEEL AND SIDE-CURTAIN AIRBAGS (upper) and with deployment of ONLY THE SIDE-CURTAIN AIRBAG (lower)

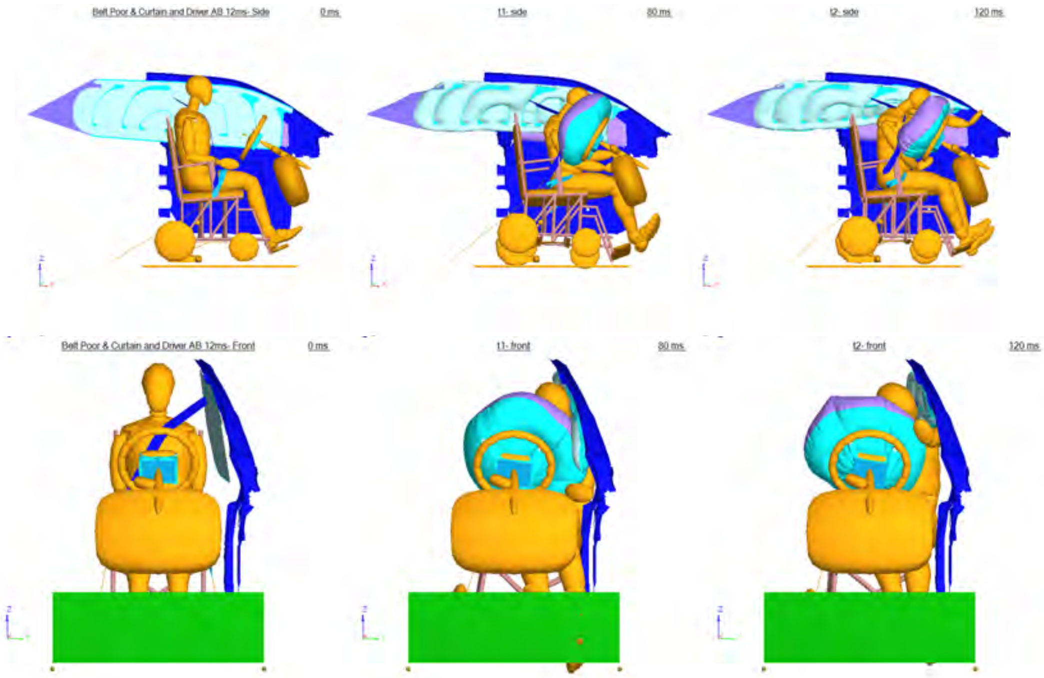


steering-wheel and side-curtain air bags

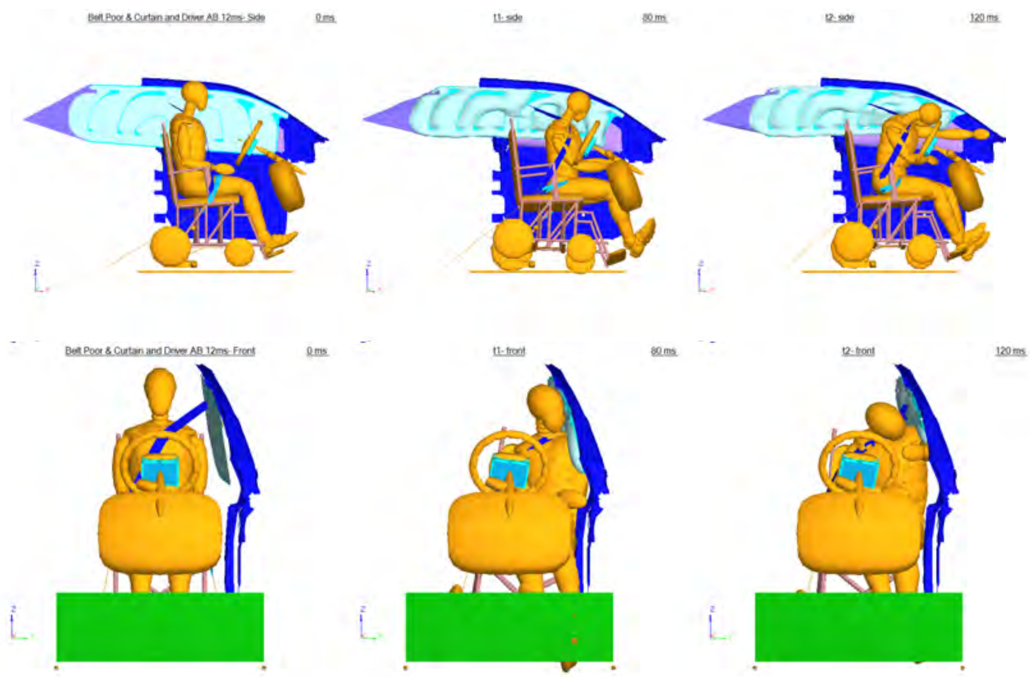


side-curtain air bag only

Figure 3.21 - Still frames at 0, 80, and 120 ms for 30-DEGREE angled frontal -impact computer simulations of the MIDSIZE-MALE ATD with GOOD BELT FIT, with deployment of BOTH STEERING-WHEEL AND SIDE-CURTAIN AIRBAGS (upper) and with deployment of ONLY THE SIDE-CURTAIN AIRBAG (lower)



steering-wheel and side-curtain air bags



side-curtain air bag only

Figure 3.22 - Still frames at 0, 80, and 120 ms for 30-DEGREE angled frontal-impact computer simulations of the MIDSIZE-MALE ATD with POOR BELT FIT, with deployment of BOTH STEERING-WHEEL AND SIDE-CURTAIN AIRBAGS (upper) and with deployment of ONLY THE SIDE-CURTAIN AIRBAG (lower)

3.7 Computer simulations of drivers positioned in close-proximity (OOP) to the steering-wheel air bag

In the measurement study of wheelchair drivers in their personal vehicles described in 2.3, one male driver was positioned such that the shortest distance between his body and the steering wheel was about 13 cm (5 in). It is also possible that drivers seated in wheelchairs may be positioned very close to the air-bag module at the time of deployment due to forward movement during pre-crash braking due to a reduced ability to brace against the steering wheel combined with poor belt fit, lack of a complete lap/shoulder belt, or no seat belt. For these reasons, a final matrix of simulations of drivers seated in wheelchairs was conducted using the small-female and midsize-male ATDs positioned in close proximity to the steering wheel at the time of air bag deployment.

3.7.1 Methods

Sixteen simulations were conducted using the small-female and midsize-male wheelchair-seated driver models. The simulations were conducted for the following conditions:

- the shortest pre-impact distance between the ATD and the steering wheel was set to 25 mm (1 in) or 125 mm (5 in), where this distance was usually between a point on the ATD's face to the upper portion of the steering wheel,
- good or poor seat belt fit, and
- deployment and non-deployment of the steering wheel air bag.

All simulations were run in the full frontal configuration with the crash pulse shown in Figure 3.2 and a 12-ms air-bag deployment delay. As in previous simulations, the steering column stiffness was set to 3 kN/mm and the steering-wheel rim stiffness was set to 50 N/mm. The seat-belt load limiter was set to 3kN and the seat-belt pretensioner was fired at 12-ms after the onset of impact deceleration whether or not the air bag deployed.

3.7.2 Results

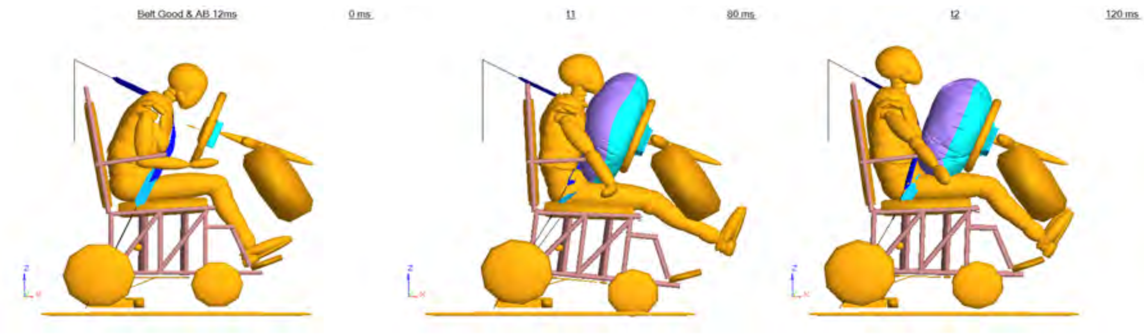
Table **3**.**7** shows the ATD response values for the sixteen conditions simulated. Shaded rows indicate simulations without air bag deployment. The bolded Nij entries in the table highlight the conditions for which the IARVs of Table **2**.**6** were exceeded. Figure 3.23 to Figure 3.26 show still frames from the simulation output videos at 0 ms, 80 ms, and 120 ms for all sixteen simulations and indicate ATD and wheelchair kinematics and interaction of the ATD with the belt restraints, air bag, and/or steering wheel.

In the column for peak chest deflections, it can be noted that the peak deflections are always higher for the simulations with air bag deployment regardless of the belt restraint condition and ATD size. This is as expected from close-proximity air bag-deployment loading of the ATD's chest. For example in a study reported by Prasad et al. (2008) in which small-female post-mortem human (PMHS) subjects were placed in direct contact with the steering=wheel depowered air bag for different positioning scenarios, the only serious and potentially fatal injuries were to the PMHS chest when it was in direct contact with the air bag module at the time of air bag deployment. It has also been shown by Hardy et al. (2001) that a small distance of even 25 mm between the occupant's body (e.g., forearm or chest) can mean the difference between serious injuries (e.g., forearm fractures) or less serious injuries (e.g., contusions).

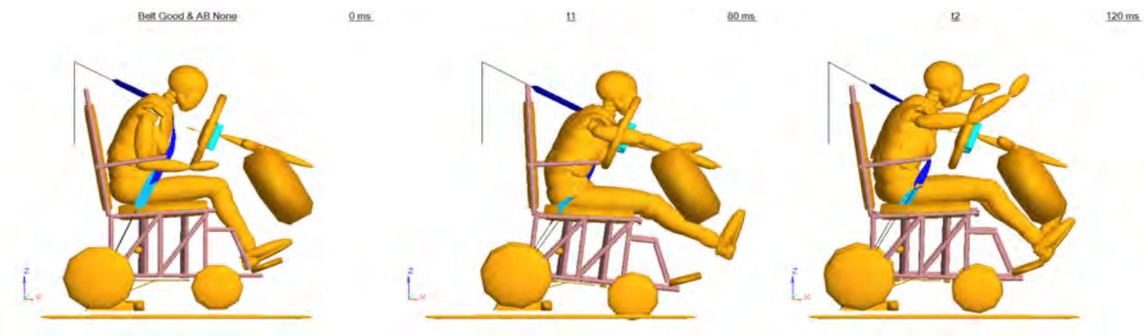
It can also be noted that, while all HIC-15 values are relatively low, they are often higher when the air bag is deployed compared to the comparable condition without air bag deployment. The only response variable that exceeds the IARV is Nij. These occur for the small-female ATD at a distance of 25 mm with good belt fit and air bag deployment for which Nij is 1.04, and for the midsize-male ATD at a distance of 25 mm with poor belt fit and no air bag deployment, for which the value is 1.18. Looking at the still frames in Figure 3.23a and Figure 3.25d, it appears that the high Nij for the small female is caused by OOP air bag-deployment loading and, for the midsize male, by direct contact of the neck with the upper rim of the steering wheel. Although the high Nij for the small female may suggest some concern for airbag-induced injuries, small-female PMHS tests conducted at UMTRI and reported by Prasad et al. (2008), suggest that neck injury is not a concern for OOP drivers loaded by deploying depowered air bags, which are probably more aggressive than advanced airbags in today's vehicles.

Table 3.7 - Summary of ATD Responses for Close-Proximity (i.e., OOP) Driver Simulations

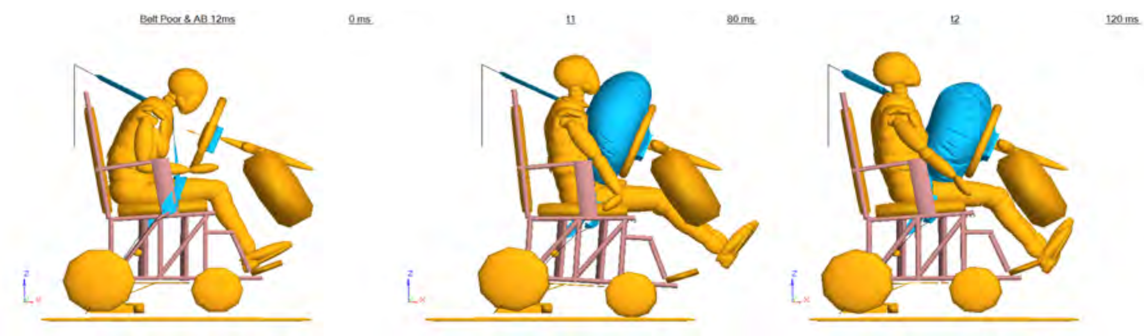
ATD	Pre-crash distance to to Steering Wheel	Belt Fit	Air bag	HIC15	Nij	Peak Chest Deflection (mm)	Peak Left Femur Load (N)	Peak Right Femur Load (N)
5F	25mm(1in.)	Good	Yes	327	**1.04**	46.6	1730	1394
5F	25mm (1in)	Good	No	158	0.43	28.1	1444	1762
5F	25mm (1in)	Poor	Yes	283	0.65	38.6	2555	2611
5F	25mm (1in)	Poor	No	93	0.38	33.7	2605	2949
5F	125mm (5in)	Good	Yes	169	0.55	49.4	1532	1532
5F	125mm (5in)	Good	No	149	0.43	31.6	1609	2293
5F	125mm (5in)	Poor	Yes	174	0.52	41.7	2978	3120
5F	125mm (5in)	Poor	No	81	0.48	32.9	3383	3552
50M	25mm (1in)	Good	Yes	140	0.52	53.8	2638	2022
50M	25mm (1in)	Good	No	82	0.48	36.3	3346	2389
50M	25mm (1in)	Poor	Yes	105	0.48	51.1	4096	4177
50M	25mm (1in)	Poor	No	133	**1.18**	34.0	4344	4411
50M	125mm (5in)	Good	Yes	131	0.60	44.9	1069	1478
50M	125mm (5in)	Good	No	52	0.60	29.9	1826	1788
50M	125mm (5in)	Poor	Yes	77	0.60	51.2	5304	5449
50M	125mm (5in)	Poor	No	49	0.60	37.3	5391	5353



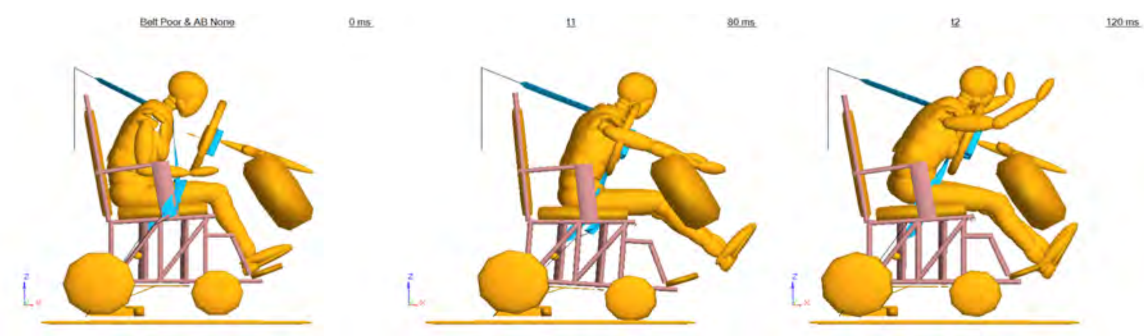
(a) - good belt fit with deployment of the steering-wheel air bag



