

INDEPENDENT SAFETY FOR WHEELCHAIR USERS IN AUTOMATED VEHICLES

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16. Abstract To allow use of automated vehicles (AVs) by people who travel while seated in their wheelchairs, UMTRI and May Mobility modified a 2021 Ford Transit to demonstrate options for safe and independent wheelchair securement and belt placement. This electric vehicle represents what might be used in a shared-use AV platform, having similar size and features to vehicles on May Mobility's platform roadmap. The vehicle was equipped with a lift and demonstrated how the vehicle floor could still be modified for wheelchair securement purposes while maintaining compatibility with floor batteries, common to many electric vehicle designs. The vehicle was equipped with a wheelchair docking system meeting specifications for a universal docking interface geometry (UDIG), which allows any wheelchair compatible attachments to dock with any vehicle equipped with anchoring hardware meeting the UDIG specifications. UDIG specifications have been included as an appendix in voluntary ISO and RESNA wheelchair standards, and the rear-mounted attachments eliminate ground clearance interference problems experienced with traditional docking systems while also producing desirable crash kinematics. Our project placed a high priority on appropriate design and use of occupant protection systems so that people traveling in wheelchairs would achieve a similar level of safety to those traveling in vehicle seats, so we also installed an automated belt donning arm and optimal seatbelt anchors. The system was evaluated for usability, comfort, and perceived safety by 12 volunteers who are regular wheelchair users, who took a short ride using the system and compatible wheelchairs. Throughout the project, the team engaged with people with disabilities through the United Spinal Association, Ann Arbor Center for Independent Living, and Feonix Mobility Rising to better understand the needs and transportation challenges of people with disabilities, and to ensure the system is usable and comfortable. This project demonstrated the feasibility of the system in AVs, addressing the challenges made by accessibility modifications posed by the hybrid architecture. Future activities to demonstrate feasibility could incorporate user feedback from the current effort, involve wheelchair manufacturers in designing compatible hardware, and a pilot deployment in an autonomous shuttle.			
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Executive Summary

Autonomous vehicles (AVs) have the potential to bring transportation independence to millions of people with disabilities, but accessibility needs to be considered from the outset of AV design and deployment. Current methods of securing wheelchairs and protecting their occupants do not allow independent travel in a public AV, because a driver or attendant is needed to secure the wheelchair.

Researchers from the University of Michigan Transportation Research Institute (UMTRI) and May Mobility addressed this barrier as a finalist in the U. S. Department of Transportation's 2020 Inclusive Design Challenge (IDC). On this project, the team installed a wheelchair docking system meeting specifications for a universal docking interface geometry (UDIG). This concept allows any wheelchair with attachment hardware meeting the UDIG specifications to dock with any vehicle equipped with anchoring hardware meeting the UDIG specifications. UDIG specifications have been included as an appendix in voluntary ISO and RESNA wheelchair standards, and the rear-mounted attachments eliminate ground clearance interference problems experienced with traditional docking systems while also producing desirable crash kinematics. UMTRI has developed prototype UDIG-compatible hardware, as well as an automatic seatbelt donning system, that was crash tested and evaluated by volunteers in the laboratory as part of a project funded by the National Highway Traffic Safety Administration.

In our IDC project, engineers from May Mobility and UMTRI adapted the prototype Automated Wheelchair Tiedown and Occupant Restraint System (AWTORS) for installation in a 2021 Ford Transit to evaluate options that would allow passengers using wheelchairs to travel safely and independently. This electric vehicle represents what might be used in a shared-use AV platform, as it shares similar dimensions and components to vehicles on May Mobility's platform roadmap. The vehicle was equipped with a lift and demonstrated how the vehicle floor could still be modified for wheelchair securement purposes while maintaining compatibility with an array of batteries located beneath the floor, common to many electric vehicle designs. Our project placed a high priority on appropriate design and use of occupant protection systems so that people traveling in wheelchairs would achieve a similar level of safety to those traveling in vehicle seats.

Throughout the project, the team engaged with people with mobility disabilities through the United Spinal Association, Ann Arbor Center for Independent Living, and Feonix Mobility Rising to better understand the needs and transportation challenges of people with mobility disabilities, and to ensure the system is usable and comfortable. In addition, the system was also evaluated through field testing with twelve volunteers who are daily wheelchair users.

This project demonstrated the feasibility of the system in AVs, addressing the challenges made by accessibility modifications posed by the hybrid architecture. While our focus was on AVs, the adaptive equipment could also be installed in traditional paratransit vehicles to improve safety and independence. Future research to demonstrate production feasibility would focus on installing the adaptive equipment in an autonomous shuttle and performing additional volunteer evaluations. This work would incorporate user feedback and further developments into the AWTORS as well as implementation on different vehicle platforms. Additional activities could include collaborations with our partners and wheelchair manufacturers to improve design, packaging, and usability, which could then be assessed by additional volunteers who travel in wheelchairs.

Technical Merit

Technical Approach

Introduction

People who remain seated in their wheelchair for motor vehicle travel require a system that secures the wheelchair to the vehicle and provides occupant protection. Such systems are commonly called Wheelchair Tiedown and Occupant Restraint System (WTORS). For this population to fully realize the promise of independent transportation when automated vehicles emerge on the market, a WTORS must be crashworthy for use in smaller vehicles (generally shorter than 25 ft long), able to be used without third-party assistance, and able to accommodate a wide range of wheelchair types. Current commercially available WTORS do not have these characteristics. A universal docking interface geometry (UDIG) and automatic seatbelt donning systems with potential to meet these characteristics have been developed through past research projects.

UDIG is a hardware interface definition for a docking system, an idea akin to a common trailer hitch geometry so that semi cabs and trailers are fully compatible across manufacturers. The UDIG geometry has been developed, defined, field-tested, and incorporated in standards (Hobson and van Roosmalen 2007; Klinich et al. 2022; Klinich, Manary, et al. 2021; Klinich, Orton, et al. 2021; van Roosmalen 2013; van Roosmalen et al. 2011; Schneider et al. 2008). Only the interface geometry is defined and it allows room for innovation as to how wheelchairs and docking systems can provide and interact with this geometry. The UDIG was a starting point for the design. It works for all types of wheelchairs: manual, power, as well as scooters. Compared to traditional docking systems that secure the wheelchair via a bolt-type attachment below the wheelchair, the location of the UDIG attachments behind the wheelchair eliminates the possibility of ground clearance problems commonly reported in the field. Previous work on UDIG has experimented with different securement designs, including one that deploys from the side of the vehicle, and determined frontal crashworthiness. University of Pittsburgh did a real-world deployment and usability testing. UMTRI recently completed an AWTORS project for the NHTSA where UDIG attachment hardware and UDIG vehicle anchors were tested with volunteers using a power and manual wheelchair (Klinich, Manary, et al. 2021). The hardware was also dynamically crash tested in frontal and side impact test conditions to assure safety performance.

Previous work shows that conventional wheelchair docking systems can take repeated tries to achieve engagement (Orton, van Roosmalen, and Schneider 2019; van Roosmalen, Ritchie Orton, and Schneider 2013). The seatbelt fit is often hindered by features of the wheelchair design, particularly the armrest. A previous UMTRI study of people using their wheelchair in privately-owned modified vehicles showed very poor seat belt fit and frequent misuse/nonuse. These problems were documented in vehicles specifically designed for one user. These same participants were fiercely attached to their independence and were willing to compromise their safety for transportation independence. The needs defined in that study shaped the design of an automatic seatbelt donning/doffing system. In the recent NHTSA AWTORS study, we developed a new version of the automatic seatbelt donning system and identified through modeling and dynamic testing belt anchoring geometries that provide good protection to different wheelchair occupant sizes.

Vehicle Selection and Modifications

The Ford Transit was selected as the platform for this project due to its similarity in size and shape to future shared AV platforms. The vehicle was converted to be electrically powered to also reflect the characteristics of future vehicles. In this vehicle (as well as most other electric vehicles), an array of batteries is located under the floor.

The team chose this ADA upfit configuration because all passengers can board from the side entrance, and the modular flooring allows the seating layout to be customizable. Previous work with designing accessible vehicles showed that riders who use mobility devices prefer to board from the sidewalk rather than having to get into the street to board a ramp behind the vehicle. The ADA upfit solution that was chosen has a sliding door on the passenger side of the vehicle with a lift that is stored on motorized tracks so that it can be moved into the doorway when needed, and stowed out of the way when not in use. The flooring, which has evenly spaced holes for anchoring cleats, allowed the team to not only test and experiment with different seat placements in the vehicle, but also provided an easy way for the UDIG and lap belt anchorages to attach to the vehicle. In the future, using this type of flooring could also allow for some vehicles in the fleet to have a UDIG attachment, some to use traditional four-point tie downs, and some to be reconfigured for maximizing the number of riders in a vehicle, without requiring any vehicles to be permanently modified.

Wheelchair Station Placement

Three factors dictated the placement of the wheelchair station within the Transit. As shown in the left photo of Figure 1, the vehicle modifications included installation of six longitudinal tracks with slots to allow reconfigurable installation of vehicle seats as well as traditional wheelchair tiedown hardware. Laterally, the wheelchair station must be centered within the first and sixth track to allow anchoring of seatbelt hardware in the first and sixth track while maintaining the minimum required 30 in clear space of width required for a wheelchair station.

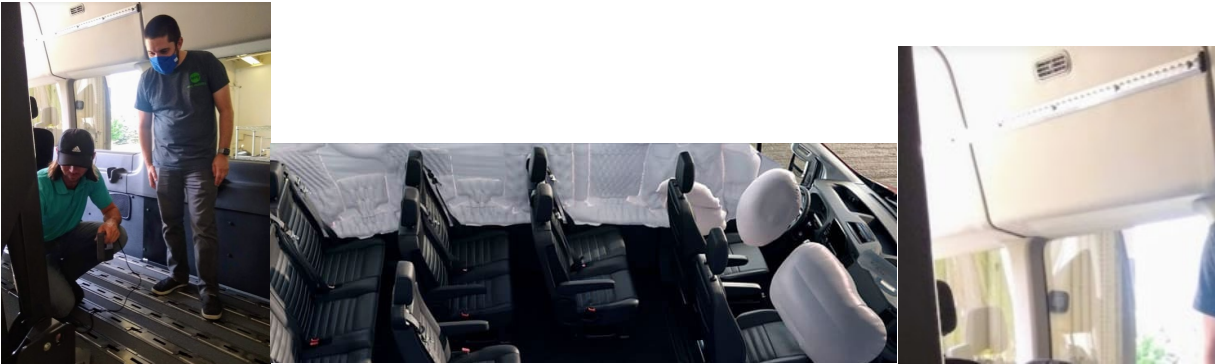


Figure 1. Location of six longitudinal floor tracks (left), photo of curtain airbag in Transit showing that it is not uniform along vehicle length (center), and closeup of upper hardware mounting track (right)

The fore-aft location of the wheelchair station needed to account for the location of occupant protection systems. As shown in the center of Figure 1 and Figure 2, the design of the side curtain airbag varies along its length. The wheelchair station was located so the occupant using a

wheelchair would be located in a similar position to an occupant using the second or third row of vehicle seats, to ensure that they would be located near a protective portion of the airbag. For the seatbelt anchors, our original intent was to mount the upper shoulder belt anchor point to the C- or D-pillar, but doing so would interfere with airbag deployment; the Transit's vehicle seats include integrated seatbelts to avoid this problem. Instead, a longitudinal hardware track was mounted above the window rearward of the D-pillar as part of the vehicle modification (seen on left and right side of Figure 1). This necessitated a "third row" wheelchair station to allow good placement of the shoulder belt anchor relative to the occupant in the wheelchair. This also had the benefit of allowing the wheelchair station a greater amount of clear space longitudinally.



