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DESIGN GUIDELINES FOR ACCESSIBLE AUTOMATED VEHICLES: MOBILITY FOCUS

KATHLEEN D. KLINICH, NICHOLE R. ORTON, MIRIAM A. MANARY

UMTRI TRANSPORTATION RESEARCH INSTITUTE UNIVERSITY OF MICHIGAN

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16. Abstract

Transportation for people with mobility impairments who use wheelchairs depends on vehicle environments that accommodate their needs for safe and easy-to-use vehicle spaces. This report provides design guidelines on how to make passenger vehicles, and particularly autonomous vehicles, accessible for people in wheelchairs. The vehicle aspects addressed include doorways, ramps, lifts, handholds, interior access routes, wheelchair spaces, wheelchair securement, occupant protection for people in wheelchairs, floor surfaces, and operable parts. The recommendations were derived from the literature and precedents set by the Americans with Disabilities Act (ADA), where applicable. In the areas of ramp strength and wheelchair positioning, where no clear precedents exist, the project team developed relevant procedures that are documented in the Appendices. This document can be used to evaluate vehicle accessibility using the "good/better/best" categories established for each topic. These guidelines promote vehicle designs that can allow more people in wheelchairs to travel more independently, more safely, and more easily.

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Introduction

Overview

The purpose of this document is to provide guidance on the design of automated vehicles to improve accessibility and accommodation for people with mobility disabilities, including people who use wheelchairs as vehicle seating. However, the recommendations are also relevant for personal and paratransit vehicles used by passengers seated in wheelchairs. The guidelines focus on design of the interior and ingress/egress features of the vehicle. The vehicle features addressed include doorways, ramps, lifts, handholds, interior access routes, wheelchair spaces, wheelchair securement, occupant protection for people in wheelchairs, floor surfaces, and operable parts. As much as possible, we have identified three levels to consider for each feature being evaluated: good, better, and best.

The majority of the good requirements are excerpted/adapted from the 2016 version of the Americans with Disabilities Act Accessibility Guidelines for Transportation Vehicles (ADAAG), and reflect minimum targeted legal requirements to be compliant with the ADA in 2022. While the ADAAG was originally developed for public transportation (such as large buses), AVs providing shared services will likely need to comply as well.

The ADAAG requirements were originally intended for large buses and other LATVs, where likelihood of high severity crashes is low because of the vehicle's high mass and travel characteristics. While we include the ADAAG specifications for reference, we expect that the majority of automated vehicles used by people with mobility disabilities will be of smaller size and mass and should thus be designed for a high-*g* crash environment and aim for meeting applicable federal regulations for occupant protection in private vehicles. While technologies that allow deployment of AVs should reduce crash involvement and severity, it will be some time before technologies are widespread enough to prevent other vehicles from crashing into an AV, even in a geofenced area with low speed limits. For this reason, we include guidelines for occupant protection considerations as well as accessibility.

For each topic, the specific reference providing the rationale for the guideline is included as a footnote with a link to the source. As much as possible, we have identified current procedures to assess requirements. Appendices include procedures (including new ones developed for these guidelines), recommended readings, highlights from relevant literature, and links to additional resources.

Assumptions and Exclusions

This document does not address the following topics that are included in the ADAAG:

- Seats
- Steps
- Communication systems
- Illumination

- Fare Boxes
- Level Boarding (related to infrastructure rather than vehicle)

Selected operational issues are addressed in the appendix of highlights from literature.

A vehicle would be considered large if it is longer than 25 feet (7.6 m) (ADAAG) or if it has GVWR greater than 4,536 kg (10,000 lb.) (NHTSA). Otherwise, it should meet requirements for small vehicles.

Definitions

From ADAAG

Boarding platform. A platform in a level boarding bus system raised above standard curb height that aligns with the transit vehicle floor height level boarding and alighting.

Fixed route service (or fixed route). Transportation service provided by a non-rail vehicle along a fixed schedule prescribed route.

Large transit entity. A public transportation provider that operates 100 or more buses in a fixed route service annually.

Large non-rail vehicle. Non-rail vehicles longer than 25 feet (7.6 m).

Level boarding bus system. A bus system where at least some stops have boarding platforms compatible with the vehicle floor height so the transition is close to level.

Non-rail vehicle. A self-propelled, rubber-tired vehicle used to provide transportation services and intended for use on city streets, highways, or busways that constitutes either a bus, over-the-road bus, or van.

Operable part. A component of a device or system used to insert or withdraw objects, or to activate, deactivate, adjust, or connect to the device or system. Operable parts include, but are not limited to, buttons, levers, knobs, smart card targets, coin and card slots, pull-cords, jacks, data ports, electrical outlets, and touchscreens.

Small non-rail vehicle. Non-rail vehicles 25 feet (7.6 m) or less in length.

Surface discontinuities. Differences in level between two adjacent surfaces.

From NHTSA

Large vehicle: buses, school buses, and MPVs (motorized personal vehicles) other than motor homes with a GVWR greater than 4,536 kg (10,000 lb.) per FMVSS 403.

Bridging devices: means that portion of a platform lift that provides a transitional surface between the platform surface and the surface of the vehicle floor within the platform threshold area.

From Dictionary

Handrail: a rail fixed to posts or a wall for people to hold on to for support.

Stanchion: an upright bar, post, or frame forming a support or barrier.

Handhold: something for a hand to grip on.

Bridgeplate: a mechanical, movable form of wheelchair ramp that is used on some low-floor light rail vehicles (LRVs) to provide for wheelchair access.

Guidelines Color Scheme

Throughout this document, drawings and graphs use the following color scheme of red for Good, yellow for Better, and blue for Best.

Ingress/Egress

At least one accessible way of boarding and alighting the vehicle is required, through lifts, ramps/bridgeplates, or lowering/kneeling the vehicle to meet the roadway surface.

Doorways

Test Procedures

SAE J1100 200911 *Motor Vehicle Dimensions* (or the latest version available) should be used to measure door width and height.

Good[1]

Doorway thresholds should be marked with a strip that is at least 1 in (25 mm wide) and contrasts with the surface.

Minimum vertical doorway clearance is:

- 65 in (1650 mm) for over-the-road buses
- 56 in (1420 mm) in small vehicles
- 68 in (1725 mm) in large vehicles

Minimum horizontal doorway width should be 32 in (810 mm).

Better

Minimum vertical doorway clearance should be 60 in (1513 mm) [2].

Door width should be 34 in (838 mm) or more[3], measured at two locations: one 1.5 in (38 mm) above the floor and a second at 28 in (713 mm)[4].

[1] Architectural and Transportation Barriers Compliance Board, Dec. 14, 2016, Americans with Disabilities Act (ADA) Accessibility Guidelines for Transportation Vehicles, 36 CFR Part 1192 [Docket No. ATBCB 2010–0004] RIN 3014–AA38. T602.4, p. 90627, to meet minimum standards in 2022.

[2] Steinfeld E, Paquet V, D'Souza CD, Joseph C, and Maisel J. 2010. *Anthropometry of Wheeled Mobility Project*. Buffalo, NY, p. 133, based on maximum seated height measured in study.

[3] Steinfeld E, Paquet V, D'Souza CD, Joseph C, and Maisel J. 2010. *Anthropometry of Wheeled Mobility Project*. Buffalo, NY, p. 134, based on maximum device width measured in study.

[4] Steinfeld E, Paquet V, D'Souza CD, Joseph C, and Maisel J. 2010. *Anthropometry of Wheeled Mobility Project*. Buffalo, NY, p. 133, based on mean armrest height measured in study.

Best

Minimum vertical doorway clearance should be 65 in (1650 mm) [5].

Door width should be 36 in (864 mm) or more[6].

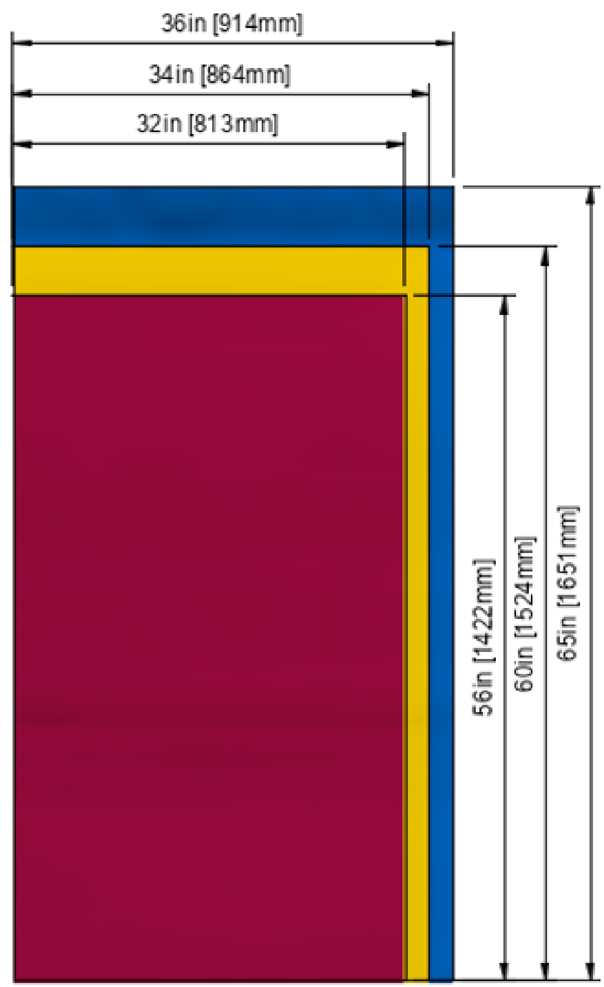

Figure 1. Illustration of good, better, best recommendations for door dimensions.

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[5] Architectural and Transportation Barriers Compliance Board, Dec. 14, 2016, Americans with Disabilities Act (ADA) Accessibility Guidelines for Transportation Vehicles, 36 CFR Part 1192 [Docket No. ATBCB 2010–0004] RIN 3014–AA38. T602.4, p. 90627, based on recommendations for over-the-road buses.

[6] Department of Justice. 2010. 2010 ADA Standards for Accessible Design, based on minimum hallway width in buildings.

Ramps

Test Procedures

Appendix C Ramp Strength

Appendix E *Checking Zone for Potential Head Contact*; adapted from FMVSS 201 test procedure.

Laboratory Test Procedure for FMVSS 201U: Occupant Protection in Interior Impact, Upper Interior Head Impact Protection

Good[7]

- Minimum ramp width is 30 in (760 mm).
- Ramp slope to road needs to be 9.5 degrees or less (1:6). Ramp slope to boarding platform needs to be 7.1 degrees or less (1:8).
- Ramps need to have edge guards on each side that are at least 2 in (51 mm) tall. They need to run from the vehicle to within 3 in (75 mm) of the end.
- Ramps 30 in (760 mm) or longer should be designed to support a 600 lb (273 kg) load, shorter ones designed to support 300 lb load (136 kg). Factor of safety of 3 or more.
- Ramp surface perimeter needs to be marked with a stripe at least 1 in (25 mm) wide that contrasts with main surface.
- When deployed, the gap between vehicle and ramp needs to be 5/8 in (16 mm) or less.
- When used, ramps need to be attached to the vehicle and need to be permanently installed and power operated on large vehicles. They need to have a way to operate manually in case of power failure.
- Ramp surfaces need to meet specifications in Surfaces section.
- Need to stow ramp when not in use.

Better

- Minimum ramp width is 34 in (838 mm) or more[8].
- Ramp slope to road is 6 degrees or less (1:10)[9].
- Taller edge guards are probably better; no data available to support a particular recommendation.

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[7] Architectural and Transportation Barriers Compliance Board, Dec. 14, 2016, Americans with Disabilities Act (ADA) Accessibility Guidelines for Transportation Vehicles, 36 CFR Part 1192 [Docket No. ATBCB 2010–0004] RIN 3014–AA38. T602.4, p. 90627, to meet minimum standards in 2022.

[8] Steinfeld E, Paquet V, D'Souza CD, Joseph C, and Maisel J. 2010. *Anthropometry of Wheeled Mobility Project*. Buffalo, NY, p. 134, based on maximum device width measured in study.

[9] Department of Justice. 2010. 2010 ADA Standards for Accessible Design, based on allowable slope for buildings based on recommendations for ramp angles permitted on running slopes with limited space.

- Ramps are designed to support a 1000 lb (454 kg) load[10]. Factor of safety of 3 or more.
- When ramp is stowed, no contactable sharp edges (<2mm radius) near the wheelchair passenger space or vehicle seating position, as determined by procedure for Checking Zone for Potential Head Contact.
- Ramps should remain stowed during a crash.
- Longitudinal centerline of ramp should be marked with a stripe at least 1 in (25 mm) wide that contrasts with the main surface[11].