(b) - good belt fit without deployment of the steering-wheel air bag

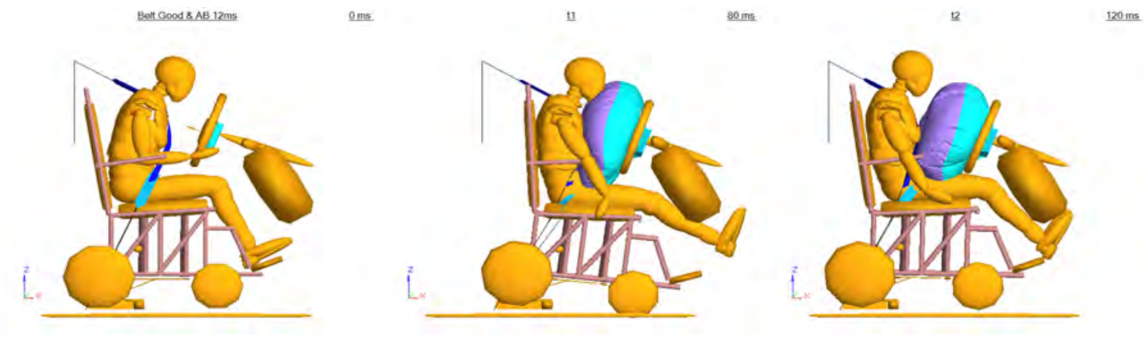


(c) - poor belt fit with deployment of the steering-wheel air bag

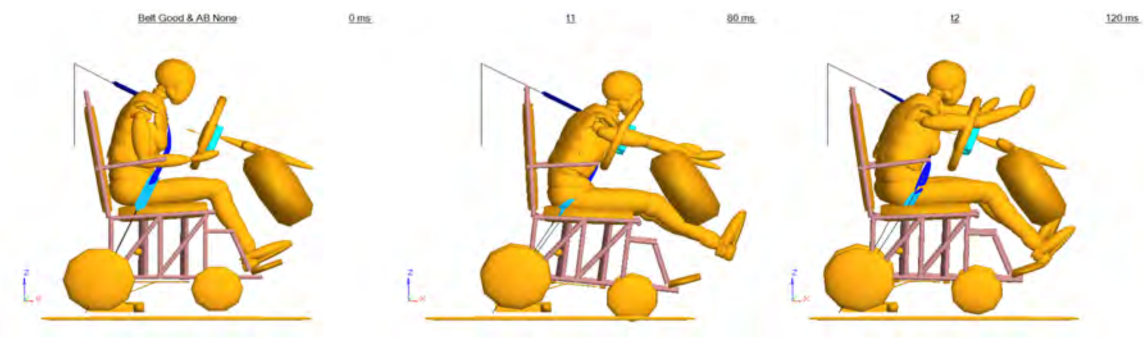


(d) - poor belt fit without deployment of the steering-wheel air bag

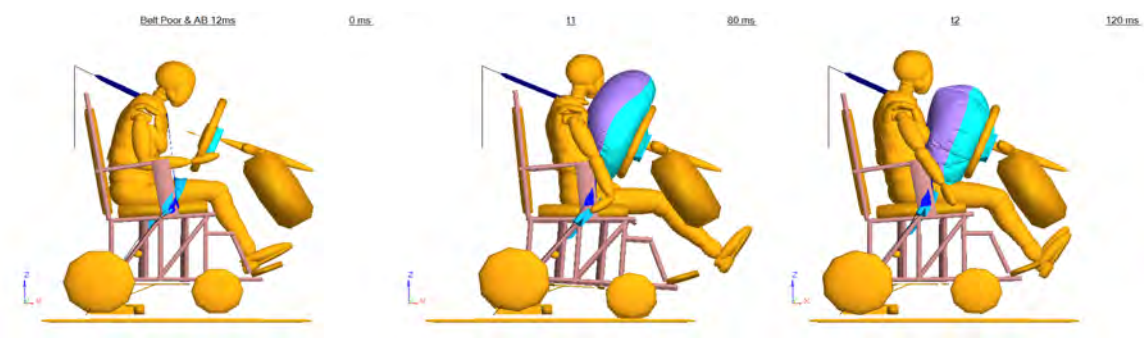
Figure 3.23 - Still frames at 0, 80, and 120 ms from computer simulations with the small-female ATD positioned 25-mm (1-inch) from the steering wheel prior to the onset of impact deceleration



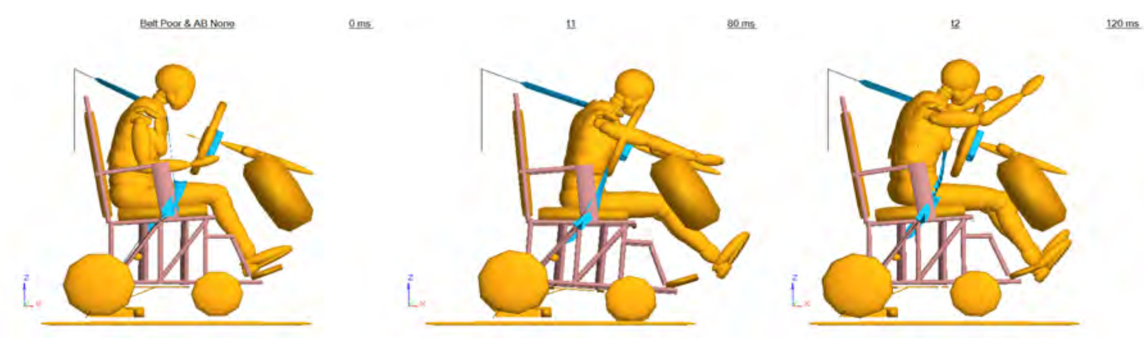
(a) - good belt fit with steering-wheel air bag



(b) - good belt fit with no steering-wheel air bag

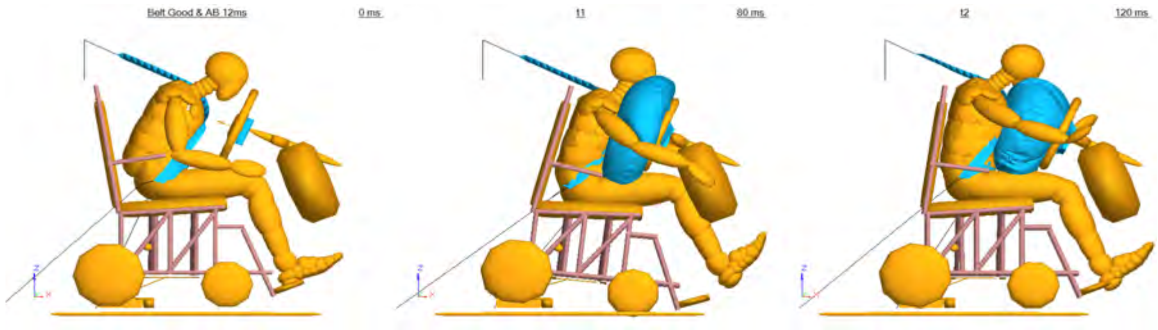


(c) - poor belt fit with steering-wheel air bag

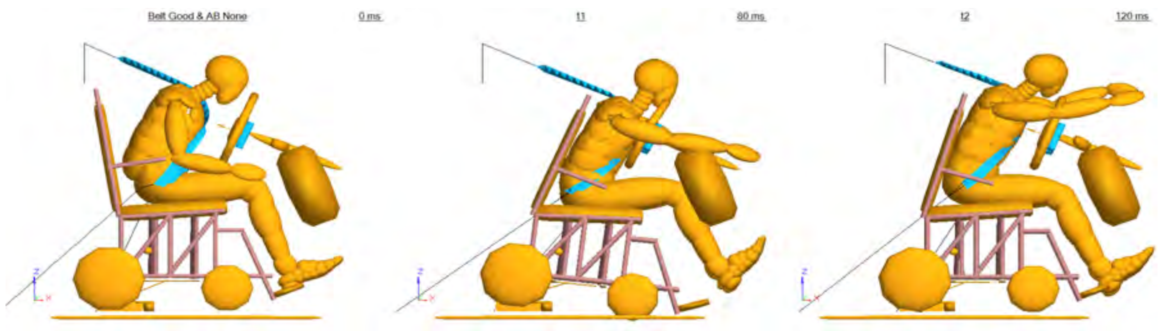


(d) - poor belt fit with no steering-wheel air bag

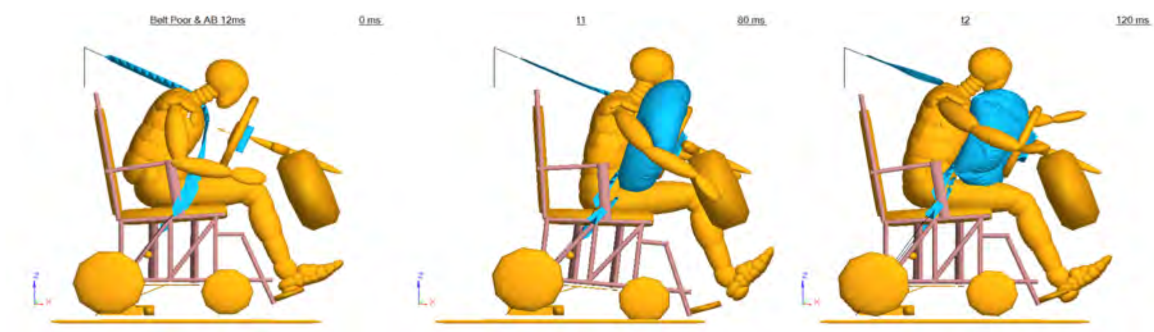
Figure 3.24 - Still frames at 0, 80, and 120 ms from computer simulations with the small-female ATD positioned 125-mm (5-inches) from the steering wheel prior to the onset of impact deceleration



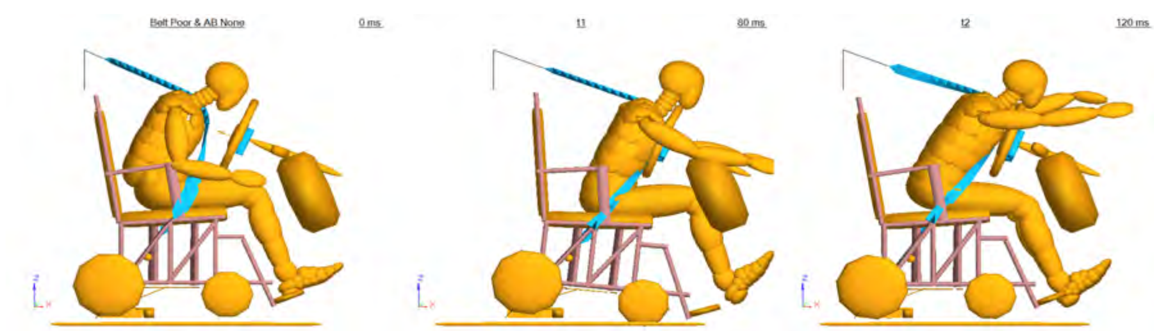
(a) - good belt fit with deployment of the steering-wheel air bag



(b) - good belt fit without deployment of the steering-wheel air bag

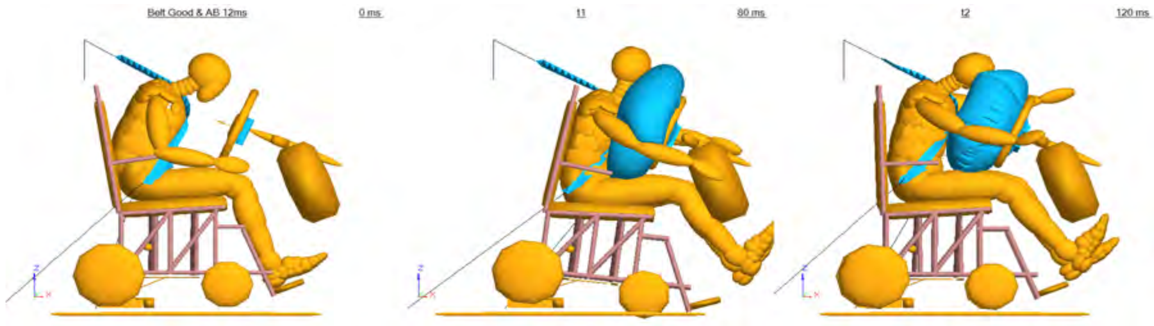


(c) - poor belt fit with deployment of the steering-wheel air bag

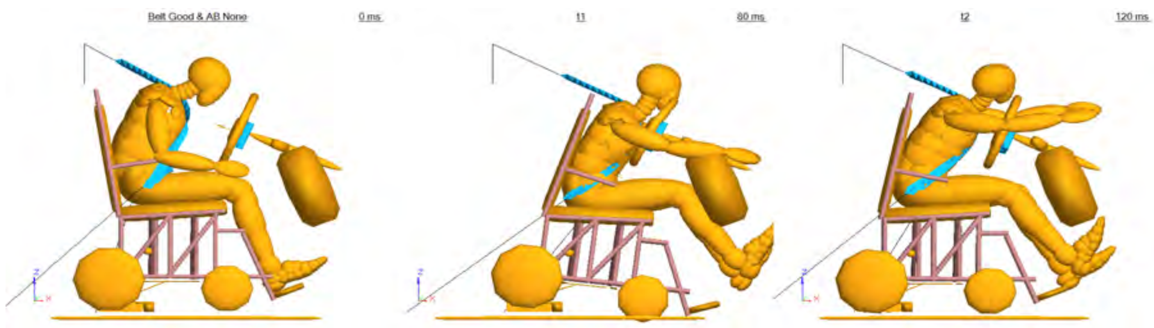


(d) - poor belt fit without deployment of the steering-wheel air bag

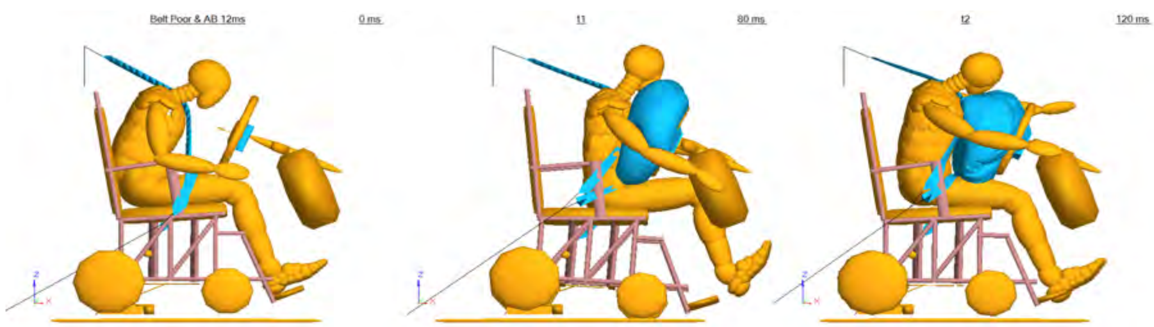
Figure 3.25 – Still frames at 0, 80, and 120 ms from computer simulations with the midsize male ATD positioned 25-mm (1-inch) from the steering wheel prior to the onset of impact deceleration



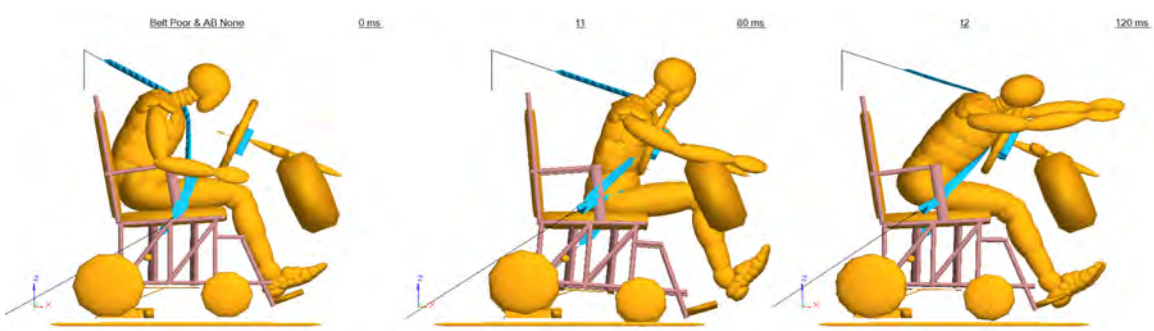
(a) - good belt fit with steering-wheel air bag



(b) - good belt fit with no steering-wheel air bag



(c) - poor belt fit with steering-wheel air bag



(d) - poor belt fit with no steering-wheel air bag

Figure 3.26 - Still frames at 0, 80, and 120 ms from computer simulations with the midsize-male ATD positioned 125-mm (5-inches) from the steering wheel prior to the onset of impact deceleration

3.8 Summary and discussion

In this Subtask, 48-kph, 20-*g* frontal sled tests with the midsize-male and small female Hybrid III ATDs with steering-wheel air-bag deployments and computer simulations of 48-kph, 20-*g* frontal impacts with both ATDs and with and without steering-wheel air-bag deployment were conducted to study the conditions under which steering-wheel air bags offer protective benefits or may be the source of serious injury to drivers seating in wheelchairs. The scenarios examined included three different belt-restraint conditions (good belt fit, poor (loose) belt fit, and no belt restraints), angled-frontal impacts, and out-of-position drivers who are positioned 125 or 25 mm from the steering wheel at the onset of frontal-impact deceleration. Simulations were also conducted for the small-female ATD seated in a surrogate wheelchair and an OEM minivan seat to compare the effects of initial posture and position and seat angle on driver kinematics and interaction with the air bag or steering wheel.

