UMTRI TRANSPORTATION RESEARCH INSTITUTE UNIVERSITY OF MICHIGAN

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Testing Wheelchairs, Wheelchair Seating Systems, and Wheelchair Tiedown and Occupant Restraint Systems (WTORS) to Industry Wheelchair Transportation Safety (WTS) Standards

Accredited to ISO/IEC 17025:2017

PJLA
Testing
Accreditation #108987

OVERVIEW

UMTRI has been involved in wheelchair-occupant safety research for more than thirty years and Biosciences researchers and test engineers have been active in leading the development of wheelchair transportation safety (WTS) standards worldwide since 1985. UMTRI's Biosciences Group conducts sled-impact tests of wheelchairs, wheelchair seating systems, and wheelchair tiedowns and occupant-restraint systems (WTORS) to evaluate their frontal-impact performance relative to crashworthiness criteria in the latest U.S. and international industry standards.

Frontal-impact testing of wheelchairs is conducted in accordance with Annex A of Section 19 of ANSI/RESNA Wheelchair Standards, Volume 4: *Wheelchairs and Transportation: Wheelchairs Used as Seats in Motor Vehicles* (Section 19, ANSI/RESNA WC-4:2017), often referred to as "WC19." This industry standard was published in December 2017 and is an updated and improved version of the original WC19 that was published in May 2000. Other WC19 wheelchair performance tests are conducted in accordance with Annex B, Annex C, and Annex E. The methods of these annexes provide for evaluating the design and performance of wheelchairs with regard to tiedown clear paths from wheelchair securement points (i.e., attachment points) to vehicle anchor points, the lateral stability of wheelchairs during travel when secured by a four-point, strap-type tiedown, and wheelchair accommodation of properly positioning vehicle-anchored belt restraints on passengers seated in wheelchairs. Wheelchairs may also be tested in accordance with international standard ISO 7176-19 (2008), *Wheeled mobility devices for use as seats in motor vehicles*.

WTORS are dynamically tested on the UMTRI impact sled using the methods of Annex A in Section 18 of Volume 4 of ANSI/RESNA Wheelchair Standards (Section 18, ANSI/RESNA

WC-4:2017), or "WC18," which is an updated and improved version of Society of Automotive Engineers (SAE) Recommended Practice J2249: *Wheelchair Tiedown and Occupant Restraint Systems for Use in Motor Vehicles*. For WTORS intended for general use, tests are conducted using an 85-kg (187-lb) surrogate wheelchair (SWC) to dynamically load the wheelchair tiedown/securement system in a 30-mph, 20-*g* frontal-impact test. A midsize or large adult-male anthropomorphic test device (ATD), or crash-test dummy, is used to load the occupant belt-restraint system. The WC18 test methods and performance criteria are very similar to those of ISO 10542-1: *Wheelchair tiedown and occupant restraint systems for use with forward-facing wheelchair-seated occupants – Part A: Requirements and test methods – Frontal impact*. However, as of December 2015, an additional test of tiedown/securement systems in WC18 requires the ATD to be restrained by a surrogate pelvic (lap) belt anchored to the SWC, thereby increasing the frontal-impact loads on the rear tiedown straps of four-point, strap-type tiedown, or on other types of securement devices.

Crashworthiness performance and seatbelt-accommodation testing of wheelchair seating systems are evaluated in accordance with test methods set forth in Section 20 of Volume 4 of ANSI/RESNA Wheelchair Standards: *Wheelchair Seating Systems for Use in Motor Vehicles* (Section 20, ANSI/RESNA WC-4:2017), which is referred to as "WC20," or with ISO 16840: *Wheelchair seating – Part 4: Seating systems for use in motor vehicles*. These standards provide a means to evaluate a complete seating system, consisting of a back support, a seat, and attachment hardware, independent of production wheelchair frames by installing the seating system on an adjustable-size surrogate wheelchair frame (SWCF). Wheelchair seating systems are tested and evaluated using the same 30-mph, 20-*g* frontal-impact conditions used in WC18 and WC19, and testing for accommodation of the proper use and positioning of vehicle-anchored belt restraints on passengers uses test methods and criteria that are very similar to those used for wheelchairs in WC19.