Best

- Minimum ramp width is 36 in (868 mm) or more[12].
- Ramp slope to road is 4.8 degrees (1:12) or less.[13]
- When stowed, all ramp hardware surfaces within the Zone for Potential Head Contact meet FMVSS 201U requirements.

Table 1. Nominal ramp lengths needed to achieve good, better, best recommendations for different vehicle sill heights.

Ground to sill height (in)	1:6 (9.5 deg) In	1:10 (6 deg) in	1:12 (4.8 deg) in	Ground to sill height (mm)	1:6 (9.5 deg), mm	1:10 (6 deg), mm	1:12 (4.8 deg), mm
2	1	20	2	50	25	500	50
4	24	40	48	10	60	100	120
6	36	60	72	150	900	1500	1800
8	48	80	96*	200	1200	2000	2400*
10	60	100*	120*	250	1500	2500*	3000*
12	72	120*	144*	300	1800	3000*	3600*

*Impractical given common sidewalk and vehicle dimensions; lowering the vehicle sill height through design or kneeling likely a better solution.

[10] Common practice per BraunAbility.
[11] Suggestion from wheelchair user advocate.
[12] Department of Justice. 2010. 2010 ADA Standards for Accessible Design, based on minimum hallway width in buildings.
[13] Department of Justice. 2010. 2010 ADA Standards for Accessible Design, based on allowable slope for buildings.

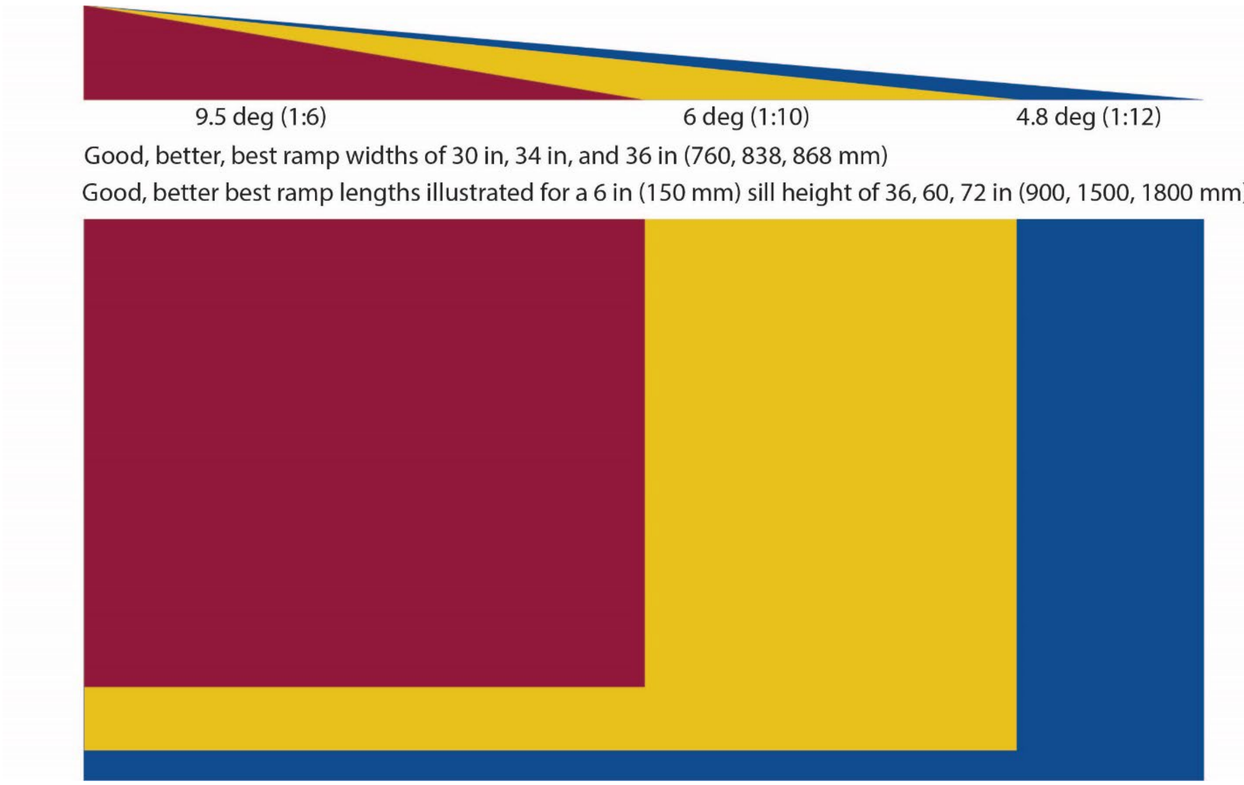

Figure 2. Illustration of ramp lengths needed to meet good, better, best recommendations for ramp angles (for a 150 mm/ in sill height), plus good, better, and best ramp widths.

Lifts

Test Procedures

NHTSA provides a detailed illustrated test procedure for FMVSS 403/404 describing lift requirements.

Laboratory Test Procedure for FMVSS 403 Platform Lift Systems for Vehicles

Laboratory Test Procedure for FMVSS 404 Platform Lift Systems in Motor Vehicles

Appendix A contains a summary of the lift requirements and procedures.

Appendix E *Checking Zone for Potential Head Contact*; adapted from FMVSS 201U test procedure.

Laboratory Test Procedure for FMVSS 201U Occupant Protection in Interior Impact, Upper Interior Head Impact Protection

Good

Lifts must meet the requirements of FMVSS 403. They should allow the wheelchair passenger to board the vehicle facing either toward or away from the vehicle.

Better

- When stowed, the lift should have no contactable sharp edges (<2mm radius) near the wheelchair passenger space or vehicle seating position, as determined by the procedure for Checking Zone for Potential Head Contact.
- Lifts should remain stowed during a crash.
- When deployed and loaded, lifts should deflect less than the allowable 3 degrees from a flat plane.
- Emergency backup system for lifts should allow operation by the wheelchair user.

Best

When stowed, all lift surfaces within the Zone for Potential Head Contact meet FMVSS 201U requirements.

Handrails, Stanchions, and Handholds (HSH)

Test Procedures

ANSI-RESNA WC4, Section 10: *Wheelchair containment and occupant retention systems for use in large accessible transit vehicles: systems for rearward-facing passengers* contains dimensional specifications for locating HSH in rear-facing wheelchair stations that may be useful when placing HSH near forward-facing wheelchair stations.

Appendix E *Checking Zone for Potential Head Contact*; adapted from FMVSS 201 test procedure.

Good[14]

- Need to have handrails or stanchions at passenger doorways that allow grasping and use from outside the vehicle and throughout the boarding and alighting process.
- Small vehicles need to have HSH to assist with onboard circulation and assistance with seating and standing. Large vehicles need to have them on all seatbacks located adjacent to the aisle (except for vehicles with high-back seats, where overhead handrails can be used).
- HSH need to have rounded or eased edges.
- Cross section requirements:
    - Outside diameter of seatback handholds need to range from 0.875 in to 2 in (22-50 mm).
    - Outside diameter of round handrails and stanchions need to range from 1.25 in to 2 in (32 mm to 50 mm).
    - Non-circular versions need to have a perimeter between 4 in and 6.25 in (100-160 mm), and a cross section less than 2.25 in (57 mm).
    - Clearance between HSH and adjacent surfaces should be 1.5 in (38 mm) or more.

Better

- HSH should have no contactable sharp edges (<2mm radius) near the wheelchair passenger space or vehicle seating position, as determined by procedure to Check Zone for Head Contact.
- Cross section requirements[15]:
    - Outside diameter of round handrails and stanchions need to range from 1.25 in to 1.4 in (32 mm to 35 mm).

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[14] Architectural and Transportation Barriers Compliance Board, Dec. 14, 2016, Americans with Disabilities Act (ADA) Accessibility Guidelines for Transportation Vehicles, 36 CFR Part 1192 [Docket No. ATBCB 2010–0004] RIN 3014–AA38. T602.4, p. 90626, to meet minimum standards in 2021.

[15] RESNA. Wheelchair Containment and Occupant Retention Systems for Use in Large Accessible Transit Vehicles: Systems for Rear-ward-Facing Passengers; ANSI/RESNA WC-4:2017 Section 10; 2017; pp. 10-18.

- Non-circular versions need to have a maximum section between 1.25 in to 1.4 in (32 mm to 35 mm) and a minimum section not less than 20 mm (0.79 in).

Best

All HSH within the Zone for Potential Head Contact meet FMVSS 201U requirements.

Passenger Access Routes

Test Procedures

During the vehicle layout/design phase, computer aided design tools can be used to evaluate clearance circles and associated wheelchair station locations.

For in-vehicle evaluation, we recommend constructing templates out of sturdy woven fabric (such as denim) because it can be manipulated more easily around obstacles without damage compared to paper, cardboard, or plastic templates. Fabric should be washed before cutting. Wheelchair template (Figure 3) should be sized to 34 x 60 in (864 x 1524 mm), with additional stitching lines in contrasting color placed at widths of 30 and 32 in (762 and 813 mm) and lengths of 48 and 54 in (1219 and 1372 mm). Additional stitching lines can be added to indicate the longitudinal centerlines for each width of station, as well the estimated range of fore-aft H-point positions located between 22 and 49 cm from the back of the template.

Access template (Figure 4) should be a circle of 60 in (1524 mm) diameter, with center point marked, and additional stitching lines in contrasting color at 48 and 54 in (1219 and 1372 mm). Additional stitching lines marking perpendicular centerlines are also helpful when aligning the station template.

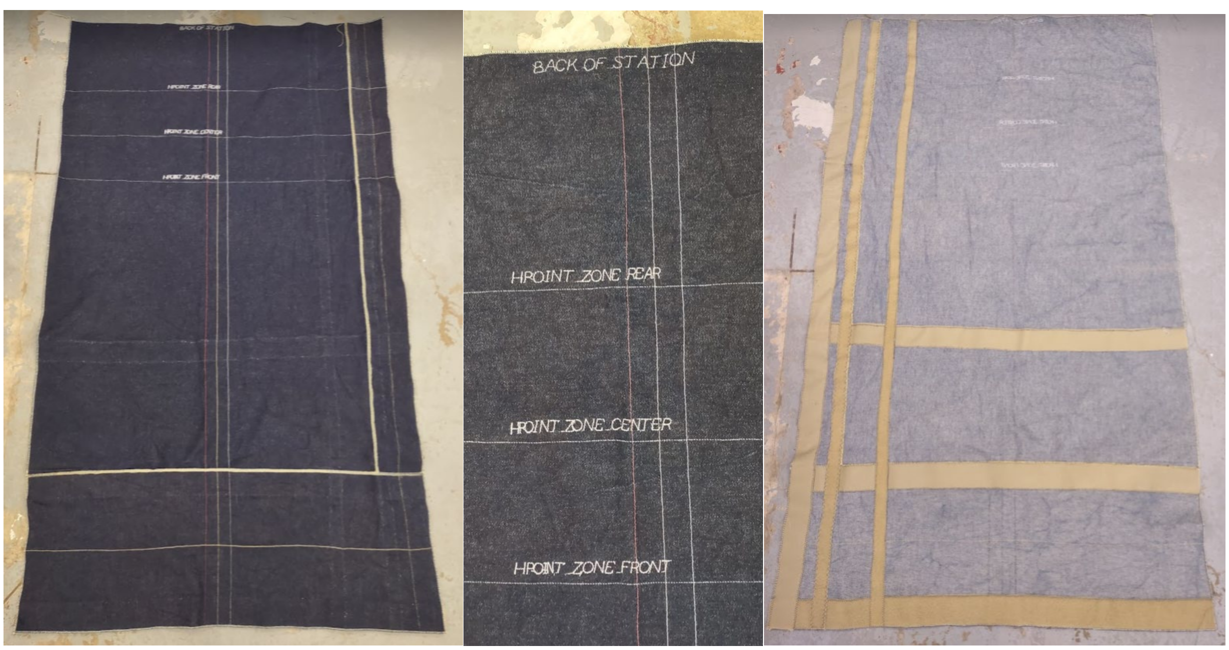

Figure 3. Example of wheelchair station template (left), closeup of markings (center), and back view of Velcro placement (right).

Figure 4. Example of passenger access template.

Good[16]

Passengers in wheelchairs need to have sufficient room to move between each accessible entrance and each wheelchair station, as well as to enter and exit wheelchair spaces.

Better[17]

Aisles should be at least 34 in (864 mm) wide. The wheelchair station should fit within a 54 in (1372 mm) diameter circle of clear space to allow room to maneuver.

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[16] Architectural and Transportation Barriers Compliance Board, Dec. 14, 2016, Americans with Disabilities Act (ADA) Accessibility Guidelines for Transportation Vehicles, 36 CFR Part 1192 [Docket No. ATBCB 2010–0004] RIN 3014–AA38. T602.4, p. 90625, to meet minimum standards in 2022.