Overall, the results of these sled tests and simulations show little basis for concern that the energy during deployment of advanced steering-wheel air bags in today's vehicles will cause serious-to-fatal injuries to drivers seated in wheelchairs. In almost all of the conditions studied, the steering-wheel air bags reduced the risk of head, neck, and chest injuries for both midsize-male and small-female drivers that can occur from contact with the steering wheel and other vehicle components if the air bag is deactivated.

In angled frontal impacts, deployment of the side-curtain air bag is important since it reduces the risk of injurious head contact with the A-pillar, side window, and other vehicle interior components. When both the steering wheel and side-curtain air bags deploy, the driver is provided with an extra measure of protection as the driver's head is cushioned between the two air bags.

The results of this study therefore support the idea that steering-wheel air bags offer tangible safety benefits for a wide range of drivers seated in wheelchairs, just as they do for drivers in vehicle seats. Therefore, the steering-wheel air bag should only be deactivated on rare occasions when a driver in a wheelchair is sitting with their chest or chin within a few inches (i.e., less than 8 inches) of the air-bag module while operating the vehicle. Similar to drivers using vehicle seats, for steering-wheel air bags to provide maximum benefit (i.e., optimal frontal crash protection) to drivers seated in wheelchairs, use of a properly positioned lap/shoulder belt restraint is important.

In the study of drivers seated in wheelchairs using their personal vehicles described in Section 2.3, it was reported by several drivers that the shoulder belt in their vehicle did not provide sufficient upper-torso support, causing them to feel unstable when maneuvering the vehicle around turns. In addition, some drivers commented that the seat-belt retractor causes the shoulder belt to be too tight, such that it pushes their torso sideways from their optimal posture for operating the hand controls. These comments suggest that many drivers seated in wheelchairs would benefit from a shoulder belt with a fixed upper anchor point on the B-pillar with the shoulder belt adjusted to provide a comfortable but somewhat snug fit when the driver is ready for travel. Such a fixed anchor point would increase stability and would also prevent forward movement of the driver's torso during pre-impact braking, thereby keeping their head and chest away from a deploying airbag during a frontal crash. Implementing fixed shoulder-belt anchor points on B-pillars should, however, be done in a manner that does not compromise the performance of seatbelt load limiters and pre-tensioners, which are known to provide improved occupant protection and a reduction in chest injuries due to shoulder belt loading during frontal crashes.

4 Subtask 4: Develop and disseminate educational materials for vehicle modifiers and their clients, and for other key stakeholder groups

The RERC on Wheelchair Transportation Safety, funded by the National Institute on Disability and Rehabilitation Research (NIDRR) for more than ten years from 2001 through 2012, convened several State-of-Science (SoS) workshops. The goal of these workshops was to identify and prioritize barriers to improving safety, usability, and independence in transportation safety for people who remain seated in wheelchairs when traveling in motor vehicles, and to identify and prioritize actions to remove these barriers (Buning and Karg, 2011; Frost et al., 2012). Representatives of key stakeholder groups were invited to participate in these SoS workshops to ensure that there was broad representation by people with different perspectives who are involved in the transportation of people with disabilities. Without exception, the leading barrier that was identified in these workshops is a “lack of knowledge” about voluntary industry standards for wheelchairs and wheelchair tiedown and occupant restraint systems (WTORS), as well as a lack of knowledge about “best practice” for safe transportation of occupants seated in wheelchairs.

In addition, the findings of Subtask 1 and the early phase of Subtask 2 confirm that people seated in wheelchairs are often not fully benefitting from available occupant-protection technologies. For example, three-point belts are either not used or are misused in the majority of cases, and many wheelchair users are not aware that their current occupant-restraint practices are insufficient to provide effective crash protection or even prevent serious injuries in non-crash events, such as emergency braking. Consumers look to vehicle modifiers, driver trainers, therapists, and clinicians for advice on how to travel more safely, but these sources often lack a clear understanding of best practice in wheelchair transportation safety and/or the materials to communicate this information effectively and accurately.

The goal of this Subtask was to develop simple, easy-to-understand educational/training materials for distribution to vehicle modifiers and their clients. These materials outline best-practices to be used when installing adaptive equipment for drivers and passengers seated in wheelchairs when riding in private vehicles, as well as best practices in the proper use of WTORS.

Toward this end, three categories of Safety Tip Sheets have been developed for vehicle modifiers with each category containing a set of three Safety Tip Sheets. The three categories are for installation and proper use of WTORS used by:

1. passengers seated in wheelchairs secured by four-point, strap-type tiedowns,
2. passengers seated in wheelchairs secured by docking-securement devices, and
3. drivers seated in wheelchairs secured by docking-securement devices.

For each category, a set of three Safety Tip Sheets provides:

1. information for installers of tiedown/restraint systems,
2. information for vehicle modifiers to tell, and demonstrate to, a client before releasing a vehicle, and

3. information for clients to take with them when they take possession of their modified vehicle.

Appendix C provides the set of Safety Tip Sheets for modifiers of vehicles to be used by passengers seated in wheelchairs secured by four-point, strap-type tiedowns. Comments received from the NHTSA on this set of Safety Tip Sheets have been incorporated into all categories of Safety Tip Sheets for vehicle modifiers, as well as into Safety Tip Sheets being developed for other WTS stakeholder groups, such as wheelchair and WTORS manufacturers, wheelchair prescribers, clinicians, certified driver trainers, rehabilitation tech suppliers, and transit providers. In particular, it is planned to distributed the Safety Tip Sheets for vehicle modifiers with the help of the National Mobility Equipment Dealers Association (NMEDA) through their "Lunch-and-Learn" program.

In addition to the Safety Tip Sheets, a brochure called *DriveSafe* is in the process of being completed. This brochure is based on a similar brochure called *RideSafe*. However, while the *RideSafe* brochure is directed primarily at documenting the key steps in providing safe transportation for passengers seated in wheelchairs, the *DriveSafe* brochure is focused on key steps to providing safe transportation and effective crash protection for people who drive while seated in wheelchairs. As with the *RideSafe* brochure, a website of the brochure (www.travelsafer.org) and an associated Powerpoint presentation that replicate the contents of the printed brochure will also be made available on a new UMTRI Wheelchair Transportation Safety (WTS) website described in the next section.

5 Subtask 5: Develop and maintain an UMTRI website on wheelchair transportation safety (WTS)

Because the website developed by the RERC on Wheelchair Transportation Safety (WTS), www.rercwts.org, has not been maintained and updated since 2012 when the RERC ended, a new Wheelchair Transportation Safety (WTS) website has been developed at UMTRI to provide stakeholders with a wide range of up-to-date resources related to transportation safety for people who travel in motor vehicles while seated in their wheelchairs. The official website address is http://wc-transportation-safety.umtri.umich.edu but the *Ridesafe* brochure page of the website can be accessed at www.travelsafer.org. In addition, the website can be quickly accessed by "Goodling" on "WC Transportation Safety." Figure 5.1 through Figure 5.6 show screen shots of different pages on the website. The educational materials include articles on various topics that were written for consumer magazines. Perhaps most importantly, this website includes updated lists of products (e.g., wheelchairs, tiedown/restraints, and wheelchair seating systems) that comply with national and international industry standards, or that have been successfully crash tested.

UMTRI's WTS website also includes resources for consumers, wheelchair and WTORS manufacturers, wheelchair prescribers, and transportation providers, as well as details of the RERC's research and publications. The Safety Tip Sheets discussed in Subtask 4, and the *RideSafe* and *DriveSafe* brochures along with their corresponding Powerpoint presentations are, or will soon be, available on one of the home tabs.

Much of the content of the RERC website was updated during transfer to the UMTRI website to reflect changes included in Volume 4 of RESNA 2012 WTS standards: *Wheelchairs and Transportation*. These updates include extensive editing of the frequently asked questions (FAQs), including detailed information on the differences between ANSI?RESNA and ISO standards (e.g., ANSI/RENSA WC19 and ISO 7176-19), as well as specific pages on each ANSI/RESNA standard. Engineering drawings for the surrogate equipment used in testing to ANSI/RESNA standards, including the surrogate wheelchair tiedown and occupant restraint systems (SWTORS) used in sled-impact testing of wheelchairs and wheelchair seating systems, the surrogate wheelchair (SWC) used in sled-impact testing of WTORS, and the surrogate wheelchair frame (SWCF) used for independent sled-impact testing of wheelchair seating systems, are available on, and can be downloaded from, the UMTRI WTS website.

Information on UMTRI's impact testing services relative to these voluntary industry standards is also included with a downloadable information brochure and an online form to request a quote for testing and reserve a test date or dates. New high-speed videos were added to the website in the educational toolbox section, and are posted on "YouTube" for public access. These videos demonstrate the importance of using WC19-compliant wheelchairs, and of providing proper wheelchair securement and occupant restraint by showing the results of sled test conducted with different misuse scenarios.

A new list of products that comply with these standards has also been developed for inclusion on the website and is regularly updated. The latter involves contacting wheelchair, WTORS, and wheelchair-seating manufacturers to confirm products that are currently marketed as being in compliance with ANSI/RESNA and/or ISO standards. To aide manufacturers in determining product compliance, downloadable checklists for full compliance to ANSI/RESNA and ISO standards are provided on the website. Manufacturers that have successfully completed crash testing at UMTRI during the past couple of years but that have not historically listed products as being in compliance with the standards are also contacted for inclusion in the listing.

Figure 5.1 - Screen shot of the home page on UMTRI's new Wheelchair Transportation Safety (WTS) website

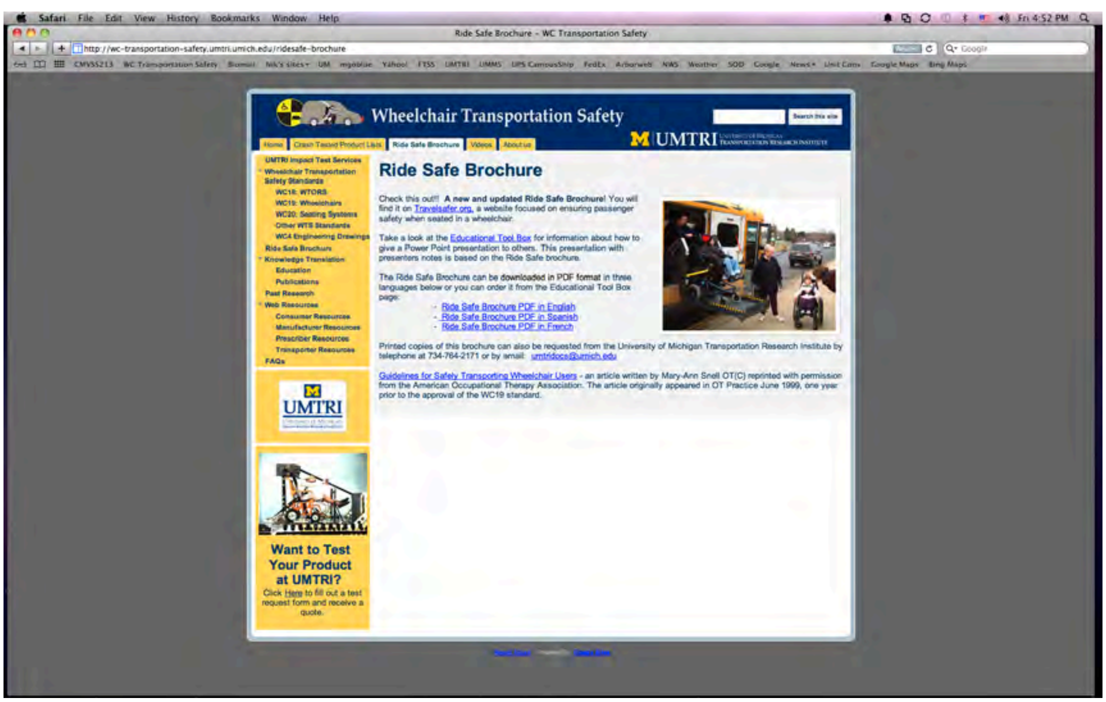


Figure 5.2 - Screen shot of the page on UMTRI's WTS website to access the *RideSafe* Brochure

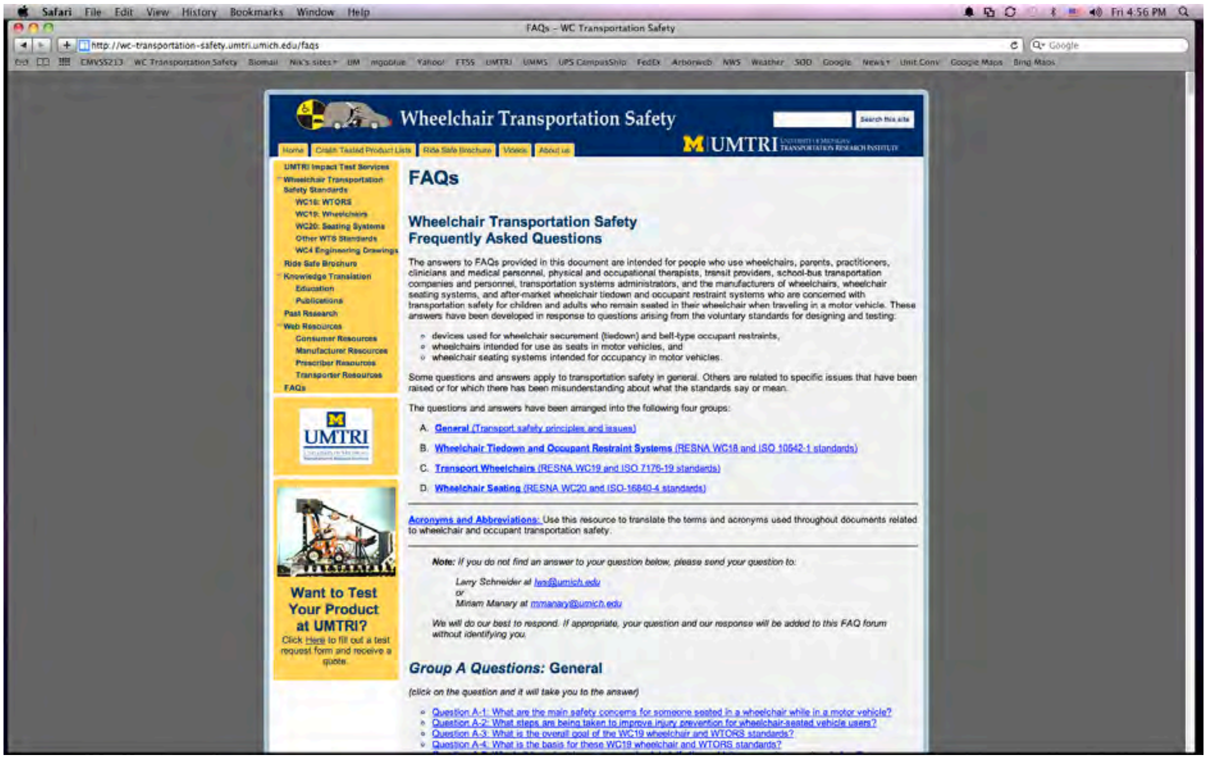


Figure 5.3 - Screen shot of the page on UMTRI's WTS website to access answers to frequently asked questions (FAQs) regarding Wheelchair Transportation Safety and related industry standards