UMTRI'S SLED-IMPACT TEST FACILITY

Impact Sled

UMTRI's impact sled is shown in Figure 1 and consists of a sled platform that travels on a sixty-foot linear track consisting of two stainless-steel tubular rails. The wheelchair, seating system, or WTORS to be tested is installed on the sled platform using appropriate test fixtures and methods specified in the ANSI/RESNA and ISO standards. The UMTRI sled generates the desired change in velocity (i.e., 30 mph), or what is known as the "delta V," by reversing direction during the impact event.

To conduct a test, the platform is accelerated from one end of the track to a pre-impact speed by means of a pneumatically powered ten-foot stroke piston. The sled travels freely on linear ball bearings to the opposite end of the track where it is decelerated by a pneumatically pressured cylinder that functions as an air spring, thereby causing the sled to reverse direction and travel back down the track. The delta V is the sum of the "in" and "out" sled speeds measured immediately before and after contact of the sled probe with the decelerator piston. In a typical wheelchair, WTORS, or seating-system frontal-impact sled test, the acceleration and deceleration pressures are set to achieve a change in sled speed between 30 and 32 mph (48 to 51 kph), and the deceleration pulse must fall within the shaded zone shown in Figure 2. The deceleration pulse of the UMTRI sled is trapezoidal in shape and is therefore similar to

the crash pulse generated in frontal barrier tests by vehicles such as full-size vans and minivans typically used by occupants seated in wheelchairs.

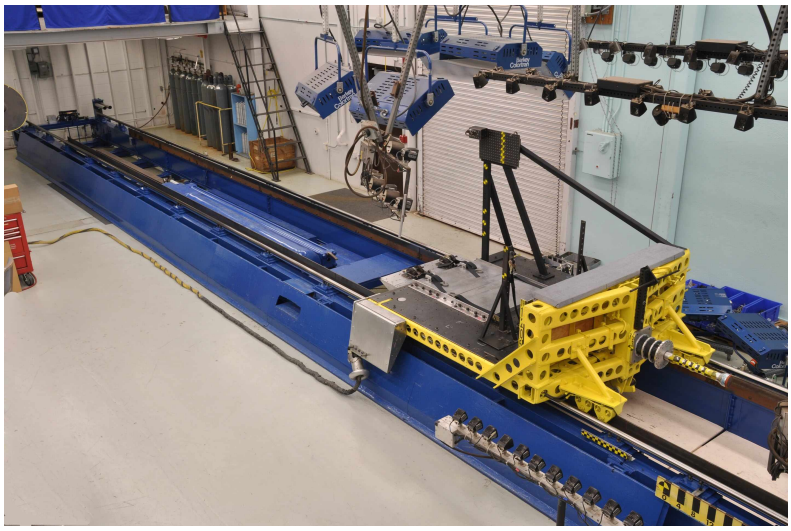

Figure 1 – UMTRI's sled impact facility

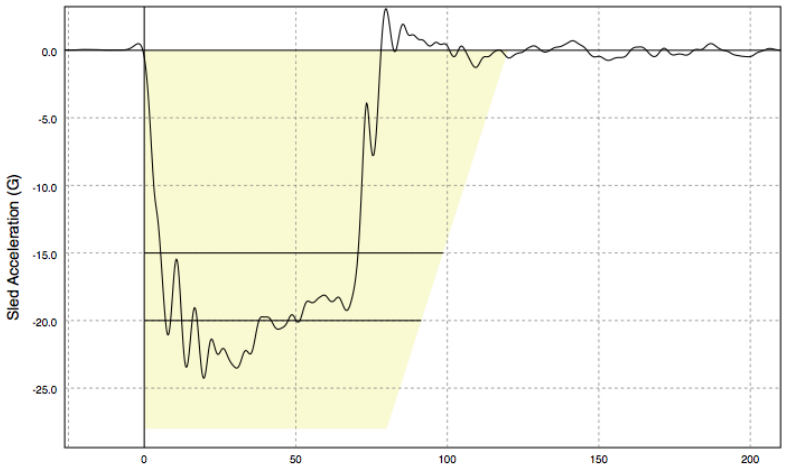

Figure 2 - Typical UMTRI 30-mph sled deceleration pulse compared to the corridor (shaded area) specified in RESNA and ISO frontal-impact test methods.