[17] Architectural and Transportation Barriers Compliance Board, Dec. 14, 2016, Americans with Disabilities Act (ADA) Accessibility Guidelines for Transportation Vehicles, 36 CFR Part 1192 [Docket No. ATBCB 2010–0004] RIN 3014–AA38. T602.4, p. 90602, proposed in NPRM but not adopted.

Best

Aisles should be at least 36 in (914 mm) wide.[18] The wheelchair station should fit within a 60 in (1524) diameter circle of clear space to allow room to maneuver.[19]

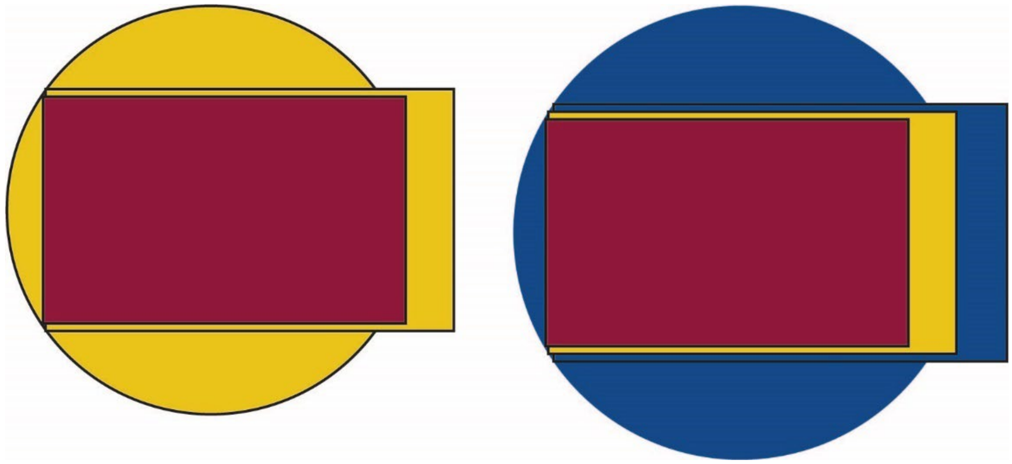

Figure 5. Illustration of placing different sizes of wheelchair templates relative to the better and best circle recommendations for clear space relative to the wheelchair station.

[18] Department of Justice. 2010. 2010 ADA Standards for Accessible Design, based on minimum hallway width in buildings.

[19] Recommendation from BraunAbility.

Wheelchair spaces

Procedures

Appendix E Checking Zone for Potential Head Contact; adapted from FMVSS 201U test procedure.

Laboratory Test Procedure for FMVSS 201U Occupant Protection in Interior Impact, Upper Interior Head Impact Protection

Placement

Good[20]

- One wheelchair station is required for vehicles with length < 25 feet, two are required for vehicles with length of $\geq$ 25 feet.
- Wheelchair stations should be placed as close as possible to accessible entrance, with one side located adjacent to passageway.
- Flip down seats over the wheelchair space are allowed when space not in use.
- Wheelchair stations should position the occupant facing the front of the vehicle. On LATVs where passengers are allowed to stand during travel, a rear-facing station is allowed, as long as there is at least one other station that is forward facing.

Better

Wheelchair stations are immediately adjacent to accessible entrances.

Wheelchair stations should be located to minimize chance of occupant head contact with interior structures. Any structures should have no contactable sharp edges (<2mm radius) near the wheelchair passenger space or vehicle seating position, as determined by procedure for Checking Zone for Potential Head Contact.

The edges and longitudinal centerline of the wheelchair station should be marked with a contrasting strip at least 1 in (25 mm) wide.

Best

Wheelchair stations are immediately adjacent to accessible entrances, and no more than a 90-degree turn is required to enter the space[21].

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[20] Architectural and Transportation Barriers Compliance Board, Dec. 14, 2016, Americans with Disabilities Act (ADA) Accessibility Guidelines for Transportation Vehicles, 36 CFR Part 1192 [Docket No. ATBCB 2010–0004] RIN 3014–AA38. T602.4, p. 90626, to meet minimum standards in 2022.

[21] Steinfeld E, Paquet V, D'Souza CD, Joseph C, and Maisel J. 2010. *Anthropometry of Wheeled Mobility Project*. Buffalo, NY, p. 93.

Wheelchair stations should be located to minimize chance of occupant head contact with interior structures. This means leaving a clear space 500 mm rearward of wheelchair seatback, and 950 mm forward of occupant head[22], unless structures have been designed to meet requirements specified by FMVSS 201U or provide occupant protection. Any structures near the wheelchair passenger space or vehicle seating position, as determined by procedure for Checking Zone for Potential Head Contact, should be designed to meet the requirements specified by FMVSS 201U.

[22] RESNA. Wheelchair used as Seats in Motor Vehicles; ANSI/RESNA WC-4:2017 Section 19; 2017; p 19-40.

Dimensions

Good[23]

Wheelchair spaces should be at least 30 in (760 mm) wide and 48 in (1220 mm) long. It is acceptable to locate wheelchair footrests under another seat if the space is at least 30 in (760 mm) wide, 9 in (230 mm) high, and 6 in (150 mm) deep.

Better

- Wheelchair spaces should be at least 32 in (813 mm) wide and 54 in (1372 mm) long[24].
- Tiedown hardware should be located outside the wheelchair station space to maximize clear maneuvering space.
- Minimum vehicle ceiling height should be 60 in (1513 mm) [25].

Best

- Wheelchair spaces should be at least 34 in wide (864 mm)[26] and 60 in long (1524 mm)[27].
- Minimum vehicle ceiling height should be 65 in (1650 mm) [28].
- Tiedown hardware should be stowable to allow for easier wheelchair maneuvering.

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[23] Architectural and Transportation Barriers Compliance Board, Dec. 14, 2016, Americans with Disabilities Act (ADA) Accessibility Guidelines for Transportation Vehicles, 36 CFR Part 1192 [Docket No. ATBCB 2010–0004] RIN 3014–AA38. T602.4, p. 90628, to meet minimum standards in 2022.

[24] Steinfeld, Edward, Victor Paquet, Clive D. D'Souza, Caroline Joseph, and Jordana Maisel. 2010. *Anthropometry of Wheeled Mobility Project*. Buffalo, NY. p. 88, to accommodate 90% of 2010 wheelchairs.

[25] Steinfeld E, Paquet V, D'Souza CD, Joseph C, and Maisel J. 2010. *Anthropometry of Wheeled Mobility Project*. Buffalo, NY, p. 133, based on maximum seated height measured in study.

[26] Steinfeld, Edward, Victor Paquet, Clive D. D'Souza, Caroline Joseph, and Jordana Maisel. 2010. *Anthropometry of Wheeled Mobility Project*. Buffalo, NY. p. 88, to accommodate 95% of 2010 wheelchair widths.

[27] Department of Justice. 2010. 2010 ADA Standards for Accessible Design. p. 109, to harmonize with side entry alcove sizes in buildings.

[28] Architectural and Transportation Barriers Compliance Board, Dec. 14, 2016, Americans with Disabilities Act (ADA) Accessibility Guidelines for Transportation Vehicles, 36 CFR Part 1192 [Docket No. ATBCB 2010–0004] RIN 3014–AA38. T602.4, p. 90627, based on recommendations for over-the-road buses.

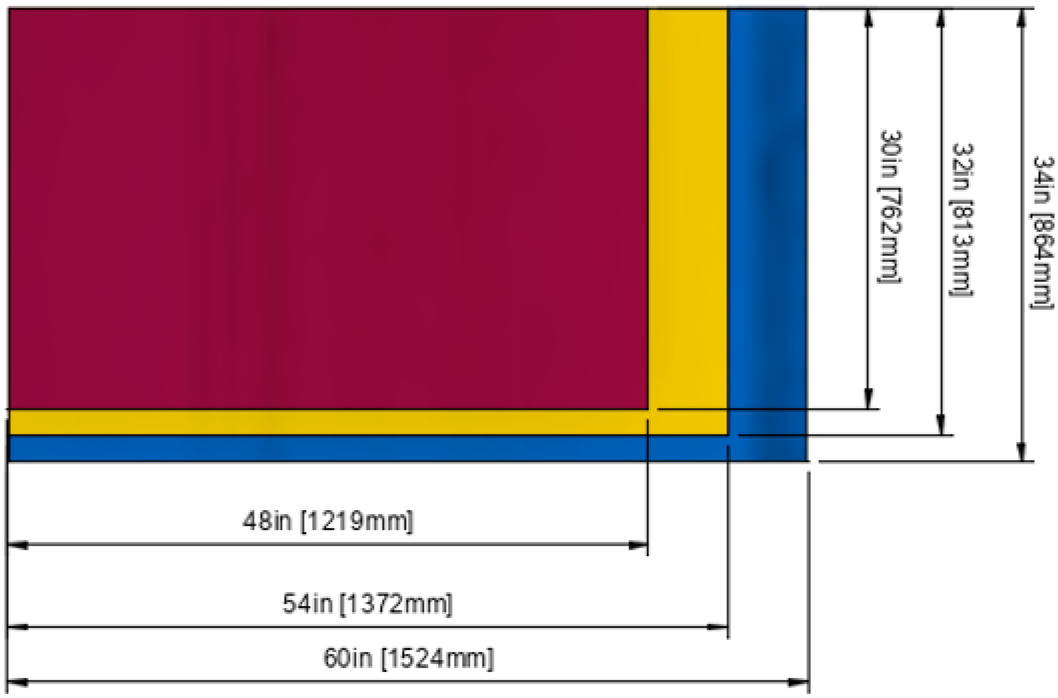

Figure 6. Illustration of good, better, and best recommendations for wheelchair station dimensions.

Securement: Large Vehicles

Procedures

ISO 10865-1:2012(E), Wheelchair containment and occupant retention systems for accessible transport vehicles designed for use by both sitting and standing passengers — Part 1: Systems for rearward facing wheelchair-seated passengers, First Edition, June 5, 2012

ANSI-RESNA WC4, Section 10: Wheelchair containment and occupant retention systems for use in large accessible transit vehicles: systems for rearward-facing passengers, Annex B: Test for Wheelchair Containment

ANSI-RESNA WC4, Section 18: Wheelchair tiedown and occupant restraint systems for use in motor vehicles

Laboratory Test Procedure for FMVSS 222 School Bus Passenger Seating and Crash Protection, Appendix C for checking floor/anchor strength.

Good[29]

- For vehicles with a GVWR ≥ 30,000 lb (13,08 kg), the securement should be designed for a minimum forward longitudinal securement load is 2000 lbf (8,800 N).
- For vehicles with a GVWR < 30,000 lb (13,608 kg), the securement should be designed for a minimum forward longitudinal securement load is 5000 lbf (22,000 N).
- When wheelchairs are secured following manufacturers' directions, the occupied wheelchair should move < 2 in (51 mm) under normal operating conditions.

Better

Rear-facing wheelchair stations need to have forward excursion barriers and padded head restraints that meet requirements of ISO 10865-1:2012(E).

Best

Rear-facing wheelchair stations need to have forward excursion barriers and padded head restraints that meet requirements of ANSI-RESNA WC4, Section 10.

Vehicle anchor points for forward-facing securement should be designed for securement loads generated in the frontal impact test of ANSI-RESNA WC4, Section 18.

Annex F of WC19 contains specifications for a Universal Docking Interface Geometry (UDIG) that has been proposed to allow development of docking systems that can be independently

[29] Architectural and Transportation Barriers Compliance Board, Dec. 14, 2016, Americans with Disabilities Act (ADA) Accessibility Guidelines for Transportation Vehicles, 36 CFR Part 1192 [Docket No. ATBCB 2010–0004] RIN 3014–AA38. T602.4, p. 90628, to meet minimum standards in 2022.

operated by the wheelchair user. Any wheelchair with UDIG-compatible attachments could be docked with any vehicle equipped with UDIG-compatible anchors. However, until UDIG attachments become more available, anchors should also be provided to allow use of 4-point strap tiedowns.

Vehicle floor strength can be evaluated using procedures in Appendix C of the Laboratory Test Procedure for School Bus Passenger Seating and Crash Protection.

Securement: Small Vehicles

Procedures

ANSI-RESNA WC4, Section 18: Wheelchair tiedown and occupant restraint systems for use in motor vehicles

Laboratory Test Procedure for FMVSS 222 School Bus Passenger Seating and Crash Protection, Appendix C, for checking floor/anchor strength.