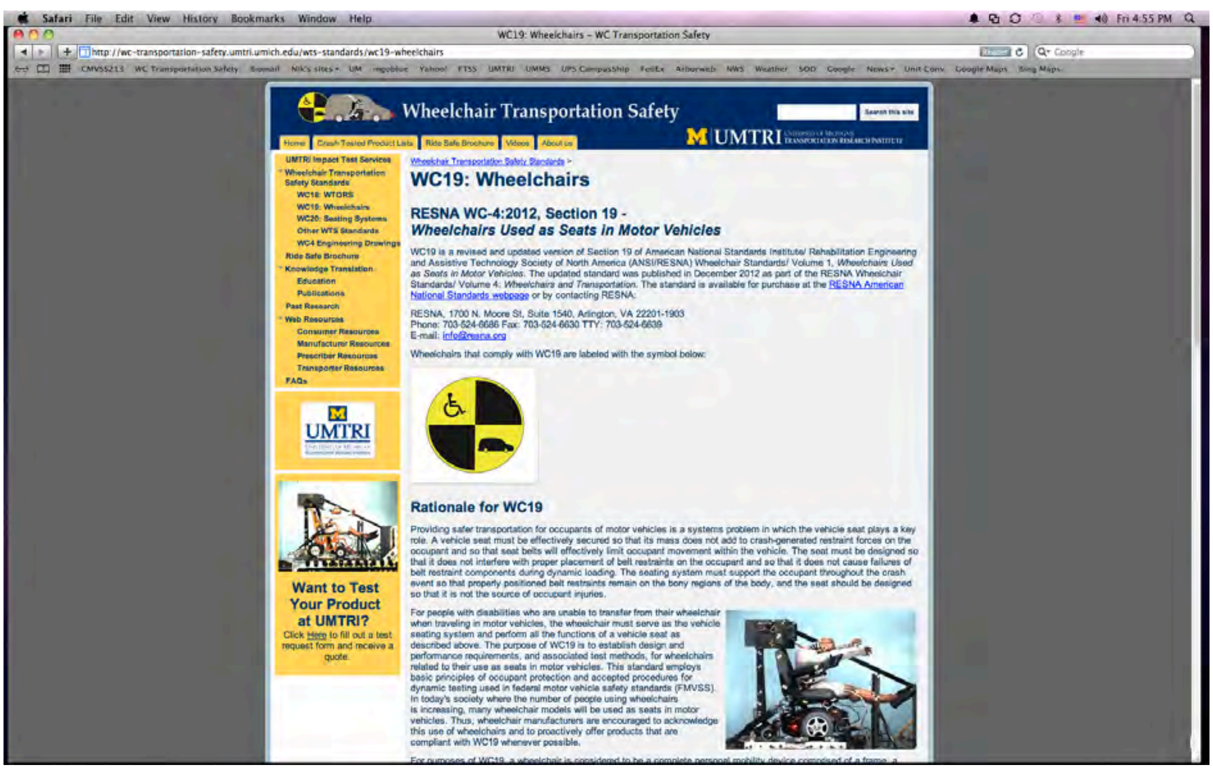


Figure 5.4 - Screen shot of the page on UMTRI's WTS website to access information on industry standards

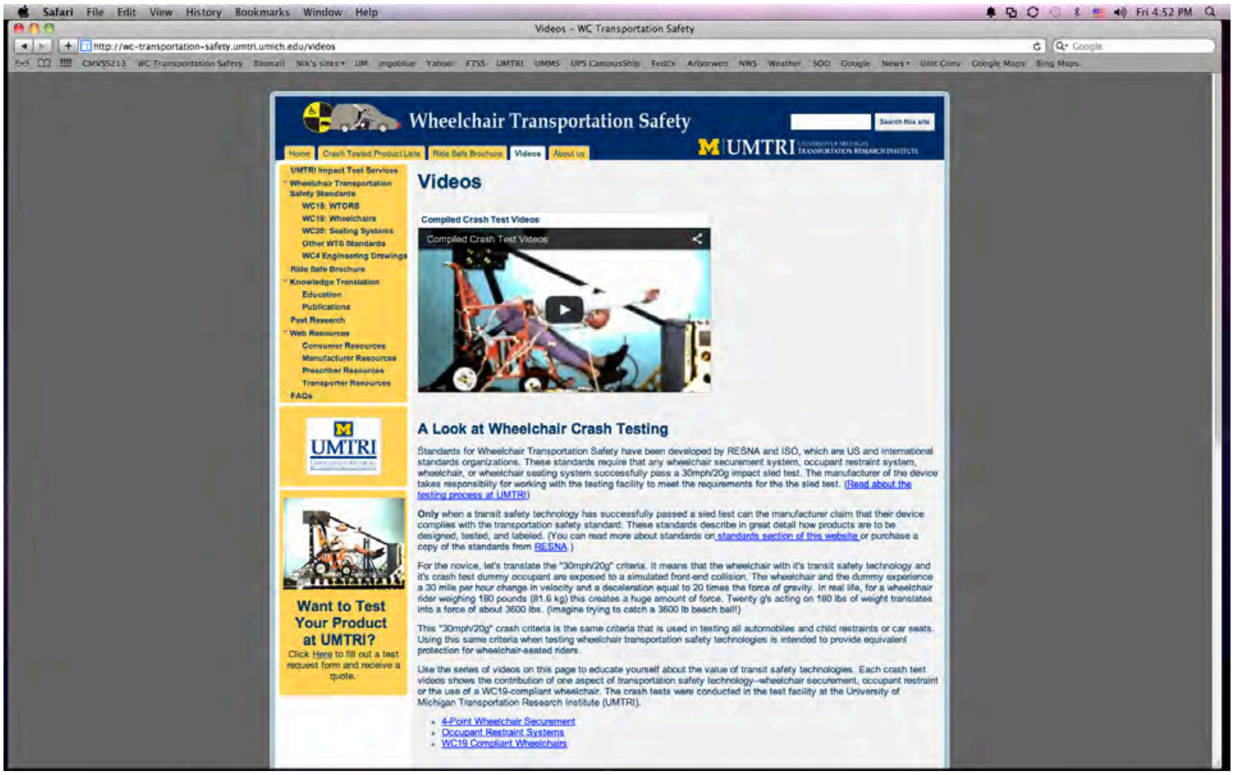


Figure 5.5 - Screen shot of the page on UMTRI's WTS website to access and download crash-test videos, including videos showing consequences of WTORS misuse

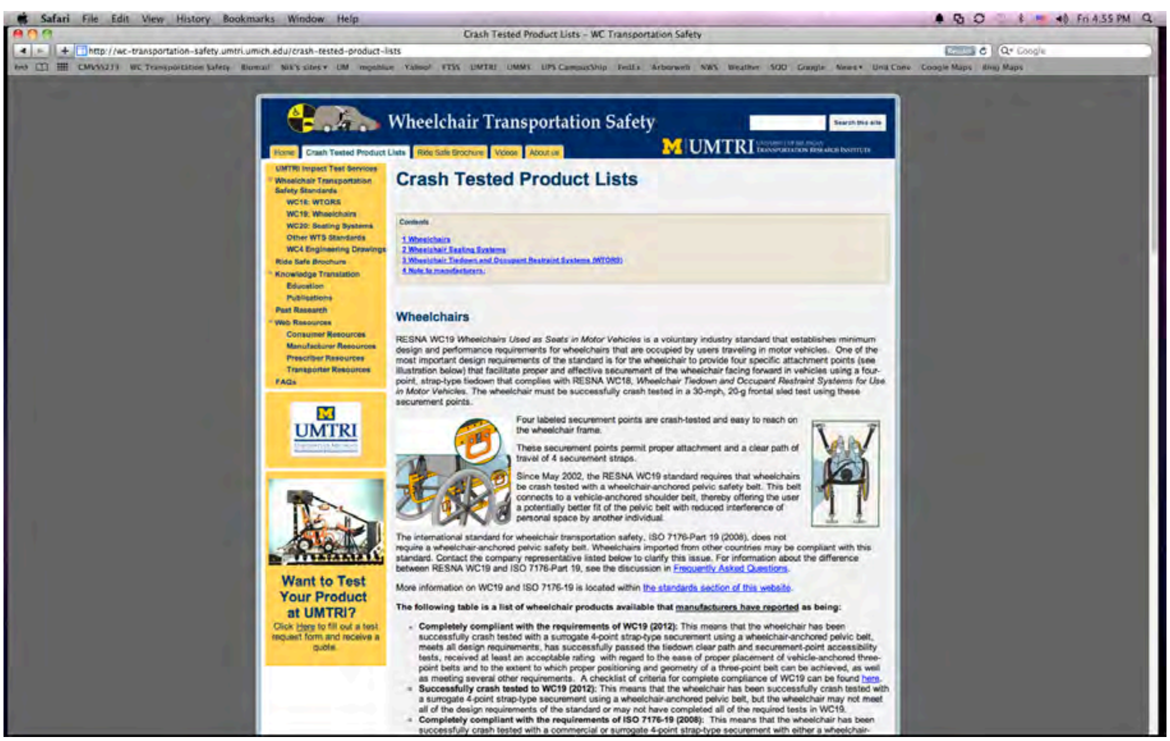


Figure 5.6 - Screen shot of the page on UMTRI's WTS website to access list of products that comply with industry standards

SUMMARY AND RECOMMENDATIONS FOR FUTURE WORK

Summary

Work was conducted on five Subtasks with the overall goal of improving transportation safety for occupants of motor vehicles seated in wheelchairs. The project addressed transportation safety for both passengers and drivers seated in wheelchairs, but a primary focus was on drivers who operate personal vehicles while seated in their wheelchairs.

The first two Subtasks involved: 1) investigation, documentation, and analysis of real-world crash and moving-vehicle non-crash events involving one or more occupants seated in wheelchairs, and 2) development and/or evaluation of improved restraint systems for front- and rear-impact protection of drivers seated in wheelchairs. The second Subtask included a measurement-and-observation study of people who drive a personal vehicle while seated in their wheelchair with the goal of better defining the wheelchair transportation safety (WTS) problem for this population of vehicle operators.

The remaining three Subtasks included: 3) investigation of potential benefits and injury risks of advanced steering-wheel airbags for drivers seated in wheelchairs using sled-impact tests and computer simulations of frontal crashes, 4) development of educational materials on wheelchair transportation safety for key stakeholder groups, and 5) development of an UMTRI website for dissemination of educational materials and related WTS information, including lists of products that manufacturers have certified as being in compliance with WTS industry standards.

Results of investigations of crash and non-crash events involving one or more occupants seated in wheelchairs indicate that a primary reason for these occupants sustaining serious-to-fatal injuries is not having or using a complete lap/shoulder belt restraint system and/or improper positioning of the seat belt on the wheelchair occupant. Although results of statistical analyses of injury factors for people seated in wheelchairs during frontal crashes in the UMTRI wheelchair-occupant crash injury database are currently limited by the relatively small sample size (35 wheelchair occupants in frontal crashes with sufficient data for analyses of injury factors), the results suggest that belt restraints used by occupants in wheelchairs are not as effective in preventing serious-to-fatal injuries as they are for people seated in vehicle seats. This may be because drivers and passengers seated in wheelchairs have lower injury tolerance than the average vehicle occupants using vehicle seats.

However, it has also been determined that occupants who remain seated in their wheelchairs when traveling in motor vehicles often have difficulty achieving proper, or optimal, positioning of lap/shoulder belt restraints. This is largely due to interference with proper positioning of vehicle-anchored lap belts by wheelchair components, and especially interference by wheelchair arm supports that cause the lap belt to be positioned high on the abdomen rather than low near the thigh-pelvis junctions or in front of the occupant and not in contact with the occupant’s body when a crash occurs. It is also due to a lack of knowledge and training regarding how to achieve proper seat-belt positioning on occupants in different types of wheelchairs. Improper positioning of lap belts reduces their effectiveness in restraining the lower torso in frontal crashes and increases the risk of lap-belt-induced abdominal injuries. In addition, positioning of occupants in wheelchairs further from the side of the vehicle compared to outboard occupants using vehicle seats often results in positioning of the shoulder belt off of the shoulder rather than near the center of the shoulder, thereby reducing the effectiveness of shoulder belts in limiting chest and head excursions.

A study of twenty-one people who drive a personal vehicle while seated in their wheelchair confirmed that it is particularly common for drivers to be using poorly positioned and/or incomplete lap/shoulder belt restraints that would offer relatively little protection in frontal crashes, and that are more likely to cause abdominal and chest injuries in a frontal crash than a properly positioned lap/shoulder belt. In many cases, this is because the driver requires a pre-buckled (i.e., passive) lap/shoulder belt due to their inability to buckle and unbuckle a standard seat belt in combination with a wheelchair that has closed-front arm supports. The latter prevent the proper placement of a passive lap belt in contact with the lower pelvis when the driver moves his/her wheelchair into the driving position. In other cases, it is because aftermarket seat-belt components with a compatible buckle receptacle have not been installed on the inboard side of the driver station to allow use of the OEM lap/shoulder belt restraint, or these components have not been installed in a location that will provide for effective restraint in a frontal crash.

In addition to a need for improvements in the design of aftermarket components that complete the OEM lap/shoulder belt after removal of the driver seat to which the OEM buckle receptacle is typically anchored, people who drive while seated in their wheelchair need their wheelchair to be equipped with, or retrofitted with, arm supports that are completely open at the front and underneath (i.e., cantilevered arm supports) if they are to fully benefit from, and not be injured by, lap/shoulder belt restraint systems in frontal crashes. There is therefore a need to educate clinicians and rehabilitation professionals about the importance of determining if there is the potential for a client to be driving a personal vehicle while remaining in their wheelchair. If the answer to this question is "yes," a wheelchair model that has demonstrated effective crashworthiness when secured in a 48-kph, 20-*g* frontal sled-impact test using a docking-securement device, and that is equipped with cantilevered arm supports, should be prescribed. For those situations in which a wheelchair user who plans to drive a personal vehicle while seated in their wheelchair has already purchased a wheelchair that has closed-front arm supports, an effort should be made to work with the wheelchair or wheelchair-seating manufacturer to retrofit their wheelchair with cantilevered arm supports.