Anthropomorphic Test Devices (ATDs) or Crash-Test Dummies

WTORS

As shown in Figure 3, several different sizes of the crash-test dummies, ranging from a 3-year-old to a large-adult male, are available at UMTRI. These include the full family of Hybrid III ATDs, currently required by the ANSI/RESNA standards (and U.S. federal safety standards), as well as Hybrid II and VIP ATDs that are allowed, along with Hybrid III ATDs, in ISO testing. The name, size, and nominal weight (i.e., mass) of each are listed in Table 1. For WTORS testing to WC18, a midsize male Hybrid III ATD, shown in Figure 4, with a nominal mass of about 170 lb (76 kg) is usually used since almost all WTORS are intended

for use by both adults and children. Manufacturers may conduct tests of WTORS using with large-male ATD, but in the U.S., such tests will only be considered as supplementary "due-care" WC18 tests.

For WTORS that are designed for limited use with pediatric or manual wheelchairs and/or children having a body mass that is considerably less than that of an adult, one of the smaller ATDs, such as the small female, 10-year old, or 6-year old might be the appropriate size ATD to use along with the a representative commercial wheelchair rather than the surrogate wheelchair. UMTRI sled engineers will provide manufacturers with advice on the appropriate size ATD to use and any product labeling requirements or warning literature related to the limited use of the WTORS.

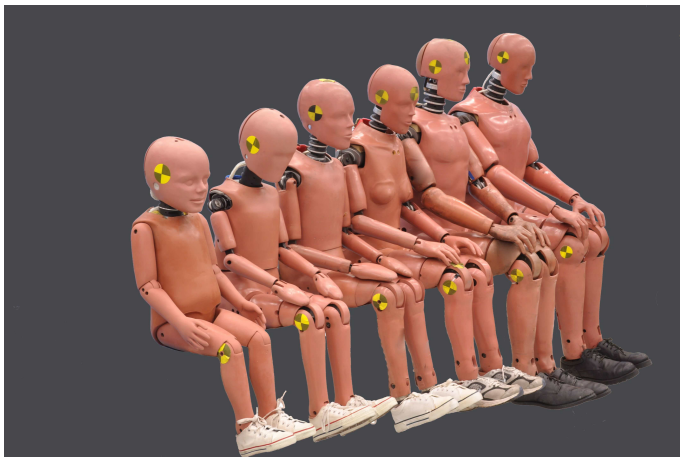

Figure 3 – UMTRI's crash-test dummies

Wheelchair and Seating Systems

For frontal-impact testing of wheelchairs and seating systems, the ATD selected is based on the weight range of user sizes for which the wheelchair and/or seating system have been designed, with an ATD near the upper end of the range being chosen for use in the test. For wheelchairs intended for use by adults up to 300 lb, a Hybrid III midsize adult male ATD is required for WC19 or WC20 testing but ISO 7176-19 (wheelchairs) and ISO 16840-4 (seating systems) allow testing with Hybrid II ATDs and the large male ATD. The latter is only used in WC19 and WC20 tests for wheelchairs and seating systems intended for use by occupants with a body mass greater than 300 lb.

For pediatric wheelchairs, the small-female ATD (nominally104 lb) is often the appropriate choice, but the new Hybrid III 10-year old ATD or the 6-year old ATD may also be appropriate for some wheelchair models and/or restraint conditions. For wheelchairs intended for use by children who weigh less than 50 lb (23 kg), testing to WC19 requires that the 3- or 6-year-old Hybrid III ATD is restrained only by a commercially available wheelchair-integrated five-point restraint harness provided by the wheelchair manufacturer. Additional mass can also be added to most ATDs to simulate an occupant mass that is between the standard ATD masses listed in Table 1. However, for WC19 testing, additional mass is only used to increase the mass of the small-female ATD to 130 lb for wheelchairs and seating

systems designed for people with a body mass ranging from 125 to 165 lb. All other testing to U.S. standards with ATDs having augmented mass is considered to be "due-care" testing and not testing to the standards.

