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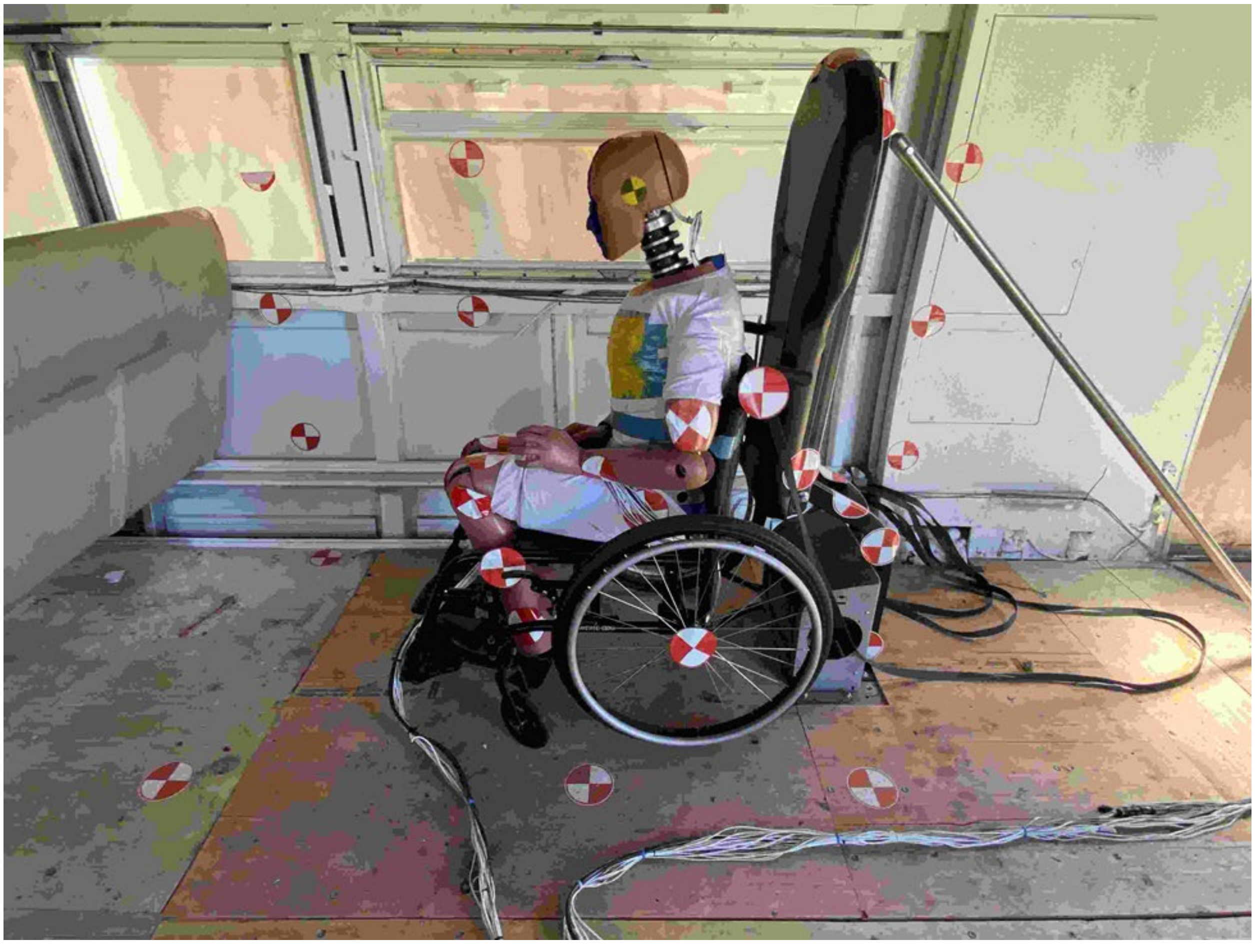
Improved Collision Protection for Train Passengers Seated in Wheelchairs: Evaluation of Active and Passive Strategies



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14. ABSTRACT

The project evaluates wheeled mobility device (WhMD) securement and occupant restraint on passenger trains. Researchers tested three off-the-shelf wheelchair securement systems in a train-to-train collision as a proof-of-concept to mitigate the effects of second impact velocity. The tests evaluated the performance of the securement devices regarding human injury, compartmentalization, structural integrity, and attachment. The team conducted a full-scale train-to-train impact test at the Transportation Technology Center in Pueblo, Colorado, on August 11, 2022. Three WhMD occupant protection experiments were installed in the M1 passenger cars behind the Crash Energy Management (CEM) locomotive in the moving consist. These experiments included different types of wheelchairs, restraint systems, and Hybrid III 50th percentile male (H3-50M) anthropomorphic test devices (ATDs) equipped with instrumentation to measure force, moment, acceleration, and displacement data. All the backboards, wheelchair securement, and occupant restraint systems used in the experiments maintained their structural integrity and remained attached to the carbodies during the tests. The injury values measured by the H3-50Ms were well below the limits and met the performance requirements specified in the APTA seat and table standards.