In efforts to improve restraint systems for frontal-crash protection of drivers seated in wheelchairs, several design approaches were considered and prototype systems were evaluated. The most promising system is referred to as the seat-belt deployment system, or SBDS. This design provides add-on vehicle components that allow drivers in wheelchairs to use the vehicle manufacturer's (OEM) lap/shoulder belt restraint in a nearly passive mode (i.e., a pre-buckled seat belt activated into position on the driver by pushing a button), while eliminating obstacles on the vehicle floor that can make it difficult to maneuver a wheelchair into the driver space and docking-securement device. A prototype SBDS has been successfully evaluated in a static minivan laboratory buck and in several 48-kph, 20-*g* frontal-impact sled tests. As with all passive belt-restraint systems, and as previously noted, optimal positioning of the lap/shoulder belt restraint on drivers seated in wheelchairs requires wheelchairs equipped with cantilevered arm supports that are open at the front and underneath.

With regard to rear-impact protection, it has been demonstrated in 25-kph,14-*g* rear-impact sled tests conducted at UMTRI that back supports of most wheelchairs, including those that comply with WTS standards, would not provide effective head and back restraint in a large percentage of rear-end collisions. Also, very few vehicles modified for use by occupants in wheelchairs, and especially for drivers seated in wheelchairs, are equipped with a crashworthy vehicle-anchored head-and-back restraint. In a few cases, a vehicle modifier and/or the vehicle owner have installed some equipment for rear-impact protection, but typically this is only a vehicle-anchored head restraint without a vehicle-anchored back support. This results in the potential for serious neck injury in a rear-impact crash as the driver's head is effectively restrained from rearward movement during a rear-end collision, while the driver's torso moves rearward due to the weak wheelchair back support, thereby resulting in potentially injurious neck-flexion bending moments and forward shear forces on the neck.

Efforts to improve rear-impact protection for drivers seated in wheelchairs included the development and successful sled-impact testing of a deployable head-and-back restraint system developed by a Biomedical Engineering (BME) senior design team under the supervision of UMTRI faculty and staff. However, upon learning of an untested, commercially available deployable vehicle-anchored head-and-back restraint system, collaborations with the inventor and a wheelchair manufacturer that purchased the rights to the system were initiated with the goal of evaluating and improving system performance, if needed. Significant design changes to the original version of this head-and-back restraint were made by UMTRI, resulting in improved rear-impact performance from the commercially availalbe version. These changes have been communicated to the manufacturer who will hopefully implement changes in the design that will lead to more effective performance of the market product.

Sled tests and MADYMO computer simulations of 48-kph frontal crashes for midsize-male and small-female crash-test dummies seated in wheelchairs in the driver space have been conducted with and without deployment of advanced steering-wheel airbags, with the goal of determining the potential benefits of these air bags for drivers seated in wheelchairs versus the risks of being seriously injured by deploying air bags. The sled tests and computer simulations used a range of seat-belt configurations, including good and poor (loose) seat-belt positioning, as well as no belt restraint. The computer models were validated using results from frontal sled-impact tests in which steering-wheel air bags were deployed, and the validated models were used in simulation matrices to investigate the protective benefits and injury risks associated with allowing steering-wheel airbags to deploy or deactivating the steering-wheelchair airbag in 48-kph frontal crashes. Simulation matrices included angled frontal crashes at 15- and 30-degrees to 12 o'clock, midsize-male and small-female drivers in wheelchairs positioned in close proximity (125 mm and 25 mm) to the air-bag module at the onset of frontal-crash deceleration, and small-female drivers seated in a wheelchair versus a minivan driver seat.

The results of these tests and simulations show relatively little basis for concern that the energy of deploying "advanced" steering-wheel air bags in today's vehicles (i.e., vehicles with a GVWR less than 8500 lb and manufactured after 2003 to 2006) will cause serious-to-fatal injuries to drivers seated in wheelchairs. Rather, the steering-wheel air bag almost always reduces the risk of head, neck, and chest injuries due to contact with the steering wheel that can occur when the air bag is deactivated. Also, in angled frontal impacts, deployment of the side-curtain airbag offers additional protection to drivers in wheelchairs, just as it does for drivers in vehicle seats.

The results of this study therefore indicate that steering-wheel air bags will generally offer tangible safety and crash-protection benefits for a wide range of drivers seated in wheelchairs just as they do for drivers in vehicles seats, and should only be deactivated on rare occasions. In particular, the only situation when consideration should be given to deactivating steering-wheel air bags for drivers seated in wheelchairs is when a driver is positioned with their chest or chin 8 inches or less from the air-bag module during normal operation of the vehicle. This is similar to vehicle manufacturer' and NHTSA guidelines on when to deactivate airbags for short drivers using vehicle seats.

With regard to the concern for drivers in wheelchairs being in close proximity to the steering-wheel airbag when the airbag deploys, it should be noted that use of a lap/shoulder belt with a fixed B-pillar anchor point rather than a retractor-based anchorage may offer several potential benefits to drivers seated in wheelchairs. In addition to offering greater torso stability in the driver's optimal posture for operating the vehicle, and removing seat-belt retractor forces that can pull drivers away from their preferred posture, both of which were problems reported by drivers in the measurement-and-observation study, a properly adjusted shoulder belt with a fixed shoulder-belt anchor point would prevent the wheelchair driver's head and torso from moving closer to the airbag module during pre-impact braking and prior to airbag deployment during a frontal crash. Implementing fixed shoulder-belt anchor points on B-pillars should, however, be done in a manner that does not compromise seat-belt load limiters and/or seat-belt pre-tensioners.

If efforts to improve transportation safety for occupants seated in wheelchairs such as those described in this report, as well as through development of WTS standards, are to have to have a meaningful impact in the real world, there is a need to educate vehicle modifiers and their clients, as well as other key stakeholders involved with wheelchair users and their transportation in motor vehicles. These efforts must communicate information regarding WTS standards and the availability of products that comply with these standards, as well as "best practice" in providing safe transportation to travelers seated in wheelchairs. Toward this end, "Safety Tip Sheets" targeted to vehicle modifiers and their clients and other key stakeholder groups have been developed, and a *DriveSafe* brochure is nearly ready for publication and distribution. The latter provides key steps to providing safe transportation and optimal crash protection for drivers who remain seated in wheelchairs, and is similar to the widely distributed and successful *RideSafe* brochure that is targeted primarily for passengers seated in wheelchairs.

In Subtask 5, a new website (http://wc-transportation-safety.umtri.umich.edu) was established at UMTRI to provide a wide range of WTS educational materials. The website includes articles on WTS written for various consumer magazines over the past decade, downloadable sled-test videos that show the potential negative consequences of several wheelchair-tiedown and occupant-restraint system (WTORS) misuse scenarios, answers to frequently asked questions, and summaries of the latest WTS standards for wheelchairs, WTORS, and wheelchair seating systems. The website provides access to the *RideSafe* brochure and can, in fact, be easily accessed using the Ridesafe website address, www.travelsafer.org. The new *DriveSafe* brochure and several sets of Safety Tip Sheets will be added to the website in the next month or two. An important feature of the website is regularly updated lists of products that comply with WTS standards, thereby providing clinicians and consumers access to these products in one easily accessible location.

Recommendations for Future Work

While significant progress has been made during this project toward improving transportation safety and crash protection for occupants seated in wheelchairs, and particularly for drivers of personal vehicles who remain seated in their wheelchairs, there is a need for additional work. To a large extent, this involves implementing the results of the work completed to date. For example, there is still a need to work with a manufacturer of commercial tiedown/restraint systems, or with a vehicle modifier, to commercialize the seat-belt deployment system (SBDS). It doing so, it will be important to receive additional feedback from wheelchair drivers on the system and how it can be further improved. Also, it would be desirable to conduct additional rear-impact sled tests of a manufacturer-improved version of the Swedish vehicle-anchored head-and-back restraint to confirm that the system provides effective occupant restraint in rear-impact collisions.

Perhaps most importantly, there is a need to continue to educate and, ideally change the policies and procedures of key stakeholder groups with regard to implementing best practice in WTS, and to prescribing and using products that fully comply with WTS standards. To some extent, this will be accomplished through the new UMTRI WTS website. However, direct communication with, and dissemination of Safety Tip Sheets and brochures to key stakeholder groups is considered essential to the educational process. For example, it is planned to include the Safety Tip Sheets targeted to vehicle modifiers in NMEDA's "Lunch-and-Learn" program and to distribute *DriveSafe* brochures to manufacturers of power wheelchairs, whose customers are typically those who drive a personal vehicle while seated in wheelchair.

It would also be beneficial to continue to investigate, analyze, and document, crash and non-crash events involving drivers and passengers seated in wheelchairs to increase the sample size of cases available for statistical analyses. Doing so would increase the power of the analysis for frontal crashes and potentially clarify the reasons why "optimal" restraint use and occupant age were not found to be significant predictors of injury, or lack of injury, in the current set of frontal crashes for occupants in wheelchairs. It would also hopefully lead to determining comparative injury risk and risk factors for occupants in wheelchair involved in side impacts, rear impacts, and rollover crashes.

Finally, questions are often posed by professionals who work with wheelchair users and who train people with disabilities to drive for which there are currently no clear evidence-based answers. These questions involve people who drive from their wheelchair as well as people who transfer from their wheelchair to a vehicle seat and use hand controls because of limited or no use of their lower extremities. For example, one attendee of a seminar at a Midwest meeting of the Association for Driver Rehabilitation Specialists (ADED) asked: "What happens when a side-impact air bag installed in the OEM driver seat back deploys if a person with disabilities is using a postural belt wrapped around their chest and the vehicle seat back?" Clearly the answer depends on the strength of the postural belt and its buckle, and may vary with the vehicle manufacturer, but an answer to this question will remain unknown without conducting appropriate static side-impact airbag-deployment tests.

A second example is related to the interaction of deploying knee-restraint air bags with driver hand-control linkages compared to the negative consequences of deactivating these air bags. A third example is related to the static air-bag deployment tests conducted two decades ago at the University of Virginia showing that assistive devices attached to the rims of steering wheels do not interfere with air-bag deployment (Dalrymple, 1996 and Dalrymple and Ragland, 1998). Since these tests were conducted using first-generation air bags that were significantly more aggressive than advanced air bags in today's vehicles, it would be beneficial to repeat these tests using advanced steering-wheel air bags from late-model vehicles to confirm that the results are still valid.

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The authors also wish to express their appreciation to the members of UMTRI sled-impact team and technical staff of UMTRI's Biosciences Group for their efforts and skills in helping to design, fabricate, and assemble test components and prototype devices, and in setting up and conducting the many sled-impact tests described in this study. Brian Eby, Charles Bradley, and Stewart Simonett made especially important contributions to these efforts.

With regard to designing and testing prototype restraint systems for improved protection of occupants seated in wheelchairs during front and rear impacts, the members of the two student Biomedical Engineering senior design teams are to be commended for their innovative design approaches and their dedication to completing fabrication and testing prototypes of their final design concepts within the time frame of their design courses. The authors are particularly appreciative of the creativity, fabrication, and programming skills of Quentin Weir, a former member of one of the student design teams, who continued to work at on improving the design and performance of the seat-belt deployment system (SBDS) and who made significant contributions to other aspects of the project following completion of his BSE degree in Biomedical Engineering.

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Finally, the authors wish to make it clear that the views and opinions expressed in this report are those of the authors and do not necessarily reflect the views and opinions of the NHTSA or the NIDRR.

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APPENDIX A
VARIABLES AND VARIABLE DESCRIPTORS FOR EXCEL VERSION OF UMTRI'S WHEELCHAIR-OCCUPANT CRASH/INJURY DATABASE

Case, Outcome and Vehicle

CASE ID
- WC-###

OUTCOME
- Fatal
- Non-fatal

CASE VEHICLE (Vehicle 1)

CASE VEHICLE YEAR

CASE VEHICLE MAKE

CASE VEHICLE MODEL

CASE VEHICLE BODY STYLE
- Van
- Bus

Impact Type

INITIAL IMPACT TYPE
- Frontal
- Offset Frontal
- Left Side
- Right Side
- Sideswipe
- Sideslap
- Rollover (in quarter turns)
- Not applicable

SECOND IMPACT TYPE
- Frontal
- Offset Frontal
- Left Side
- Right Side
- Sideswipe
- Sideslap
- Rollover (in quarter turns)
- Not applicable

Crash Partner

OBJECT/VEHICLE STRUCK
- Vehicle 2
- Ground
- Pole
- Tree
- Median Barrier
- Guardrail
- Utility Pole
- Road Sign
- Curb
- Not Applicable

VEHICLE YEAR (Vehicle 2)

VEHICLE MAKE (Vehicle 2)

VEHICLE MODEL (Vehicle 2)

BODY STYLE (Vehicle 2)
- PickUp (PU)
- Dump
- SUV
- Sedan
- Bus
- Trailer
- Unknown

Impact Severity

SEVERITY/DELTA V
- ## mph
- Minor
- Moderate
- Severe
- Very Severe
- Unknown
- Not applicable

DIRECT DAMAGE LENGTH
- ## cm
- Unknown

DIRECT DAMAGE LENGTH (Vehicle 2)
- ## cm
- Unknown

MAXIMUM CRUSH
- ## cm
- Unknown

Impact Description

PDOF
- 0-360
- Unknown
- Not applicable

PDOF (Vehicle 2)
- 0-360
- Unknown
- Not applicable

CDC
- ##????#
- Unknown
- Not applicable

CDC (Vehicle 2)
- ##????#
- None
- Unknown
- Not applicable

RELEVANT INTRUSION
- ## cm + location
- None
- Unknown

Injury Description

OCCUPANT EJECTED?
- Yes
- No
- Unknown

MAIS
- 0-6
- Unknown
- Not applicable

MOST SEVERE INJURY
- Text description
- Unknown

SOURCE OF MOST SEVERE INJURY
- Text description
- Unknown

SECOND MOST SEVERE INJURY
- Text description
- Unknown

SOURCE OF SECOND MOST SEVERE INJURY
- Text description
- Unknown

Occupant Description

AGE
- 0-99
- Unknown

GENDER
- M
- F
- Unknown

STATURE
- ## cm
- Unknown

MASS
- ## kg
- Unknown

DISABILITY
- Description
- Unknown

Location of Wheelchair Occupant

ROW

- First
- Second
- Third
- Fourth
- Other (specify): ___________________
- Unknown

LATERAL POSITION

- Left
- Center
- Right
- Other (specify): ___________________
- Unknown

ORIENTATION IN VEHICLE

- Facing forward
- Facing left
- Facing right
- Facing rearward
- Angled (specify): ___________________
- Unknown

Wheelchair

TYPE

- Standard manual
- Stroller
- Sport manual
- Power assist
- Powerbase
- Three-wheel powered scooter
- Four-wheeled powered scooter
- Other (specify): ___________________
- Unknown

WC19 COMPLIANT

- Yes
- No
- Unknown

POST-CRASH CONDITION

- No or minor damage/deformation
- Moderate damage/deformation
- Major damage/deformation
- Other (specify): ___________________
- Unknown

Vehicle Access

TYPE

- Ramp
- Lift
- Other (specify): ___________________
- Unknown

LOCATION

- Right side
- Left side
- Rear
- Unknown

Seating System

TYPE

- Sling seat and seatback
- Rigid seat and seatback (with or without padding)
- Special contoured seating system
- Other (specify): ___________________
- Unknown

ADJUSTMENTS

- Fixed seat and seatback
- Fixed seat and reclining seatback
- Tilt seating system
- Other (specify): ___________________
- Unknown

POST-CRASH CONDITION

- Seat and back support intact
- Seat broken/deformed
- Back support broken/deformed
- Seat and back support broken/deformed
- Other (specify): ___________________
- Unknown

Steering Controls if Wheelchair Driver

TYPE

- Standard with assistive device on wheel rim
- Power assisted with adaptive steering wheel
- Standard – no devices
- Other (specify): ___________________
- Not applicable/not driver
- Unknown

POST-CRASH CONDITION

- No damage
- Deformed
- Broken
- Detached from vehicle
- Other (specify): ___________________
- Not applicable/not driver
- Unknown