Figure 2. Location of wheelchair station in ~third row relative to vehicle interior geometry.

Docking System Design

The design of the docking station for the IDC project was based on the previous designs developed by UMTRI for the NHTSA AWTORS study. The main changes were to make the anchors compatible with the available floor brackets and to improve packaging to allow a more integrated and polished appearance of the anchors. Our installation of the UDIG anchors needed to also allow use of four-point tiedown hardware to secure the volunteers' own wheelchairs during their test session.

Figure 3 (left) shows a closeup of the UDIG anchor hardware, while Figure 3 (right) shows how it is secured to the track using anchors. After the volunteer backs into the station until their wheelchair attachments are contacting the front surface of the vehicle anchor, the two hooks move outward to engage with the attachments and secure the wheelchair. The hooks operate with independent actuators so the person does not have to have their wheelchair attachments centered exactly relative to the hooks. So the system will still work if one anchor hook needs to move 10 cm and the other one 15 cm to engage with the attachments that are spaced 25 cm apart.



Figure 3. Closeup of UDIG vehicle anchors (left) and how it is secured to track with compatible anchors (right).

Wheelchair Selection and Attachment Design

In the previous NHTSA AWTORS study performed by UMTRI, the UDIG hardware was developed for a commercial manual and power wheelchair, which both met WC19 requirements for frontal crashworthiness. The attachments were connected to the wheelchair near crash-tested securement points that would be used to secure the wheelchair using a four-point strap tiedown system as required by WC19. Feedback from wheelchair users on the attachment designs included suggestions to make them look more integrated into the wheelchair design, as well as to minimize weight of the attachments for the manual wheelchair, because every ounce of extra weight can make a manual wheelchair harder to use. For the IDC, we purchased two different wheelchairs to allow demonstration of how to design UDIG-compatible attachments for additional commercial products.

Figure 4 shows the attachments designed for the Sunrise Quickie 2 manual chair and the Permobil F3 Corpus. For the Quickie attachments, we switched to using bent tubing which both minimized weight and improved appearance. The attachments are connected to the wheelchair below the crash tested securement points. The UDIG attachments do not interfere with either the anti-tip legs or use of the hooks to secure with strap tiedowns. The Permobil attachments were welded and then painted to improve appearance and account for the greater strength needed to secure the heavier power wheelchair. They were also connected to the wheelchair near the crash tested securement points, which can still be used to secure the wheelchair with tiedowns. As directed by the UDIG specifications, neither of the attachments extend beyond the most rearward point on the wheelchair. This is a UDIG requirement, because extra length would make wheelchairs more difficult to navigate.



Figure 4. Photos of the UDIG attachments for the manual wheelchair (left) and power wheelchair (right).

Seatbelt Geometry and Features

UMTRI's previous work with volunteers on the NHTSA AWTORS study evaluated multiple belt geometries and identified one set of anchorages that provided the best lap and shoulder belt fits across a range of volunteer sizes. This was identified as the target geometry for the Transit seatbelt system. The outboard lap belt anchor geometry was achieved by mounting a bracket of the appropriate height to the first longitudinal track at the desired fore-aft location. A similar inboard lap belt anchor was achieved through appropriate design of the donning arm length and height.

The modifications to the Transit included installation of an upper hardware track for mounting the shoulder belt anchor. The location of this track is intended to prevent interference with airbag deployment, but its location would place the shoulder belt anchor much higher than optimal as determined by our volunteer work in the NHTSA study. Instead, as shown on the left side of Figure 5, we mounted an aftermarket height adjuster between the mounting track and floor that placed the shoulder belt D-ring closer to the targeted location. We secured D-ring hardware at the appropriate height and mounted the shoulder belt retractor to the top of the UDIG anchor station (Figure 5, center).

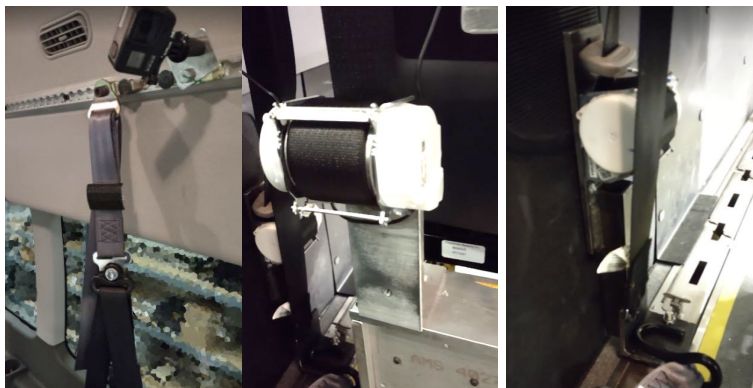


Figure 5. D-ring attached to belt anchored at top track and floor (left), shoulder belt retractor secured to top of UDIG anchor (center), outboard lap belt anchor (including retractor) mounted to floor track (right).

To allow navigation of the wheelchair around the seatbelt held forward by the donning arm, we needed an extra-long seatbelt. The NHTSA AWTORS installation used a single retractor at the shoulder belt with the strongest spring tension available commercially, but because of the extra seatbelt length, it was not strong enough to fully retract the seatbelt into the retractor without the volunteer feeding in the slack. To address this issue for the IDC, we decided to use a dual retractor system, with one retractor mounted to control tension through the D-ring and the second as part of the outboard lap belt anchor as shown in the center and right of Figure 5.

Automated Donning Arm Design

A previous research study developed a prototype donning arm that held the belt out of the way as the occupant navigated into the wheelchair station, then rotated to the floor where it was anchored with a latch mechanism (Weir et al. 2011). As the arm rotated, it placed the lap belt in position over the occupant's pelvis. An iteration of the donning arm was evaluated in the NHTSA AWTORS project, with several different geometric configurations evaluated to identify which geometry provided the best belt fit across a range of subjects, as well as how to locate the donning arm to maximize maneuverability into the wheelchair station.

For the IDC, we designed a donning arm so it could be placed near the driver's seat to maximize room for maneuvering into the wheelchair station. The geometry of the inboard anchor is similar to the outboard anchor geometry to provide a symmetric belt fit. An actuator mounted above the base of the donning arm allows the occupant to control donning and doffing of the seatbelt. The donning arm latches into hardware that locks the arm and seatbelt in place for travel. The vertical structure on the lock hardware helps guide the arm into the correct location to allow locking, even when the belt tension pulls the arm towards the occupant. A backup manual mechanism was provided to release the lock should the powered controller release not function properly.

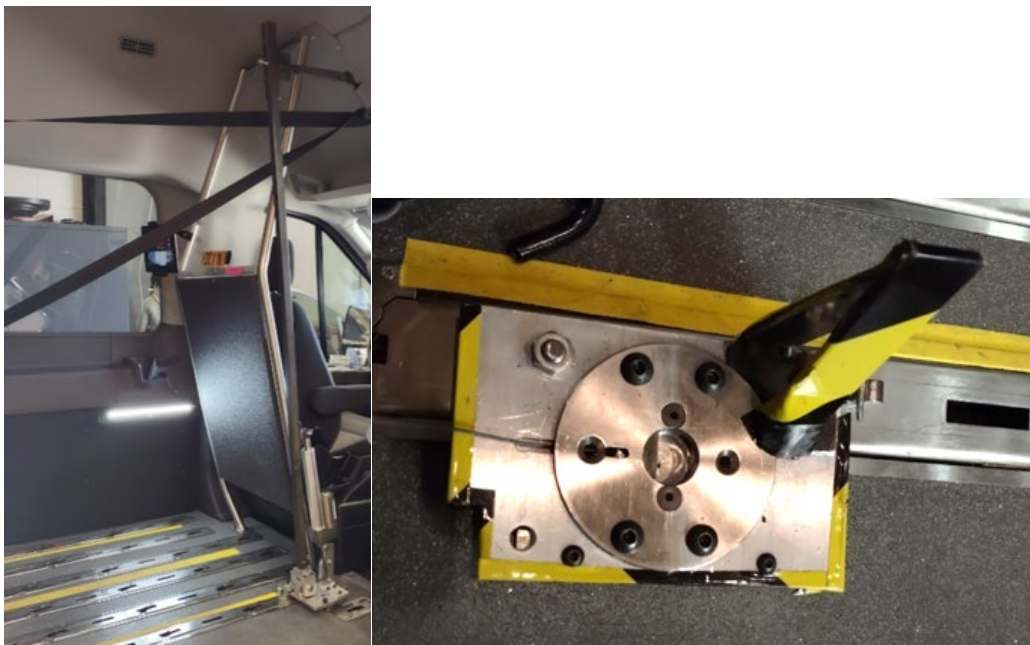


Figure 6. Automated donning arm located near driver seat holds the belt out of the station before deployment (left), and hardware to lock the arm in place once deployed (right).

Wheelchair Crash Testing

After volunteer testing was completed, we performed frontal crash tests of the two wheelchairs used with volunteer testing and equipped with UDIG-compatible attachments. Procedures were based on those from the voluntary RESNA wheelchair safety standard, WC19. WC19 assesses the wheelchair's ability to perform the functions of a motor vehicle seat by evaluating crashworthiness, compatibility with seatbelt systems, and ease of securement. The main focus of these tests was to determine if the add-on UDIG hardware could sustain crash loads and if the wheelchair compliance with WC19 was altered by the addition of UDIG attachments, since the wheelchairs initially complied with WC19 requirements when secured with a four-point, strap-type tiedown system.

The frontal crash test of WC19 is of similar severity to the frontal crash test used in the federal safety standard to test child safety seats. For these tests, a midsize male Hybrid III crash test dummy (the same dummy used in frontal testing of vehicle seats) represented the wheelchair occupant. The wheelchair was secured with UDIG and the occupant was protected with a three-point lap+shoulder belt that was fully anchored to the vehicle, to best replicate the configuration in the test vehicle. The impact performance of the wheelchair is evaluated on eighteen pass/fail criteria. Appendix A contains sets of photos illustrating kinematics of the wheelchair and ATD during impact loading, as well as a summary sheet of the crash performance criteria required by WC19. Both wheelchairs equipped with UDIG met all requirements. The tests also allowed measurement of the restraint forces applied to the wheelchair through the UDIG fixture that can be helpful for wheelchair designers who are trying to implement UDIG. These tests demonstrate the viability of designing add-on attachments for two additional commercial wheelchair products.