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wheeled mobility device, wheelchair, compartmentalization, securement, WhMD, occupant protection, passenger railcar, railcar

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gm)
1 pound (lb) = 0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2) = 1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg)
= 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

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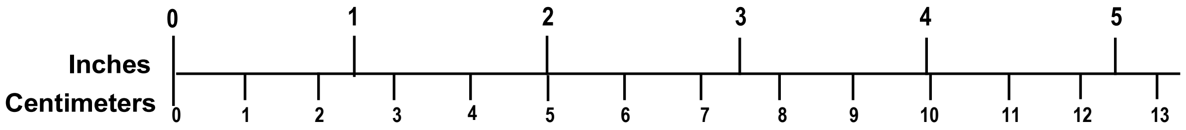
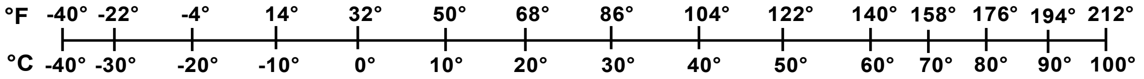


QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO



For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

Acknowledgements

Researchers acknowledge the support of engineers from the Volpe National Transportation Center (Volpe Center). Volpe Center engineers developed the test requirements and coordinated with Q'Straint and MxV Rail (formerly Transportation Technology Center, Inc.) to adapt the securement and restraint equipment installation to passenger railcars. Thanks to Q'Straint for their donated wheelchair securement equipment, installation of the equipment, and support of this research effort.

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Executive Summary

The Federal Railroad Administration (FRA) funded Oregon State University (OSU) to support the development of recommendations for improved accessibility of passenger trains. The research was conducted between April 28, 2017, and March 31, 2023, in a final phase of a long-term effort to develop and validate inclusive and universal recommendations for accessibility of the next generation of high speed and intercity passenger rail.

Currently, there are no requirements for securement of wheeled mobility devices (WhMD) or restraint of the occupants on passenger trains. People are protected on passenger railcars during accidents by compartmentalization of the seated passenger between rows of seats or between a seat and an energy-absorbing workstation table. Secondary Impact Velocity (SIV) is another factor to consider in occupant protection. In a train collision, secondary impact occurs when an unrestrained occupant launches from their initial position and impacts an interior structure. Depending on the deceleration of the train during the collision and the interior configuration, secondary impacts can cause significant injuries and fatalities.

Researchers evaluated wheeled mobility aid securement and passenger compartmentalization on passenger trains. The project objectives included testing three off-the-shelf wheelchair securement systems in a train-to-train collision as a proof-of-concept to mitigate the effects of SIV and evaluate the securement devices' performance in regard to human injury, compartmentalization, structural integrity, and attachment.

The team conducted a full-scale crash test at the Transportation Technology Center (TTC) in Pueblo, Colorado, on August 11, 2022. The full-scale crash test comprised of a train-to-train impact test between a F40 locomotive equipped with Crash Energy Management (CEM) components coupled to two M1 passenger railcars and a stationary conventional F40 locomotive backed by two empty hopper cars. The impact speed for the test was 24.3 mph. The team installed three WhMD occupant protection experiments in the M1 passenger cars behind the CEM locomotive in the moving consist. These experiments included different types of wheelchairs, securement and restraint systems, and Hybrid III 50th percentile male (H3-50M) anthropomorphic test devices (ATDs) equipped with instrumentation to measure force, moment, acceleration, and displacement data.

The passenger railcar immediately behind the CEM locomotive contained Experiment 1 (i.e., the baseline experiment) and included an ATD seated in a standard manual wheelchair, backed against a rear-facing backboard. The rear-facing backboard did not include any active mobility aid securement system or passenger restraint. The second trailing passenger railcar contained Experiments 2 and 3. Experiment 2 used a Q'Straint One™ securement system that held a forward-facing surrogate wheelchair (SWC) with four floor-mounted straps with hooks and a three-point seat belt that restrained the H3-50M ATD. Experiment 3 used a Q'Straint Quantum® securement system consisting of a rear-facing backboard actively holding a rigid SWC in place with side grips on the wheels of the SWC, and a three-point seat belt restrained the H3-50M ATD. Each WhMD with ATD was placed in a 59 by 30 inch space as recommended by FRA and the US Access Board Rail Vehicle Access Advisory Committee (RVAAC) for accessibility and maneuverability on-board passenger railcars.

The post test results showed that no damage was observed on either the Q'Straint One™ system (i.e., Experiment 2) or the Q'Straint Quantum® backboard (i.e., Experiment 1). In Experiment 3,

there was some damage to the backboard on the Q'Straint Quantum® system due to the handles and the weighted plate of the SWC. All the backboards, wheelchair securement, and occupant restraint systems used in the experiments maintained their structural integrity and remained attached to the car bodies during the tests. At the end of the tests, the ATDs were all seated in the wheelchair or SWCs. During the test, high speed cameras installed on the railcars showed the three WhMDs and their ATDs accelerating vertically upward due to the vertical acceleration of the locomotive and car bodies during the crash. All the wheelchairs and ATDs remained compartmentalized in each of the three experiments. The injury values measured by the H3-50Ms met the performance requirements specified in the American Public Transportation Association (APTA) seat and table standards. All injury values were well below the performance limits.

The experiments performed during the train-to-train crash test results showed that "off-the-shelf" securement systems designed and tested for bus transit provided adequate protection of ATD seated in SWC or WhMD. The three ATDs used in the experiments measured forces, accelerations, displacements, and moments that were used to compute injury criteria. The computed values were significantly lower than the industry standards for injury criteria for head, chest, femur, and neck. All the securement and restraint systems limited the motion of the manual and SWCs and the three-point restraint systems reduced the displacement of the ATDs. No wheelchair cushions were used in the tests and there was no additional baggage on the back of the manual wheelchair.