Wheelchair-Anchored Postural Lap Belts

AVAILABLE

- Yes
- No
- Unknown

USED

- Yes
- No
- Unknown

POST-CRASH CONDITION

- Unused
- No damage
- Detached from wheelchair
- Deformed or unbuckled
- Other (specify): ___________________
- Unknown

Wheelchair-Anchored Postural Chest Belts	Wheelchair-Anchored Postural Harness
AVAILABLE Yes No Unknown USED Yes No Unknown POST-CRASH CONDITION Unused No damage Detached from wheelchair Deformed or unbuckled Other (specify): ___________________ Unknown	AVAILABLE Yes No Unknown USED Yes No Unknown POST-CRASH CONDITION Unused No damage Detached from wheelchair Deformed or unbuckled Other (specify): ___________________ Unknown
Wheelchair-Anchored Sub-ASIS Bar	**Wheelchair-Anchored Lateral Postural Supports**
AVAILABLE Yes No Unknown USED Yes No Unknown POST-CRASH CONDITION Unused No damage Detached from wheelchair Deformed or unbuckled Other (specify): ___________________ Unknown	AVAILABLE Yes No Unknown USED Yes No Unknown POST-CRASH CONDITION Unused No damage Detached from wheelchair Deformed or unbuckled Other (specify): ___________________ Unknown

Wheelchair Tiedown/Securement	Rear Head Restraint
AVAILABLE Four-point strap Auto-engage docking Wheel-rim clamps Frame clamps None Other (specify): ___________________ Unknown **USED** Four-point strap Auto-engage docking Wheel-rim clamps Frame clamps None Other (specify): ___________________ Unknown **TIEDOWN MISUSE** Proper use Improper use Unused Unknown **POST-CRASH CONDITION** System intact with no signs of failure or deformation System intact but deformed Partial failure of load-carrying component but did not release wheelchair Failure of a load-carrying component resulting in partial or complete release of wheelchair Other (specify): ___________________ Not applicable Unknown **DAMAGE LOCATION** No damage Strap/webbing D-ring Securement hook Vehicle/tiedown anchorage Wheelchair to docking interface Anchorage on seat Fastener Other (specify): ___________________ Not applicable Unknown	**AVAILABLE** None Attached to wheelchair Attached to vehicle Other (specify): ___________________ Unknown **POST-CRASH CONDITION** No damage Detached from wheelchair Detached from vehicle Deformed Other (specify): ___________________ Not applicable Unknown

Occupant Belt Restraint

TYPE

None
Lap belt only
Lap belt with separate shoulder belt
Lap belt with separate shoulder harness
Shoulder belt only
3-point harness
4-point harness
5-point harness
Other (specify): ___________________
Unknown

USED

None
Lap belt only
Lap belt with separate shoulder belt
Lap belt with separate shoulder harness
Shoulder belt only
3-point harness
4-point harness
5-point harness
Other (specify): ___________________
Unknown

MISUSE

None
Yes (specify): _________________
Not applicable
Unknown

REPORTED MISUSE REASON

None
Discomfort
Uninformed
Accessibility
Other (specify): ___________________
Not applicable
Unknown

SOURCE OF BELT RESTRAINT

None
Original vehicle belts (OEM)
After-market belts
Other (specify): ___________________
Not applicable
Unknown

Occupant Belt Restraint (continued)

BELT MODIFICATIONS

None
Extender
User modification (e.g., pins/tape)
Other (specify): ___________________
Not applicable
Unknown

POST-CRASH CONDITION

Belt hardware intact with not signs of webbing failure or damage

Belt hardware intact but with partial or complete failure of webbing

Webbing intact but evidence of partial or complete hardware failure

Other (specify): ___________________

Not applicable

Unknown

Airbag

AVAILABLE

Yes
No
Unknown

DEPLOYED

Yes
No
Unknown

Occupant Restraint Anchor-Point Locations	
LAP BELT - INBOARD On vehicle On tiedown straps or other tiedown structure in vehicle On wheelchair No lap belt available Other (specify): ___________________ Unknown LAP BELT - OUTBOARD On vehicle On tiedown straps or other tiedown structure in vehicle On wheelchair No lap belt available Other (specify): ___________________ Unknown SHOULDER BELT(S) - LOWER On vehicle On tiedown straps or other tiedown structure in vehicle On lap belt On wheelchair No shoulder belts available Other (specify): ___________________ Unknown SHOULDER BELT(S) – UPPER On vehicle (B-pillar or sidewall) On wheelchair No shoulder belts available Other (specify): ___________________ Unknown POST-CRASH CONDITION No damage Fastener pulled through anchor point Significantly deformed component Failed or partially failed component Webbing torn or partially torn Other (specify): ___________________ Not applicable Unknown	

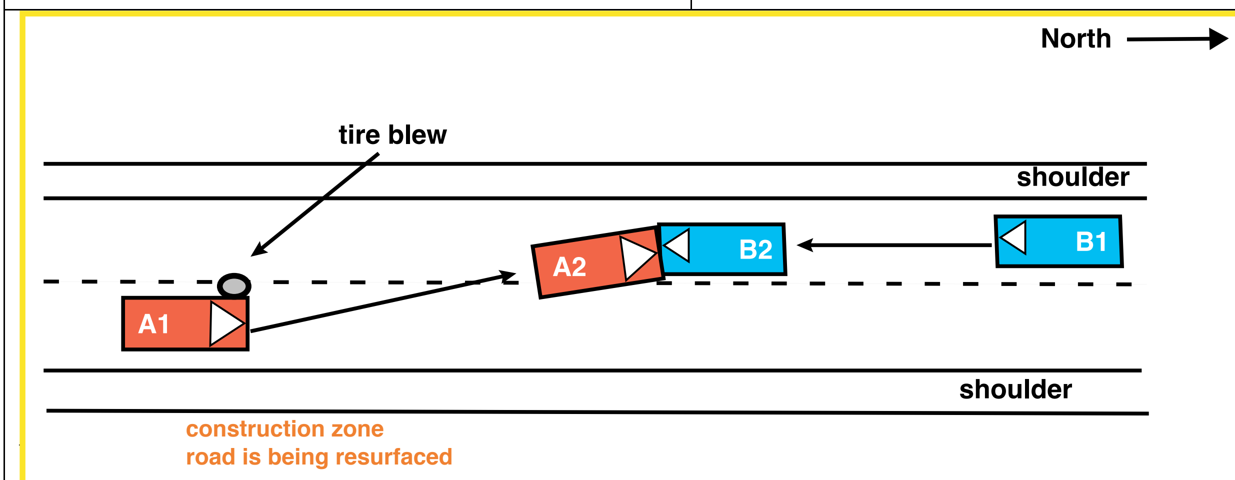
APPENDIX B
EXAMPLES OF CASE SUMMARIES

Example #1
SEVERE FRONTAL CRASH INVOLVING FATALLY INJURED DRIVER SEATED IN A WHEELCHAIR

CRASH SCENARIO

Case Vehicle A:	1992 Ford Econoline E-150 van
Object/vehicle struck:	1992 Chevrolet K-1500, 2 door pickup truck
Impact type:	frontal
Impact severity:	36 mph Delta V
Weather:	daylight, clear
Road conditions:	dry asphalt

The case vehicle was a 1992 Ford Econoline E-150 full-sized van that was being driven by a 32-year-old male driver seated in a powered wheelchair. The vehicle was traveling north at an unknown speed on a two-lane asphalt road that was under construction when the left-front tire blew out, causing the driver to lose control of the vehicle. The vehicle crossed the centerline and struck head-on into vehicle (B), a 1992 K-1500 pickup truck that had been traveling south on the same road at an unknown speed.



VEHICLE DAMAGE

Case Vehicle Information:		**Relevant intrusions:**
Direct damage length:	158	Instrument panel – 5 cm to rear
Maximum crush:	69	Steering wheel – 20 cm to rear
PDOF:	5	
CDC:	12-FDEW-4	

Exterior photos:

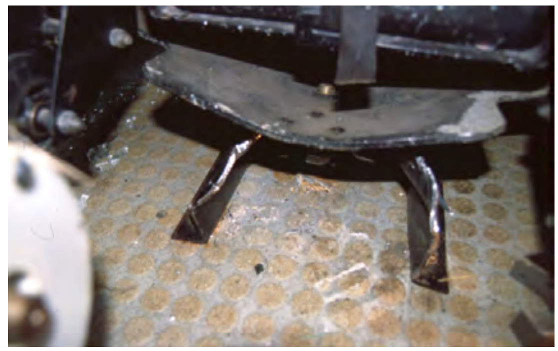
Interior photos:

WHEELCHAIR AND WHEELCHAIR SECUREMENT

Description:		Damage:	
Wheelchair:	AVS WC Ranger X CRM Series, motorized with rigid seat	Wheelchair:	moderate
Orientation:	forward facing	Seating system:	back support broken
Postural supports:	lap belt	Postural supports:	no damage
Head restraint:	none	Tiedown system:	partial failure and significant deformation, but did not release wheelchair
Tiedown/use:	auto-engage docking; used correctly		

Wheelchair Photo:

Tiedown System Photo:



OCCUPANT AND OCCUPANT RESTRAINT

Case occupant:	driver	The driver was seated in a power wheelchair that was secured in the driver station by an auto-engage docking tiedown. The driver was restrained by an aftermarket vehicle-anchored 2-point shoulder belt that had been modified with safety pins to assist with belt positioning. He was also using a postural wheelchair-anchored lap belt. The vehicle was not equipped with a steering-wheel air bag and a tri-pin assistive device was attached to the lower rim of the steering wheel.
Age/gender:	32-year-old male	
Stature/mass:	185 cm, 73 kg	
Disability:	paraplegic	
Occupant restraint:	modified 2-point shoulder belt attached to vehicle	

Restraint System

Shoulder belt modified by safety pins

Tri-pin attached to lower steering-wheel rim

Postural lap belt

Routing of 2-pt shoulder belt over WC arm support

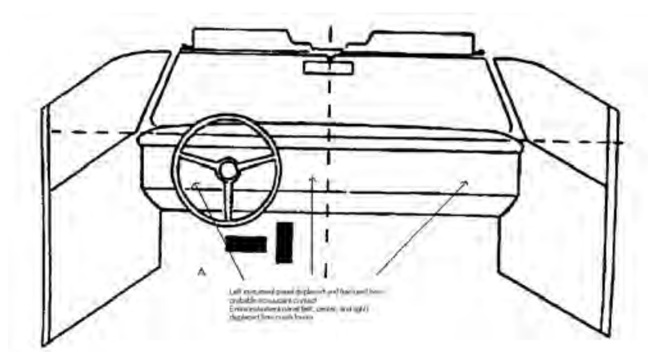
OCCUPANT KINEMATICS AND INJURIES

	Body Part	Injury	AIS	Source/Mechanism/Factors
1	Thorax, lungs, bilateral	multiple lacerations with hemothorax, (1000 ml of blood in each pleural cavity)	5	shoulder belt
2	Thorax, lung, bilateral	multiple contusions	4	shoulder belt
3	Thorax, sternum	fracture	2	shoulder belt
4	Thorax, chest skin	multiple abrasions	1	shoulder belt
5	Abdomen, liver	laceration with blood loss	2	shoulder belt
6	Abdomen, spleen	lacerations	2	Tri-pin assistive steering device
7	Abdomen, skin	multiple abrasions	1	shoulder belt, tri-ping assistive steering device
8	Upper extremities, left and right posterior forearms	abrasions	1	steering/braking control devices, instrument panel
9	Lower extremities, bilateral knee and leg	abrasions	1	knee bolster
10	Lower extremities, right ankle	abrasions	1	toepan/floor or wheelchair foot supports

Occupant Kinematics:

During the frontal impact, the driver moved forward into the shoulder belt, steering wheel, and knee bolster. He sustained numerous thoracic and abdominal injuries including multiple bilateral lung lacerations and hemothorax, multiple lung contusions, a fracture to the sternum, a laceration to the liver, and multiple abrasions to the abdomen, probably due to loading by the two-point loosely positioned shoulder belt. He also sustained a laceration to the spleen, probably due to contact with the tri-pin steering device, as indicated by a circular abrasion on the left side of the abdomen. He sustained abrasions to the left and right posterior forearms, probably from contact with the steering/braking control devices or the instrument panel. He sustained abrasions to both knees and legs from contact with the knee bolster, and abrasions to the right ankle from contact with the toepan or the wheelchair foot supports.

Occupant Contact:



Left instrument panel displaced and fractured from probable occupant contact with lower extremities.

Significance and Key Observations: The fatal chest and abdomen injuries sustained by this driver seated in a power wheelchair are probably the result of several factors, including the lack of a steering-wheel air bag, the use of a two-point shoulder belt without a load limiter that was most likely loosely positioned on the driver (modified by safety pin and routed over right armrest) and not in good contact with the driver's torso prior to the crash, the lack of a crashworthy lap belt, and the presence of a rigid tri-pin steering device attached to the steering-wheel rim. In addition, although the docking-type securement system did not release the wheelchair, it severely deformed, which probably allowed some of the wheelchair mass to add to the restraint forces on the driver's chest and abdomen, thereby contributing to the fatal injuries.

Example #2
ROLLOVER OF A PARATRANSIT VAN INVOLVING AN ADULT MALE SEATED IN A MANUAL WHEELCHAIR WHO WAS EJECTED DURING THE ROLLOVER

CRASH SCENARIO

<table>
<tr><td>Case Vehicle A:

Object/vehicle struck:

Impact type:

Impact severity:

Weather:

Road conditions:</td><td>Paratransit van

Unknown make/model passenger car/ground

Rear end/rollover

N/A

Unknown

Unknown</td><td>The case vehicle was a paratransit van that was traveling on a four-lane roadway. The sole passengers was an adult male who was sitting in a manual wheelchair secured in the center back row of the van. The vehicle was contacted from behind by an unknown vehicle, which caused the driver of the van to lose control. The vehicle swerved to the left and entered into a four quarter-turn rollover with the passenger side leading. During the rollover, the passenger in the wheelchair was ejected out of a rear side window and he sustained multiple bilateral lower-extremity fractures. Following the rollover, the wheelchair was still effectively secured at the back of the van.</td></tr>
<tr><td colspan="3">Scene details

Not determined</td></tr>
</table>

VEHICLE DAMAGE

Exterior Damage:		**Relevant intrusions:**
Direct damage length:	Unknown	None
Maximum crush:	Unknown	
PDOF:	Unknown	
CDC:	Unknown	

Exterior photos of Exemplar Van

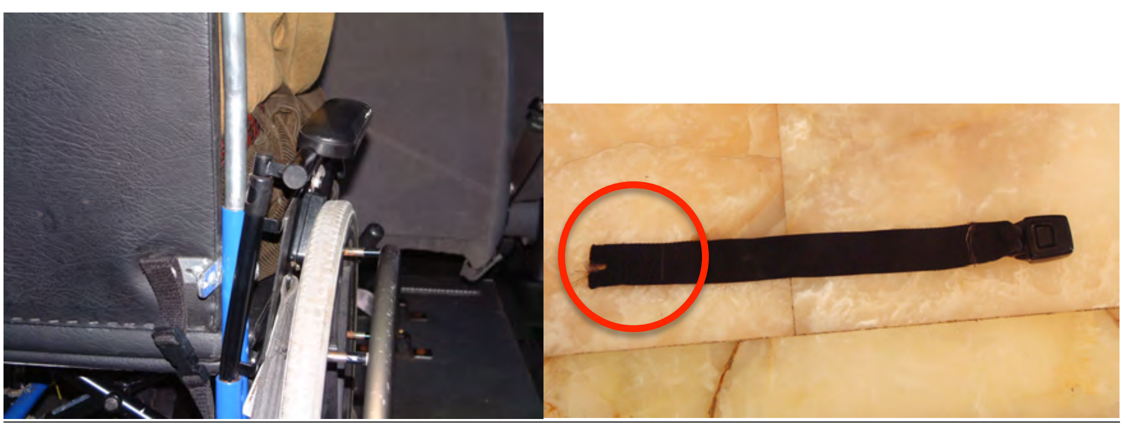
WHEELCHAIR AND WHEELCHAIR SECUREMENT

Description:		**Damage:**	
Wheelchair:	Invacare	Wheelchair:	Outward bending of right arm support
Orientation:	forward facing	Seating system:	None
Postural supports:	postural lap belt	Postural supports:	Postural lap belt torn at wheelchair anchorage
Head restraint:	unknown	Tiedown system:	None
Tiedown/use:	4-point strap tiedown		

