

Crashworthiness of WC19 Wheelchairs in Horizontal Dynamic Aircraft Seating Tests

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Abstract

At present, commercial air travel rules do not allow people to sit in their own wheelchairs during flight. However, airline seating often does not meet medical needs. In response to current requests to allow this seating option, we researched the crashworthiness and safety of wheelchairs for potential use in aircraft. For motor vehicle travel, many wheelchairs meet voluntary standards for crashworthiness and safety per RESNA WC19. This project assesses whether WC19-compliant wheelchairs can meet FAA aircraft seating standards when secured using 4-point tiedowns. For the FAA horizontal impact testing, computer modeling indicated that a trapezoidal sled pulse was sufficient to represent the more typical triangular pulse, and that due to the flexibility of the tiedown webbing, the effect of the simulated pitch/roll element was minimal. During the initial two horizontal impact tests, fracture of the left front wheelchair caster was observed. The remaining five wheelchairs were tested with an added vehicle-mounted lap belt and were successful at meeting occupant retention and structural integrity requirements. The outcomes show that it may be possible for people to remain seated in a WC19-compliant wheelchair for air travel without a significant decrement in safety.

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Introduction

People who use wheelchairs number about 5.5 million in the US population, but wheelchairs are not permitted for use as seats on commercial aircraft. Conventional aircraft seating often cannot meet the medical needs, like skin pressure management and postural support, which many wheelchair users require [1]. Some wheelchair users transfer to airline seating and have their wheelchairs transported as checked baggage, often resulting in damage. There is also a social stigma attached to the process of boarding separately, transferring, and receiving assistance to transfer to an aircraft seat. The US Access Board held a public listening session in December 2021, and many wheelchair users reported being dropped during transfer to the aircraft seat. One wheelchair user and disability activist died in November of 2021 from injuries caused by the absence of her bespoke wheelchair due to damage sustained during transport in an aircraft cargo hold [2].

The Americans with Disabilities Act [3] and the US Access Board's Americans with Disabilities Act Accessibility Guidelines (ADAAG) [4] mandate that public transportation is accessible to people with disabilities. The ADA covers airports, but aircraft are not subject to the rules and the accommodations of other forms of public transportation because the application of the accessibility requirement was deemed too difficult. The successful accommodation of wheelchair users in other modes of public transportation has ignited interest in allowing people to fly while seated in their wheelchairs. The Federal Aviation Administration (FAA) Reauthorization Act of 2018 directed the US Access Board to assess the technical feasibility of accommodating wheelchairs onboard aircraft. This resulted in a National Academy of Sciences (NAS) project to address the questions [1].

A 12-member NAS committee was assembled to gather, research, and report relevant information. They listened to testimony from federal agencies, wheelchair and wheelchair tiedown makers, aircraft and aircraft interior designers, flight attendants and pilots, proponents of disability rights, airline companies, industry trade associations, and consumer groups. Several stakeholders were wheelchair users with first-hand experience with travel difficulties, damaged wheelchairs, and injuries resulting from aircraft travel.

The NAS panel work focused on technical feasibility in four key areas: doorway openings, interior maneuvering space, aircraft floor strength, and suitability of wheelchairs as aircraft seats. The panel concluded that the majority of transport aircraft doors would allow ingress/egress of most commercial wheelchairs. Aircraft aisle widths are generally narrower than those of common wheelchairs, so wheelchair spaces would need to be adjacent to doorways. One considered scenario noted that a wheelchair space would likely take up two rows of conventional aircraft seats, and that the displaced mass of the seats

and passengers would exceed the mass of a single person and a heavy power wheelchair, resulting in sufficient floor strength to manage the crash load of the system. Additionally, a two-row space would allow room for the wheelchair user to enter and occupy the space with enough clearance for a wheelchair securement system.

The NAS panel report observes that wheelchairs meeting voluntary WC19 crashworthiness standards for use as seats in motor vehicles have four dedicated securement brackets for attaching tiedown straps in standardized locations, and provide the option for a crashworthy, wheelchair-anchored, lap belt. Additionally, the WC19 frontal impact test is similar to, but more severe than, the FAA horizontal impact test mandated for aircraft seating. However, the suitability of the WC19-compliant wheelchairs to comply with the FAA vertical crashworthiness and flammability criteria was noted as uncertain. The NAS committee concluded that traveling on an aircraft while seated in a wheelchair was technically achievable. The report suggested testing of WC19 wheelchairs per the horizontal impact criteria as a next step.