Good:

Because the crash environment of a small vehicle differs from an LATV, the static loading and movement requirements described in ADAAG are not sufficient to provide adequate crash protection for a person seated in a wheelchair in a small vehicle. Current designs of rear-facing wheelchair seating stations are also not sufficient to provide adequate occupant protection in small vehicles. Although not legally required, vehicle hardware for forward-facing securement of wheelchairs in small vehicles should meet requirements of ANSI-RESNA WC4, Section 18.

Better[30]

Vehicle anchors for forward-facing securement should meet requirements of ANSI-RESNA WC4, Section 18.

Hardware for anchoring 4-point strap tiedown systems should be located between 48 to 51 in (1219 and 1295 mm) apart longitudinally. Laterally, hardware should allow securement at a range between 12 to 30 in (300 and 760 mm). As shown in Figure 7, the ideal angle for attaching the rear 4-point strap tiedowns is 30 to 45 degrees relative to the floor. From the top view, rear anchors should be located straight back from the wheelchair attachment points, while the front anchors should be located in front of and outboard relative to the wheelchair attachment points.

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[30] RESNA. Wheelchair Tiedown and Occupant Restraint Systems for Use in Motor Vehicles; ANSI/RESNA WC-4:2017 Section 18; 2017; pp. 1–93.

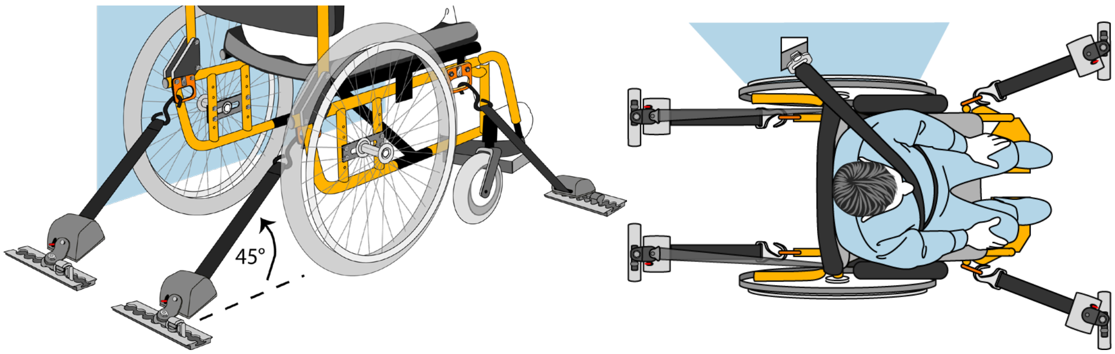

Figure 7. Illustration of ideal sideview tiedown angle between 30-45 degrees and lateral positions of tiedowns.

Best

FMVSS 222 procedures for evaluating the strength of wheelchair securement points on school buses can be used to evaluate floor strength needed to secure wheelchairs. The FMVSS 222 procedure applies a load of 13344 N (3000 lbf) to each anchor. The procedure can be adapted to apply higher loads.

Figure 8 shows the rear tiedown peak securement loads from ~1500 tests run using WC19 protocols, where the commercial wheelchair is secured to a rigid floor; these loads were measured with a steel floor and deformation of a typical vehicle floor would mitigate loads. X-axis values correspond to the sum of the peak left and right tiedown loads. These data can be used to calculate a load based on the combined mass of wheelchair and occupant with or without a wheelchair-anchored lap belt. For example, to design a floor to secure a combined occupant weight of 500 lb using vehicle-mounted belts, the regression equation calculates the target applied load for each anchor location to be (20.302 * 500/2)=5088 lbf using the FMVSS 222 test procedure.

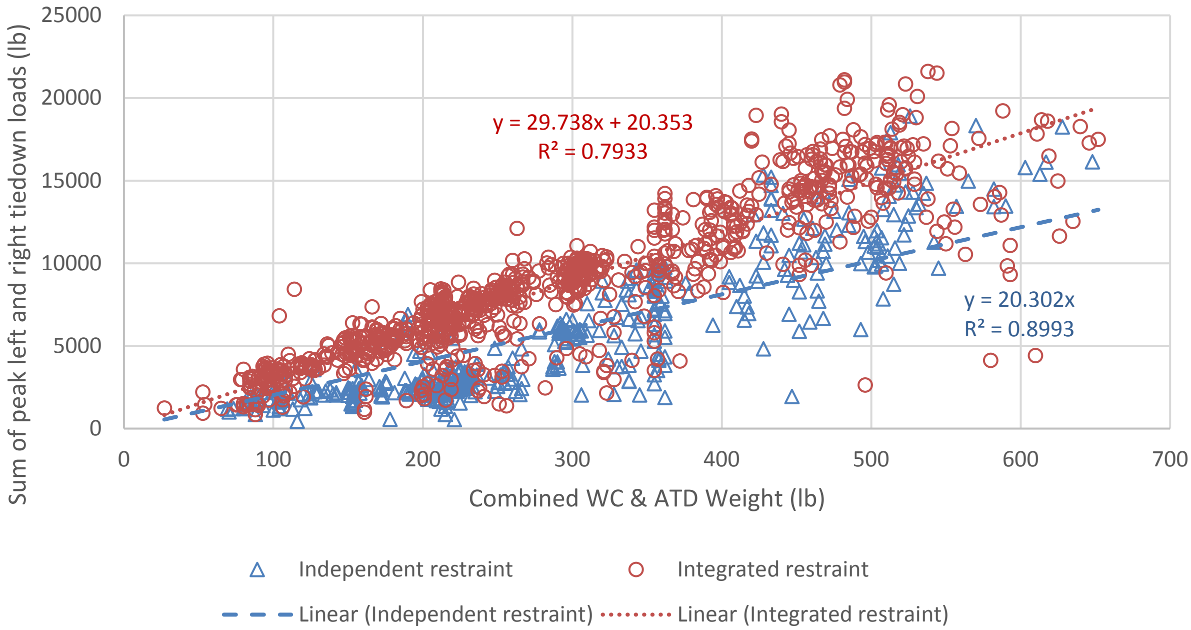

Figure 8. Combined rear tiedown loads measured in ~1500 tests run using WC19 protocols.

Annex F of WC19 contains specifications for a Universal Docking Interface Geometry (UDIG) that has been proposed to allow development of docking systems that can be independently operated by the wheelchair user. Any wheelchair with UDIG-compatible attachments could be docked with any vehicle equipped with UDIG-compatible anchors. However, until UDIG attachments become more available, anchors should also be provided to allow use of 4-point strap tiedowns.

Occupant restraint systems

Procedures

ANSI-RESNA WC4, Section 18: Wheelchair tiedown and occupant restraint systems for use in motor vehicles

ISO 7176-19 (2022), *Wheelchairs for Use as Seats in Motor Vehicles, Annex G*

Laboratory Test Procedure for FMVSS 209 Seat Belt Assemblies

Laboratory Test Procedure for FMVSS 201U Occupant Protection in Interior Impact, Upper Interior Head Impact Protection

Laboratory Test Procedure for FMVSS 210 Seat Belt Assembly Anchorages

Good[31]

Seatbelt systems for wheelchair seating stations must meet the requirements of FMVSS No. 209, and must not be used as a substitute for wheelchair securement systems.

Better[32]

Seatbelt systems should comply with the requirements of WC18. Seatbelt anchorage systems should meet requirements of FMVSS 210.

Best

The goal of occupant protection for people in wheelchairs is that they should have a level of occupant protection that is comparable to other occupants in the vehicle. Findings from research studies to examine occupant protection systems designed for wheelchair stations are summarized below.

For frontal impacts, providing a lap-and-shoulder belt system with good anchorage geometry is the first step in protecting an occupant in a wheelchair. Specific recommendations developed through computational modeling and volunteer testing are included in the next section of this document (Klinich et al. 2021). Simulations showed that with good belt geometry, and the minimum wheelchair space fore/aft length of 48 in (1219 mm), likelihood was low for head contact with a forward component during a 30 mph/20 g severity frontal crash of a midsized male seated in a wheelchair. If optimal belt geometry is not feasible, use of a SCARAB airbag mounted to a forward structure (back of driver's seat) provided improved protection. A factor

[31] Architectural and Transportation Barriers Compliance Board, Dec. 14, 2016, Americans with Disabilities Act (ADA) Accessibility Guidelines for Transportation Vehicles, 36 CFR Part 1192 [Docket No. ATBCB 2010–0004] RIN 3014–AA38. T602.4, p. 90628, to meet minimum standards in 2022.
[32] RESNA. Wheelchair Tiedown and Occupant Restraint Systems for Use in Motor Vehicles; ANSI/RESNA WC-4:2017 Section 18; 2017; pp. 1–93.

to consider is that people seated in wheelchairs do not have the benefit of anti-submarining features found in a vehicle seat, and given the minimum space requirements, do not have a knee bolster or forward seat structure available to limit lower extremity motion if lap belt fit is inadequate.

For wheelchair seating stations placed in the front row, installations should allow use of the available standard airbag (Hu et al. 2020; Schneider et al. 2016), based on a study to investigate restraint system designs for wheelchair users. MADYMO models of a surrogate wheelchair, docking or 4-point tie-down system, 3-point seatbelt, knee bolster, steering wheel, and driver airbag were validated against multiple sled tests with varied ATD sizes, belt fit, and airbag conditions. The parametric simulation results clearly demonstrate that wheelchair-seated occupants without a seatbelt or a seatbelt with poor belt fit experience higher injury risks in frontal crashes. The simulation studies also demonstrated that a properly deployed driver airbag can provide important safety benefits for occupants with a wide range of sizes who are seated in wheelchairs in frontal crashes.

In simulations of nearside impacts without intrusion, use of a lap-and-shoulder belt with an outboard D-ring, coupled with a standard side curtain airbag, provide comparable protection for an occupant seated in a wheelchair. Because curtain airbag designs are not uniform in properties along their length, wheelchair stations should position the occupant using a wheelchair in a similar fore-aft location compared to the original design for occupants seated in a vehicle seat.

In simulations and tests of farside impacts, the lap-and-shoulder-belt was ineffective at keeping the occupant seated within the wheelchair. The study was able to demonstrate effectiveness of a prototype CATCH (Center Airbag To Contain Humans) at keeping the occupant seated within wheelchair during a farside impact.

The procedure in Appendix E should be used to identify any nonglazed surface with potential for head impact. Any rigid components within this area should include energy-absorbing materials that meet requirements of FMVSS 201U.

Annex G of ISO 7176-19 (2022) contains procedures for evaluating wheelchairs in rear impact. However, research on rear impact occupant protection systems for wheelchair users has been limited. While some wheelchairs are equipped with structures resembling head restraints to provide postural support, they are likely not effective head restraints for rear impact conditions unless they have been crash tested. In addition, some wheelchairs have a minimum height seatback component to allow the user to have better reach for daily activities; an example is shown below in Figure 9. Experience with examining rebound in voluntary frontal wheelchair impact tests suggests that wheelchairs with a top of seatback level below the dummy's scapula do not contain the dummy effectively on rebound, and would be expected to do the same in rear impact. Many people in wheelchairs who benefit from a low seatback can also effectively transfer to conventional vehicle seating.

Figure 9. Example of a manual wheelchair with low seatback.

Providing rear impact protection is complicated by the need to maintain a path to the wheelchair station for vehicles with rear entry/exit. A few commercial products [33,34] that provide vehicle-mounted head-and-back restraint for people seated in wheelchairs are available. For these devices to be effective the head and back support surfaces must be able to be located very close to the wheelchair users head and back. Some wheelchair designs do not allow this because they have structural features on the back of the wheelchair. For a system like this to be effective in a vehicle that transports many different people in wheelchairs, the challenge of placing the head and back restraint close enough to the occupant's head to be effective is even greater, because the system must account for the range in occupant positions resulting from the range in occupant and wheelchair sizes/designs as well as potential differences in occupant posture resulting from disabilities.

Rear-facing wheelchair stations on large buses include requirements for a padded backboard, as well as a forward panel to restrict movement. These types of structures might be considered potential solutions for restricting rearward occupant movement in a rear impact. However, they have not been assessed for use with small vehicles and must still be evaluated for occupant fit.

[33] https://www.amf-bruns-mobility.com/products/head-backrest/futuresafe
[34] https://www.paravan.com/product-solutions/securement-systems/paravan-head-and-back-rest

Locating Seatbelt Anchorages Relative to Wheelchair Stations

General recommendations

Minimizing the amount of webbing improves protection because shorter length allows less elongation.

Lap belt anchors should be located as close to the occupant's hip joint as possible while still allowing space to maneuver the wheelchair.

Recommended placement for lap belt anchors will provide a 45-degree angle relative to the occupant's hip joint; allowable range is 30 to 60 degrees relative to horizontal.

Recommended placement for shoulder belt anchors will route the belt centered over the occupant's shoulder. Closer to the neck also offers good protection if it does not cause discomfort.