Team/Expert Consultation

AV manufacturers have recognized that to allow independent AV use by people who travel while seated in wheelchairs, they should consider their needs at the beginning of the vehicle design process. Manufacturers have also realized that standardizing an approach to secure wheelchair users in AVs would be more useful than each manufacturer developing their own solution, and would benefit wheelchair-seated travelers by providing hardware that works across transportation options. In 2019, the Alliance for Automotive Manufacturers and Volkswagen both hosted workshops to discuss how AVs could be accessible for people with disabilities. Three UMTRI team members were able to participate in these meetings. Key stakeholders that met represented government agencies, wheelchair manufacturers, vehicle manufacturers, disability advocates, adaptive equipment manufacturers, and consumer organizations. Many of the participants had personally experienced transportation challenges due to lack of accommodations for mobility disabilities and expressed the need for easy-to-use, on-demand transportation. The main recommendation from these workshops was that a collaborative effort among all stakeholders, including potential users of new technologies, would be needed to accomplish the goal of designing accessible AVs. The UMTRI team members used the feedback received to develop prototype AWTORS that were installed in two static laboratory vehicle mockups that were assessed by nine volunteers who are regular wheelchair users. Their feedback resulted in design modifications and some initial guidelines for locating wheelchair seating stations equipped with the AWTORS within the IDC vehicle to improve access and usability.

The Ann Arbor Accessible Automation (A⁴) team was led by researchers at the University of Michigan Transportation Research Institute (UMTRI) and May Mobility, an automated vehicle company headquartered in Ann Arbor. May Mobility team members brought expertise in developing automated vehicles to the project; they have had pilot deployments in eight cities to date, including Ann Arbor. Their company places a high priority on ensuring accessible vehicles in their AV fleets. In addition to the prototypes developed through the recent NHTSA-sponsored AWTORS project, the UMTRI team members bring decades of expertise in occupant protection strategies, as well as expertise in wheelchair transportation safety issues gained through multiple research projects and standards development efforts in the field.

May Mobility has engaged in wheelchair accessibility testing and deployment at its existing and previous routes in Ohio, Rhode Island, and Michigan. Prior to the current project, May Mobility staff participated in the following activities:

- Attending disability awareness training facilitated by Feonix-Mobility Rising, to understand the needs and constraints of travelers with disabilities
- Conducting three in-field testing sessions of their wheelchair ramp and securement system
- Ongoing in-house testing of their existing wheelchair ramp and manual securement system
- Obtaining user feedback that highlighted that the need for improvement of May Mobility's safety operator training in wheelchair securement.

Additionally, May Mobility and UMTRI held a feedback session with members of United Spinal that focused on our original Inclusive Design Challenge proposal. The feedback received was generally positive, but did highlight areas of improvement for the team to focus on during the challenge. Specific feedback related to the fact that not all wheelchairs are crash tested and therefore may not meet the current design requirements for the automated lap belt, and general concern about added weight and reduction in turning radius associated with adding additional hardware to wheelchairs. The team continued our engagement with United Spinal members during the Challenge and incorporated strategies to address these issues during the volunteer testing phase.

On a quarterly basis throughout the project, May Mobility and UMTRI hosted virtual meetings with the team's advisors from United Spinal Association, BraunAbility, Feonix-Mobility Rising, and the Ann Arbor Center for Independent Living (AACIL). During each meeting, the group discussed project updates, showed progress on technology and testing, and solicited feedback from the advisors, several of whom are wheelchair users. These meetings were helpful and essential communication points to make sure the project goals were on track, the advisors were informed of progress, and advisor feedback was collected and implemented.

On December 6, 2021, the project team hosted a focus group made up of experienced paratransit drivers to give feedback on what the project team had done to date. We were able to get their perspective as seasoned service providers in this space, who have a deep reservoir of knowledge and experience of the nuances of wheelchair placement and securement as well as appropriate use of seatbelts with wheelchair users. Drivers from transit agencies in Minnesota, Nevada, and Michigan traveled to Ann Arbor to get an overview of progress so far, a shop and vehicle tour, a

live demonstration, and a feedback session. It was extremely helpful to get their perspective as we went into volunteer testing with wheelchair users. The drivers came from the following transit agencies: WAVE in Ann Arbor, RTC Washoe in Reno, Arrowhead Transit outside Minneapolis, and SMART in Detroit. They had the opportunity to try the docking and donning systems. There was a feedback session after the demonstration and system testing, where the drivers suggested better marking of the wheelchair station and ramp. They also thought the system had potential for improving independence in current paratransit vehicles and buses, as well as future AV applications.



Figure 7. Paratransit drivers and members of Team A⁴ team evaluate and provide feedback on the prototype installation.

User-Centered Design and Desirability

User Interface

The docking and donning systems each have separate controls, shown in Figure 8. The wiring was hidden below the vehicle packaging, and the location of the controls was placed based on recommendations for reach from the University of Buffalo Wheelchair Anthropometry Study (Steinfeld et al. 2010). If needed, there is extra stowed wire so the controls can be pulled out and moved closer to the occupant. The buttons to control the docking actuators were modified with soft raised cylinders that could be operated with a fist rather than fingers if needed. The rocking control button of the donning arm can also be operated with a fist, making both more accessible to a wider range of users.



Figure 8. Controllers for UDIG anchors and donning arm.

Based on feedback from our paratransit drivers, we marked the edges of the wheelchair station as well as the centerline with contrasting tape to help the user navigate the wheelchair into the station. Based on a suggestion from an advising wheelchair user, we also placed a contrasting centerline on the lift. Both are shown in Figure 9.



Figure 9. Wheelchair station edges and centerline (left) and ramp centerline (right) marked with contrasting yellow tape.

Two streaming video cameras were placed to facilitate navigation of the wheelchair into the station. One is an overhead view of the docking station, which displays to a screen on the back of the driver's seat as shown in the left side of Figure 10. This allows the user to see how the rear attachments are lining up relative to the UDIG anchor hooks. LED lights located on the top of the UDIG anchor station are visible through the camera as well; they are wired to shut off when the anchors are fully engaged with the attachments. Having the lights go off to indicate engagement, rather than on, helps illuminate the anchor area and improve visibility as well as providing confirmation of engagement. The second streaming video shows an overhead view of the wheelchair station and ramp entry. As shown in the right side of Figure 10, the screen is located on the back of the right-front passenger seat so it is visible to the occupant as they enter the station from the lift.



Figure 10. Screen mounted behind driver seat shows top view of UDIG vehicle anchors to assist passenger in aligning and docking their wheelchair (left), and screen mounted on front passenger seat showing path from lift to wheelchair station (right).

Volunteer Testing Methods

To demonstrate that our vehicle and components functioned as intended, we performed testing to evaluate the usability and acceptability of new prototype automated wheelchair-securement and occupant-restraint concepts with volunteers who are regular wheelchair users. Testing involved participants going for a short ride in our wheelchair-accessible electric vehicle while seated in specially equipped wheelchairs. We determined whether subjects could enter the wheelchair passenger space and engage the prototype UDIG docking securement system as well as, or better than, current docking systems, using both manual and power wheelchairs. In addition, we evaluated how quickly subjects can use controls to don and doff the prototype automated seatbelt systems. We measured the quality of the lap and shoulder belt fit for the belt system. We also received volunteer feedback regarding the ease of use, comfort, and perceived safety of the system and vehicle after a short ride in the vehicle.

To participate in our study, subjects were required to be 18 years or older, regularly use a wheelchair, not be pregnant, be able to transfer to our study wheelchairs and be picked up from a location within 20 minutes of UMTRI. Test sessions lasted up to 3 hours, including travel time to/from their home, and subjects were paid \$40 to participate. All protocols were approved by the University of Michigan Institutional Review Board. Subjects were recruited through the University of Michigan volunteer site, umhealthresearch.org, as well as through virtual and actual posting of subject recruitment flyers.

Participants were picked up at their home or location of choice by the study team. The Transit was also equipped with traditional 4-point strap tiedown securement system that was used to secure the volunteer's own wheelchair for travel to UMTRI. The Transit was parked on the road at the end of the participant's driveway. When the study team arrived at the volunteer's home, the subject was given a written description of what the study involves and signed a written consent to participate. The experimenters photographed the Transit near the pickup point and documented sloped driveways and any other potential barriers to pick up at the home.

The volunteer approached the vehicle in their wheelchair, with the experimenter assisting if needed. Using the deployed lift, the volunteer entered the vehicle and maneuvered to the wheelchair seating station. The volunteer was given a choice to ride in their own wheelchair or to transfer to a modular vehicle seat. If they chose to ride in their own wheelchair, the experimenter secured the wheelchair using a four-point strap tiedown system, and the volunteer deployed the automatic belt donning system. If they chose to transfer, the volunteer was required to wear the seat-integrated vehicle seatbelt, and their wheelchair was secured in the back of the Transit. The volunteer's ingress and egress to the vehicle, as well as their efforts to maneuver to the wheelchair station, were documented with video cameras focusing on the wheelchair station and the doorway. After arriving at the UMTRI lab, the volunteer removed the seatbelt, the experimenter removed the tiedowns, and the volunteer transferred back to their wheelchair if needed. The volunteer then exited the vehicle using the lift.

The experimenter then instructed the volunteer on where to apply reference target stickers to visible portions of their body to display approximate locations of the elbows, sternum, clavicles, hips, knees, chin. This was done to help determine anatomical landmarks when estimating posture using photos and scans of the volunteer. We took front and sideview photos of the volunteer in front of a reference grid and recorded their 3D posture with a Kinect camera measurement tool. The photographs allow estimation of key body dimensions while minimizing

close contact between investigator and subject. Collecting the posture with the Kinect will allow us to create avatars with realistic posture and shape that can be used in computer models to design better wheelchair stations.

The next step was to show the volunteer a video on operation of the UDIG system and donning arm. The volunteer then transferred to one of two study wheelchairs, one manual and one power, that were equipped with UDIG attachment hardware. Photos and Kinect camera measurements were again taken in front of the reference grid. After some practice in the lab maneuvering the wheelchair, the volunteer entered the vehicle using the lift, and maneuvered to the wheelchair station. They then backed into the wheelchair station until the UDIG attachments on the wheelchair were lined up with the UDIG anchors in the vehicle and used the controls to engage the anchors with the attachments. They then used the controls to operate the automated belt donning arm to deploy and lock the seatbelt. The volunteer, driver, and experimenter went on a 10–12-minute ride on a route close to UMTRI.

Upon return to UMTRI, the experimenter took photos of the volunteer in the vehicle, as well as recorded their 3D posture using a handheld Sense measurement tool. The scan was recorded by holding the handheld device about a foot away from the volunteer and wheelchair and moving it around to capture images of the surfaces. The photos and Sense scans allow us to digitize points on the seatbelt and quantify the quality of belt fit while minimizing close contact. We can also estimate dimensions and shapes of wheelchair components from these data.

Next, the volunteer exited the vehicle, and filled out a Qualtrics survey regarding their experience. Questions include ease of use of UDIG securement and donning arm, comfort of seatbelt, comfort during ride, and feeling of security with UDIG system. The purpose of this survey was to identify how the volunteer thinks the system is working. The process was then repeated for the second study wheelchair. Afterwards, the volunteer filled out a different survey regarding their general travel experiences (Wheelchair Volunteer Questionnaire) and a race/ethnicity form.