Performance requirements for seating in transport aircraft are prescribed in Title 14 Part 25 of the Code of Federal Regulation [5] Sections 25.561 and 25.562. Section 25.562 includes dynamic horizontal and vertical impact tests, which approximate loading conditions that may occur under potential crash scenarios. These tests employ an instrumented midsize male anthropomorphic test device (ATD), or crash test dummy, representing a nominal aircraft seat occupant that is restrained by a lap belt. The frontal (horizontal) impact test is performed with the seat rotated at 10° to the left or right relative to the impact direction. The horizontal deceleration pulse is 16 g achieved within a 90 ms window that is associated with a change in velocity of at least 48.2 km/h. This test also simulates floor deformation. The results verify the strength of the seat and the risk of injury from interacting with the plane's interior. To pass, the seating cannot deform in a way that blocks evacuation. The ATD measures head acceleration and femur compression, which are used to evaluate injury potential. CFR 25.562 also mandates that "items of mass" cannot shift or break free.

In addition to the standard, FAA Advisory Circular 25.562-1B, entitled "Dynamic Evaluation of Seat Restraint Systems and Occupant Protection on Transport Airplanes/with Change 1" [6], outlines considerations and details regarding methods of testing to the standard. SAE Aerospace Standard AS8049D, "Performance Standard for Seats in Civil Rotorcraft, Transport Aircraft, and General Aviation Aircraft," provides added insight on how to test aircraft seats to meet FAA regulation [7]; Seat Type A-T used in Transport Airplanes and addressed in 14 CFR part 25 is relevant for the current work. Section 3.5 establishes protocols for recoding deformations post-test and gives added information for the two dynamic test conditions. The ideal impact pulse shapes for these standards are isosceles triangles. The standard gives examples of

methods for simulating floor deformation, an ATD positioning procedure, and clarifies the conditions when HIC should be calculated [limited to tests where the head strikes a forward bulkhead with the distance from the Seating Reference point to the bulkhead of less than 107 cm (42 in.)].

The Rehabilitation Engineering Society of North America (RESNA) developed a set of industry standards that set forth methods to quantify, define, design, and test wheelchairs along with wheelchair components. These standards are developed under the rules of the American National Standards Institute (ANSI) and include RESNA Volume 4 Section:18 “Wheelchair Tiedowns and Occupant Restraint Systems (WTORS)” (aka WC18) [8] and RESNA Volume 4 Section:19 “Wheelchairs used as Seats in Motor Vehicles” (aka WC19) [9]. Similar global standards exist from the International Organization for Standardization (ISO) that are designated as ISO 10542-1 and ISO 7176-19, respectively. A salient difference between WC19 and ISO 7176-19 is that only WC19 requires testing with a wheelchair-mounted crashworthy lap belt. The standards include test methods for frontal and rear impacts. To meet best-practice guidance for traveling seated in a wheelchair, a person needs to have a WC19-compliant wheelchair and a full WTORS.

For wheelchair users traveling as passengers in minivans, vans, or modes of public transportation, the most widely used tiedown method for securing the wheelchair to the vehicle is a 4-point tiedown system. This uses four straps that are anchored to reinforced points on the vehicle floor and hooked onto the wheelchair frame. The floor track hardware used in vehicles is similar to the track hardware used on aircraft. The 4-point tiedown allows a single WTORS to secure a wide range of wheelchair sizes/types. WC19 wheelchairs have labeled securement brackets for use with the tiedowns. An attendant typically secures the passengers' wheelchairs to the vehicle with the four straps. If the passenger is in a non-WC19-compliant wheelchair, the tiedown hooks should attach to the frame of the wheelchair. If a wheelchair were permitted as aircraft seating, airport or flight personnel would need to assist with securement.

Seatbelt fit for wheelchair seated passengers is often compromised by other wheelchair features, such as armrests that interfere with the lap belt contact low on the pelvis. WC19 offers a solution by requiring wheelchairs to offer the option of a wheelchair-anchored, crashworthy lap belt that has a standard interface to connect with a vehicle-mounted shoulder belt. While available, few people choose to purchase this feature. However, the NAS report identified crash-tested lap belts attached to the wheelchair as the most workable option for using wheelchairs as aircraft seating.