A recent study of 44 manual wheelchairs and 28 power wheelchairs estimated the location of the hip joint center of a crash dummy seated in the wheelchair by digitizing pretest photos of WC19 tests. In these tests, the targeted angle of the rear 4-point strap tiedown is 45 degrees, the optimal recommended position. Using these data, the wheelchair station should be located fore-aft in the vehicle such that the H-point horizontal range shown in the figure overlaps with the H-point range of the vehicle seats that are removed to install a wheelchair station.

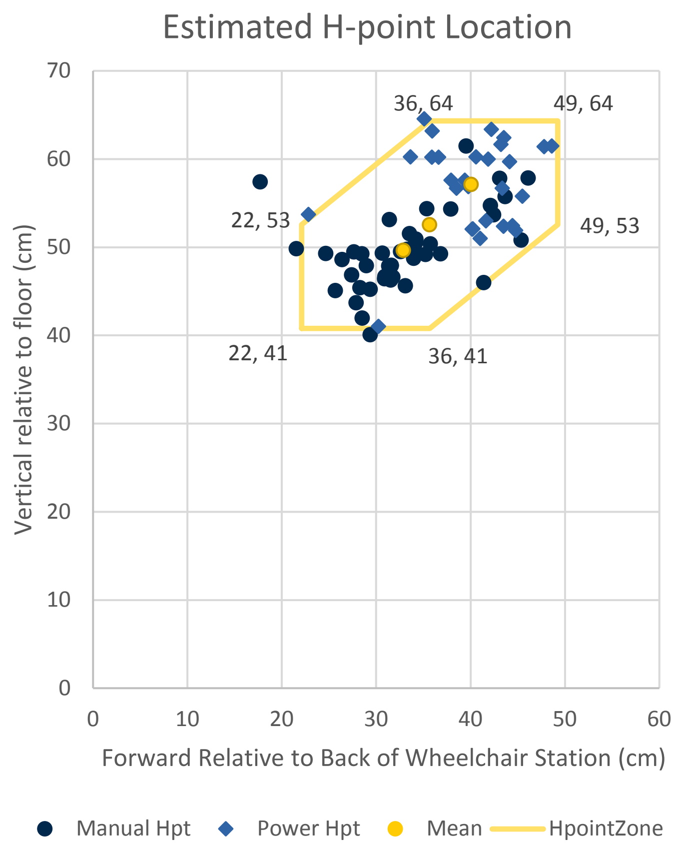

Figure 10. Estimated range of H-points for occupants seated in wheelchairs relative to rear boundary of wheelchair station.

Specific recommendations

When performing WC19 tests, the seatbelt D-ring is optimally located relative to the ATD seated in the wheelchair, so the test can focus on wheelchair performance. Ewing et al. (2010) performed an image analysis to digitize the optimal D-ring location from pretest photos of 342 wheelchairs. Since the goal of the study was to identify good locations for shoulder belt anchors on school buses, the dataset includes many pediatric wheelchairs. The origin is set to the fore-aft location of the rear tiedown floor anchors. A plot summarizing results is shown in Figure 11. The average vertical distance to the floor is 1285 mm (std 80 mm), while the average fore-aft distance is 178 mm (std 126 mm) forward of the rear tiedown. For a passenger vehicle application, locating the rear boundary of the wheelchair station 178 mm rearward of a vehicle-mounted D-ring location, would provide reasonable belt fit for a range of wheelchair sizes.

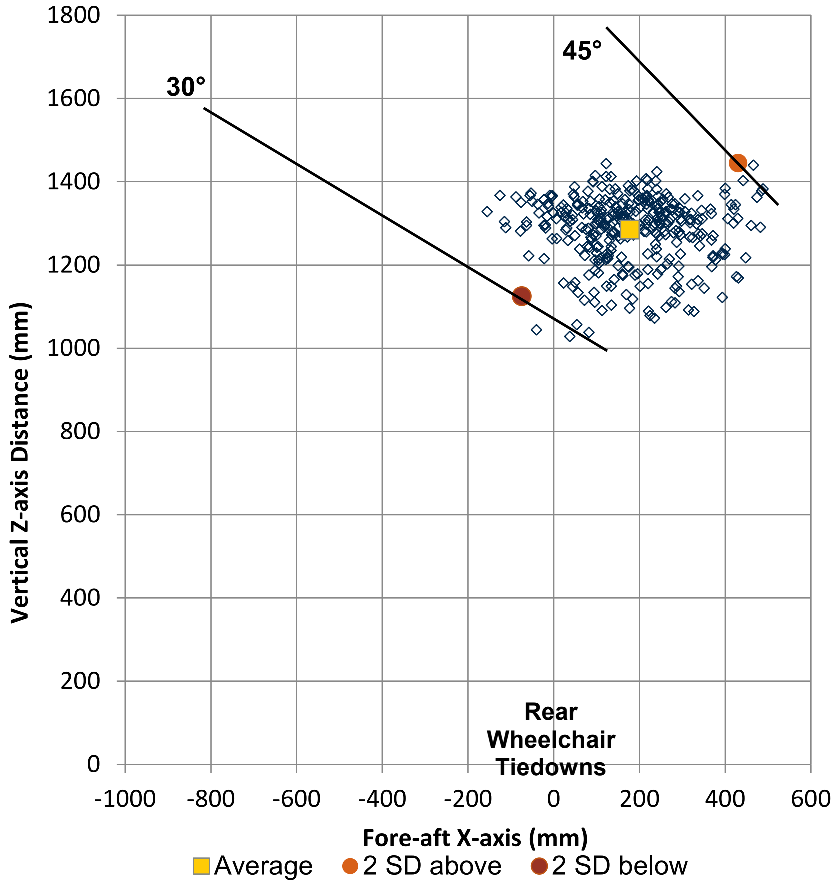

Figure 11. Optimal D-ring location measured from pretest photos of 342 wheelchair sled tests, with origin located at rear tiedown floor anchorage.

In 2021, UMTRI completed a NHTSA-sponsored research study to develop an automated wheelchair tiedown and occupant restraint system (Klinich et al. 2021). The project involved computational modeling, prototype construction, volunteer assessment, and dynamic testing. Recommendations for belt geometry for a wheelchair station are shown in Figure 12. The origin is on the floor, at the rear center boundary of the wheelchair station. The modeling performed in this study used the surrogate wheelchair base described in WC20. Restraint systems optimized for this fixture worked in a similar manner when they were evaluated with modeling and testing of a commercial and manual wheelchair. Because this study focused on optimal restraint for a midsized male, this belt geometry differs from the findings of Ewing et al. (2010) reported above.

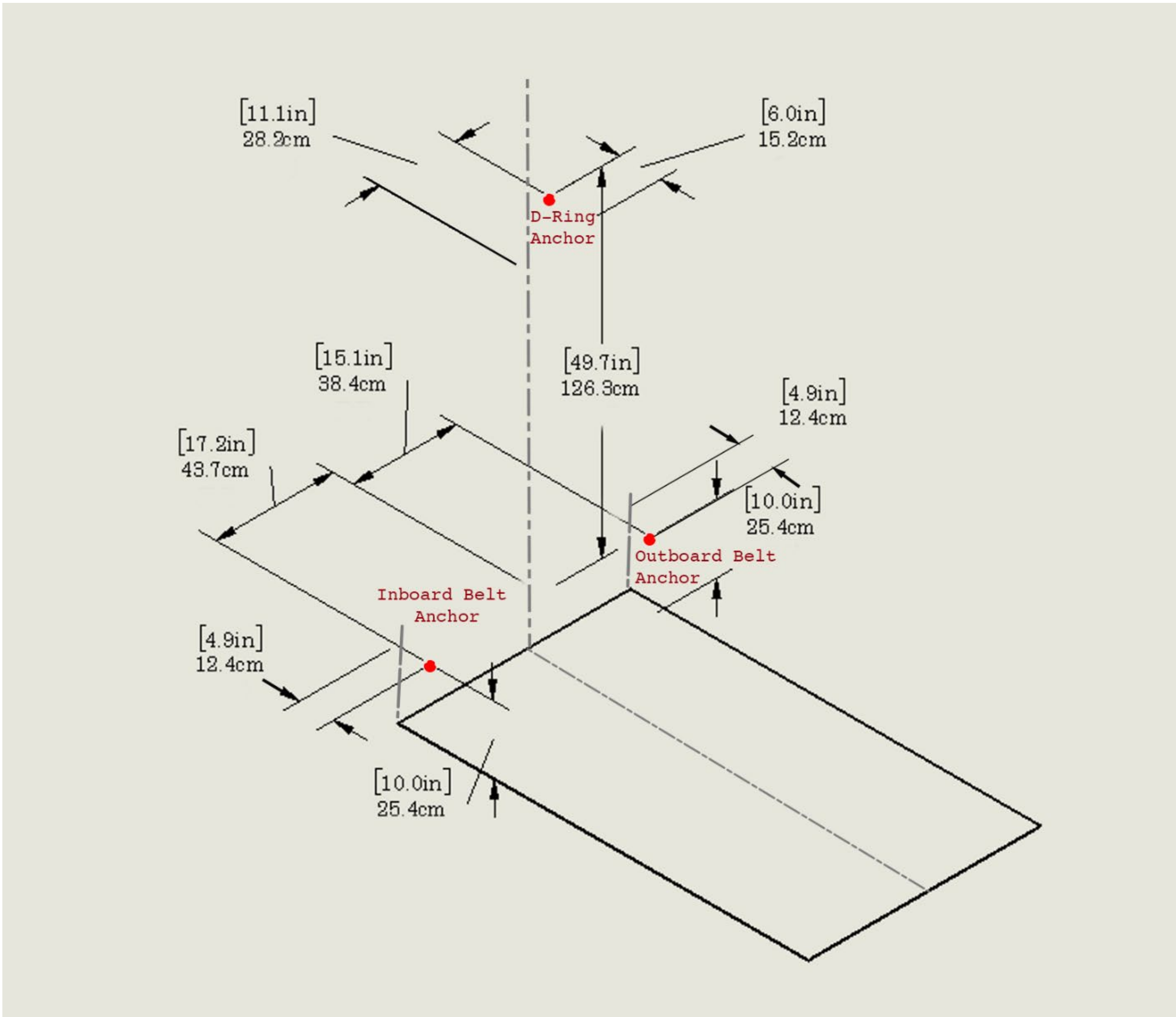

Figure 12. Illustration of recommended belt geometry from NHTSA AWTORS study.

Surfaces

Procedures

ISO 7176-13:1989 Wheelchairs-Part 13: Determination of coefficient of friction of test surfaces.

RESNA WC Vol 1 Section 13- Determination of coefficient of friction of test surfaces

Good[35]

- Openings
  - should be less than 0.625 in (16 mm) in width or length.
  - Elongated openings should be oriented with long direction aligned perpendicular to vehicle travel direction.
  - Exception 1: openings for wheelchair securement components can be up to 0.875 in (22 mm) wide if they contrast visually with floor.
  - Exception 2: Ramps can have one opening that is up to 1.5 in x 4.5 in (38 mm x 115 mm) for use as a handhold during manual operation.
- Surface discontinuities
  - up to 0.25 in (6.4 mm) are allowed
  - over 0.5 in (13 mm) are not allowed
  - between 0.25 in and 0.5in (6.4 and 13 mm) need a bevel with a slope of 45 degrees (slope1:2) or less

Better

- Floor surface material should have a coefficient of friction in the range of 0.65 to 0.8[36].
- Minimize number of floor transitions.
- Openings should be less than 0.5 in (13 mm) in width or length.[37]

Best

Floor surface material should have a coefficient of friction between 0.65 and 0.8 when wet and dry.

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[35] Architectural and Transportation Barriers Compliance Board, Dec. 14, 2016, Americans with Disabilities Act (ADA) Accessibility Guidelines for Transportation Vehicles, 36 CFR Part 1192 [Docket No. ATBCB 2010–0004] RIN 3014–AA38. T602.4, p. 90628, to meet minimum standards in 2021.

[36] RESNA. Wheelchair Containment and Occupant Retention Systems for Use in Large Accessible Transit Vehicles: Systems for Rear-ward-Facing Passengers; ANSI/RESNA WC-4:2017 Section 10; 2017; p. 12.

[37] Department of Justice. 2010. 2010 ADA Standards for Accessible Design, based on maximum openings in buildings.

Operable parts

Good

Controls should be located between 24-48 in (610-1220 mm) above floor.

For wheelchair spaces, controls need to be located between 24-36 in (610-915 mm) forward of the rearmost point of the wheelchair space, measured horizontally.

Controls need to be usable with one hand and shall not require tight grasping, pinching, or twisting of the wrist. Maximum force to activate components should be 5 lbf (22.2 N) or less.