The research team concluded that the rear-facing backboard was both the lowest cost and simplest system that met all the injury criteria. The rear-facing backboard can be used completely independently and does not require any additional assistance from trained staff. There is often baggage or equipment behind the seat of a WhMD which prevents full contact with the backboard and hence increased potential for head and neck compression and injury. The backboard itself requires further research, design and testing to provide additional head and neck protection when headrests are not attached directly to the WhMD.

The team also determined that there may be interior carbody configurations and personal preferences that require forward-facing securement. In these circumstances, a four-point tie down system would be appropriate. However, the forward-facing four-point tie down securement system requires trained assistance to attach the belts to the appropriate areas on the WhMDs.

1. Introduction

The Federal Railroad Administration (FRA) funded Oregon State University (OSU) to support the development of recommendations for improved accessibility of passenger trains. The research was conducted between April 28, 2017, and March 31, 2023, in a final phase of a long-term effort to develop and validate inclusive and universal recommendations for accessibility on the next generation of high speed and intercity passenger rail. In the first three phases of this research, the team developed recommendations for space to accommodate wheeled mobility devices (WhMD) on passenger rail vehicles. However, researchers found the increased space that permits maneuverability of these devices increased the risk to passengers seated in them during rail vehicles collisions or derailments [1]. Passengers are protected on board railcars during accidents by compartmentalization of the seated passenger between rows of seats or between a seat and an energy-absorbing workstation table [2]. Currently there are no requirements for securement of WhMD or restraint of the occupants on passenger trains, although there is ongoing research by the Volpe National Transportation Center (Volpe Center) and others on occupant protection of passengers on board railcars.

Volpe Center provided support to this project by analyzing the relative motion of WhMD and the occupant under accident scenarios on a railcar [3]. Researchers evaluated the protection provided by wheeled mobility aid securement, occupant restraint, and compartmentalization on passenger trains.

1.1 Background

Under the initial project phases, OSU developed inclusive and universal recommendations for accessibility on the next generation of high speed and intercity passenger rail [1]. Working with the Passenger Rail Investment and Improvement Act of 2008 (PRIIA) Next Generation Equipment Committee, OSU researchers developed recommendations for accessibility on single-level and bi-level coach cars. Some of the recommendations were incorporated into the specifications for the PRIIA Bi-level passenger railcar and will ultimately be included in the passenger railcars that are under procurement using those specifications. Additionally, the recommendations developed were the basis for new recommendations for rail vehicles accessibility developed by the US Access Board Rail Vehicle Access Advisory Committee (RVAAC).

The team conducted spatial assessment of the impact of the recommendations on the interior space of a single-level coach car and reviewed additional recommendations identified by RVAAC for feasibility [4], [5]. Passengers who use WhMDs need extra space to maneuver into and out of the accessible space. In previous research, FRA recommended a larger accessible space on board passenger railcars; a space of 59 by 30 inches provides the necessary maneuvering space for large WhMDs to enter the accessible area and allow a clear aisle pathway. However, in reviewing the recommendations for larger and multiple adjacent accessible spaces on the railcar, researchers identified the lack of compartmentalization as a potential safety issue. It is desirable for passengers on railcars to be kept within the confinements of their seats during accidents to limit their exposure to secondary impact injuries. Seatbacks and armrests provide the compartmentalization needed so that passengers do not fly out of their seating area during accidents. However, there are currently no requirements for WhMD users to be restrained or their devices to be secured while riding on passenger railcars, although there is a requirement for storage of manual WhMD in 49 Code of Federal Regulations Part 37.

Another factor to consider in occupant protection is Secondary Impact Velocity (SIV). In a train collision, secondary impact occurs when an unrestrained occupant launches from their initial position and impacts an interior structure. Depending on the deceleration of the train during the collision and the interior configuration, secondary impacts can cause significant injuries and fatalities. Rapid deceleration of the train and a long travel distance for an occupant can result in a high SIV.

"Secondary impact refers to the impact between the occupant and some part of the interior, usually the forward seat, table, or bulkhead. Before a collision, the occupants travel at the same speed as the train. As the rail vehicle decelerates during the primary impact, unrestrained occupants gain velocity with respect to the car. The velocity of the occupant at the time of impact with an interior structure is referred to as the secondary impact velocity (SIV). The SIV generally increases with the distance traveled relative to the car for a range of typical seat pitches. At larger relative displacements, the SIV reaches a maximum value approximately equal to the closing speed of the train(s), assuming a plastic collision with a stationary train (the closing speed is the difference in velocity of the two colliding objects). The SIV, along with the stiffness and geometry of the interior structures impacted by the occupant, determine the severity of the secondary impact." [3]

Prior work by the Volpe Center has demonstrated that the large open seating areas (e.g., those recommended for access by larger WhMD) may increase SIV experienced by passengers and the severity of secondary impact injuries during train collision

This report includes results from modeling and a controlled crash test of two locomotives and adjacent passenger cars, as well as a discussion of the motion of wheeled mobility devices and the occupants during the controlled crash test.

1.2 Objectives

The project objectives included testing three off-the-shelf wheelchair securement systems in a train-to-train collision as a proof-of-concept to mitigate the effects of SIV and evaluate the performance of the securement devices in regard to human injury, compartmentalization, structural integrity, and attachment per the American Public Transportation Association (APTA) passenger seat and workstation table safety standards [6], [7].