This project evaluated whether WC19-compliant wheelchairs could pass the FAA horizontal impact test requirements. This article describes how the aircraft seating test methods were adapted for use with

wheelchairs and provides test results for WC19 wheelchairs under FAA horizontal dynamic testing requirements for aircraft seating. More in-depth information on these methods and results is reported by Klinich et al. [10].

Methods

Steps needed to adapt FAA seating crashworthiness protocols for testing wheelchairs include defining wheelchair securement methods, estimating wheelchair station geometry to determine whether bulkhead representation is needed, evaluating the effect of sled pulse shape, and assessing the need for yaw, pitch, and roll simulation.

Wheelchair Securement

Established best practices for securing wheelchairs [11] specifies that the wheelchair should face forward, toward the primary direction of vehicle travel. The sideview angle of the rear tiedown straps should be between 30° and 45°, and the tiedowns should extend straight back from the rear securement brackets, parallel to the wheelchair centerline. The front straps should be anchored forward of, and spaced slightly wider than, the front wheelchair securement brackets, to increase stability. These recommendations are similar to the tiedown configurations used in WC18 and WC19 testing. For this testing we used the same tiedown geometry specified in WC19 protocols when testing to the FAA procedures. The specific language prescribed for securing wheelchairs with tiedowns for testing per WC19 [9] includes methods for adjustments and tension settings that were used during testing. The tests for this project were conducted with the surrogate 4-point tiedowns used to test wheelchairs to WC19.

Implementation of the tiedown geometry typically used in motor vehicles is based on a wheelchair station footprint of 760 mm (30 in.) wide and 1220 mm (48 in.) long. Because space is at a premium in the aircraft cabin, we used computer modeling (MADYMO, Siemens, Inc.) to evaluate the effects of a more compact wheelchair station footprint where the tiedowns were anchored to the floor directly below the wheelchair securement points. A previously validated model of a surrogate wheelchair base fixture was used in simulations [12] using a triangular sled pulse (16 g, 90 ms, delta V of 48.2 km/h). [Figure 1](#) compares peak forward occupant and wheelchair excursion at $t = 180$ ms under frontal loading between the two tiedown geometries. The wheelchair and Hybrid III midsized male ATD move forward substantially more with vertical tiedowns compared to the best-practice tiedown configuration. Peak rear tiedown tension values increase with the more vertical tiedown orientation from 14–17 kN to 19–20 kN, while lap belt loads increase from 9 to 11 kN.

FIGURE 1 Comparison of excursions under frontal loading conditions for recommended (red) and vertical (blue) tiedown geometry at 180 ms.



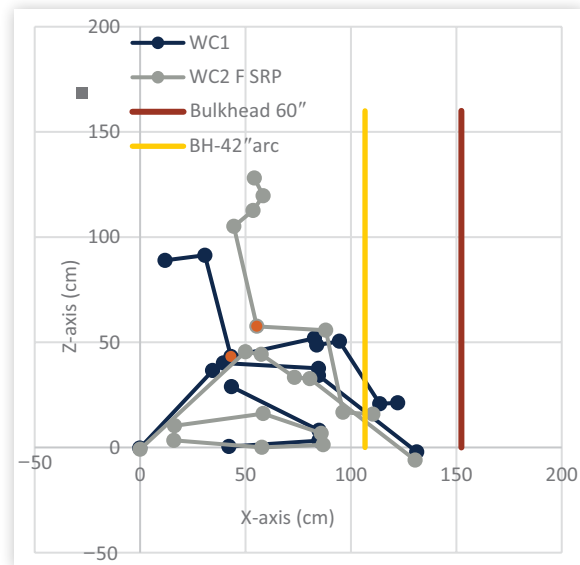
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Wheelchair Station Location and Potential Occupant Contact with Bulkhead