Photos of Wheelchair Secured in Vehicle

Damaged Wheelchair With Right Arm Support Bent Outward

and Postural Belt Torn from Wheelchair Anchor Point



OCCUPANT AND OCCUPANT RESTRAINT

<table>
<tr><td>Case occupant:</td><td>Center rear</td><td rowspan="5">The adult male case occupant was seated in a manual forward-facing wheelchair in the center of the back of the vehicle. The wheelchair was properly secured to the vehicle using a four-point, strap-type tiedown with two straps in front and two at the rear. The wheelchair passenger was using a postural lap belt attached to the wheelchair and was reportedly also using an aftermarket lap/shoulder-belt restraint with a s shoulder belt that manually connects and disconnects from the lap belt by means of a pin-bushing anchorage on the buckle latch plate. Importantly, the anchorage ends of the lap belt hook to D-rings on the rear tiedown straps and there was no mechanism for adjusting the distance between the buckle receptacle and the lap belt anchorage.</td></tr>
<tr><td>Age/gender:</td><td>Adult male</td></tr>
<tr><td>Stature/mass:</td><td>Unknown</td></tr>
<tr><td>Disability:</td><td>Unknown</td></tr>
<tr><td>Occupant restraint:</td><td>3-point lap/shoulder belt</td></tr>
</table>

Restraint System

Shoulder belt at back of van

Lap-belt buckle with lower end of shoulder belt attached

Lap-belt buckle with end-release button located close to rim of left wheelchair wheel

OCCUPANT KINEMATICS AND INJURIES

	Body Part	Injury	AIS	Source/Mechanism/Factors
1	Bilateral femur fractures	fracture	2	Occupant ejection, ground
2	Bilateral metatarsal fractures	fracture	2	Occupant ejection, ground

Occupant Kinematics:	Occupant Contact:
During the rollover crash, the passengers seated in the forward-facing manual wheelchair came out of the wheelchair and was ejected from the vehicle. The passenger sustained multiple fractures to both lower extremities, probably due to contact with the ground.	Ground

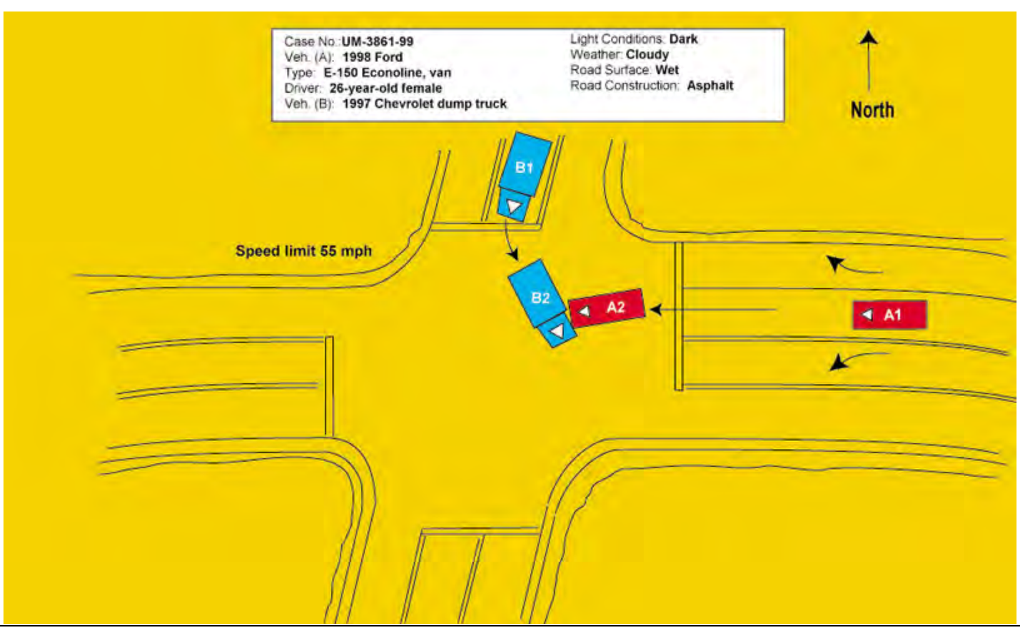
Significance and Key Observations: In this four quarter-turn rollover of a paratransit van, the manual wheelchair was effectively secured and the occupant of the wheelchair who, according to the driver of the van, was using the available aftermarket three-point lap/shoulder belt restraint system. However, during the rollover, he was completely ejected from the vehicle, resulting in significant lower extremity fractures. A reconstruction of the configuration of the wheelchair securement and positioning of lap-belt buckle using the actual wheelchair and tiedown/restraint equipment involved and a similar-sized male occupant indicated that the buckle receptacle on the right half of the lap belt would have been positioned just below the steel rim of the right wheelchair wheel. Based on this reconstruction, it is believed that the end-release button of the buckle receptacle was contacted and depressed by the wheel rim during the rollover, which completely released the restraint system from the passenger, thereby allowing him to come out of the wheelchair and be ejected out the side window of the van. This case points to the importance of positioning the seat-belt buckle away from hard structures on the side of the wheelchair, especially when the buckle is designed with an end-release button. It also points to the importance of providing adjustment in the distance between the lap-belt anchorages and the buckle receptacle so that the buckle can be place away from hard wheelchair components and against the body of occupants seated in wheelchairs.

Example #3
FRONTAL CRASH OF A FULL-SIZE VAN INVOLVING AN ADULT MALE SEATED IN A POWER WHEELCHAIR IN THE CENTER OF THE SECOND ROW

CRASH SCENARIO

Case vehicle A:	1998 Ford E-150 Econoline van
Object/vehicle struck:	1997 Chevrolet dump truck
Impact type:	frontal
Impact severity (mph):	20-mph Delta V
Weather:	dark, unlit
Road conditions:	wet asphalt

Case vehicle A, a 1998 Ford Econoline full-sized van was transporting a passenger seated in a forward-facing power wheelchair in the center of the second row. The van was traveling west at an unknown speed in the center turn lane. A 1997 Chevrolet dump truck had been stopped facing south at the four-leg intersection. As both vehicles entered the intersection, the front of the van struck the left side of the dump truck cab and box in an L-type collision.



VEHICLE DAMAGE

Case Vehicle Information:		**Relevant intrusions:**
Direct damage length:	172 cm	none
Maximum crush:	47 cm	
PDOF:	0 degrees	
CDC:	12-FDAA-7	

Exterior photos:

Interior photos:

WHEELCHAIR AND WHEELCHAIR SECUREMENT

Description:		**Damage:**	
Wheelchair:	Crash-tested powered Permobil Chairman Corpus with four securement points	Wheelchair:	a linkage in the adjustable back support was broken
Orientation:	forward facing	Seating system:	backrest adjustment linkage failed
Postural supports:	chest and lap belts attached to wheelchair using screws through metal grommets on wheelchair	Postural supports:	failed at grommet attachment
Head support:	upper part of back support	Tiedown system:	no damage
Tiedown/use:	4-point strap tiedown used correctly		

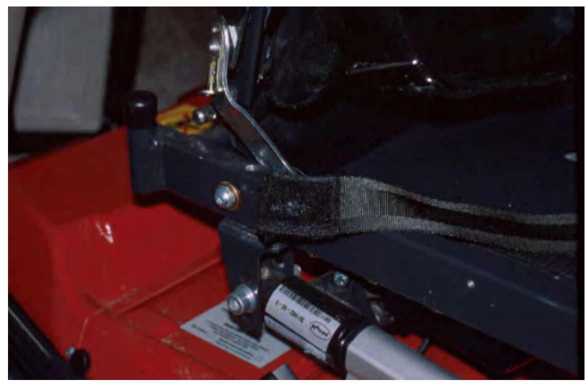
Wheelchair Photo:

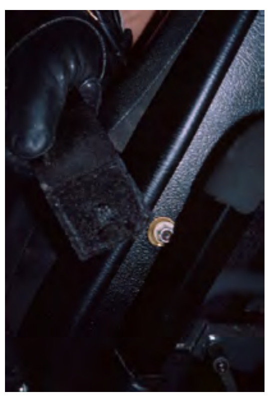
Tiedown System Photo:

OCCUPANT AND OCCUPANT RESTRAINT

<table>
<tr><td>Case occupant:</td><td>center second</td><td rowspan="5">The case occupant was seated facing forward in a power wheelchair in the center of the vehicle in the second row. His power wheelchair was secured to the vehicle by four tiedown straps but he was using only wheelchair postural chest and lap belts and not the available after-market vehicle-anchored lap/shoulder belt. During the crash, the both postural belts failed on one side at the screw/grommet attachments to the wheelchair, allowing the passenger to come out of the wheelchair seat late in the frontal-crash desceleration.</td></tr>
<tr><td>Age/gender:</td><td>28-year-old male</td></tr>
<tr><td>Stature/mass:</td><td>170 cm, 73 kg</td></tr>
<tr><td>Disability:</td><td>C6/C7 quadriplegic</td></tr>
<tr><td>Occupant restraint:</td><td>after-market vehicle-anchored lap/shoulder belt <u>not</u> used</td></tr>
</table>

<u>**Restraint system:**</u>



OCCUPANT KINEMATICS AND INJURIES

	Body Part	Injury	AIS	Source/Mechanism/Factors
1	Head, left posterior	laceration	1	contact with the wheelchair as the postural straps failed and occupant slid out of wheelchair
2	Head, brain	loss of consciousness < 1 hour	2	contact with the wheelchair as the postural straps failed and occupant slid out of wheelchair
3	Upper extremity, right second finger	fracture	1	contact with right-front passenger seat
4	Abdomen, spleen	contusion	2	postural straps

Occupant Kinematics:	Occupant Contacts:
During the frontal impact, the wheelchair-seated male passenger moved forward into the postural straps, causing them to fail at the grommet attachment. When the postural straps on the wheelchair failed, the passenger slid out of the wheelchair and his head contacted the wheelchair. He lost consciousness for less than one hour and sustained a laceration to the posterior aspect of his head, probably from head contact with the wheelchair. He sustained a contusion to the spleen due to loading by the postural straps, and a fracture to the right second finger, probably from hand contact with the right-front passenger seat.	Occupant's head contacted wheelchair. Right finger contacted back of right-front passenger seat.

Significance and Key Observations: Although the wheelchair-seated passenger was not using the vehicle-anchored, three-point belt, this case is considered to be a transit-wheelchair/tiedown "success story" because a heavy, powered wheelchair was effectively secured by a standard-compliant tideown system attached to crash-tested securement points, and the wheelchair user sustained relatively minor injuries in a moderate frontal impact.

APPENDIX C
SAFETY TIP SHEETS FOR VEHICLE MODIFIERS AND THEIR CLIENTS

Safety Tips
for Vehicle Modifiers and Equipment Installers
who prepare personal vehicles for use by passengers seated in wheelchairs secured by four-point, strap-type tiedown systems

GENERAL GUIDELINES

1) Always:
   - follow the National Mobility Equipment Dealers Association (NMEDA) guidelines to ensure that vehicle modifications are completed and adaptive equipment is installed in accordance with the highest industry standards and best practices,
   - follow the instructions provided by the tiedown/restraint manufacturer when installing anchorages in the vehicle so that the passenger seated in a wheelchair is facing the front of the vehicle.

2) When possible, encourage clients to purchase a crash-tested wheelchair that complies with the industry safety standard; "Wheelchairs used as seats in motor vehicles," usually referred to as ***WC19 wheelchairs***.
   - A WC19 wheelchair will be permanently labeled with the circular symbol below, or with words on permanent label stating that the wheelchair complies with WC19.

Symbol indicating compliance
with industry safety standards

   - A WC19 wheelchair will have four easily accessible, crash-tested tiedown-strap "securement-point" brackets, identified by a hook symbol,

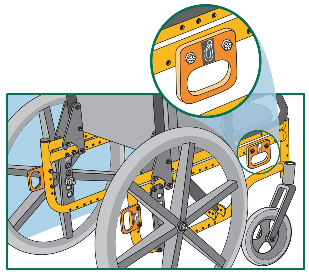


Illustration of securement-point brackets on a WC19-wheelchair designated by hook symbols

- A WC19 wheelchair provides the option of using a crash-tested wheelchair-anchored lap belt to which the lower end of a diagonal shoulder belt provided by the tiedown manufacturer can be connected to complete a lap/shoulder-belt restraint system similar to those provided by the vehicle manufacturer.
- A WC19 wheelchair is rated for the proper use and positioning of vehicle-anchored lap/shoulder belts. **The client should purchase a wheelchair with a "good" to "excellent" rating.**

SELECTING AND USING WHEELCHAIR TIEDOWN STRAPS AND VEHICLE ANCHOR POINTS

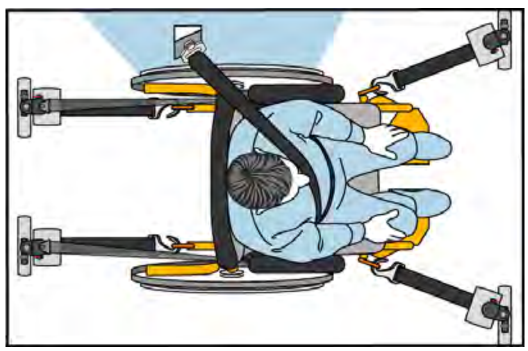
3) Install a four-point, strap-type wheelchair tiedown system that complies with current industry standards as indicated by the circular symbol shown on the previous page for WC19 wheelchairs, or words stating that it complies with SAE Recommended Practice J2249.

Illustration of a wheelchair secured by a four-point, strap-type tiedown

4) Select anchor points on the vehicle floor for the tiedown straps and seat belts that will provide effective wheelchair securement and occupant restraint in crash situations and during emergency vehicle maneuvers, such as sudden braking to avoid a collision.

Warning: Never attach anchorage hardware to movable or detachable vehicle components.

- Locate tiedown anchor points that will position the wheelchair close to the side of the vehicle so that a shoulder belt will cross over the middle of the passenger's shoulder (see illustration below).
- The distance between the front and back tiedown anchor points should be at least 48 inches whenever space allows.
- Anchor points for the left and right rear tiedown straps should be between 12 and 16 inches apart so they are directly behind attachment points on the wheelchair.
- Anchor points for the front tiedown straps should be spaced wider than the wheelchair whenever possible to increase lateral stability during travel.

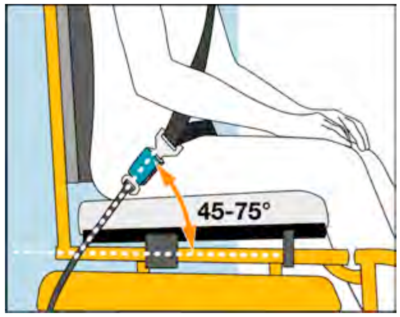


Top view of secured wheelchair showing rear tiedown straps going straight back to vehicle anchor points and front tiedown straps angled outward to wider vehicle anchor points

- For passenger wheelchair stations in the front row of a vehicle, locate the anchor points to position the wheelchair so that the passenger's chest and face are at least 12" from the dashboard, **and do not deactivate the dashboard air bag.**

SEAT BELTS FOR PASSENGERS IN WHEELCHAIRS

5) It is very important that both a lap-plus-shoulder belt restraint system is available for use by passengers seated in wheelchairs.
6) The vehicle lap/shoulder belt restraint system can only be used if a seat-belt buckle receptacle that is compatible with the latch plate ("tongue" of seat belt) on the vehicle seat belt is installed on the side of the wheelchair closest to the center of the vehicle.