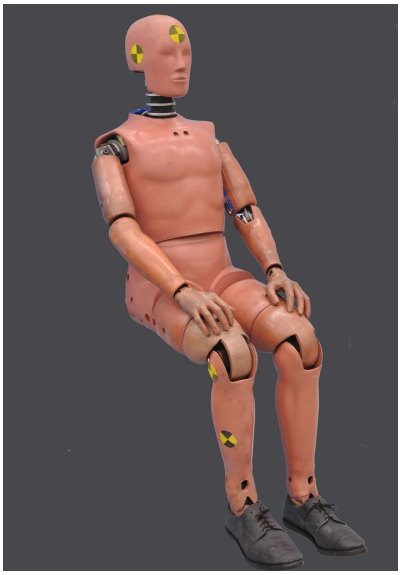

Figure 4 – Midsize Adult Male Hybrid III ATD (crash-test dummy)

Table 1
UMTRI ATDs
Available for Use in WTORS, Wheelchair, and Seating System Sled-Impact Testing

	Nominal Weight (lb)	Seated Height (in)	Buttock-Knee Length (in)	Hip Breadth (in)	Knee Height (in)
Hybrid III 3-Year Old	37.5	22.5	12.7	7.0	10.4
Hybrid III 6-Year Old	50.0	25.6	14.9	8.8	13.5
Hybrid III 10-year Old	77.6	28.5	18.0	10.4	14.8
VIP Small Adult Female	106	31.0	19.0	14.0	16.8
Hybrid III Small Adult Female	108	31.0	21.0	12.4	16.0
Hybrid II Midsize Adult Male	168	35.0	23.0	15.5	20.0
Hybrid III Midsize Adult Male	172	34.8	23.3	14.4	19.5
VIP Large Adult Male	225	38.0	24.0	16.5	20.0
Hybrid III Large Adult Male	225	36.8	24.9	16.0	20.5

Instrumentation, Data Acquisition, and Signal Processing

Although not required by the current WTORS and wheelchair crash-test standards, most ATDs used in UMTRI sled-impact tests are instrumented with head and chest (thoracic spine) triaxial accelerometers. The sled platform is also instrumented with four accelerometers to measure the sled deceleration-time history during each test for comparison with the specified corridor shown in Figure 2. The change in sled speed during impact deceleration (i.e., the delta V) is measured directly by a light-based sensor that detects the time of sled travel between precisely spaced "fingers" on the sled track immediately prior to and after the sled

deceleration pulse. The delta V is also computed by integration of the deceleration-time pulse.

Measurement of force-time traces in tiedown straps and belt restraints is also not required by the standards, but this information can be useful to manufacturers, particularly in the event of a component failure. Therefore, webbing load cells are often used on belt restraints and on tiedown straps when this is feasible and desired by the test sponsor. In addition, strain-gaged rod-end anchorage components of the surrogate four-point, strap-type tiedown used in sled-impact tests of wheelchairs and wheelchair seating systems measure the force-time histories in the rear tiedown straps during all wheelchair and seating-system frontal-impact tests conducted to WC19 and WC20.

All signals generated by accelerometers and load cells used in a sled-impact test are digitized in real time using a dedicated data-acquisition system (DAS) mounted to the sled, and are processed and digitally filtered according to the requirements of SAE J211. The polarities of all signals are adjusted to conform to the sign convention of SAE J1733. Data from ATD head and chest accelerometers are processed through algorithms to determine peak head resultant acceleration, head injury criterion (HIC), and the 3-ms clipped resultant chest (i.e., thoracic spine) acceleration. Time history graphs of the individual transducer signals, as well as calculated resultants (e.g., result head acceleration), are generated within minutes after a test, along with peak values for head and chest accelerations, and the calculated value of HIC.

Accelerometers and load cells used in sled tests are calibrated every year, or more frequently if there is any indication that a transducer is not working properly. Chest-deflection potentiometers in the Hybrid III ATDs are generally not used in wheelchair and WTORS testing but are calibrated prior to each test when they are used, as may be requested by a sponsor. In addition, the outputs of two of the sled accelerometers are routinely compared to ensure that the difference in peak values is less than 0.5 *g*.