To comply with the ADA, a wheelchair station should measure 760 mm (30 in.) wide and 1220 mm (48 in.) long to accommodate most wheelchairs [14]. In buildings, the recommended size for alcoves (an area recessed into a wall) is 864 mm (34 in.) wide and 1524 mm (60 in.) long [15]. The ADA does not specify if the tiedown systems are within or outside the space. FAA Advisory Circular 25.562-1B [6] notes that seats that could be located adjacent to a bulkhead should be tested with a simulated bulkhead if the space between the SRP of the seat and the bulkhead is less than 102 cm (42 in.). If contact with the bulkhead occurs, femur loads and ATD HIC (head injury criteria) should be documented. We analyzed whether a bulkhead representation should be included in our horizontal dynamic test fixture for wheelchair testing and where to locate the wheelchair within the wheelchair station. We used available data from commercial wheelchairs previously assessed at UMTRI using WC19 test procedures. In a previous effort, landmarks were digitized on sideview photos of 75 different wheelchairs. Landmarks include the most rearward wheelchair points above and below the seatpan, the most forward point, the center and floor contact points for each set of wheels (2 or 3 pairs), an estimation of the P-point, the seat bight location (junction of the seat cushion and seatback), and locations of the rear and front securement brackets on the wheelchair frame.

Based on the methods in SAE AS6909, the bight of an occupied wheelchair was used as the SRP. With the origin set to the rearmost point on the wheelchair, the location of the bight in the X-axis ranges from 9 to 55 cm and the mean value is 29 cm for the 75 wheelchairs measured. The manual wheelchair in Figure 2 has a bight located near the average x-value, while the power

FIGURE 2 Tested geometry with tiedowns located at rear of station, bulkhead located 152 cm (60 in.) forward, indicating that the average SRP would be rearward of the 107 cm (42 in.) arc requiring representation of bulkhead during testing.



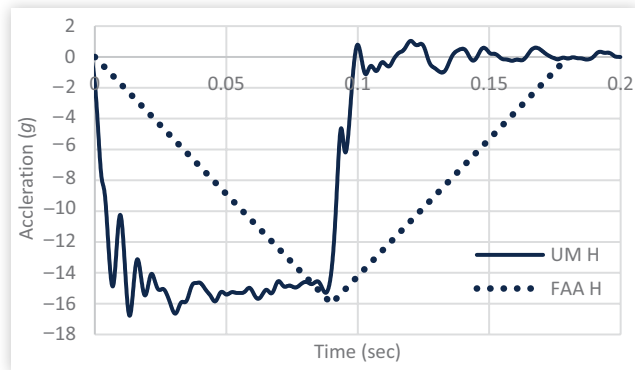
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wheelchair has the maximum forward x-value. This figure illustrates a 152-cm (60 in.)-long wheelchair station (maroon line), representing the recommended length of alcoves in buildings, which require similar maneuvering to enter as the situation of navigating into an aircraft row from a narrow aisle. The tiedowns floor anchored points are located at the rear edge of the station ($x = 0$) and the wheelchair securement geometry reflects recommended practice. The yellow line placed 107 cm (42 in.) from the bulkhead shows that the average SRP is behind the estimated contact range, although the most forward SRP is approximately 10 cm (4 in.) forward of this location. Because the available space for a wheelchair station would be the same regardless of the many individual wheelchair sizes, this configuration likely reflects a realistic testing environment for future aircraft wheelchair stations. This geometric analysis of 75 wheelchairs suggest that more than 60% have SRP more than 107 cm rearward of the bulkhead, minimizing potential for head contact and eliminating the requirement for the calculation of HIC. Based on discussions with our FAA advisors, we did not include a bulkhead in our testing, because more than half of wheelchairs have low potential for head contact based on this geometric analysis.

Sled Pulse

The horizontal impact test pulse specified in 14 CFR Part 25 has a minimum ΔV of 48 km/h and a peak acceleration of 16 g that must be achieved within 90 ms. No minimum rise time is specified, but AS8049 describes the ideal shape as triangular. Figure 3 compares the ideal FAA

FIGURE 3 Comparison of ideal and UMTRI versions of the FAA horizontal pulse.



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horizontal pulse with a trapezoidal pulse produced by the UMTRI sled that meets the pulse requirements.