The volunteer then transferred to their own wheelchair, and used the lift to enter the vehicle. Once they were secured in the 4-point tiedown system or transferred onto the vehicle seat and donned the occupant restraint, we took the same set of photos and 3D measurements. The participant then filled out the forms to receive payment, and the experimenter and driver returned the volunteer to their pickup location.

Functions as Intended

Volunteer Testing Results

The table below shows the characteristics of the 12 volunteers who participated in our study. Seven of the volunteers transferred to a vehicle seat for the ride to UMTRI, while five rode in their own wheelchairs secured by 4-point strap tiedowns.

Table 1. Summary of volunteer characteristics.

ID	Gender	Age	Height (in)	Weight (lb)	BMI	Type of wheelchair	Reason for wheelchair use
IDC01	W	41	63	153	27.1	Manual	Spinal cord injury
IDC02	W	52	62	191	35.0	Manual	Knee surgeries, back pain, osteoarthritis
IDC09	M	61	69	158	23.3	Manual	Paraplegia
IDC11	W	51	64	270	46.5	Manual	Right foot and ankle amputee
IDC12	M	27	66	125	20.2	Manual	Spina Bifida
IDC13	W	69	66	345	55.7	Power	Blood clot disorder in lower left leg, ankle, and foot.
IDC16	M	75	65	146	24.3	Manual	Above knee amputation
IDC20	M	70	62	206	37.7	Manual	Foot operations on both feet
IDC21	M	63	73	256	33.8	Power	Multiple Sclerosis
IDC22	W	70	70	125	18.0	Power	Multiple Sclerosis, knee and back issues
IDC23	M	64	71	214	29.9	Manual	Spinal cord injury
IDC24	M	29	75	158	19.8	Manual	Spinal cord injury

Photos illustrating the range of belt fits seen with the power wheelchair among participants are shown in Figure 11, while results in the manual wheelchair are shown in Figure 12. About half of the volunteers had acceptable belt fit, with the shoulder belt centered on the shoulder and lap belt located below the top of the pelvis. Like we see in belt fit studies of the general population, volunteers generally have better belt fit with lower BMI. Volunteer 23 had the lap belt positioned too high over his abdomen, because of his curved spinal posture resulting from his medical condition. Volunteer 13, our volunteer with the highest BMI, was unable to route the belt properly under the wheelchair armrests and her arm with the power wheelchair, and was unable to perform a trial using the manual wheelchair. The participants with the belt routed more over the abdomen did not route the shoulder belt under the wheelchair armrest as recommended.

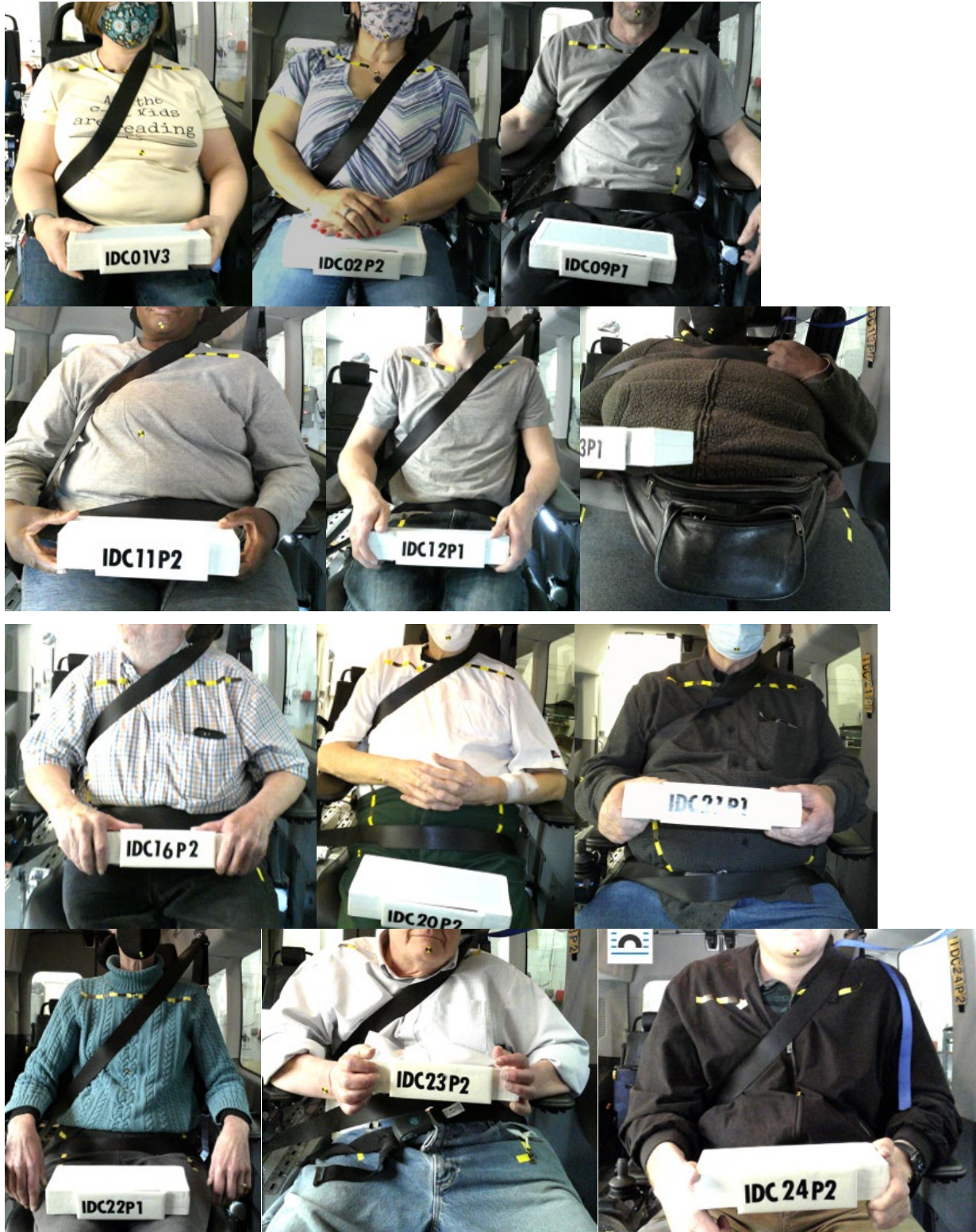


Figure 11. Illustration of participant belt fit in power wheelchair

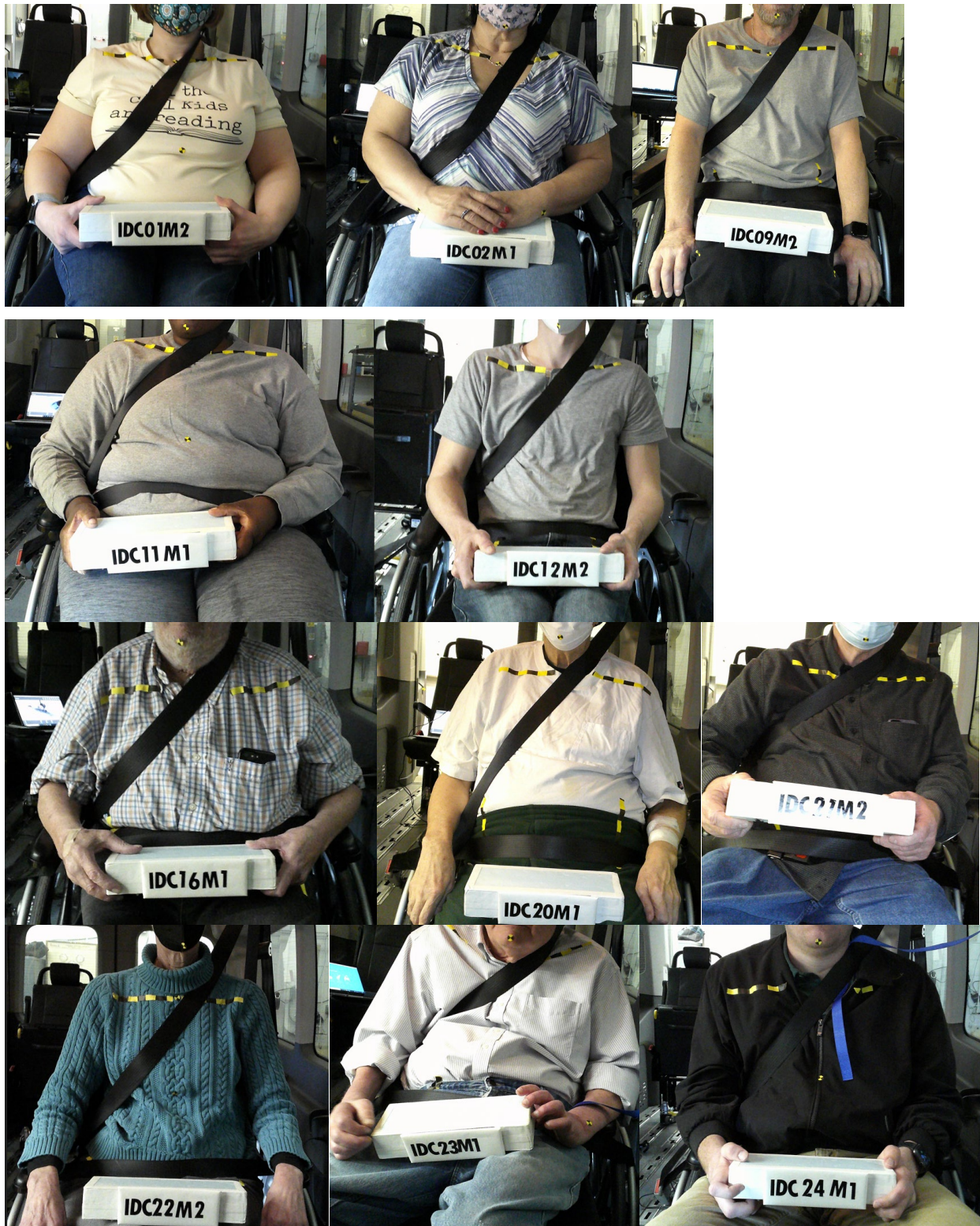


Figure 12. Illustration of participant belt fit in manual wheelchair

A plot of shoulder belt score vs. participant BMI is shown in Figure 13, including scores for those who transferred to a vehicle seat (T) instead of traveling in their own wheelchair (V) as well as manual (M) and power (P) wheelchairs. Shoulder belt score is the horizontal distance between the top of the occupant’s sternum and the inside edge of the shoulder belt (Reed, Ebert-Hamilton, and Rupp 2012); yellow lines mark the range where the belt score located the belt appropriately on the shoulder. None of the participants had shoulder belt position too far outboard on the arm, which is a common occurrence in paratransit vehicles using the vehicle mounted D-ring position, indicating that our shoulder belt location prevented this type of poor belt fit. However, many participants had the belt too close to their neck. Trendlines show that belt fit becomes more inboard with increasing BMI. For lap belt fit shown in Figure 14, lower scores are better, while 3 or less is acceptable. Lap belt was too high in 8 of 31 trials and also showed the trend of worse fit with higher BMI across all conditions. Lap belt fit was better in the power wheelchair compared to the manual wheelchair. The recommended sideview lap belt angle is 45 to 75 degrees relative to horizontal. Across all trials, the mean value was 46 degrees, with a range of 34 to 56 degrees; the angle was below 45 in 13 out of 28 wheelchair trials.