Digital photos and high-speed videos

Photo and high-speed video documentation of each test includes pre- and post-test color photos taken with a high-resolution digital camera and high-speed digital videos that record the kinematics of the ATD and test components during the impact event at 1000 frames per second. For wheelchair and seating-system tests, two off-sled high-speed side-view video cameras are typically used, with one placed to view the main impact event and capture peak forward excursions of the wheelchair and ATD, and the other positioned to record the ATD rebound kinematics, interaction with the wheelchair back support, and peak rearward head excursion. For WTORS tests, a side-view camera is typically used and a second camera is often positioned to obtain a close-up rear-oblique view, or an overhead view, of the tiedown/securement system and the surrogate wheelchair.

These digital videos are reviewed immediately after each test to evaluate the performance of the tested components and to determine peak forward excursions of the ATD's head and knees and of the wheelchair or SWC seat (i.e., seat reference point P). For wheelchair and seating-system tests, peak rearward excursions of the ATD's head are also determined as an indication of back-support performance during ATD rebound loading. Copies of digital

photos are provided with each test report (see below) along with selected sequence frames from the high-speed videos to show the critical kinematics and results.

CONDUCTING SLED-IMPACT TESTS FOR WTS STANDARDS

Objectives and Performance Criteria

In typical government regulatory crash testing, injury criteria computed from ATD head, chest, neck, and thigh instrumentation are compared to, and must be less than, maximum-allowed reference values that have been related through research to the likelihood of serious injuries. Examples are the Head Injury Criterion, or HIC, the peak 3-ms-clipped chest resultant acceleration, and peak chest anterior-to-posterior deflection. While an instrumented ATD is typically used in testing wheelchairs, WTORS, and seating systems, and many of these injury criteria are calculated and provided to the sponsor with the test report, these measures are not currently used in the pass/fail criteria for wheelchairs, seating systems, or WTORS in these voluntary industry standards. This is because the primary purpose of the sled-impact tests is to evaluate the dynamic strength of the WTORS, seating system, or wheelchair during 30-mph, 20-*g* frontal-impact loading conditions, and because representative vehicle components for the ATDs to interact with are not included in the tests. Thus, the primary performance criteria specified in these standards for the frontal-impact sled tests are observations of structural and component failures based on post-test inspection of the test samples, and peak horizontal excursions of the wheelchair (surrogate or production) and the ATD's knee and head, based on analysis of high-speed videos. Because most crash-related injuries to vehicle occupants are caused by contact with vehicle interior components, the horizontal excursion limits serve as the primary injury performance criteria in these standards.

The primary purpose of the ATD in these impact tests is to produce representative dynamic forces on the wheelchair, seating system, and/or WTORS that would be generated by a typical wheelchair occupant, and to represent wheelchair-occupant kinematics (i.e., movements and excursions) during a 30-mph frontal crash. As has historically been the practice in government safety testing, and as previously noted, the midsize-male ATD (i.e., about 50th percentile by U.S. male stature and weight) is used for testing wheelchairs, seating systems, and WTORS intended for general use by adults.

In WTORS frontal-impact testing, the wheelchair tiedown/securement system is dynamically loaded by a rigid and reusable surrogate wheelchair (SWC) with a static mass of 187 lb (85 kg). For testing wheelchair-seating systems, a surrogate wheelchair frame (SWCF) that is specified in Annex B of WC20 is used to represent a typical wheelchair frame, and includes some components that deform during frontal-impact loading. These include deformable and replaceable bars that connect the back-support posts to the SWCF and aluminum bars by which the front wheels are mounted to the SWCF. For required wheelchair testing to WC19, the wheelchair is secured by a surrogate four-point strap-type tiedown that is specified in Annex D of WC19 and that provides for measurement of the force-time histories at the rear tiedown-strap anchor points.