Computer modeling was used to explore the kinematic implications of the two different pulses. The UMTRI pulse causes the ATD to begin deceleration earlier in the event; however, the ATD's peak forward movement is similar for both conditions. Both pulses result in a maximum horizontal (x) head displacement near 825 mm and maximum vertical (z) displacements near -810 mm. These similar peak movements occur with roughly a 40 ms offset. The pelvis horizontal (x) excursion is somewhat increased with the UMTRI pulse, with the difference in peak excursion occurring about 50 ms earlier. The two impact pulses generate remarkably similar trajectories for the ATD head and pelvis. This analysis draws similar conclusions to a prior FAA comparison of triangular vs. trapezoidal pulses [16]. The other ATD measures also occur about 40–50 ms earlier with the UMTRI pulse and are slightly increased. Peak values for UMTRI vs. triangular pulses are 56 vs. 53 g for peak chest resultant acceleration, 53 vs. 46 g for peak pelvis acceleration, 18.3 vs. 15.4 kN for peak ATD-to-seat force, 26.1 vs. 23.4 for peak WC-to-floor force, 23.0 vs. 19.8 for peak seatbelt-to-ATD contact force, and 7.1 vs. 6.0 for peak lumbar axial force. These data show that the UMTRI pulse provides impact conditions that meet or exceed those seen in the ideal triangular pulse loading. These findings suggest that wheelchairs passing requirements using our pulse should also meet the requirements when tested using a more triangular pulse.

Yaw, Pitch, and Roll

For the WC19 frontal impact test, the wheelchair is forward-facing with the wheelchair centerline coincident with the primary impact direction. For the FAA horizontal impact test, the wheelchair is rotated in the horizontal plane 10° left/right (yaw). Additionally, the FAA protocol calls for simulating the effects of floor deformation through the use of deformable floor anchors that simulate

±10° pitch and ±10° roll. However, wheelchairs would likely be secured by non-rigid 4-point strap tiedowns, and floor deformation would have little effect on strap tension. Computer modeling was used to compare outcomes with and without floor deformation, which found the peak values of ATD-to-seat force and WC-to-floor force are slightly higher with the deformed floor condition (ATD: 15.4 vs. 15.2 kN, WC: 23.4 vs. 19.4 kN), while the peak head X excursion and pelvis X excursion are slightly higher with the non-deforming condition (head: 870 vs. 824 mm, pelvis: 235 vs. 208 mm). Based on the minimal response differences and consultation with our FAA advisors, we performed our impact tests without simulating the deformed floor condition.

Wheelchair Selection and Test Matrix

Table 1 describes the test plan, including test number, wheelchair model, wheelchair mass, wheelchair type, any prior tests conducted on the wheelchair, the abbreviation used in the data plots, and occupant restraint type. Wheelchairs were selected to represent a range of common designs that comply with WC19. The wheelchair masses range from 10 to 179 kg. Two manual chairs had previously been tested with static pull protocols but did not appear to have significant structural damage (indicated by _S in the data abbreviation). The power wheelchairs that had undergone static protocols were damaged and deemed not suitable for this test series. Instead, two power wheelchairs tested as part of other research programs were used (denoted by _DF and _DL). An FAA Hybrid III midsized male ATD was used in all tests and was restrained by a wheelchair-anchored (WA), along with a vehicle-anchored (VA) lap belt, in tests WA2304 through WA2308, as shown in Figure 4.

Results

During the first two tests with the same wheelchair model, the left front caster wheel fractured. However, all subsequent horizontal dynamic tests, conducted with an extra vehicle-attached lap belt, were successful, without any structural failures.

With the first two tests performed with the Ki Mobility Catalyst 5, one previously tested statically and the second untested, the front left caster wheel detached late in the impact event. In the first test, the left footrest also detached. We identified several contributing factors for why they failed FAA testing but passed WC19. The restraint by only a lap belt and no shoulder belt, coupled with the orientation 10° from frontal, allows the ATD head to rotate and hit left leg, transferring added force into caster. We also questioned whether the steeper UMTRI pulse contributed, even though the failure happens late

TABLE 1 Dynamic horizontal test matrix.* (Data taken from Ref. [13].)