Better

Occupants with limited dexterity benefit from controls that could be operated with a closed fist rather than fingers. An example of modifying recessed buttons with soft raised extensions is shown Figure 13.

Figure 13. Controller with flush buttons modified with soft raised extensions.

Best

Controlling operations through voice, smartphone, and/or tablet would be most accessible.

References

ADA/ADAAG

Architectural and Transportation Barriers Compliance Board, Dec. 14, 2016, Americans with Disabilities Act (ADA) Accessibility Guidelines for Transportation Vehicles, 36 CFR Part 1192 [Docket No. ATBCB 2010–0004] RIN 3014–AA38.

Department of Justice. 2010. 2010 ADA Standards for Accessible Design.

ANSI-RESNA Procedures

RESNA. Determination of Coefficient of Friction of Test Surfaces; ANSI/RESNA WC-1:2019 Section 13.

RESNA. Wheelchair Containment and Occupant Retention Systems for Use in Large Accessible Transit Vehicles: Systems for Rear-ward-Facing Passengers; ANSI/RESNA WC-4:2017 Section 10; 2017; pp. 1–42.

RESNA. Wheelchair Tiedown and Occupant Restraint Systems for Use in Motor Vehicles; ANSI/RESNA WC-4:2017 Section 18; 2017; pp. 1–93.

RESNA. Wheelchair used as Seats in Motor Vehicles; ANSI/RESNA WC-4:2017 Section 19; 2017; pp. 1–93.

RESNA. Wheelchair Seating Systems for Use in Motor Vehicles; ANSI/RESNA WC-4:2017 Section 20; 2017; pp. 1–58.

FMVSS Procedures

NHTSA (2016) Laboratory Test Procedure for FMVSS 201U: Occupant Protection in Interior Impact, Upper Interior Head Impact Protection,TP-201U-2.

NHTSA (2008) Laboratory Test Procedure for FMVSS 403 Platform Lift Systems for Vehicles TP-403-01

NHTSA (2005) Laboratory Test Procedure for FMVSS 404 Platform Lift Systems in Motor Vehicles TP-404-00

NHTSA (2007) Laboratory Test Procedure for FMVSS 209 Seat Belt Assemblies TP-209-8

NHTSA (1994) Laboratory Test Procedure for FMVSS 210 Seat Belt Assembly Anchorages TP-210-09

NHTSA (2011) Laboratory Test Procedure for FMVSS 222 School Bus Passenger Seating and Crash Protection TP-222-05, Appendix C

ISO Procedures

ISO 10865-1:2012(E), Wheelchair containment and occupant retention systems for accessible transport vehicles designed for use by both sitting and standing passengers — Part 1: Systems for rearward facing wheelchair-seated passengers, First Edition, June 5, 2012

ISO 7176-19 (2022), *Wheelchairs for Use as Seats in Motor Vehicles, Annex G*

SAE Procedures

SAE J1100_200911 Motor Vehicle Dimensions

Literature

Ewing KA, Manary MA, Schneider LW. (2010) Locations and Adjustment Ranges of Shoulder-Belt Upper Anchor Points Needed to Optimize Belt Fit on Wheelchair-Seated Students. RESNA Annual Conference Proceedings.

Hu J, Orton NR, Manary MA, Boyle KJ, Schneider LW. (2020) Should airbags be deactivated for wheelchair-seated drivers? *Traffic Inj Prev* 21, S37–S42.

Klinich KD, Manary MA, Boyle KJ, Orton NR, & Hu J. (2022) Development of an automated wheelchair tiedown and occupant restraint system for automated vehicles (Report No. DOT HS xxx xxx). National Highway Traffic Safety Administration.

Schneider LW, Manary MA, Orton NR, Hu J, Klinich KD. (2016) Wheelchair Occupant Studies. University of Michigan Transportation Research Institute

Steinfeld E, Paquet V, D'Souza CD, Joseph C, and Maisel J. (2010) Anthropometry of Wheeled Mobility Project. Buffalo, NY.

Appendix A: Relevant Federal Procedures

Lift Requirements

NHTSA provides a detailed illustrated test procedure for FMVSS 403/404 describing lift requirements.

Laboratory Test Procedure for FMVSS 403 Platform Lift Systems for Vehicles

Laboratory Test Procedure for FMVSS 404 Platform Lift Systems in Motor Vehicles

A summary is included below.

- Clear space test. Clear space on platform, measured 2 in (50 mm) above the surface, should be 30 in x 48 in x 30 in (762 mm x 1219 mm x 762 mm) or larger.
- Gap and slope measurement. When the lift is loaded with standard mass (272 kg/600 lb), there should be no gaps vertically between the ground and lift or between the vehicle and lift >0.25 in. No horizontal gaps >0.5 in. If there is a gap between 0.25-0.5 in the platform or vehicle surface slope can't exceed 1:2 ratio (26.6°). Above 13 mm gap, slope can't exceed 1:8 ratio (7.13°).
- Platform deflection measurement. Measured relative to the vehicle floor, the platform should deflect no more than 1.8° during the entire range of lift operation when unloaded. When loaded with 272 kg (600 lb), the platform should not deflect more than 3° from its unloaded position.
- Edge guard height. Edge guards must be at least 1.5 in high measured relative to the platform surface.
- Slip Resistance test. Minimum coefficient of friction is 0.65.
- Environmental test. Check component hardware resistance corrosion.
- Threshold warning signal test. Checks threshold warning system which is activated when one wheel is on the threshold area and the lift platform is more than 25 mm (1 in) below the vehicle floor.
- Test to determine occupancy of outer barrier and interlock function. This test determines compliance with two interlock requirements. The platform should stop if the wheelchair retention device is not deployed, and the platform is greater than 76 mm (3 in) off the ground. When the wheelchair retention device is in the form of an outer barrier, it assures that the outer barrier will not deploy when occupied by portions of the passenger's body or mobility aid.
- Test to determine occupancy of inner roll stop and interlock function. This test assures that the platform stops if the inner roll stop does not deploy when specified. It also assures that the inner roll stop will not deploy when occupied.
- Wheelchair retention device impact test. This is a dynamic test using the wheelchair test device, which measures the wheelchair retention device's ability to keep a wheelchair entirely on the platform surface.

- Inner roll-stop test. This is a dynamic test using the wheelchair test device, which measures the inner roll stop's ability to keep a wheelchair entirely on the platform surface.
- Static load tests. There are three static load tests, which test the strength of the lift structure. Static load I test requires that the lift be deployed, lowered (loaded), raised (unloaded), lowered (unloaded), raised loaded then stowed. This sequence is referred to partially or in its entirety as a test procedure for several requirements. It also must be repeated after the Static II test. The Static II test is a proof test. When the lift is loaded with three times the standard load (816 kg) for two minutes, it must not suffer separation, fracture or breakage and must remain operational after the test. The Static III test is the ultimate load test. When the lift is loaded with four times the standard load for two minutes, it must not suffer separation, fracture, or breakage. It is not required that the lift be operational after the Static III test.
- Fatigue endurance test. This test assures a minimum endurance of working parts by cycling the lift in a fashion that represents normal usage.
- Handrail test -Assures that handrails will not exhibit breakage or excessive deformation (>25 mm deflection) when loads similar to those experienced during normal usage are applied (445 N). Required to maintain 38 mm clearance from vehicle under load (no hand pinch points).
- Wheelchair retention device overload test. Tests for a minimum strength of the wheelchair retention device.

Head Impact Protection

Laboratory Test Procedure for FMVSS 201U: Occupant Protection in Interior Impact, Upper Interior Head Impact Protection

After using the procedure in Appendix E: Checking Zone for Potential Head Contact, potential head contact points should be assessed using the FMVSS 201U test Procedures.

Wheelchair Securement Anchorages and Devices

Laboratory Test Procedure for FMVSS 222 School Bus Passenger Seating and Crash Protection, Appendix C, summarized below

1. Attach a load application device to the wheelchair anchor point. Angle of applied load should range from 30 to 60 degrees relative to horizontal, and +/- 45 degrees relative to longitudinal. Direction of applied load should be forward for rear anchors and rearward for front anchors.
2. Apply a test force of 13,344 N, at a rate of not more than 133,440 N/s. The force should be achieved within 30 s, and held for 10 s.
3. Damage to the anchor/surrounding area is allowed if the force can be applied and maintained during the specified time.

Seatbelt Assemblies

Laboratory Test Procedure for FMVSS 209 Seat Belt Assemblies

Appendix B: Relevant Procedures from SAE, RESNA, ISO

Interior Dimensions

SAE J1100_200911: Motor Vehicle Dimensions

For use in measuring:

- Door width
- Door height

Surface friction

ISO 7176-13:1989 Wheelchairs-Part 13: Determination of coefficient of friction of test surfaces.

RESNA WC Vol 1 Section 13- Determination of coefficient of friction of test surfaces

In both procedures, the test method consists of drawing a given block at a defined speed over the test surface. The bottom side of the block is covered with a layer of standard rubber. RESNA WC1-13 (2019) was based on ISO 7176-13:1989 but updated to remove inconsistencies and specify different frictional requirements.

Wheelchair Displacement

This procedure specifies the equipment, test conditions and procedures for measuring the potential for undesirable lateral, forward, rearward, and rotational movement of an occupied wheelchair. This is done by simulating the maximum horizontal forces that may act on an occupied wheelchair during emergency driving maneuvers, and then measuring the wheelchair movement that has occurred.

The procedure uses the manual surrogate wheelchair (MSWC), scooter surrogate wheelchair (SSWC) and 75kg test dummy specified in ANSI/RESNA Vol-4: WC10. It requires a means to apply a horizontal load according to the table below through the combined center of gravity of the MSWC and test dummy (as defined in WC10). The test load is applied in both the longitudinal and lateral directions. The procedure also requires a means to measure the lateral, longitudinal, and rotational movements of the test wheelchair to an accuracy of $\pm$ 3mm and $\pm$ 1°, respectively.

Table 2. Test force and direction of application for measuring wheelchair displacement

Direction	Applied force on MSWC (kN)	Applied force on SSWC (kN)
Longitudinal towards front of vehicle	1.1	1.7
Longitudinal away from front of vehicle	0.34	0.5
Lateral	0.84	1.2

1) Secure the MSWC into the wheelchair passenger space using the wheelchair securement system according to the manufacturer's instructions. Leave the wheelchair brakes disengaged.
2) Locate the rear reference point (RRP) and front reference point (FRP) on the surrogate wheelchair per Annex D of WC10 and mark the initial positions on the floor using a plumb bob or laser indicator.
3) Apply a horizontal force of 1.1 kN through the combined CG of the MSWC and test dummy in the direction toward the front of the vehicle and hold the load for at least 3 seconds.
4) While test load is applied, mark and record the maximum movement of the RRP and FRP on the floor, as well as any tipping of the WC.
5) Repeat the test two more times to calculate an average maximum movement and/or rotation in any direction.
6) Repeat steps 2 through 5, but instead apply a force of 0.34 toward the rear of the vehicle.
7) Repeat steps 2 through 5, but instead apply a force of 0.84 laterally in one direction.
8) Repeat step 7, using the opposite lateral direction if space in the vehicle allows.

Figure 14. Demonstration photos of forward push test (left) and lateral pull test (right)

Appendix C: Ramp Strength

1. Move the vehicle to a flat, level surface with enough clear space for ramp deployment.

2. Deploy the ramp and extend to its full length. Measure the slope of the ramp at 4 equally spaced locations along the length of the ramp. If slope varies along length, measure the slope at the steepest location present for at least 250 mm of length.

3. Mark the midpoint along the ramp centerline from the transition point to the vehicle to the edge that meets the ground.

4. Place an open crate with a base exterior dimensions of 24 in x 24 in (610 mm x 610 mm) centered on the midpoint of the ramp as marked in step 3 and shown in Figure 15.

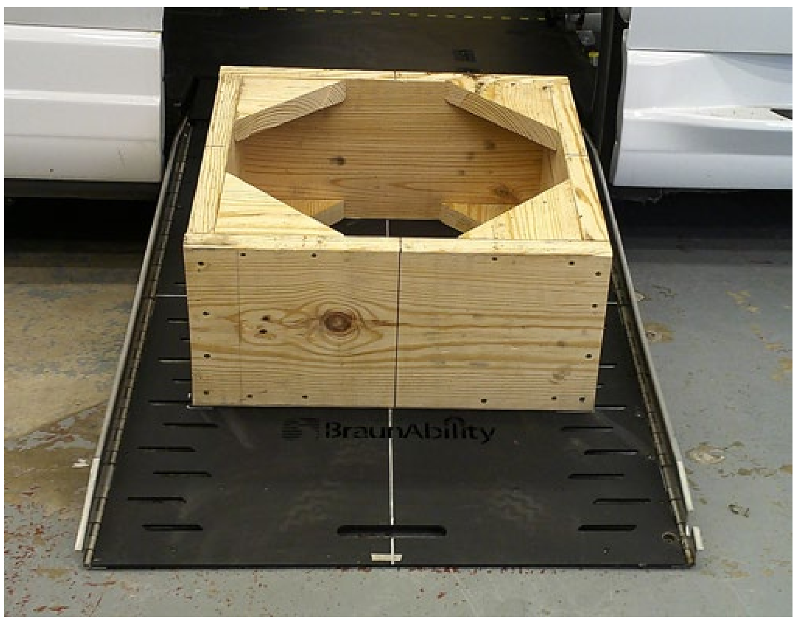

Figure 15. Placement of loading crate along ramp centerlines.