1.3 Overall Approach

The purpose of the research was to evaluate occupant protection of seated wheelchair passengers during train accidents. To answer these questions, researchers used two approaches, computer modeling and train-to-train crash tests. The team used computer modeling to determine the attachment strength necessary to ensure that the securement and restraint devices would not separate from the carbody during the collision. A surrogate wheelchair (SWC) was used for both the modelling and crash testing to produce results that could be evaluated with known industry standards rather than test any specific model of wheelchair. In addition to APTA standards for passenger rail, the team also referenced the Rehabilitation Engineering Society of North America (RESNA) standards for wheelchairs and transportation and RESNA WC4 Sections 10, 18 and 19 (used for rubber tire public transit application) [8]. Only two SWCs meeting the RESNA standards were available. , so Researchers used a Quickie QXI, a commonly available lightweight folding manual wheelchair, in the baseline experiment. Hybrid III 50th percentile male anthropomorphic test devices (H3-50M ATDs) were used in each experiment.

1.4 Scope

This report focuses on the three experiments installed on the train-to-train crash test. The experiments used “off the shelf” wheelchair securement and restraint systems for compartmentalization of wheelchair-seated passengers during collision conditions.

1.5 Organization of the Report

- Section 2 describes the modelling testing
- Section 3 describes the test results
- Section 4 includes a discussion of the results
- Section 5 presents conclusions and future actions

2. Modeling and Testing

Engineers in the Structures and Dynamics Division at the Volpe Center have previously conducted research for FRA to identify safety hazards during accidents, support the development and testing of mitigation strategies, and provide a technical basis for industry safety standards and federal regulations related to occupant protection on passenger trains. In previous accident investigation studies, researchers identified passenger seats and workstation tables as contributing to secondary impact injuries, developed prototype seats and tables that demonstrated the safety benefits of occupant compartmentalization and crashworthy features, and contributed to the APTA passenger seat and table safety standards. Previous investigations of passenger train accidents and the identification of causal mechanisms of passenger injury and fatality during such events led to the WhMD securement and compartmentalization experiments in this study. These previous investigations demonstrated the need for compartmentalization of passengers and the use of energy-attenuating seats and workstation tables [3], [7].

2.1 Description of Test Plans

Prior to conducting the full-scale crash tests, Volpe Center researchers performed computer modelling to determine the interior dynamics of the interior occupant experiments, and to develop strategies for the attachment of the WhMD securement and passenger restraint systems to the train carbody framework. Researchers selected off-the-shelf passenger securement and restraint systems used in transit buses for the experiments; therefore, they needed to determine an appropriate attachment strategy, since the railcar floor design is not the same as a typical transit bus floor. Through this modeling effort, the team developed detailed designs of the interface system between the securement and restraint systems and the carbody.

2.2 Full Scale Crash Test

Researchers conducted full-scale crash tests at the Transportation Technology Center (TTC) in Pueblo, Colorado, on August 11, 2022. TTC is comprised of 52 square miles of land leased from the State of Colorado, and it is the cornerstone of railway research, testing, and training for the U.S. railway industry. The tests were conducted on the Precision Test Track, used for impact testing of various types of rail vehicles and locomotive components. Figure 1 shows a map of the TTC test tracks.

The full-scale crash test was comprised of a train-to-train impact test between a F40 locomotive equipped with Crash Energy Management (CEM) components coupled to two M1 passenger cars and a stationary conventional F40 locomotive backed by two empty hopper cars. Handbrakes were applied on the empty hopper cars. The target impact speed was 21±2 mph, while the actual impact speed for the test was 24.3 mph. Figure 2 shows the locomotives and consists prior to the crash test.