ID	Wheelchair	Mass (kg)	Type	Prior test	Abbrev.	Restraint
WA2301	Surrogate Wheelchair Base	57	Fixture	NA	SWCB	Wheelchair-anchored lap
WA2302	Ki Mobility Catalyst 5	10	M, folds laterally	Static	KMC5_S	Wheelchair-anchored lap
WA2303	Ki Mobility Catalyst 5	10	M, folds laterally	None	KMC5_0	Wheelchair-anchored lap
WA2304	TiLite ZRA	14	M, rigid	Static	TLZ_S	Wheelchair-anchored lap + Vehicle-anchored lap
WA2305	Convaid Safari SFT 810	20	M, folds laterally and fore-aft	None	CVS_0	Wheelchair-anchored lap + Vehicle-anchored lap
WA2306	Ki Mobility Catalyst 5	10	M, folds laterally	Aircraft horizontal, replaced front casters	KMC5*_AF	Wheelchair-anchored lap + Vehicle-anchored lap
WA2307	Pride Mobility 3	179	P, base with suspension	Dynamic frontal	PM3_DF	Vehicle-anchored lap
WA2308	Quantum Q6 Edge 2	162	P, base with suspension	Dynamic lateral	QE2_DL	Wheelchair-anchored lap + Vehicle-anchored lap

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* Static = prior non-impact test; Dynamic = previously tested in frontal/lateral impact protocols.

M: Manual, P: Powered

in the event. Because we had available a FEM of the KMC5 developed in a previous study [17], we conducted simulations using the UMTRI and triangular FAA pulses to examine the strain levels at the point of failure. The maximum strain occurred in the same element for each simulation, and the values were similar (0.199 for UMTRI, 0.216 for triangular), although the peak values occurred at 120 ms for UMTRI and at 165 ms for triangular.

All tests achieved the target peak acceleration of 16 g (within 0.2 g) and the targeted minimum change in velocity of 48.2 km/hr. Figure 5 shows the lap belt loads from the horizontal dynamic tests. In Figure 5, the solid lines show the load from the wheelchair-attached lap belt, while the dashed lines show the loads from the vehicle-mounted lap belt. Using the vehicle-mounted lap belt substantially decreased the loads in the wheelchair-mounted lap belt.

FIGURE 4 Example of wheelchair secured by surrogate 4-point strap tiedowns, with the ATD secured by the wheelchair-anchored lap belt and an additional vehicle-anchored lap belt.



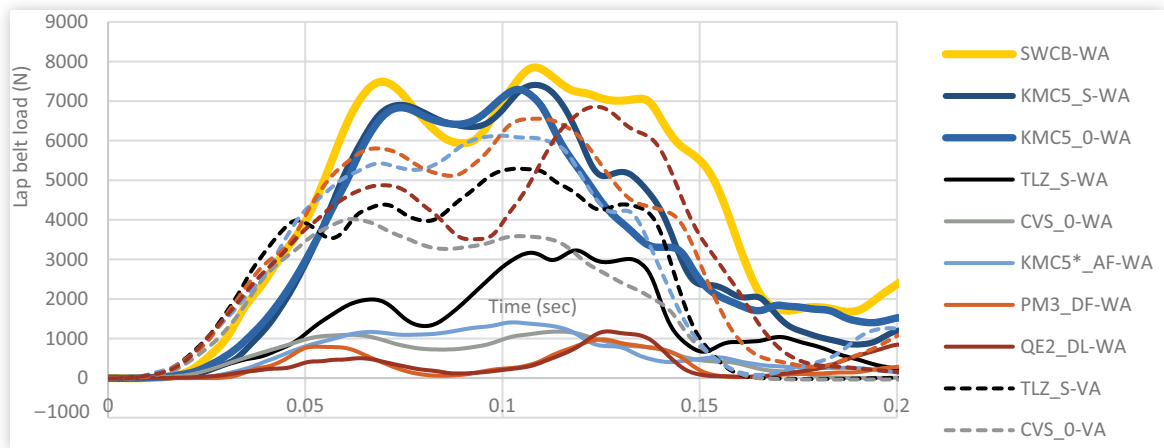
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Prior to head-to-leg contact, peak resultant head acceleration ranged from 70 to 105 g. Per FAA protocol, HIC is only calculated when ATD head contact occurs with something other than the ATD. All tests resulted in tensile loading of the lumbar spine. Head trajectories digitized from the head CG target in each test are shown in Figure 6, with the origin at the WC seat/seatback junction. A line representing a 107 cm (42 in.) bulkhead is included for reference. Generally, the tests with the additional vehicle-anchored lap belt had lower excursions than those without. All tests with the commercial wheelchairs had head CG trajectories of less than 900 mm relative to the SRP, indicating that head contact with a bulkhead positioned at 107 cm (42 in.) would be unlikely.