5. Using a hoist or other means, fill or load the crate with weights to achieve a static load of 1800 or 3000 lb (816 to 131 kg) to meet either the good or better recommendation with a factor of safety of at least 3. The higher load can be achieved by filling the crate with 100 bars of steel with external dimensions of 2 in x 2 in x 27 in (51 mm x 51 mm x 686 mm), each weighing approximately 31 lb (13.9 kg).

6. Measure the slope of the ramp at 4 equally spaced locations along the ramp length. Ramp should not deflect more than 3 degrees from original slope in either longitudinal or lateral direction.[38]

[38] Allowable deflection requirement specified for lift strength testing in FMVSS 403/404.

Figure 16. Demonstration of static ramp strength test procedure: applying static load through loading crate, and slope measurement before and after loading.

Appendix D: Wheelchair Positioning Procedure

Introduction

These procedures adapt the methods for evaluating wheelchair dynamic performance on a sled using the procedures of WC19 so they can be used to evaluate occupant protection systems in vehicles through computational modeling or vehicle crash testing. The WC19 procedures were inspired by FMVSS 208 seating procedures.

Like crash test dummies are used as human surrogates to design occupant restraint systems, two surrogates for wheelchairs are available when designing occupant restraint systems for wheelchairs. The surrogate wheelchair defined in WC18 for evaluating WTORS can be used to represent a wheelchair. The surrogate wheelchair was designed to provide a representative mass distribution and provides realistic loading to tiedown systems in frontal impacts. The disadvantage of using the surrogate wheelchair is that its closed armrest structures are not compatible with conventional vehicle seatbelts; removing the front of armrest structure or creating a 25-mm gap between the armrest and the seatback in models for testing would be a reasonable accommodation to allow its use. The surrogate wheelchair base defined in WC20 for evaluating seating systems could also be used to represent a wheelchair when used with a supplemental seating system.

Wheelchair Adjustment

1) For wheelchairs with seats that adjust from front-to-back, adjust to the midpoint of the range, or to the location recommended by the wheelchair manufacturer for the size of ATD being tested.
2) For wheelchairs with multiple anchor points for belt restraints, choose the midpoint of the range, or the location recommended by the wheelchair manufacturer for the size of ATD being tested.
3) If desired, replace electronic components with substitutes having the same dimensions, mass, and center of gravity. For batteries, electrolyte fluid can be replaced with water. Batteries or their substitutes should represent the heaviest allowed for use with the wheelchair.
4) Inflate tires to the midpoint of the manufacturer's suggested pressure range.
5) If using, install the wheelchair-anchored lap belt or 5-point harness.
6) For wheelchairs with reclining seatbacks, adjust the seatback angle to 10 degrees rearward of vertical, measured along the centerline of the unloaded seatback.
7) For wheelchairs with adjustable seat cushions, or tilt seating systems, adjust to 10 degrees above horizontal, measured at the centerline of the seat cushion.
8) Tighten and lock any adjustments according to manufacturer's directions.
9) Apply the wheelchair brakes if present.

Wheelchair Securement

When securing a wheelchair using commercial tiedowns, follow the WTORS manufacturers' instructions for use. The following directions are for use when securing a wheelchair using four surrogate wheelchair tiedowns, defined in WC19, in a vehicle or simulation.

1) Vehicle anchor points should be symmetric about the longitudinal centerline of the wheelchair station. The wheelchair centerline should be aligned with the longitudinal centerline of the wheelchair station within +/- 3 degrees.
2) The fore-aft distance between front and rear anchor points should be 1220 +/- 12 mm (48 +/-0.5 in). An alternative fore-aft distance of 1296 +/- 12 mm (51 in +/- 0.5) is allowed to accommodate larger wheelchairs (or if trying to comply with ISO test procedures).
3) Laterally, the rear anchor points should be within +/- 25 mm of the rear securement points on the wheelchair.
4) Laterally, the front anchor points should be aligned with or outboard relative to the front securement points on the wheelchair. Lateral distance should range from 300 to 760 mm (12 to 30 in).
5) Adjust the surrogate tiedown length to 495 mm (19.5 in). Attach the surrogate tiedowns to the four securement points on the wheelchair. With the rear tiedowns taut, measure the side-view angle of the rear tiedown straps between the anchor points on the floor and the hooks at the wheelchair.
    a. If the angle is below 45 degrees, the strap adjustment is complete.
    b. If this angle is above 45 degrees, lengthen the rear tiedown straps until the tiedown straps are within 45 +/- 3 degrees when secured to the rear anchor points.
6) When the desired length is achieved, tension the front tiedown using the ratchet mechanisms to a tension between 100 and 200 N (22 to 44 lbf).

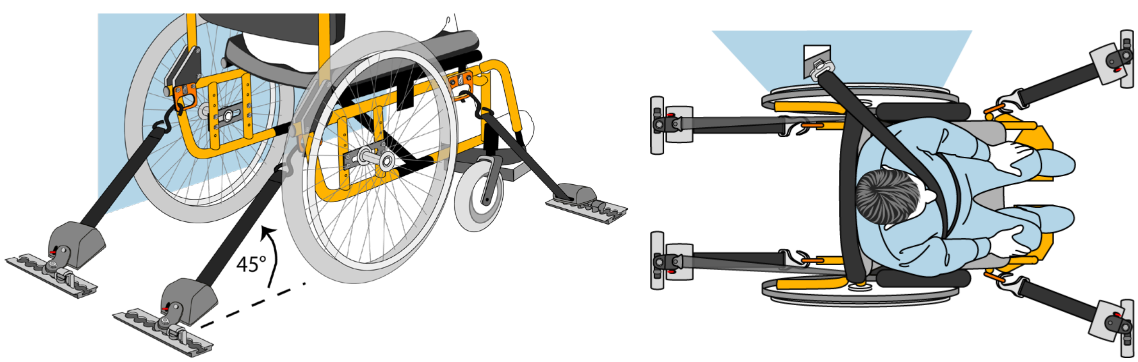

Figure 17. Illustration of ideal sideview tiedown angle between 30-45 degrees and lateral positions of tiedowns.

ATD Positioning

1) Adjust joints of ATD to 1 g setting as directed in ATD user's manual. The ATD should wear snug fitting cotton clothing as specified in federal standards for crash testing.

2) Position the ATD in the wheelchair sitting upright and symmetrically about the wheelchair longitudinal centerline. The back of the pelvis/buttocks should be as close as possible to the bottom of the back support.
3) Position the feet on the footrests.
4) Place the elbows on the wheelchair arm supports (if provided) and prop the hands on the ATD thighs, so that the upper torso is supported in an upright position.
5) Place high-contrast targets on the ATD's knee joint and head CG.

Seatbelt Placement using Add-On Occupant Restraints

1) Attach the floor anchorages of the seatbelt restraint to the floor so that they are located longitudinally between the rear tiedown anchorages and the wheelchair and laterally within 50 mm (2 in) of the wheelchair side frames to achieve sideview pelvic-belt angles between 30° and 75° to the horizontal.
2) The lap belt should be placed low across the front of the pelvis on the upper thighs, not on the abdomen. When possible, the lap belt should be angled between 45° and 75° to the horizontal when viewed from the side. Some wheelchair features, like armrests, can interfere with good belt fit. To avoid placing the lap belt over the armrest and to keep the lap belt low on the pelvis, it may be necessary to pivot the armrests out of position, insert the belt between the armrest and the seatback, or through openings between the backrest and seat.

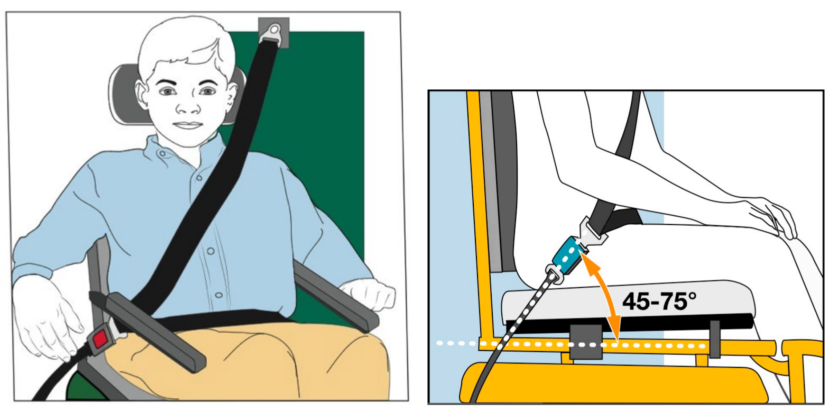

Figure 18. Illustration of recommended belt fit.

3) The diagonal shoulder belt should cross the middle of the shoulder and the center of the chest, and should connect to the lap belt near the hip of the wheelchair rider. The upper shoulder-belt anchor point or guide should be anchored above and behind the top of the occupant's shoulder, so that the belt is in good contact with the shoulder and chest while traveling. A side-view angle of 30° ± 5° is achieved with the anchor point located 300 mm ± 15 mm (11.8 in. ± 0.6 in.) behind and 173 mm ± 15 mm (6.9 in. ± 0.6 in.) above the top of the ATD's shoulder.

Requirements after dynamic testing/simulation

The wheelchair should be in an upright position.

The ATD should be in an upright seated posture, meaning that that the torso leans less than 45 degrees from vertical when viewed from any direction.

IARVs for ATDs seated in wheelchairs should meet those used with the same IARVs used with ATDs seated in vehicle seats.

Fore-aft excursions of the wheelchair point P, ATD knee center, ATD front of the head (forward), and ATD back of the head (rearward) should be calculated according to WC19 specifications and fall within required limits provided for each ATD size.

Appendix E: Checking Zone for Potential Head Contact

As mentioned in Wheelchair Spaces, the station should be positioned to minimize chance for head contact with structures. In addition, stowed ramps and lifts should be placed relative to the wheelchair station and other vehicle seats to minimize the chance for head contact with the ramps or lifts. If potential for head contact exists using this procedure, the components should be designed to pass the requirements of FMVSS 201U.

Figure 18 shows a drawing of the head contact tool from the 1989 version of the FMVSS 201 test procedure, while Figure 19 shows a photo of an adapted version of the tool with an adjustable base that replaces the vehicle seat and allows placement of the tool within an unoccupied wheelchair seating station. The height of the base can be adjusted from 41 to 64 cm, representing the estimated range of H-point heights relative to ground based on image analysis of 72 wheelchairs. The base can be placed at different fore-aft locations of the seating station to represent the range of estimated H-point fore-aft locations relative to the rear of the seating stations, estimated to range from 22 to 49 cm forward of the rear of the wheelchair station. The adjustable arm is attached to the base with a rotating joint. The arm length adjusts from 29 to 33 in (34 to 864 mm), representing the seated height range from small female to large male. The 6.5 in (165 mm) diameter hemisphere represents a headform.

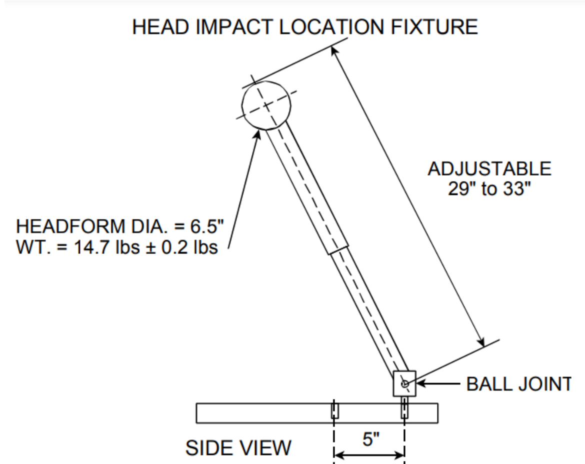

Figure 19. Diagram of head contact tool from 1989 FMVSS 201 procedure.