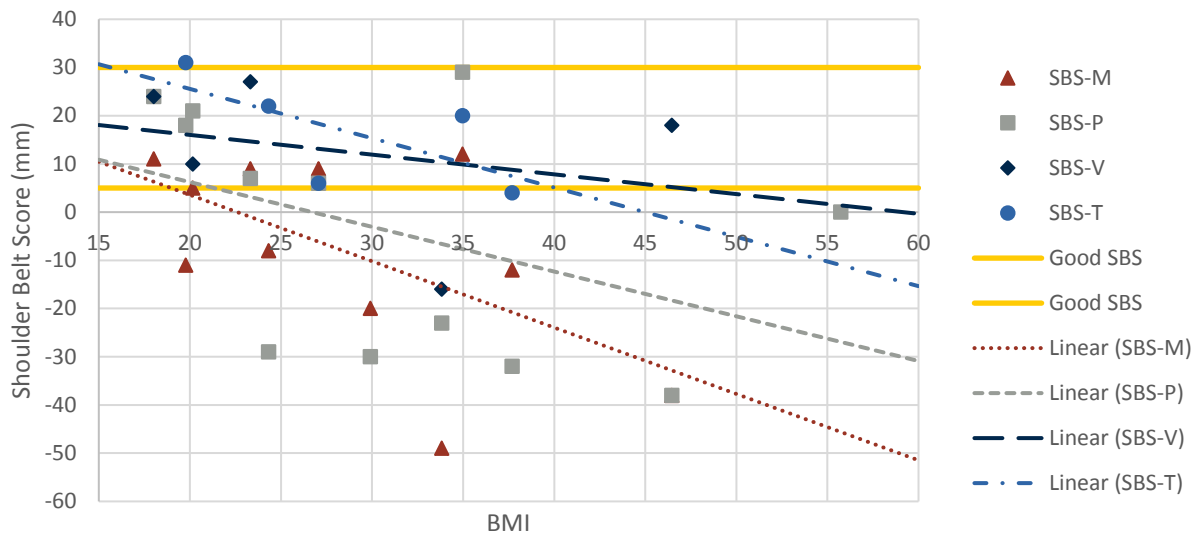


Figure 13. Shoulder belt score vs. participant BMI.

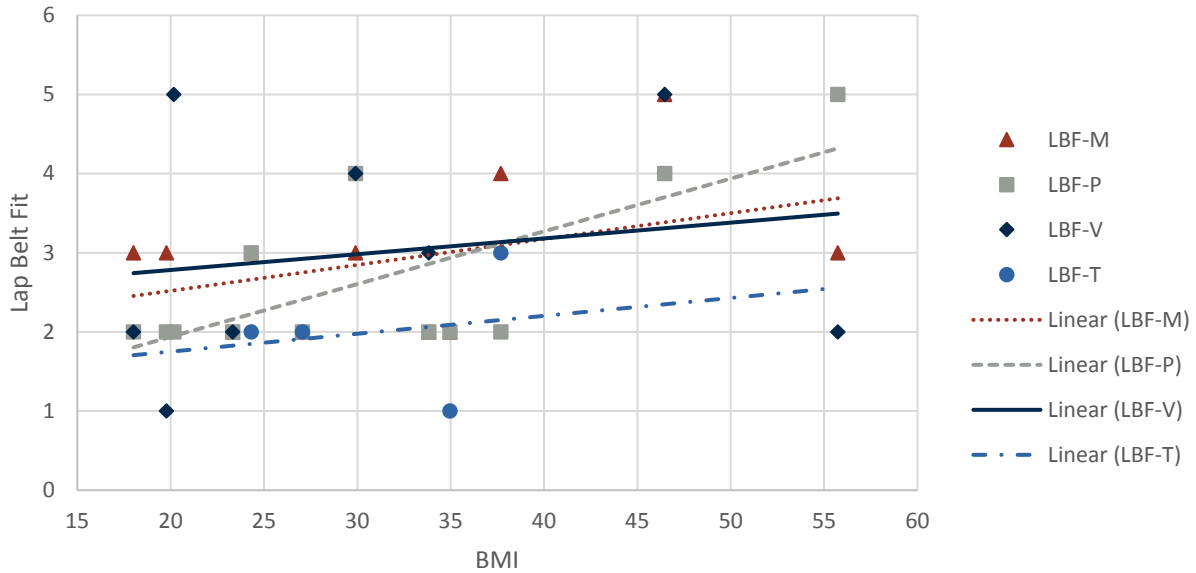


Figure 14. Lap belt fit vs. participant BMI.

An analysis of time duration for each task for the power wheelchair trials is shown in Figure 15. Average entry time was just over 2 minutes to navigate, 12 sec to dock, and 50 sec to don the belt for a total average time of just over three minutes. For exiting, average doffing time was 36 seconds, undocking 5 seconds, and exit navigation just over a minute for a total average exit time under two minutes. If all participants could perform all tasks as quickly as the fastest volunteer, minimum total entry time would be just over a minute for each, plus lift time. Results for the manual wheelchair are shown in Figure 16. Overall, they were faster than the power wheelchair because more of the participants were regular wheelchair users. Mean entry times for navigation, docking, and donning were 48, 10, and 30 seconds, respectively, for a combined mean time of 89 seconds. The mean exit times for doffing, undocking, and navigation were 30, 5, and 26 seconds, respectively, bringing the combined mean time to 61 seconds. The fastest combined time across volunteers would be 41 seconds for entry and 40 for exit.

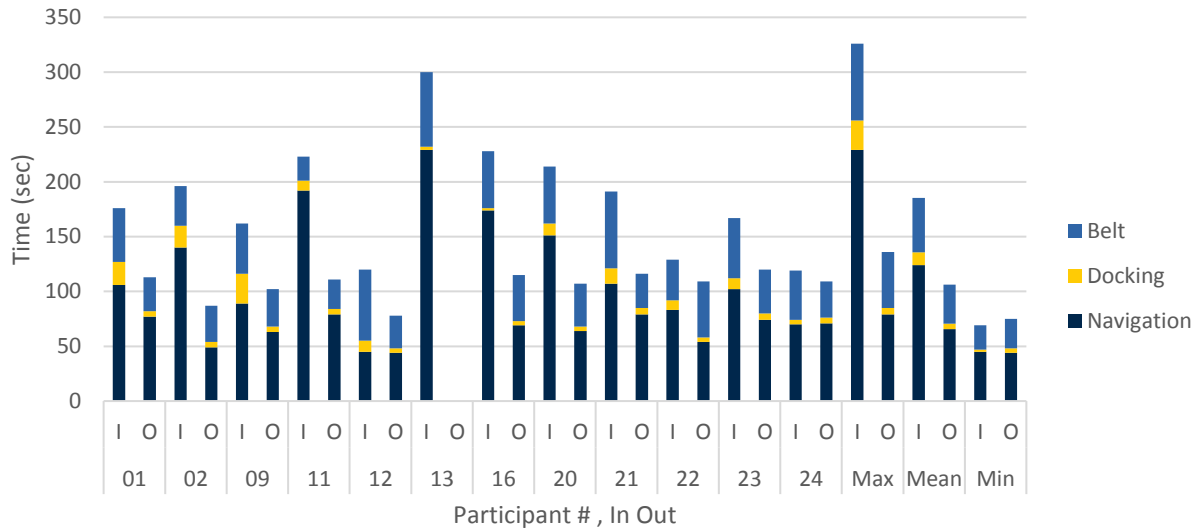


Figure 15. Summary of power wheelchair task durations for going in (I) and out (O) of the vehicle by participant, plus, mean, minimum, and maximum times.

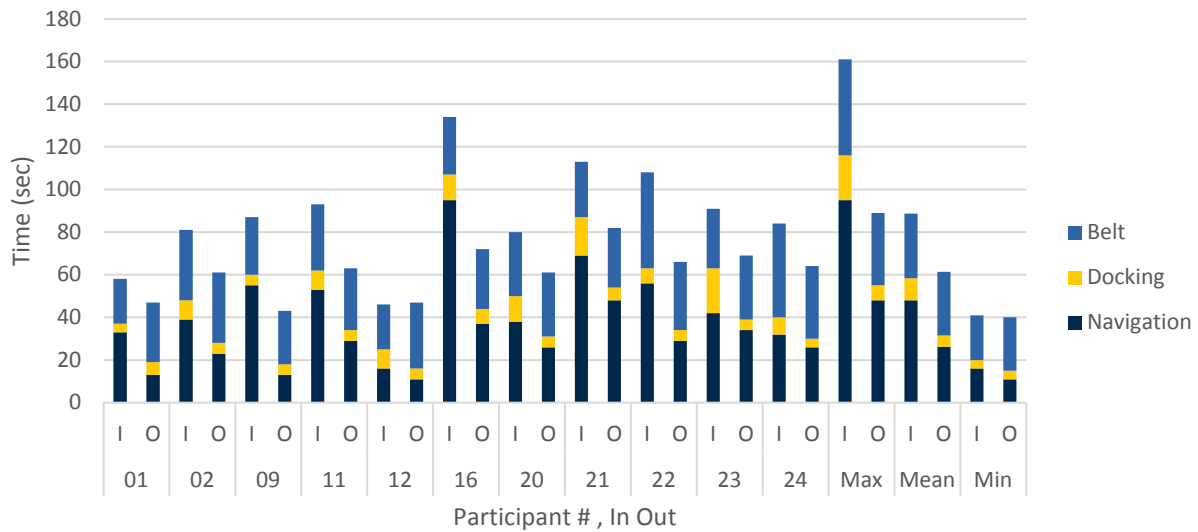


Figure 16. Summary of manual wheelchair task durations for going in (I) and out (O) of the vehicle by participant, plus, mean, minimum, and maximum times.

When reviewing the videos of the power wheelchair trials, all volunteers entered the vehicle rearward on the lift, and only one had problems maneuvering around the seatbelt on entry, where the belt caught on the seatback. Participants moved forward to align in the station an average of 5 times, with a range between one and nine. However, only one person needed to shift again to reposition themselves after they tried docking the wheelchair. Most of the participants helped guide the belt away from their face and routed it under their armrests as it was donning. Upon exit, the belt usually caught on the wheelchair seatback or armrests as it was being removed, and all participants helped move the belt. Navigation out of the station was easier on exit, with an average of two times moving forward to exit to the ramp. For the trials with the manual chair,

two of the volunteers entered the lift facing forward, while the rest were rearward. Volunteers moved forward to align in the station an average of 2 times, with a range between 0 and 5; three volunteers lined up on the first try without moving forward to align. Two participants needed to shift slightly after they tried docking. During entry, the shoulder belt caught on the wheelchair push handle for several participants, and during donning, the belt caught on the armrest or handle for four trials. As with the power chair trials, most participants held the belt away from their faces as it was donning, helped route it under the armrests, and snugged the belt once it was applied.