Discussion

To maximize the chance of success in modifying FAA test procedures to evaluate wheelchairs, we used 4-point strap tiedowns in WC19 configuration to secure the wheelchairs. This allowed loading of the wheelchair's securement brackets under their design conditions. Targets for WC19 geometry are a rear tiedown strap angle positioned between 45° and 30°; the rear tiedowns are located directly rearward from the securement points, while front tiedowns are located outboard and forward of the front securement points to provide better lateral stability. If an alternate tiedown anchor geometry is proposed for aircraft, additional testing of WC19 wheelchairs would be needed to ensure that the securement brackets are strong enough under a different loading path. Although the angled tiedown geometry could pose a tripping hazard, lessons learned from using this tiedown configuration on public and school buses could be applied to aircraft implementations. The recommended geometry leads to reduced head excursion and floor loads compared

FIGURE 5 Lap belt load from all horizontal tests.



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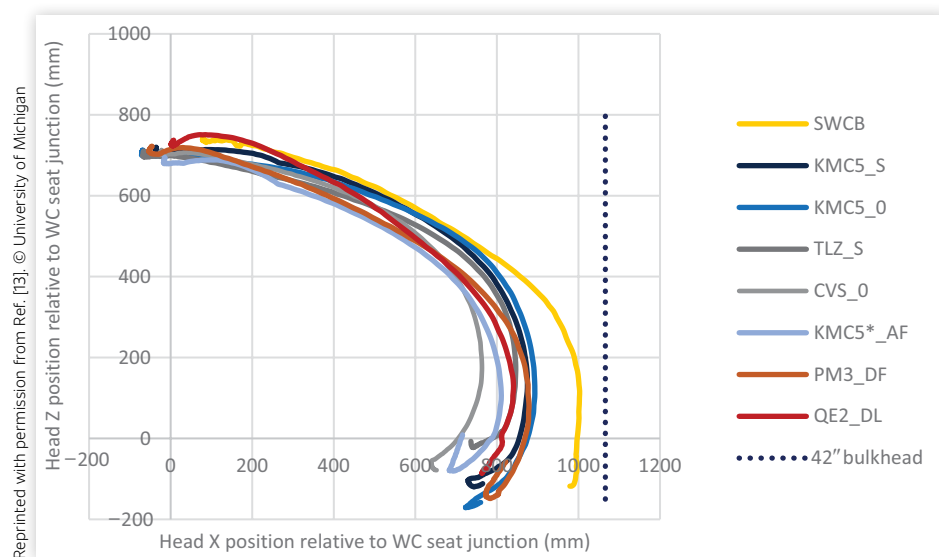
to a geometry that anchors tiedowns straight down from securement brackets.

Our original test plan for this project called for first testing wheelchairs under static loading conditions, then performing dynamic testing on the same wheelchairs. We had concerns whether the prior static testing might weaken the wheelchairs to the point where they would not pass the dynamic testing. Comparison of tests WA2302 and WA2303 on the same KMC5 wheelchair with and without prior static testing and similar results in terms of ATD signals and similar front left caster failures did not support this concern. For future testing of wheelchairs, we recommend conducting the dynamic tests before conducting the static tests.

For the dynamic horizontal testing, wheelchairs were able to pass the FAA requirements when the ATD was restrained by the wheelchair-anchored lap belt available

on WC19 products, plus an extra vehicle-anchored lap belt. As shown by the lap belt loads in Figure 5, adding the vehicle-mounted lap belt substantially reduced the loads carried by the wheelchair-mounted lap belt. An FAA expert observing the tests proposed this approach, which had been considered by the FAA as a strategy because it might be challenging to verify that an aircraft passenger’s wheelchair was actually equipped with a crash-worthy lap belt. Because the additional vehicle-mounted lap belt allowed the wheelchairs tested to meet the horizontal testing requirements, future testing of wheelchairs under FAA conditions should also use an additional vehicle-mounted lap belt. Test WA2307 involved testing of a wheelchair previously tested to ISO 7176-19 standards; it did not have the option for a wheelchair-anchored lap belt. It did pass the FAA requirements, suggesting that the vehicle-mounted lap belt option may facilitate

FIGURE 6 ATD head path relative to the wheelchair seat junction from all horizontal tests.



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the use of ISO certified wheelchairs. However, additional testing of more products would be needed to confirm this preliminary result, because WC19 wheelchairs experience more load during frontal impact compliance testing than ISO-compliant wheelchairs.