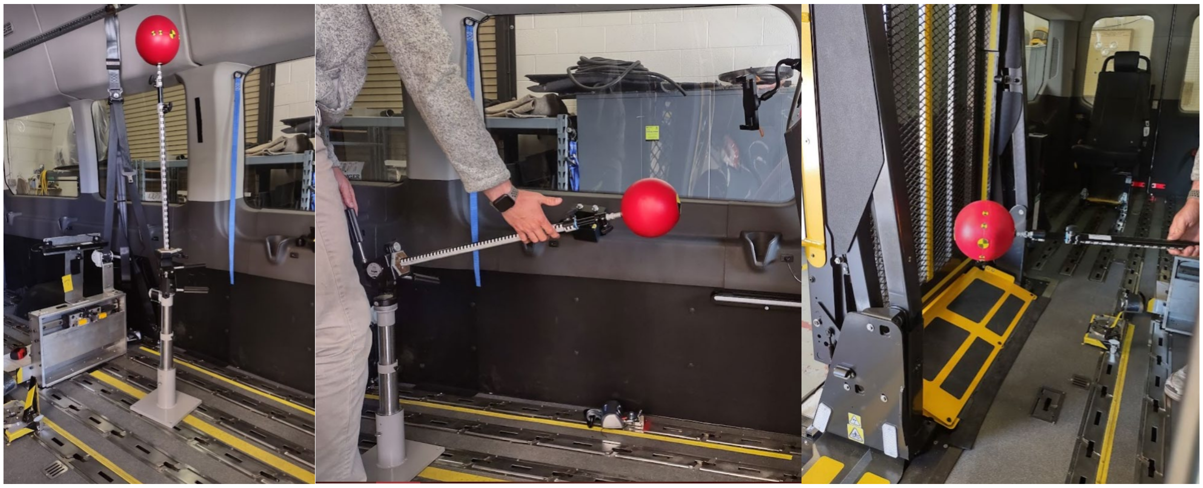

Figure 20. Photos demonstrating use of adapted tool, set to the forward-high location of the wheelchair station (left). When the upper component is adjusted to the longest setting, it would not contact the forward panel behind the driver (center) or the stowed wheelchair lift (right).

The Potential Head Contact area is defined as any nonglazed surface inside the vehicle that are contactable with the tool using the following procedure (or its graphical equivalent using computer aided design.)

1. The procedure should be repeated with the base placed on the lateral centerline of the wheelchair station, in four configurations: rear+low, rear+high, forward+low, forward+high, with the points based on the zone specified in Figure 20. An alternative option would be to check at six locations corresponding to the vertices of the estimated H-point zone shown in Figure 20.

2. Determine all contact points forward of the base location above the base height using the pivot point to “top-of-head” dimension allowed by the device and the interior dimensions of the vehicle. Potential contacts should be checked using the lowest (29 in [74 cm]) and highest (33 in [84 cm]) settings of the upper adjustable component.

3. The procedure can be performed virtually.

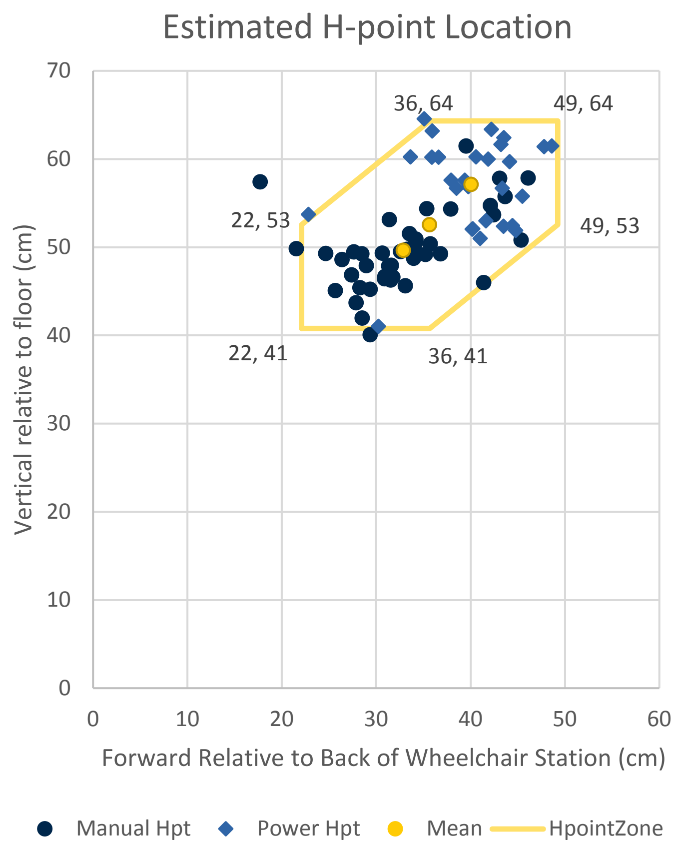

Figure 21. Estimated range of H-points for occupants seated in wheelchairs relative to rear boundary of wheelchair station.

Appendix F: Checklist for vehicles <25 feet

Topic	Specific	Measurement	Good	Better	Best
Ingress/egress	Number of accessible entrances		1	2	
Doorways	Height at center		56 in	60 in	65 in
Doorways	Width		32 in	34 in	36 in
Doorway	Threshold marked with 1” wide contrast strip		present		
Ramp	Width		30 in	34 in	36 in
Ramp	Edge guard height		2 in	>2 in	>>2 in
Ramp	Edge guard distance to end		3 in		
Ramp	Maximum slope		9.5 deg	6 deg	4.8 deg
Ramp	Perimeter striping 1 in wide		Present		
Ramp	Longitudinal striping 1 in wide			Present	
Ramp	Gap to vehicle		<5/8”		
Ramp	Static test load		1800 lb	3000 lb	
HSH	Seatback handhold OD		0.875 to 2 in		
HSH	Round handrail stanchion OD		1.25 to 2 in	1.24 to 1.4 in	
HSH	Non-round handrail perimeter		4 to 6.25 in		
HSH	Non-round handrail cross section		2.25 in	1.24 to 1.4 in	
HSH	Minimum clearance		≥ 1.5 in		
Access routes	Width of aisle			34 in	36 in
Access routes	Wheelchair station fits within circle size			54 in	60 in
Wheelchair Space Dimensions	Width		30 in	32 in	34 in
Wheelchair Space Dimensions	Length		48 in	54 in	60 in
Wheelchair Space Dimensions	Height			60 in	65 in

Appendix G: Recommended Reading

RideSafe Brochure

Development of an Automated Vehicle Tiedown and Occupant Restraint System for Occupants Seated in Wheelchairs

National Aging and Disability Center Toolkit for the Assessment of Bus Stop Accessibility and Safety

National Academies of Science, Engineering and Medicine (2021) Special Report 341: Technical Feasibility of a Wheelchair Securement Concept for Airline Travel: A Preliminary Assessment

Appendix H: Highlights from Literature

Karen L. Frost, Gina Bertocci & Craig Smalley (2020) Ramps remain a barrier to safe wheelchair user transit bus ingress/egress, Disability and Rehabilitation: Assistive Technology, 15:6, 629-636, DOI: 10.1080/17483107.2019.1604824

Frost et al. 2020 reports that ramp slopes become too steep if operators do not "kneel" the vehicle before deploying the ramp, or deploy the ramp to the street rather than to curb/sidewalk. They also report problems in navigating the threshold of the ramp if it is worn, deployed to an uneven surface, or have ice build-up. Wet or snowy ramps can decrease friction and increase difficulty.

Auto Alliance. 2019. AVs and Increased Accessibility.

The Auto Alliance organized a 3-workshop series to address automated vehicles and accessibility, including legal and policy issues. To ensure that AVs are accessible for people with disabilities, collaboration will be needed among users, vehicle manufacturers, AV designers, wheelchair manufacturers, assistive device manufacturers, and government agencies. They provide a summary of inclusive design considerations that could be a starting point for best practice guidelines for AV design, and recommend that people with disabilities be consulted throughout the design process. Additional regulatory guidance beyond that provided by the ADA and Access board would be useful. No current production wheelchair tiedown systems are suitable for use in AVs, and additional research is needed to develop a feasible automated WTORS. Wider use of crashworthy wheelchairs is limited by current policies regarding insurance reimbursement of transit features on wheelchairs.

United States Department of Transportation. 2018. U.S. Department of Transportation Public Listening Summit on Automated Vehicle Policy Summary Report.

Part of the Public Listening Summit on Automated Vehicles hosted by the US Department of Transportation addressed disability and accessibility concerns. Clearer guidance on accessibility requirements for AVs are needed. They pointed out that different types of disabilities (vision, hearing, cognitive, or mobility) may require different accommodations. They noted that standardization of auxiliary mobility aides, such as wheelchair lifts or accessible displays, would facilitate use of vehicles where a human driver is not present.

Bayless, Steven H. and Sara Davidson. 2019. *Driverless Cars and Accessibility*.

The Intelligent Transportation Society of America published a report on Driverless Cars and Accessibility: Designing the Future of Transportation for People with Disabilities. Fully automated vehicles offer people with disabilities new opportunities for independent access to employment, health care, and education. Deployment of AVs could potentially increase annual vehicle miles traveled substantially, as AARP estimates that up to one-third of people in the US do not currently drive. AVs would be beneficial to people with temporary disabilities, and may allow older people to remain in their homes longer. While technologies are available that would allow people with different types of disabilities use an AV, standards and best practice recommendations would be welcome. Strategies for dealing with emergency situations is a key issue, as well as other non-driving tasks typically handled by a driver (ingress/egress, passenger monitoring.) Additional infrastructure is needed to accommodate people before and after they travel in an AV. Deployment of AVs may change the transportation system, reducing private vehicle ownership and increasing ride-sharing opportunities. Collaboration among a wide range of stakeholders will be needed to ensure that future transportation options are available to everyone.

Claypool, Henry, Amitai Bin-nun, and Jeffrey Gerlach. 2017. Self-Driving Cars: The Impact On People With Disabilities.

A white paper discussing the impact that self-driving cars could have on the lives of people with disabilities (Claypool, Bin-nun, and Gerlach 2017) indicates that approximately 6 million Americans with disabilities have trouble accessing the transportation they need. Limited transportation options can result in reduced economic opportunities, isolation, and diminished quality of life. Improving transportation options for people with disabilities could lead to greater employment and substantial savings from fewer missed medical appointments. As automated vehicles are introduced to the fleet, service providers and manufacturers need to ensure that the needs of people with disabilities are considered in their design.

Klinich KD, Manary MA, Orton NR, Boyle KB, Hu J (2022) A Literature Review of Wheelchair Transportation Safety Relevant to Automated Vehicles. *International Journal of Environmental Research and Public Health.* 19(3):1633.

This literature review summarizes wheelchair transportation safety, focusing on areas pertinent to designing automated vehicles (AVs) so they can accommodate people who remain seated in their wheelchairs for travel. In these situations, it is necessary to secure the wheelchair to the vehicle and provide occupant protection with a Wheelchair Tiedown and Occupant Restraint System (WTORS). For this population to use AVs, a WTORS must be crashworthy for use in smaller vehicles, able to be used independently, and adaptable for a wide range of wheelchair types. Currently available WTORS do not have these characteristics, but a universal docking interface geometry and prototype automatic seatbelt donning systems have been developed. In the absence of government regulations that address this situation, RESNA and ISO have developed voluntary industry standards to define design and performance criteria to achieve occupant protection levels for wheelchair-seated passengers that are similar to those provided by conventional vehicle seats.

Ewing KA, Manary MA, Schneider LW. (2010) Locations and Adjustment Ranges of Shoulder-Belt Upper Anchor Points Needed to Optimize Belt Fit on Wheelchair-Seated Students. RESNA Annual Conference Proceedings.

Achieving proper fit of the shoulder-belt for the wide range of students who remain in their wheelchairs during transport in school buses requires adjustability of the location of the upper shoulder-belt anchor point. In this study, optimal upper shoulder-belt anchor point locations from 342 wheelchair frontal-impact sled tests conducted in accordance with ANSI/RESNA WC19 were used to determine the fore-aft adjustment ranges needed to achieve proper shoulder-belt fit in two bus configurations. The range of preferred locations for the upper shoulder-belt anchor point runs from approximately 737 mm (29 in) behind the rear wheelchair tiedown anchor points to 508 mm (20 in) forward of the rear tiedown anchor point, depending on the height of the bus windows where these anchor points are typically installed.

Appendix I: Additional Resources

Travelsafer.org

Inclusive Design Reference Hub

We Will Ride

The Autonomous Vehicle Alliance Roadmap Project

The Autonomous Vehicle Industry Association (AVIA)

App for checking how signs/markings/instructions appear to someone who is color blind:

https://play.google.com/store/apps/details?id=asada0.android.cvsimulator&hl=en_US&gl=US

https://apps.apple.com/us/app/chromatic-vision-simulator/id389310222