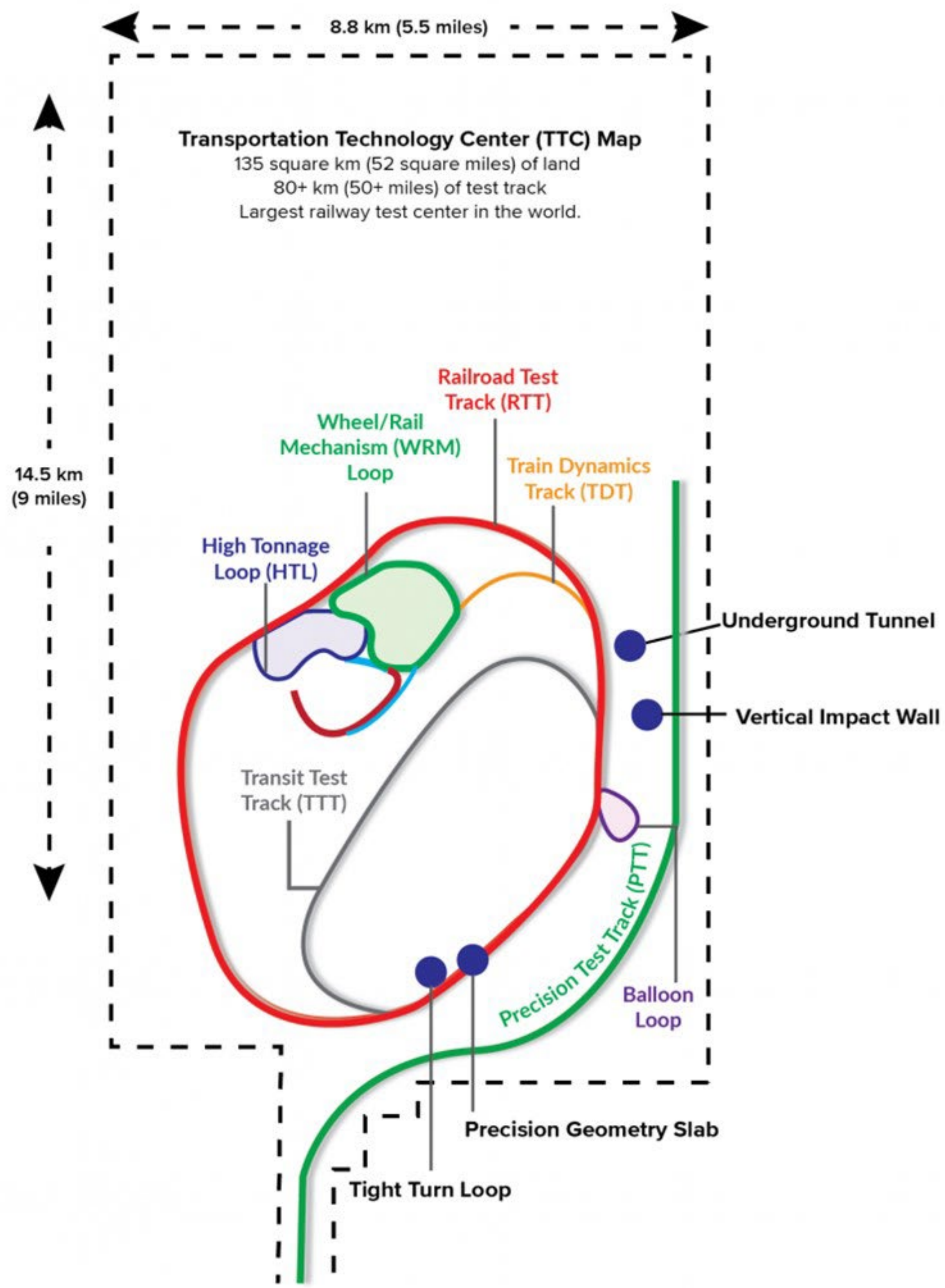


Figure 1. Map of TTC test tracks

Figure 2. Locomotives prior to the crash tests

2.3 Occupant Protection Experiments

Researchers installed three WhMD occupant protection experiments in the M1 passenger cars behind the CEM locomotive in the moving consist. These experiments included different types of wheelchairs, restraint systems, and Hybrid III 50th percentile male (H3-50M) anthropomorphic test devices (ATDs) equipped with instrumentation to measure force, moment, acceleration, and displacement data.

Two of the three experiments consisted of wheelchair securement devices and three-point occupant restraint systems, commonly used on transit buses, to evaluate securement and restraint of passengers seated in WhMDs. One experiment used a rear-facing backboard and no occupant restraint as the baseline experiment to evaluate rear-facing compartmentalization strategy for passenger safety. Figure 3 shows the location of the three experiments in the train-to-train impact test.

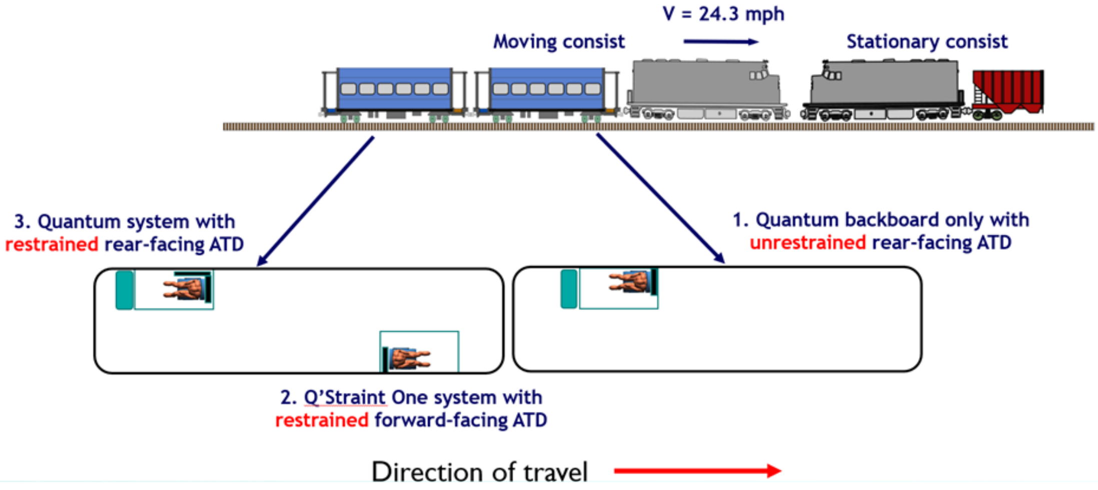


Figure 3. Train to train impact test

The moving consist contained the three occupant experiments inside the two passenger railcars that trailed the leading locomotive of the moving consist. The lead locomotive was equipped with a retrofitted CEM system [2]. The passenger railcar immediately behind the CEM locomotive contained Experiment 1, which was the baseline experiment using a rear-facing backboard. This experiment evaluated the rear-facing compartmentalization strategy and did not use any active mobility aid securement system or passenger restraint. The second trailing passenger railcar contained Experiment 2, which used a Q'Straint One™ securement system. This securement system held a forward- facing SWC with four floor-mounted straps with hooks, and a three-point seat belt restrained the H3- 50M ATD. Experiment 3 used a Q'Straint Quantum® securement system consisting of a rear- facing backboard and a securement system which actively held a rigid SWC in place with side grips on the wheels of the SWC, and a three-point seat belt restrained the H3-50M ATD. Each WhMD with ATD was placed in a 59 by 30 inch space, as recommended by FRA and RVAAC for accessibility and maneuverability on-board passenger railcars.