Buckle receptacle attached to rigid cable stalk to keep receptacle off floor and more accessible

7) A more effective restraint system for passengers in wheelchairs can usually be achieved by installing a complete lap/shoulder belt restraint system provided by the manufacturer of the wheelchair tiedown system that is labeled with the circular symbol noted above or that complies with SAE J2249.
8) Whether using the vehicle seat belt with a compatible buckle receptacle installed on the inboard side of the wheelchair, or a complete lap/shoulder belt restraint system provided by the tiedown manufacturer, it is important to locate the anchor points for tiedown straps and the seat belt so that, when the passenger's wheelchair is effectively secured:
    - the angle of the lap belt is no less than 30 degrees and preferable greater than 45 degrees to the horizontal,
    - the shoulder belt crosses over the middle of the shoulder closest to the side of the vehicle to an upper anchor point or D-ring on the vehicle that is behind and above the top of the passenger's shoulder, and
    - the junction of the lap and shoulder belt is near the hip of the passenger.

Good shoulder belt positioning over the center of the shoulder and chest

9) When ready for travel, the lap belt should:
    - be as snug as possible consistent with user comfort,
    - with the seat-belt buckle positioned against the passenger's body and <u>not</u> in contact with, or close to, rigid wheelchair components.

OTHER FACTORS TO CONSIDER

10) If a rear head restraint is installed in the vehicle to reduce the risk of neck injury in rear impacts, it is very important to also install a vehicle-anchored back restraint to limit rearward movement of the passenger's upper torso during rear impacts.

11) Cover or fill any open pockets in the vehicle floor that were previously used to anchor vehicle seats to make it easier to maneuver an occupied wheelchair into the wheelchair-passenger space.

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For more information on industry safety standards and best practice for providing transportation safety for passengers seated in wheelchairs, refer to the *RideSafe* brochure that can be obtained online at www.travelsafer.org**, and to other educational materials that are available at** www.rercwts.org.

Safety Tips

for Vehicle Modifiers to Tell and Show Their Clients, Family Members, and/or Caregivers

before releasing personal vehicles that have been modified for use by passengers seated in wheelchairs secured by 4-point strap-type tiedown systems

SECURING THE WHEELCHAIR

1) If the client doesn't have a wheelchair that complies with the industry wheelchair transportation safety (WTS) safety standard, known as a WC19-wheelchair, tell them about these crashworthy wheelchairs that are designed for use as seats in motor vehicles with four easily accessible places for attaching hooks of tiedown straps, and encourage the client to purchase a WC19-wheelchair the next time they are in the market for a new wheelchair.

Illustration of a WC19 wheelchair secured by a four-point, strap-type tiedown

2) If the client does not have a WC19 wheelchair, help the client **identify and permanently mark** four easily accessible places (two in front and two in back) on the wheelchair frame for attaching hooks of tiedown straps.

3) For some non wheelchairs that do not comply with WC19 and that have frames with large cross sections, show the client how "securement loops" available from most wheelchair-tiedown manufacturers can be permanently attached to the wheelchair frame to provide easily accessible locations for attaching hooks of tiedown straps.

Illustration of securement loops attached to the back of a wheelchair frame
to provide easily accessible places for attaching tiedown hooks

4) Demonstrate how the client's wheelchair can be effectively secured facing forward in the vehicle using all four tiedown straps, and

   - emphasize the importance of using all four tiedown straps to secure the wheelchair,
   - **warn the client never to attach tiedown straps and hooks to movable or detachable wheelchair components, such as arm supports and foot supports or wheels**,
   - demonstrate how to remove slack from tiedown straps and to make sure that all tensioning mechanisms, including retractor anchorages, are effectively locked, and
   - demonstrate how it should not be possible to cause any noticeable movement of a properly secured occupied wheelchair when manually pushing or pulling on the wheelchair in any direction.

PROPER USE OF SEAT BELTS

5) Inform the client that they should also use a crash-tested, three-point seat belt (a lap belt plus diagonal shoulder belt) with the lower end of the shoulder belt connected to the lap belt near the hip of the passenger seated in a wheelchair.

6) Encourage the client to use postural belts and supports attached to the wheelchair when traveling to help maintain a more upright seated posture.

7) **Warn the client not to rely on postural belts that are attached to their wheelchair for crash protection when traveling in their vehicle.**

8) Show the client how to position the seat belt, and particularly a vehicle-anchored lap belt, with their specific wheelchair so that the lap belt makes good contact with the lower part of the pelvis and so that arm supports and other components don't interfere with good belt positioning.

9) **Warn the client that placing lap belts over or in front of arm supports will reduce the effectiveness of the seat belts in preventing serious injuries in a crash and can increase the risk of serious injury from occupant restraint forces from the lap belt.**

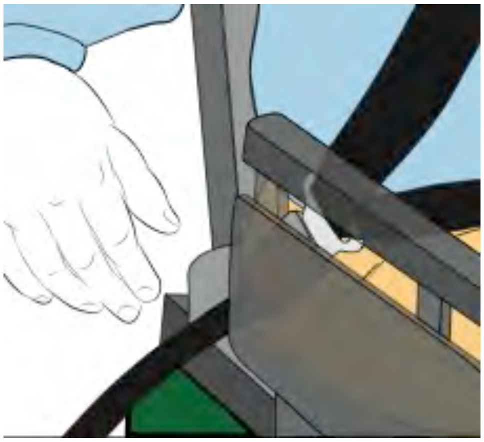
Improper positioning of a vehicle-anchored lap belt
over (left) and in front of (right) wheelchair arm supports

- If the client has a ***WC19 wheelchair*** with a wheelchair-anchored crash-tested lap belt and you have installed a seat belt with a disconnecting shoulder belt, show the client how the lower end of the vehicle-anchored shoulder belt can be attached to the pin-bushing anchorage on the lap belt near the hip of the passenger on the side opposite to where the shoulder belt crosses over the passenger's shoulder.

- If the client has a wheelchair with arm supports that are attached to the wheelchair at or near the back-support posts such that they are open at the front and underneath (cantilevered arm supports), show the client how the lap belt can be placed and buckled under the arm supports so that it is in good contact with the lower pelvis.

Proper positioning of a vehicle-anchored lap belt low on the pelvis with
wheelchair arm supports that attached to the wheelchair back-support posts

- If the client has a wheelchair with arm supports that are not open at the front but there are sufficiently large gaps between the arm supports and the wheelchair back support, show the client how the lap belt can be inserted into these gaps to achieve proper lap-belt positioning in good contact with the lower part of the pelvis.



Lap belt placed in gap between arm support and back to achieve proper positioning of the belt low on the pelvis

- If the client's wheelchair has arm supports that are attached to the wheelchair frame at the front so that it is not possible to slide the lap belt under the front of the arm supports, but the arm supports can be rotated up or sideways at the front, show the client how this feature can be used to help achieve proper positioning of the lap belt in good contact with the lower part of the pelvis.
- If the client's wheelchair requires "threading" of the anchorage ends of the lap belt through the opening between the seat and back support on each side of the passenger to achieve good lap belt positioning low on the pelvis, demonstrate how this is done by inserting the ends of the lap belt through the seat openings on each side of the passenger from the front.

NOTE: Seat belts provided by tiedown manufacturers often provide stiffened lap-belt webbing with small anchorage hardware that make it easier to thread the anchorage ends of the lap belt through openings between the wheelchair back and seat on both sides of the passenger. The anchorages are then manually connected to anchorage fittings on the vehicle floor behind the wheelchair.

Lap belt threaded into opening between the seat and back support to achieve proper positioning low on the pelvis

10) Show the client where to position the seat-belt buckle and the junction of the shoulder and lap belt such that:
    - the buckle is located against the passenger's body and not in contact with, or close to, rigid wheelchair components that could depress the buckle release button or contact and break the buckle assembly during a crash, and
    - the junction of the shoulder belt and lap belt is positioned near the passenger's hip on the side opposite to where the upper end of the shoulder-belt is attached to the vehicle or inserted through a D-shaped ring.

OTHER IMPORTANT POINTS

11) **Warn the client that they should never sew, pin, tie or otherwise modify the webbing of seat-belt systems.**
12) Provide the client with your contact information and tell the client that they should contact your company if they are having any problems with using the tiedown system, with proper positioning of the seat belt, or if the seat belt is not comfortable.
13) Give the client copies of the ***RideSafe Brochure*** and the list of ***Safety Tips for Clients*** who ride as passengers in vehicles when seated in a wheelchair secured by a four-point, strap-type tiedowns.

Safety Tips

for Clients of Vehicle Modifiers

who will be riding as passengers in personal vehicles while seated in their wheelchair secured by a 4-point-strap-type tiedown system

WHEELCHAIR-TIEDOWN AND OCCUPANT-RESTRAINT EQUIPMENT

1) Check your wheelchair tiedown straps and the seat-belt restraints regularly:

   - Make sure that each tiedown-strap assembly and any tensioning or locking mechanisms are working properly so that your wheelchair is held securely in place.

   - Make sure that all equipment is clean and that anchorage hardware fastened to the vehicle floor, such as steel or aluminum track, is free of debris so that all tiedown strap and belt restraint anchorage components will effectively engage with and lock into vehicle anchor points.

   If you notice problems with any equipment not functioning properly or if the restraint system is uncomfortable or not fitting properly, make an appointment with your vehicle modifier (your company's phone number here) as soon as possible.

2) If you plan to purchase a new wheelchair in the future, look for a wheelchair model that meets your needs and that also complies with industry wheelchair transportation safety (WTS) standards, commonly referred to as a ***WC19 wheelchair***.

   - These wheelchairs will have one or more permanent labels with words stating that the wheelchair complies with WC19, or will be permanently marked with one or more of the symbol shown below.

Symbol indicating compliance with industry wheelchair transportation safety standards

- A WC19-wheelchair will have four easily accessible brackets with rectangular openings for attaching hooks of the four tiedown straps, and will have been successfully crash tested using these brackets to secure the wheelchair with four tiedown straps.
- A WC19-wheelchair will have a rating from excellent to poor regarding how easy it is to properly position a vehicle-anchored three-point lap/shoulder belt restraint system on a passenger in the wheelchair. Select a wheelchair model with a "good" to "excellent" rating.
- A WC19-wheelchair will provide the option for a passenger seated in the wheelchair for using a crashworthy lap belt that is anchored to the wheelchair to which the lower end of a vehicle-anchored shoulder belt can be easily attached near the hip to complete a three-point lap/shoulder belt restraint system similar to that used by passengers in the vehicle seats.

SECURING YOUR WHEELCHAIR

3) Always secure your wheelchair to the vehicle **using all four tiedown straps**.
4) Check to make sure that all anchorages are securely fastened to hardware on the floor (such as a length of steel or aluminum track), and that all straps are attached securely to the wheelchair frame using WC19 securement-point brackets or portions of the wheelchair frame that have been identified and marked by you and your vehicle modifier.

NOTE: As illustrated below, for some wheelchairs that do not comply with WC19 and that have frames with large cross sections, you may need to permanently attach "securement loops" to the wheelchair frame to provide a way to easily and effectively secure the wheelchair.

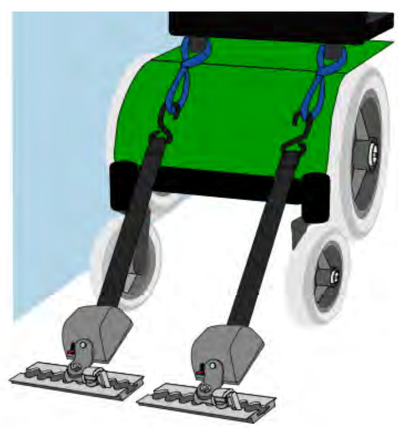


Illustration of securement loops attached to the back of a wheelchair frame to provide easily accessible places for attaching tiedown hooks

5) Make sure that all tiedown straps are tensioned and locked before traveling.

PROPER USE OF SEAT BELTS

6) Always use both the lap and diagonal shoulder portions of the seat-belt system when traveling in your vehicle.

7) Use postural belts and other types of postural supports attached to your wheelchair to help you sit as upright as possible, but **don’t rely on these belts and supports for safety and crash-protection during travel**.

8) If you have a WC19 wheelchair and are using a crash-tested lap belt anchored to the wheelchair (indicated by a label on the belt stating that the lap belt complies with WC19 or by the circular symbol above), complete the three-point lap/shoulder belt restraint system by attaching the lower end of the shoulder belt to the pin-bushing anchorage on your lap belt.

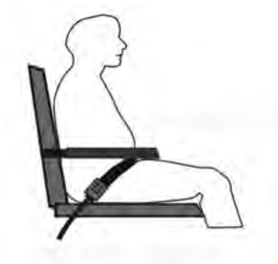
9) Whether you are using a vehicle-anchored or wheelchair-anchored lap belt, properly position the seat belt on the wheelchair passenger by:

   - making sure that the lap belt is positioned low across the pelvis,
   - making sure that the shoulder belt crosses over the middle of the shoulder closest to the side of the vehicle and diagonally across the chest, and
   - placing the connection between the lap and shoulder belts near the hip opposite to the side where the upper anchorage of the shoulder belt is attached to the vehicle.

10) Never place the lap-belt portion of the vehicle seat belt over, or in front of, the wheelchair’s arm supports as shown below since this will reduce ability of the seat belt to provide protection from serious injury in a crash and will increase the risk of serious injuries from restraint forces applied to the body by the seat belt.

Improper positioning of the lap-belt portion of a vehicle
seat belt over (left) and in front of (right) wheelchair arm supports

   - To achieve proper positioning of the lap belt low on the pelvis, it is best if your wheelchair has arm supports that are attached to the wheelchair at the back (for example to the back-support posts) so they are completely open in front and underneath as shown below.



Proper positioning of a vehicle-anchored lap belt with wheelchair arm supports that are attached to the back-support posts and completely open at the front and underneath

- For wheelchairs with arm supports that are connected to the wheelchair frame at the front so that it is not possible to slide the lap belt under the front of the arm supports, proper positioning of a vehicle-anchored lap belt can often be achieved by inserting the two halves of the lap belt into sufficiently large gaps between the arm supports and the back support.

Lap belt placed in gaps between arm supports and the back support to achieve proper positioning low on the pelvis

- For wheelchairs with arm supports that are not open underneath at the front but that can be rotated upward or sideways, this feature can be used to help achieve proper positioning of a vehicle-anchored lap belt in contact with the lower part of the pelvis.

- For some wheelchairs, achieving proper positioning of the lap belt low on the pelvis may require "threading" the stiffened anchorage ends of the lap belt through openings between the wheelchair back support and the seat on each side of the passenger.

Lap belt threaded into opening between the wheelchair seat
and back support to achieve proper positioning low on the pelvis

11) When ready for travel the seat-belt buckle should lie comfortably against the front of the pelvis and should not be in contact with, or close to, rigid wheelchair components that could contact and depress the buckle release button, or that could contact and break the buckle assembly during a crash.
12) Never sew, pin, tie, or otherwise modify the webbing of seat-belt systems.
13) Contact your vehicle modifier (your company's phone number here) if you are having any problems with proper seat-belt positioning or if the seat belt is not comfortable.
14) Rear head supports on wheelchairs are postural supports and are not designed to offer protection for the head and neck in rear-impact collisions. However, they may provide some benefit in reducing the risk of injuries during rear impacts if positioned high enough (at least as high as the ears) and close to the back of the head.

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For more information on best practice in transportation safety for passengers seated in wheelchairs, refer to the *RideSafe Brochure* provided by your vehicle modifier and that can be obtained online at www.travelsafer.org, and to other educational materials that are available at www.rercwts.org.