For the horizontal dynamic testing, we did not simulate the pitch and roll typically used to represent floor deformation during the testing of a wheelchair. This requirement intends to show that aircraft seats rigidly secured to the aircraft floor remain in place should the floor deform in a crash. Wheelchairs would not be rigidly attached to the floor in the same manner as typical airplane seating, but instead would be secured by 4-point tiedown straps that include webbing. The tensions among the four tiedowns would shift under floor deformation but would not be expected to fail. Simulations of the horizontal dynamic test with and without floor deformation confirmed this expectation.

This study has several limitations. While wheelchair models were selected to represent a range of styles and masses, only six different commercial wheelchair models were tested, and results may differ for other models. In addition, some wheelchairs had been previously tested under additional scenarios, which would not be the case when testing aircraft seating. While the tested wheelchairs did not have visible damage, prior testing could have affected performance. A bulkhead representation was not included during testing based on geometric analysis and advice from FAA, and none of the tests would have resulted in head contact, but this could differ for other wheelchair models. In addition, wheelchairs with recline features were only tested in baseline upright positions, so the effect of recline on crashworthiness and injury risk is unknown.

A final study limitation is that the ideal triangular-shaped FAA pulse cannot be achieved on the UMTRI sled, which generates pulses that are trapezoidal in shape. However, our pulse can achieve all the horizontal pulse requirements of 14 CFR 25 of reaching the peak acceleration and change in velocity within 90 ms, but the faster rise time means it achieves them earlier than required. Consequently, the UMTRI pulse provides more severe loading than is required. Simulations suggest that ATD kinematics would be earlier but similar in magnitude. The UMTRI FAA pulse produces peak ATD measures and forces between the wheelchair, ATD, and floor that are 13–18% higher (across six tests) compared to the triangular FAA pulse. When comparing the area under the curves, those produced by the UMTRI FAA pulse are 2–11% larger. As a result, we hypothesize that wheelchairs meeting dynamic horizontal FAA requirements at UMTRI should have no challenges when tested using the triangular FAA pulse.

The purpose of this study was to determine whether wheelchairs meeting ground vehicle crashworthiness requirements for wheelchairs, defined by WC19, would be suitable as aircraft seating. Initial results are positive. However, the current use of WC19 wheelchairs is limited.

The UMTRI has another project to evaluate the posture of occupants in wheelchairs, and only 2 of 99 participants owned a WC19 wheelchair. The Food and Drug Administration (FDA) regulates wheelchairs as medical devices and does not require crashworthiness testing. Wheelchairs used as vehicle seats are currently not addressed by NHTSA. Although the cost of WC19 hardware (\$200 to \$500) is small compared to the total cost of wheelchairs (\$1500 to \$20,000+), most insurers, besides the Veterans Administration, do not cover it. Because of this payment aspect as well as product liability concerns, promotion of the WC19 option availability is limited. While some wheelchair models can be retrofitted, many users would not be able to pay the cost themselves.

Conclusions

This project developed methods to adapt FAA horizontal dynamic testing requirements to evaluate wheelchairs as potential aircraft seating. They were used to test five commercial wheelchairs that meet voluntary ground vehicle crashworthiness standards. Computer simulations showed minimal differences with and without floor deformation when the wheelchair is secured by 4-point strap tiedowns, so floor deformation was not evaluated during physical testing. Simulations also demonstrated that the triangular FAA pulse and the trapezoidal pulse produced by the UMTRI sled led to similar kinematics. Testing was successful using the surrogate 4-point tiedowns and geometry defined in WC19. When both a wheelchair-mounted lap belt and a vehicle-mounted-lap belt were used to restrain the ATD, two power and three manual wheelchairs were able to meet horizontal dynamic testing requirements. Pending outcomes from companion efforts addressing dynamic and static FAA testing, these results support future efforts to allow passengers to travel in their own WC19 wheelchairs on aircraft.

Authors' Contributions

The authors confirm contribution to the article as follows: study conception and design: K. Klinich, M. Manary, K. Boyle, N. Orton; data collection: M. Manary, N. Orton, T. Vallier; analysis and interpretation of results: K. Klinich, M. Manary, K. Boyle, N. Orton; draft manuscript preparation: K. Klinich, N. Orton. All authors reviewed the results and approved the final version of the manuscript.

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