2.3.1 Experiment 1

The team conducted this experiment in the first M1 passenger car (i.e., 8332) of the moving consist. The ATD was seated in a standard manual wheelchair and compartmentalized with a Quantum backboard and a commuter seat. Figure 4 is a picture of the manual Quickie QXI wheelchair. The wheelchair was placed facing the rear of the railcar with its back against the backboard. There were 59 inches of maneuverable longitudinal space between the backboard and the commuter seat.

Figure 4. Quickie QXI manual wheelchair

Figure 5 shows the Quantum backboard being interfaced with the railcar floor structure. Figure 6 shows the final experiment setup that consisted of the backboard, wheelchair, ATD, and commuter seat. Targets were added on the floor, wall, and experiment components to aid in the analysis of the footage from two interior high-speed (HS) cameras. The ATD and wheelchair were tethered to prevent excessive damage to the equipment after it was allowed to travel within the 59 inches of maneuverable space.

Figure 5. Installation of Quantum backboard restraint device

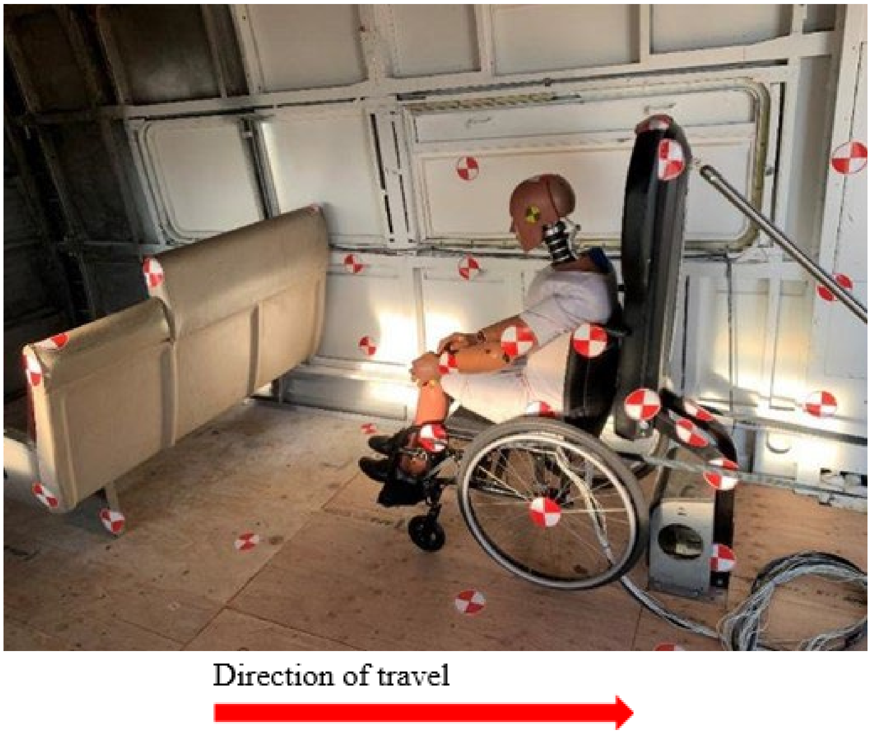


Figure 6. Experiment 1 pre-crash final setup

2.3.2 *Experiment 2*

This experiment was located in the second M1 car (8221) of the moving consist. It was installed at the leading end of the vehicle with respect to the travel direction (i.e., the end of the railcar closest to the impact point). Experiment 2 consisted of a restrained, forward-facing H3-50M ATD seated in a SWC. The Q'Straint One system secured the SWC, which was secured to the floor at four locations by flexible straps attached to J hooks. The ATD was restrained to the SWC with a three-point restraint system, a shoulder strap that was attached to sidewall of the car, and a lap belt attached to the floor. The Q'Straint One is a four-point tie down system that cannot be used independently by the wheelchair user; assistance is required to fully secure the mobility device. The four-point tie down system provides the highest level of securement and is designed and tested to be used on smaller vehicles (e.g., paratransit vehicles) where the accelerations for crashes may be in the order of 20 g. Four-point securement systems have been used in public transit and personal vehicle applications for almost 50 years.

Figure 7 and Figure 8 show the installation of the Q'Straint One system and final pre-test setup of Experiment 2, respectively. Targets were added on the floor, wall, and experiment components. The ATD and SWC were tethered to prevent excessive damage to the equipment in case the restraint system failed, with allowable travel of approximately 5 feet.

Figure 7. Q'Straint One System (wheelchair shown for demonstration, not the SWC wheelchair that was used in the test)

Figure 8. Experiment 2 forward-facing ATD pre-crash final setup

2.3.3 *Experiment 3*

Experiment 3 was located in the second M1 car (8221) of the moving consist. It was installed at the trailing end of the railcar with respect to the travel direction. i.e., the cab end of the railcar and the end furthest from the point of impact. Experiment 3 included a restrained, rear-facing H3-50M ATD seated in a SWC and secured by a Q'Straint Quantum system.

The Q'Straint Quantum securement and restraint system was initially designed for use on large, low-floor transit buses. A key feature of the Q'Straint Quantum system is that it permits the wheelchair user to be independent and autonomous in securement and greatly improves personal dignity, yet still provides safety for the wheelchair user. The Q'Straint Quantum is not designed to be used by scooter users who are recommended to transfer to a fixed seat.