Appendix B contains plots summarizing the post-trial survey responses of the volunteers. When asked about the feeling of security once docked, over 80% of manual trials and almost 60% of power trials were excellent, with most of the remainder good. For the ability to use the docking system without help, ratings were better for the manual chair compared to the power chair, but the rating was “could be better” in fewer than 20% of trials. When comparing ease of maneuvering each wheelchair to their own, about 2/3 of power trials indicated varying degrees of more difficulty, while 40% of manual trials were more difficult than their own wheelchair. When asked how difficult to navigate into the station compared to other securement systems, 58% of power trials and 9% of manual trials indicated it was more difficult to use UDIG. When asked about the ease of lining up with the UDIG anchors, 90% of manual trials rated good or excellent compared to 67% of power trials.

When asked whether they would recommend the docking system to a friend, the average rating was 7.9 out of 10, with a range from 4 to 10. When asked whether they would recommend the seatbelt system to a friend, the average rating was 7.6 out of 10, also with a range of 4 to 10.

Our test procedure involved picking volunteers up from their homes. Our strategy to allow lift operation was to pull the vehicle parallel to the participants’ driveways. We were able to successfully transport all of the participants. Figure 12 shows some examples of the pickup locations, including the steepest driveway, one without a curb cut, and a pilot test with an icy driveway.

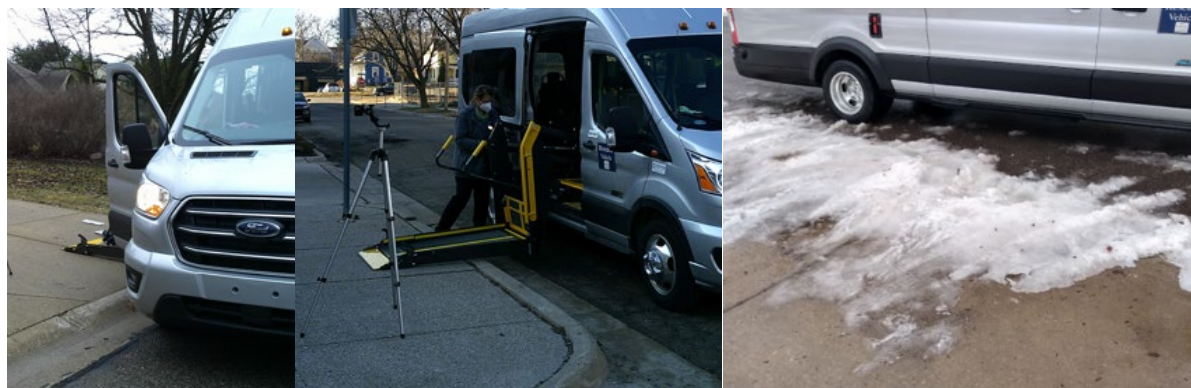


Figure 17. Examples of more challenging pickup locations.

Discussion

Reviewing the general comments shared by volunteers, many of them noted that they were happy we were doing this type of research, and they loved the idea of an independent ride in the future. In the post-test survey, several expressed a strong preference for a ramp rather than a lift to access the vehicle.

All participants were able to successfully dock the wheelchair in all trials. People had more difficulty navigating the power wheelchair compared to the manual wheelchair. This may be due partly to the longer length of the power wheelchair, and that only three participants had previous experience with power wheelchairs. There were a few instances of difficulty navigating the wheelchair around the floor anchor for the donning arm, which could be addressed by a recessed anchor design in future iterations. Several commented that they liked the forward tablet placement showing when the anchors were engaged, as well as the lights going off to confirm.

With the seatbelt, the main challenge was that many participants had the shoulder belt routing too close to their face as it was donning, as well as catching on wheelchair armrests. Almost all participants manually assisted with routing of the belt as they donned it, which may not be possible for someone with a more severe disability. The initial testing of the donning arm in the AWTORS project only used one seatbelt retractor, and that provided insufficient tension to snug the belt around the occupant. For the IDC installation, we tried to correct the issue by using two retractors for the seatbelt webbing, which had the consequence of the belt being pulled too tightly as the belt was donning. Future efforts can vary the spring tension of the retractors so they snug the belt with less interference during donning. Another challenge with the belt donning is that some volunteers had trouble getting it to go under the wheelchair armrests. Future efforts will evaluate the placement of the donning arm to balance between allowing more space to maneuver and providing geometry that is more effective at donning the belt without assistance, as the shorter donning arm used in the AWTORS study had fewer interference problems.

Production Feasibility

Path to Production

A barrier to deployment of the UDIG system in AVs is that wheelchairs need to have specialized attachment hardware to use the system. Over the past four years, the UMTRI team has successfully designed add-on UDIG-compatible attachment hardware for five different commercial wheelchair models. Providing wheelchair manufacturers with expertise and resources to develop UDIG-compatible attachments for more products would make UDIG-compatible docking a more viable solution for AVs (as well as traditional buses, paratransit vehicles and potentially future aircraft).

Future research should involve collaboration with one or more wheelchair manufacturers to develop options for add-on UDIG-compatible attachments on additional products. Currently, people who want to drive or ride in modified vehicles independently while seated in their wheelchair need to have a docking bolt added to their wheelchair to allow safe and independent securement to a floor-mounted docking station. Until UDIG-compatible wheelchairs are more widely available, people who want to travel independently in AV shuttles will need to have a UDIG-compatible attachment added to their wheelchair to allow safe and independent securement to a vehicle-mounted UDIG anchorage. These development efforts should include volunteer evaluation and crash testing of additional wheelchair models with more refined UDIG-

compatible attachments. A priority will be to incorporate the wheelchair attachments, so they are less obtrusive and of minimal weight, because every extra ounce added to a manual wheelchair makes use more difficult.

Testing and Deployment Approach

Our successful completion of Stage II Inclusive Design Challenge activities demonstrated the feasibility of installing UDIG-compatible hardware and a seatbelt donning system, as well as a lift, on an electric vehicle. The project vehicle shares features with the AV shuttles under development by May Mobility, including an array of batteries located beneath the floor and similar interior cabin space restrictions. Usability evaluations by regular wheelchair users have identified potential areas for improvement.

Potential future research activities include further laboratory assessment of the viability of the seatbelt donning system through evaluation by volunteers seated in their own wheelchairs. Concerns include how the seatbelt could be routed around armrests, whether there is enough space to maneuver into position without interference from prepositioned belts, and whether the belts can catch on wheelchair components or accessories as they were being positioned.

Impact: Intuitive, Inclusive, Beneficial

In our volunteer testing, participants were shown a short video on how the UDIG docking system works before their test session began. All of the participants were able to successfully dock their wheelchair, often on the first try. In our IDC project, we mounted an overhead camera on the anchors, with a forward display visible to allow the occupants to see their attachments as they were navigating into position. The indicator lights turned off when the anchors were engaged and provided effective indication of successful docking. These two user interface techniques seemed to improve docking success compared to the AWTORS study where they were not available. We believe that these results from the volunteer testing where minimal training was provided indicate that the system is useful. All participants were also able to operate the donning arm.

The system is inclusive because UDIG attachments can be designed for all types of wheeled mobility devices: manual wheelchairs, power wheelchairs, and scooters. Locating the attachments on the back of the wheelchair prevents ground clearance issues commonly seen with docking systems that use a hardware hanging below the wheelchair. In addition, since it may be some time before UDIG attachments are widely available, we demonstrated that the wheelchair station could also be equipped with anchors for 4-point strap tiedowns, and a person using a wheelchair could be secured with this method without interference from the UDIG anchors. The seatbelt donning arm successfully applied the seat belt to protect people in their own wheelchairs even when secured by 4-point tiedowns as long as their wheelchairs had armrests that allowed access of the lap belt to the pelvic area. When this was not the case, the belt could be unbuckled and routed through the armrests appropriately. Future versions of the system may include voice control and audio indications to confirm proper securement and occupant restraint for those with low or no ability to see.

For people with disabilities who do not drive, AVs would provide a welcome opportunity for independent, on demand travel. AVs must be designed with accessibility in mind. The lack of a human driver in autonomous vehicles creates many gaps in the trip journey that are not addressed by solutions on the market today. Wheelchair securement is among the most complex aspects of an AV trip and will require much collaboration between AV manufacturers,

regulators, and wheelchair manufacturers to agree upon safe standards. Having a uniform type of independent docking system, such as the UDIG already defined in voluntary standards, would be a better option than each AV manufacturer developing their own wheelchair securement approach.

According to the American Community Survey (ACS), 6.9% of people in the US report having an ambulatory disability, which increases rapidly with age (Erickson, Lee, and von Schrader 2019). In the 2017 National Household Travel Survey, 25.5 million people over age five report disabilities that limit their ability to travel (Brumbaugh 2018). Of these, 11.6% use a manual wheelchair, 3.9% use power wheelchairs, and 4.4% use scooters, indicating that about 5 million people use wheeled mobility devices in the US. Technologies developed for use in automated vehicles can benefit these individuals, as well as their families and caregivers. In addition, the technologies developed to provide AV solutions could also be used in traditional paratransit vehicles, buses and even aircraft to allow safer and more independent travel by people who remain seated in their wheelchairs for travel.

References

- Hobson, Douglas A., and Linda van Roosmalen. 2007. "Towards the next Generation of Wheelchair Securement—Development of a Demonstration Udig-Compatible Wheelchair Docking Device." *Assistive Technology* 19(4):210–22. doi: 10.1080/10400435.2007.10131878.
- Klinich, Kathleen D., Miriam A. Manary, Kyle J. Boyle, Nichole R. Orton, and Jingwen Hu. 2021. *Development of an Automated Tiedown and Occupant Restraint System for Automated Vehicle Use*.
- Klinich, Kathleen D., Nichole R. Orton, Joshua Fischer, and Miriam A. Manary. 2022. *Volunteer Evaluation of Wheelchair Accessibility in Vehicles*.
- Klinich, Kathleen D., NR Orton, L. Malik, E. Zak, M. St. Amour, and MA Manary. 2021. *Volunteer Evaluation of an Automated Wheelchair Tiedown and Occupant Restraint System*.
- Orton, Nichole R., Linda van Roosmalen, and Lawrence W. Schneider. 2019. "Summary of Occupant, Wheelchair Tiedown and Occupant Restraint System Configuration Data for Wheelchair-Seated Drivers and Front-Row Passengers in Private Vehicles." <https://deepblue.lib.umich.edu/handle/2027.42/152116> (November).
- Reed, Matthew P., Sheila M. Ebert-Hamilton, and Jonathan D. Rupp. 2012. "Effects of Obesity on Seat Belt Fit." <http://dx.doi.org/10.1080/15389588.2012.659363> 13(4):364–72. doi: 10.1080/15389588.2012.659363.
- van Roosmalen, Linda. 2013. "The BusBuddy - An Independent Wheelchair Securement System for Use in Fixed Route Transportation." *Transportation Research Board, 92nd Annual Meeting*.
- van Roosmalen, Linda, Patricia Karg, Douglas A. Hobson, Michael J. Turkovich, and Erik Porach. 2011. "User Evaluation of Three Wheelchair Securement Systems in Large Accessible Transit Vehicles." *The Journal of Rehabilitation Research and Development* 48(7):823. doi: 10.1682/JRRD.2010.07.0126.
- van Roosmalen, Linda, Nichole Ritchie Orton, and Lawrence Schneider. 2013. "Safety, Usability, and Independence for Wheelchair-Seated Drivers and Front-Row Passengers of Private Vehicles: A Qualitative Research Study." *Journal of Rehabilitation Research and Development* 50(2):239–52. doi: 10.1682/JRRD.2011.11.0217.
- Schneider, Lawrence W., Miriam A. Manary, Douglas A. Hobson, and Gina E. Bertocci. 2008. "Transportation Safety Standards for Wheelchair Users: A Review of Voluntary Standards for Improved Safety, Usability, and Independence of Wheelchair-Seated Travelers." *Assistive Technology* 20(4). doi: 10.1080/10400435.2008.10131948.
- Steinfeld, Edward, Victor Paquet, Clive D. D'Souza, Caroline Joseph, and Jordana Maisel. 2010. *Anthropometry of Wheeled Mobility Project*. Buffalo, NY.
- Weir, Quentin J. A., Brian J. Eby, Miriam A. Manary, Nichole R. Orton, and Lawrence W. Schneider. 2011. "A Seatbelt Deployment System for Drivers Seated in Wheelchairs." in *RESNA 31st Conference Proceedings, Arlington, VA*. Arlington, VA.