Wheelchair Tests

Required crashworthiness tests of wheelchairs are performed using a sponsor-supplied production or prototype wheelchair and the surrogate four-point, strap-type tiedown system noted above and specified in Annex D of WC19. As shown in Figure 5, the wheelchair is positioned facing forward on a 3/8-inch thick steel platform and secured with the surrogate four-point, strap-type tiedown. The securement hooks of the four surrogate tiedown strap assemblies are attached to the wheelchair and/or seat frame at the manufacturer's designated securement points. An appropriate-size ATD (for the wheelchair's user capacity) is placed in the wheelchair seating system and restrained using a belt-type restraint system consisting of both upper and lower torso belts. WC19-compliant wheelchairs intended for occupants with a body mass greater than 50 lb (about 6 years old) must be tested with a pelvic/lap belt provided by the wheelchair manufacturer that anchors to the wheelchair or seat frame, and that provides a specified pin-bushing anchorage on each half of the lap belt for attaching the lower end of a vehicle-anchored shoulder belt. For these tests, a surrogate shoulder belt is provided by UMTRI to connect between the lap-belt pin-bushing anchorage and a rigid structure that simulates a vehicle sidewall for the upper shoulder-belt anchor point. As previously noted, for wheelchairs intended for use by children less than 50 lb (23 kg), WC19 requires testing the wheelchair with a fully integrated (i.e., wheelchair/seating system anchored) five-point restraint harness similar to that provided on standard child safety seats.

Figure 5 – Wheelchair secured facing forward on the UMTRI sled using the surrogate four-point, strap-type tiedown

Manufacturers may also choose to conduct "due-care" tests of their wheelchairs using a three-point belt restraint with the lap belt anchored to the sled platform. For these tests, UMTRI provides a complete surrogate vehicle-anchored lap/shoulder belt restraint system.

While WC19 and ISO 7176-19 require that manufacturers design and test their wheelchairs for securement by a four-point, strap-type tiedown, wheelchair manufactures are encouraged to test appropriate wheelchair models when secured by methods other than the four-point, strap-type tiedown using the procedures in Annex A of WC19. For example, many powered wheelchairs are used by people who drive while seated in their wheelchairs, in which case the wheelchair is secured by an auto-engage docking-securement device. Manufacturers of wheelchair models that are likely to be used by drivers who are not able to transfer to the vehicle seat should therefore conduct a frontal-impact test with the wheelchair secured by a

particular commercially available docking securement device. For these tests, most wheelchairs will need to be modified by attaching a specific securement adaptor to the frame of the wheelchair to provide the structural component that will engage with the docking-securement device mounted to the vehicle floor (i.e., to the sled platform).

WTORS

Sled impact tests of wheelchair tiedown and occupant restraint systems intended for general use are performed using the 187 lb (85 kg) surrogate wheelchair (SWC) specified in Annex E of WC18 and ISO 10542-1. As shown in Figure 6, the SWC is placed facing forward on the sled platform and secured with the sponsor's tiedown/securement system. A midsize adult-male ATD is placed in the SWC seat and restrained using a vehicle-anchored three-point belt restraint that is set up using geometry specified in the test procedures of the standards. As previously noted, as of December 2015, WC18 requires wheelchair tiedown/securement systems be tested with a SWC-anchored surrogate lap belt, thereby increasing the forces on the tiedown/securement system for the situation where a person using a WC19-compliant wheelchair is also using a crash-tested wheelchair-anchored lap belt.

In cases where a WTORS has been designed for limited use with a specific wheelchair and/or occupant because of special wheelchair features required for securement or lower wheelchair mass, the sled impact test is conducted with a representative sample of the production wheelchair model rather than with the SWC. In these cases, the test is a "system" test that evaluates the dynamic strength of the WTORS-plus-wheelchair *system*, and the WTORS must be clearly labeled to indicate the limitations of its use.

Figure 6 – 187-lb surrogate wheelchair (SWC) loaded with the Hybrid III midsize-male ATD retrained by a commercial lap/shoulder-belt restraint and secured facing forward on the UMTRI sled by the WTORS manufacturer's strap-type tiedown system

Wheelchair Seating Systems

Sled-impact tests of wheelchair seating systems are performed using the surrogate wheelchair frame (SWCF) specified in Annex B of WC20, which is referred to as a surrogate wheelchair base (SWCB) and specified in Annex B of ISO 16840-4. The width of the SWCF is adjustable and is set to accommodate the seating-system width by assembling the SWCF with the appropriate center cross-frame section. The back support and seat are attached to the

back-support posts and seat rails of the SWCF using attachment hardware provided by the manufacturer, and the back support and seat are positioned according to the manufacturer's instructions. The seat rails can be changed to accommodate the manufacturer's attachment hardware.