The Q'Straint Quantum system secured the SWC. The ATD was restrained using a three-point restraint system and the shoulder strap was attached to the sidewall of the car. The ATD was compartmentalized with a rear-facing backboard and a rear-facing commuter seat in case any of the restraints failed. Figure 9 shows installation of the Q'Straint Quantum securement system. Figure 10 shows the final experiment setup consisting of the Q'Straint Quantum system, SWC, ATD, and commuter seat. Targets were added on the floor, wall, and experiment components to aid in the analysis of the footage from two interior HS cameras. The ATD and SWC were tethered to prevent excessive damage to the equipment in case the restraint system failed, with allowable travel of approximately 5 feet.

Figure 9. Q'Straint Quantum System

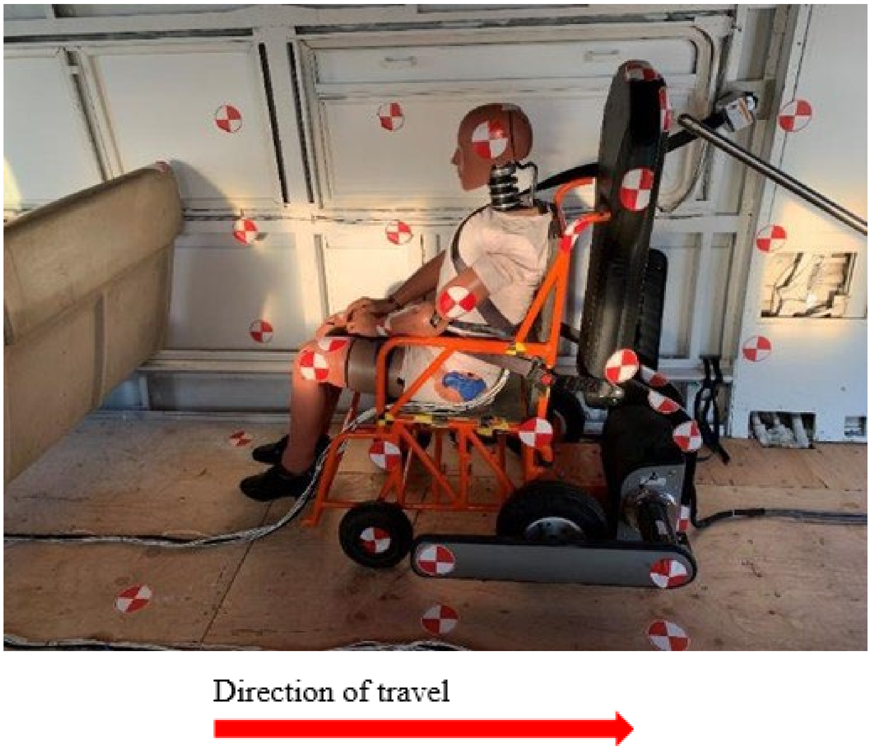


Figure 10. Experiment 3 rear-facing Q'Straint Quantum final pre-crash setup

2.3.4 High-Speed Photography

Six HS cameras were used to document the three ATD experiments. These included an overhead and side view of each experiment during the train-to-train impact event. All onboard HS cameras were crashworthy and rated for peak accelerations of 100 g. The final alignment and sighting of the cameras was done when the locomotives were positioned at the impact point prior to the start of test. In addition, lights were installed to provide illumination to the interior of the M1 cars for the occupant protection experiments.

2.4 Conduct of Test

As stated previously, the train-to-train test with the three experiments was comprised of an impact between a moving F40 locomotive equipped with CEM components coupled to two trailing M1 passenger cars and a stationary conventional F40 locomotive backed by two empty hopper cars. Handbrakes were applied on the empty hopper cars. The test target impact speed was 21±2 mph and the actual impact speed for the test was 24.3 mph.

2.4.1 Post-Test Inspection of Experiments

In the onboard occupant compartmentalization experiments, researchers observed no damage on either the Q'Straint One system (Experiment 2) or the Q'Straint Quantum backboard (Experiment 1), as shown in Figure 11 and Figure 12, respectively.