Appendix A: Dynamic Test Results

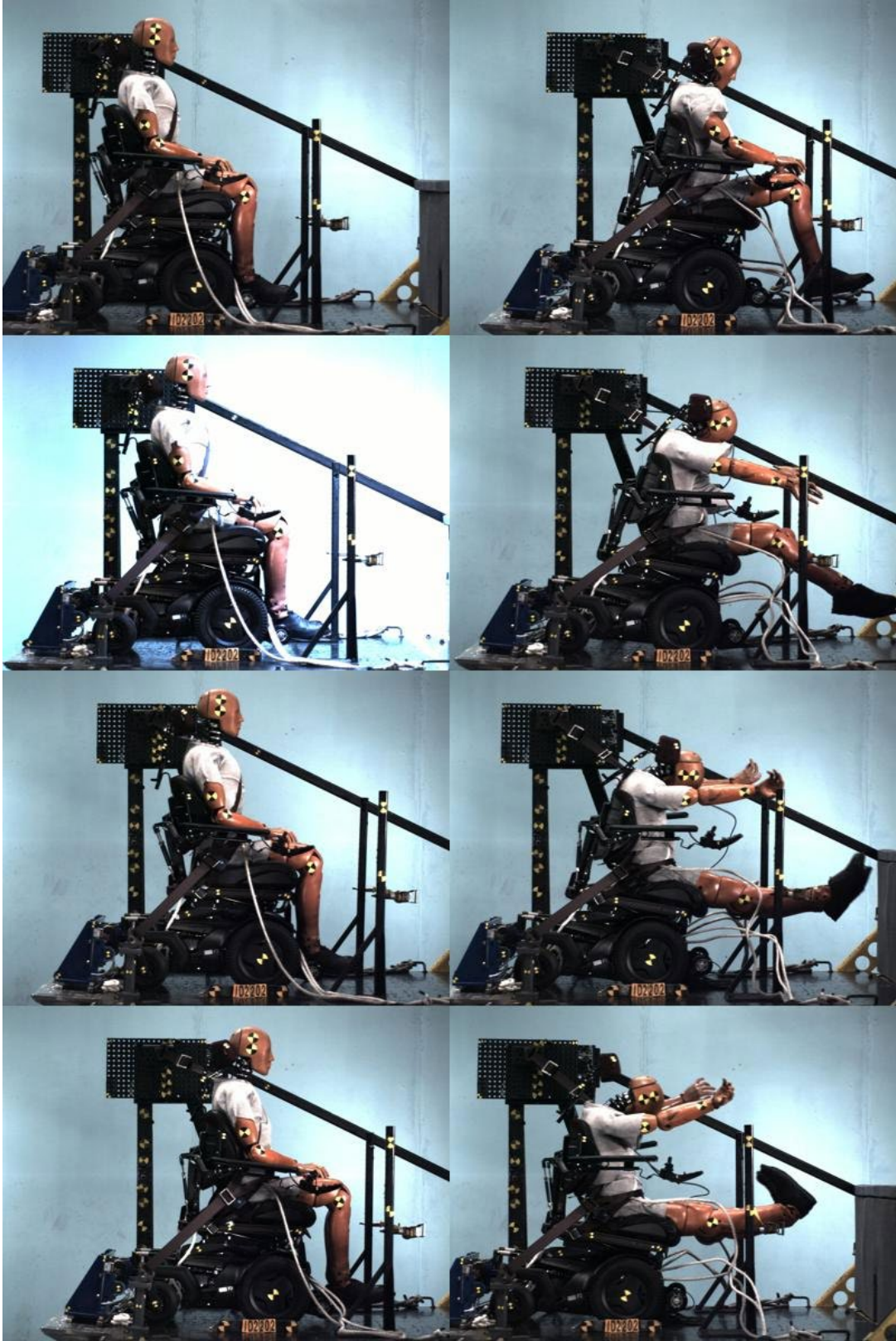


Figure 18. Kinematics of power wheelchair during frontal crash testing.

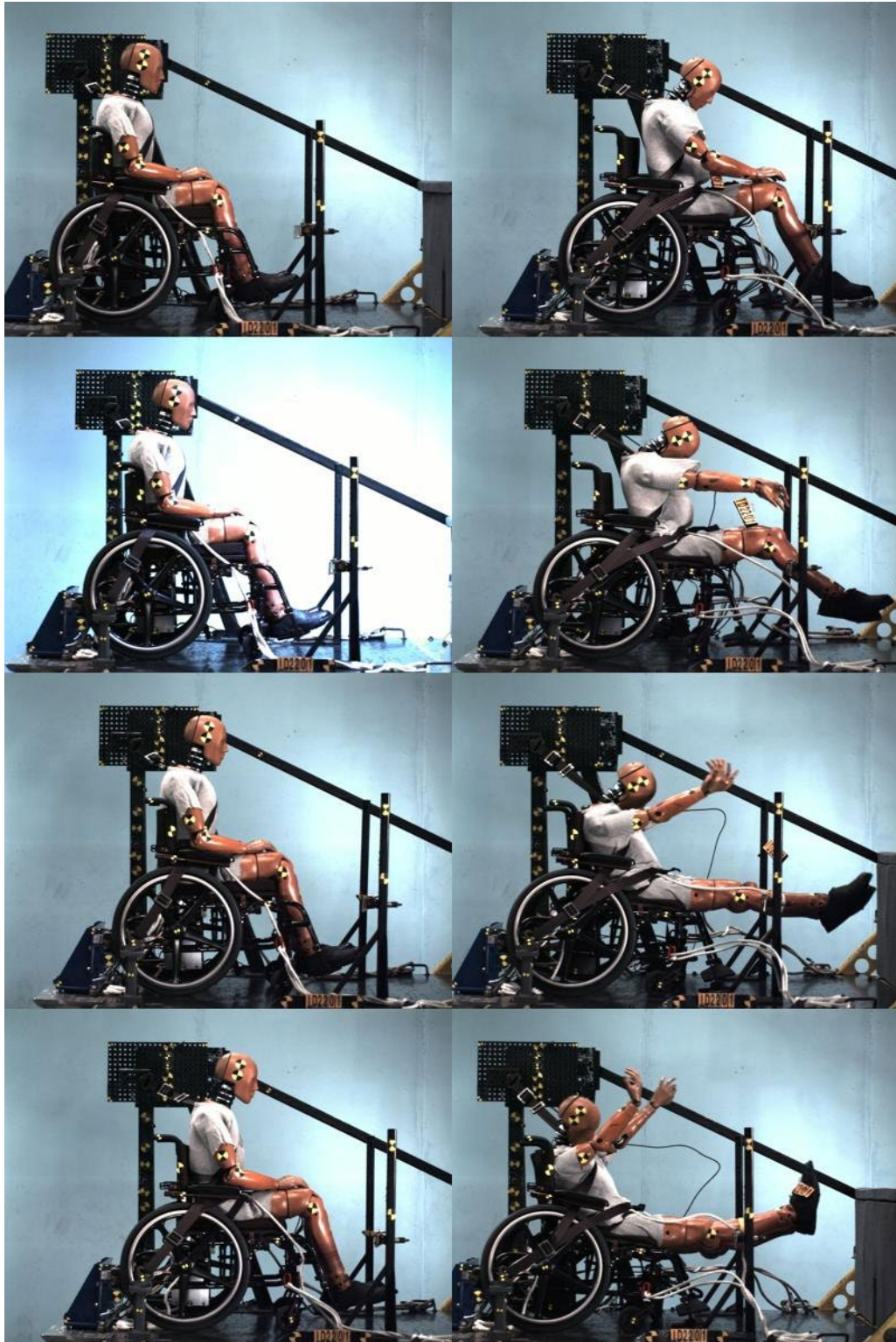


Figure 19. Kinematics of manual wheelchair during frontal crash testing.

Summary of Criteria in ANSI/RESNA WC-4:2017 Section 19: Sled Test ID 2201-Quickie 2 with UDIG

WC19 Clause	Requirement Description	Description of Observed Performance	Pass/Fail
5.3.2a	Structural components of the WC securement points shall not completely fail	No structural components of the WC securement points completely failed.	Pass
5.3.2b	Deformation of WC securement points must not prevent disengagement of hook	The deformation of the securement point brackets did not impede UDIG disengagement.	Pass
5.3.2c	WC upright and on test platform	The WC was upright on the test platform.	Pass
5.3.2d	ATD must be in WC seat with torso leaning not more than 45°	The ATD was in the WC seat with the torso reclined 25 degrees.	Pass
5.3.2e	Detached hardware cannot exceed 150 g	No hardware with mass exceeding 150 g detached during the test.	Pass
5.3.2f	WC must not have sharp edges with potential for occupant contact	No sharp edges were exposed.	Pass
5.3.2g	Primary load-carrying components cannot completely fail, unless there is a backup mechanism that does not fail	No primary load carrying parts completely failed.	Pass
5.3.2h	Forward excursion of Point P < 200 mm	32 mm	Pass
5.3.2h	Forward knee excursion < 375 mm	306 mm	Pass
5.3.2h	Forward head excursion < 650 mm	243 mm	Pass
5.3.2h	Rearward head excursion < 450 mm	403 mm	Pass
5.3.2i	Ratio of ATD knee excursion to Point P excursion must exceed 1.1.	Ratio of knee to Point P excursion = 7.0	Pass
5.3.2j	Locking mechanisms of tilt seating cannot completely fail.	N/A	Pass
5.3.2k	Post-test height of ATD H-point shall be \geq 20% of pretest height	Average H-point height decreased 10%.	Pass
5.3.2l	Seating system cannot break free from WC at any attachment point.	The seating system remained attached.	Pass
5.3.2mi	Batteries must be within WC footprint	NA – WC has no batteries.	NA
5.3.2mii	Batteries must remain attached to battery compartment	NA – WC has no batteries.	NA
5.3.2miii	Batteries cannot move into the WC user's space.	NA – WC has no batteries.	NA
5.3.2n	WC cannot cause complete failure of the surrogate WTORS.	There were no surrogate UDIG anchor failures.	Pass
5.3.2o	WTORS shall remain engaged with WC securement points.	WC remained engaged with UDIG.	Pass
5.3.2p	WC-anchored belt restraints shall not detach or completely fail.	NA – Vehicle anchored belt used.	NA