The SWCF with seating system installed is placed facing forward on the sled platform and secured by the surrogate four-point, strap-type tiedown system specified in Annex D of WC19. The securement hooks of the rear tiedown strap assemblies are attached to the lower rear securement points provided on the SWCF and the front tiedown hooks are attached to the front securement points. An appropriate size ATD is placed in the seating system based on information from the manufacturer about the user capacity of the seating system, and the ATD is restrained using a three-point belt restraint system consisting of an SWCF-anchored lap (WC19) or a vehicle/sled-anchored lap belt (ISO 16840-4 allows testing with either a vehicle-anchored or SWCB-anchored lap belt) and a diagonal shoulder belt. Additional "due-care" WC19 tests may also be conducted using a surrogate three-point belt restraint with a lap belt anchored to the sled platform.

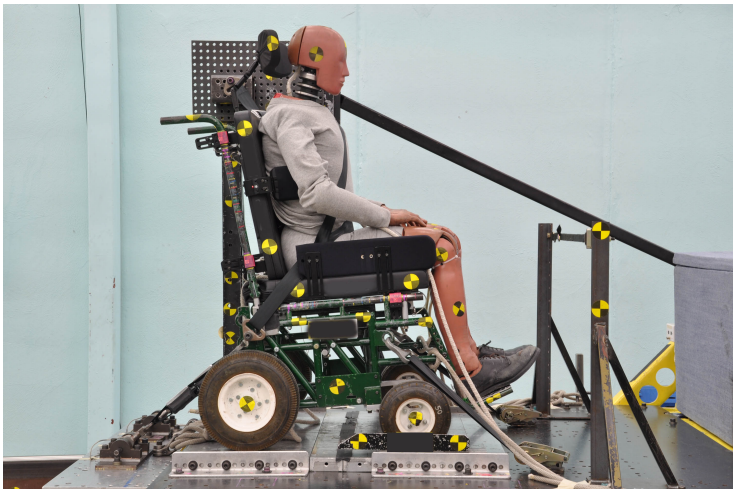

Figure 7 – Manufacturer's seating system installed on the surrogate wheelchair frame (SWCF) secured facing forward on the UMTRI sled by the surrogate four-point, strap-type tiedown and loaded with a Hybrid-III midsize-male ATD

ON-LINE ACCESS TO TEST RESULTS

Pre- and post-test pictures, high-speed videos, and instrumentation data are available to download by test sponsors via a shared DropBox location. Access to test results is protected by sponsor-assigned usernames and passwords. This allows sponsors to access their test results for recent and past tests conducted at UMTRI as requested. Copies of the digital photos and video frames are also provided in CD/DVD format or on a flash drive upon request.

MACHINING AND WELDING CAPABILITIES

UMTRI has machining and welding facilities and technical support staff that enables fabrication of test fixtures as needed for a test setup, or modification of test components before and between tests. The latter allows manufacturers to quickly evaluate how changes in

product design might resolve problems noted in a test. When these additional services are needed, the cost of labor and materials is added to the standard per-test cost at the time of invoicing.

TEST REPORT

Upon completion of each test, a written report is prepared that includes:

- a narrative describing the test setup and equipment being tested
- a table summarizing test-setup geometry
- a narrative describing the test results including a statement of whether the equipment tested complies with all applicable performance criteria of industry standards
- a table summarizing test results, including:
  - sled velocity and acceleration
  - peak forward head, knee, and wheelchair excursions
  - peak forward wheelchair, SWC, SWCF, and/or ATD excursions
  - peak rearward ATD head excursion (wheelchair and seating-system tests only)
  - peak ATD head and 3-ms chest accelerations and resultant accelerations
  - head injury criterion (HIC)
  - peak chest deflection (when used upon sponsor request)
  - neck forces and moments (when neck load cells are included per sponsor request)
  - peak belt-restraint loads (as measured)
  - peak loads in surrogate rear tiedown straps
  - peak loads in WTORS tiedown straps (when measured)
- a table summarizing compliance of the equipment tested to performance criteria of applicable voluntary standards
- color pre-test digital photos
- color time-sequence photos taken from high-speed videos
- color post-test digital photos
- copies of force-time plots of all instrumentation

This report is usually provided in PDF format that is sent to the sponsor within one to two weeks of the test date.