Note: WC = wheelchair, N/A = not applicable

Summary of Criteria in ANSI/RESNA WC-4:2017 Section 19: Sled Test ID 2202 – Permobil F3 Corpus with UDIG

WC19 Clause	Requirement Description	Description of Observed Performance	Pass/Fail
5.3.2a	Structural components of the WC securement points shall not completely fail	No structural components of the UDIG WC securement points completely failed.	Pass
5.3.2b	Deformation of WC securement points must not prevent disengagement of hook	The deformation of the securement point brackets did not impede UDIG disengagement.	Pass
5.3.2c	WC upright and on test platform	The WC was upright on the test platform.	Pass
5.3.2d	ATD must be in WC seat with torso leaning not more than 45°	The ATD was in the WC seat with the torso upright.	Pass
5.3.2e	Detached hardware cannot exceed 150 g	No hardware with mass exceeding 150 g detached during the test.	Pass
5.3.2f	WC must not have sharp edges with potential for occupant contact	No sharp edges were exposed.	Pass
5.3.2g	Primary load-carrying components cannot completely fail, unless there is a backup mechanism that does not fail	No primary load carrying parts completely failed.	Pass
5.3.2h	Forward excursion of Point P < 200 mm	32 mm	Pass
5.3.2h	Forward knee excursion < 375 mm	207 mm	Pass
5.3.2h	Forward head excursion < 650 mm	364 mm	Pass
5.3.2h	Rearward head excursion < 450 mm	298 mm	Pass
5.3.2i	Ratio of ATD knee excursion to Point P excursion must exceed 1.1.	Ratio of knee to Point P excursion = 6.4.	N/A
5.3.2j	Locking mechanisms of tilt seating cannot completely fail.	N/A	Pass
5.3.2k	Post-test height of ATD H-point shall be \geq 20% of pretest heights	Average H-point height did not decrease 4%.	Pass
5.3.2l	Seating system cannot break free from WC at any attachment point.	The seating system remained attached.	Pass
5.3.2mi	Batteries must be within WC footprint	Batteries remained within WC footprint.	Pass
5.3.2mii	Batteries must remain attached to battery compartment	Batteries remained attached.	Pass
5.3.2miii	Batteries cannot move into the WC user's space.	Batteries did not move into occupant space.	Pass
5.3.2n	WC cannot cause complete failure of the surrogate WTORS.	There were no surrogate WTORS failures.	Pass
5.3.2o	Tiedown hooks of WTORS shall remain engaged with WC securement points.	UDIG remained engaged.	Pass
5.3.2p	WC-anchored belt restraints shall not detach or completely fail.	NA – Vehicle anchored belt used.	NA

Note: WC = wheelchair, N/A = not applicable

Appendix B: Plots of Volunteer Survey Responses

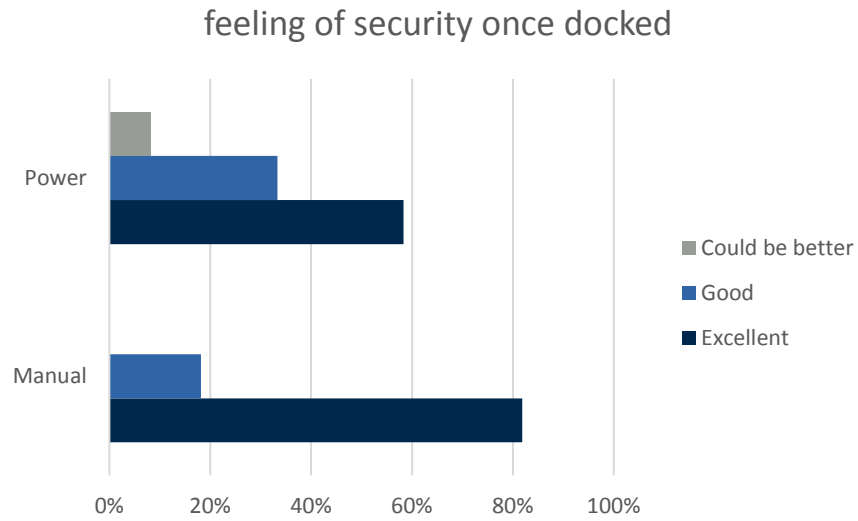


Figure 20.

Figure 21. Ratings of feeling of security once docked by wheelchair type.

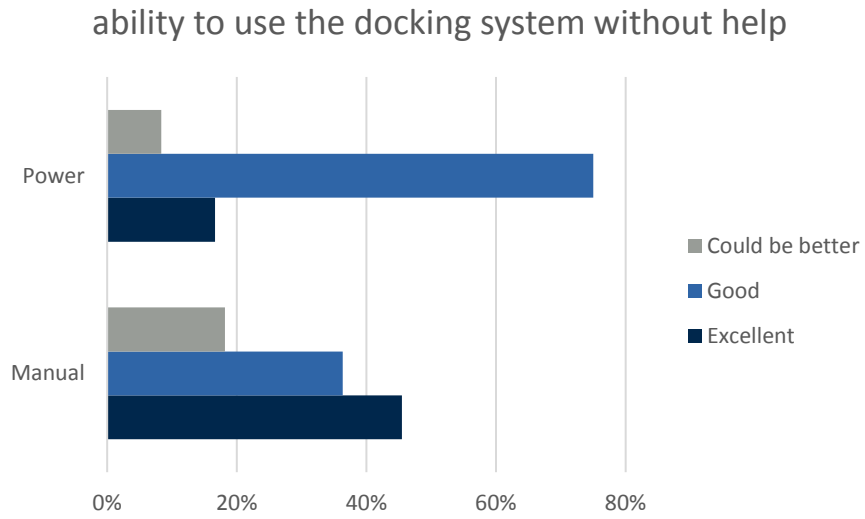


Figure 22. Ratings of ability to use the docking system without help by wheelchair type.

level of difficulty involved in maneuvering the test wheelchair compared to your own wheelchair

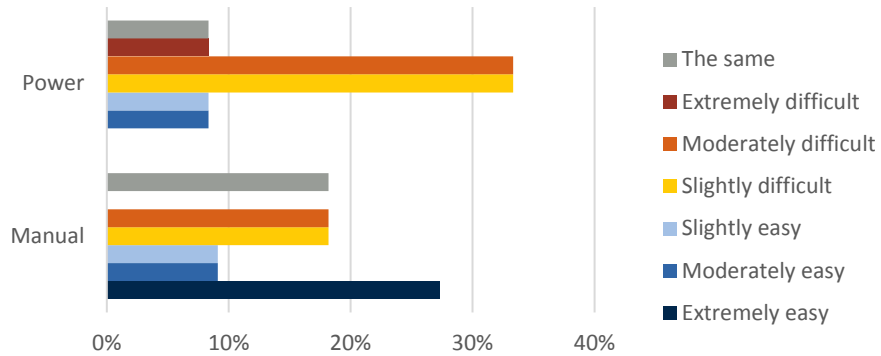


Figure 23. Ratings of level of difficulty in maneuvering the test wheelchair compared to your own wheelchair by wheelchair type.

level of difficulty involved in turning the wheelchair into the UDIG space compared to other securement systems

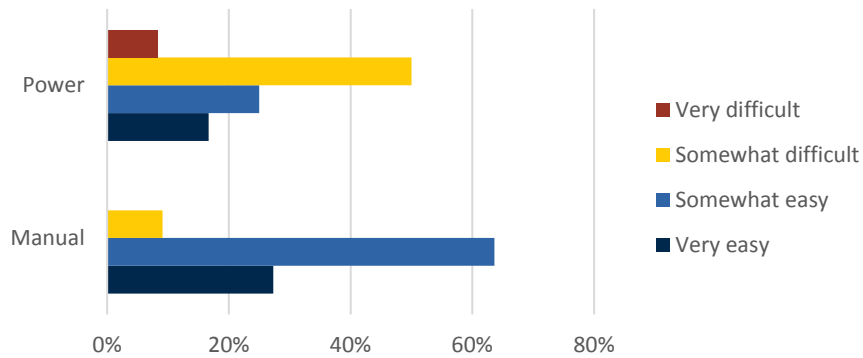


Figure 24. Ratings of level of difficulty in turning the wheelchair into the UDIG space compared to other securement systems by wheelchair type.

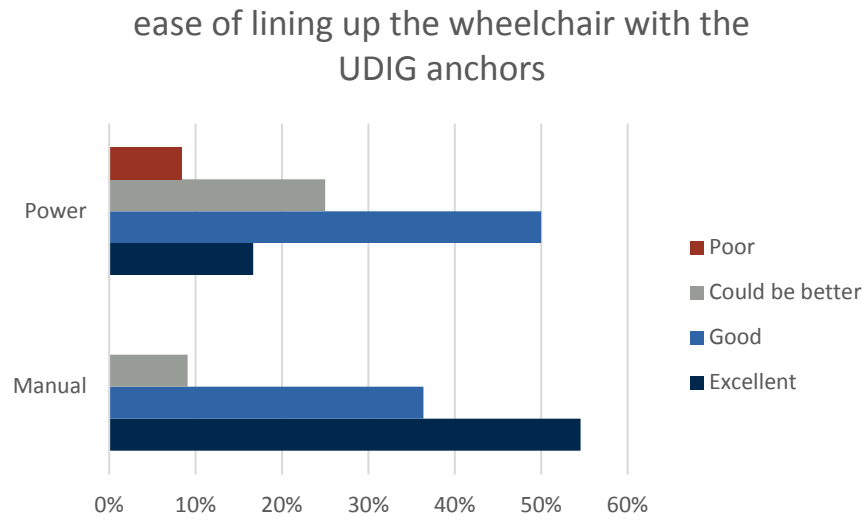


Figure 25. Ratings of level of difficulty in lining up the wheelchair with the UDIG anchors by wheelchair type.

Appendix C: Media Activity

- Press announcements were posted to UMTRI and May Mobility websites
<https://maymobility.com/may-mobility-umtri-awarded-funding-advance-to-semi-finalist-round-of-usdot-inclusive-design-challenge/>
- The project was highlighted on the updated Wheelchair Transportation Safety website
<https://wc-transportation-safety.umtri.umich.edu/recent-research/>
- UMTRI, May Mobility, and United Spinal gave an overview of the project in a PAVE seminar on February 3, 2021 <https://youtu.be/w2D9rJexYnI>
- The project was mentioned at UMTRI's Wheelchair Transportation Safety Open House
<https://www.umtri.umich.edu/wheelchair-transportation-safety-open-house/>
- May Mobility posted a blog on their website following the Design Charette
<https://maymobility.com/may-mobility-continues-to-drive-av-accessibility-with-update-on-inclusive-design-challenge/>