Figure 11. Post impact Unrestrained Quantum backboard

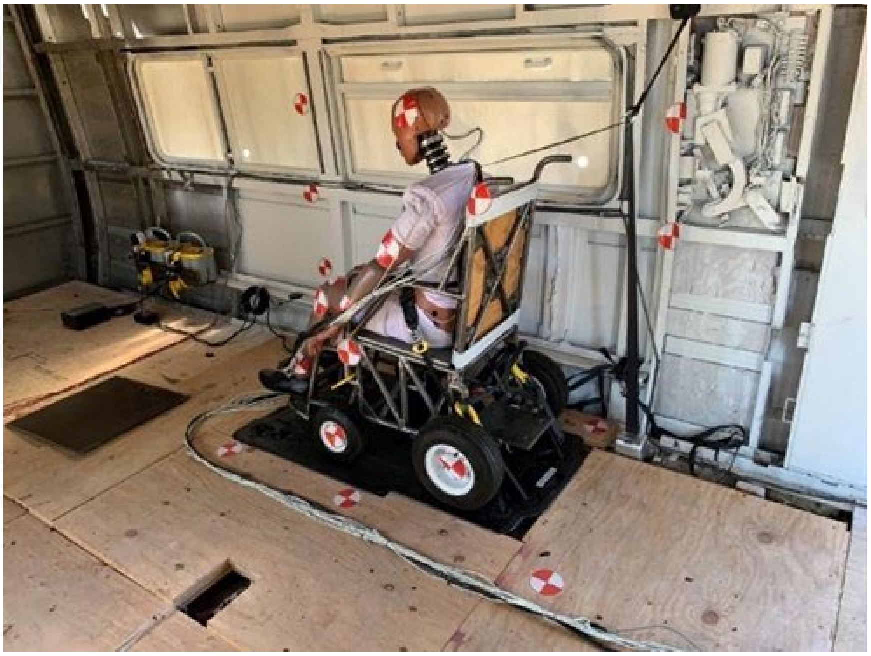


Figure 12. Post impact Q'Straint One

However, the team did observe some damage on the fully operational Q'Straint Quantum system (Experiment 3). The backboard in the full Q'Straint Quantum system showed holes in either side where the SWC's handles contacted the backboard during the impact. This backboard damage is shown in Figure 13.

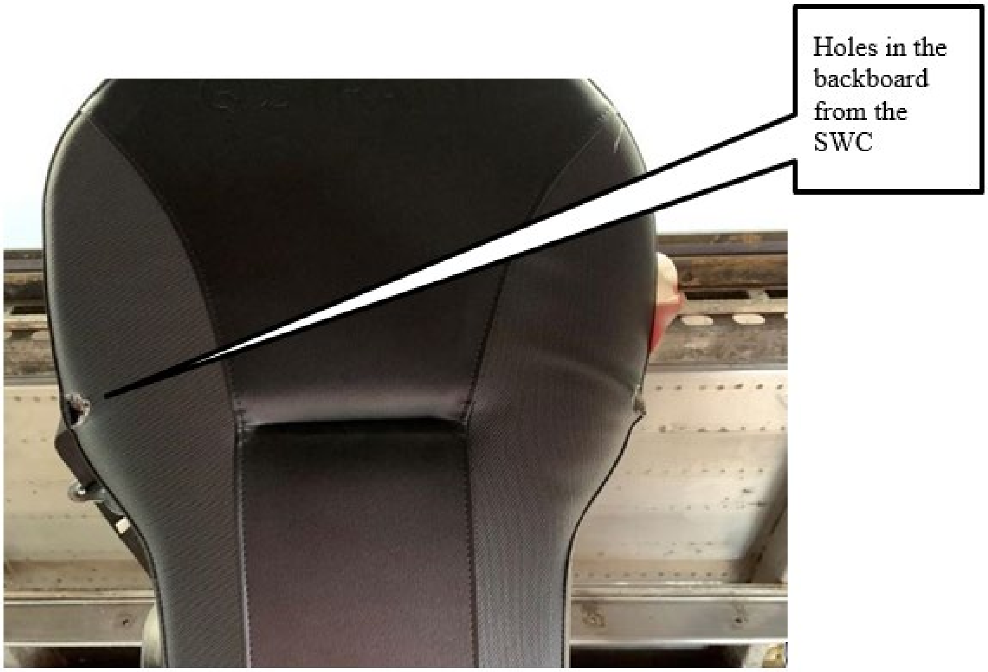
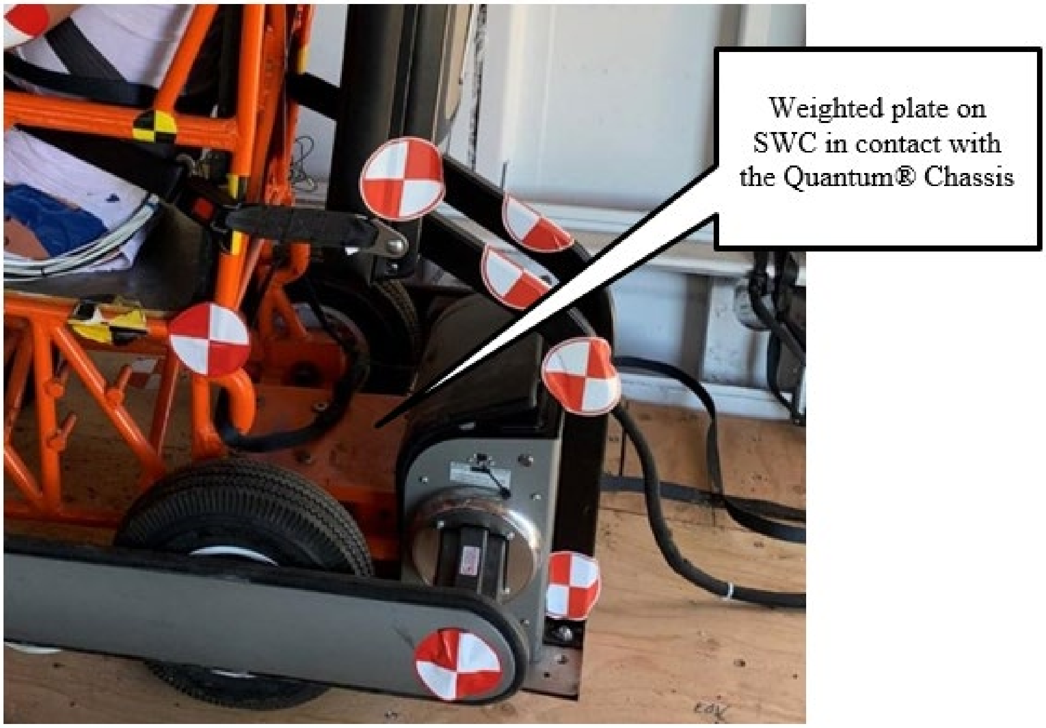


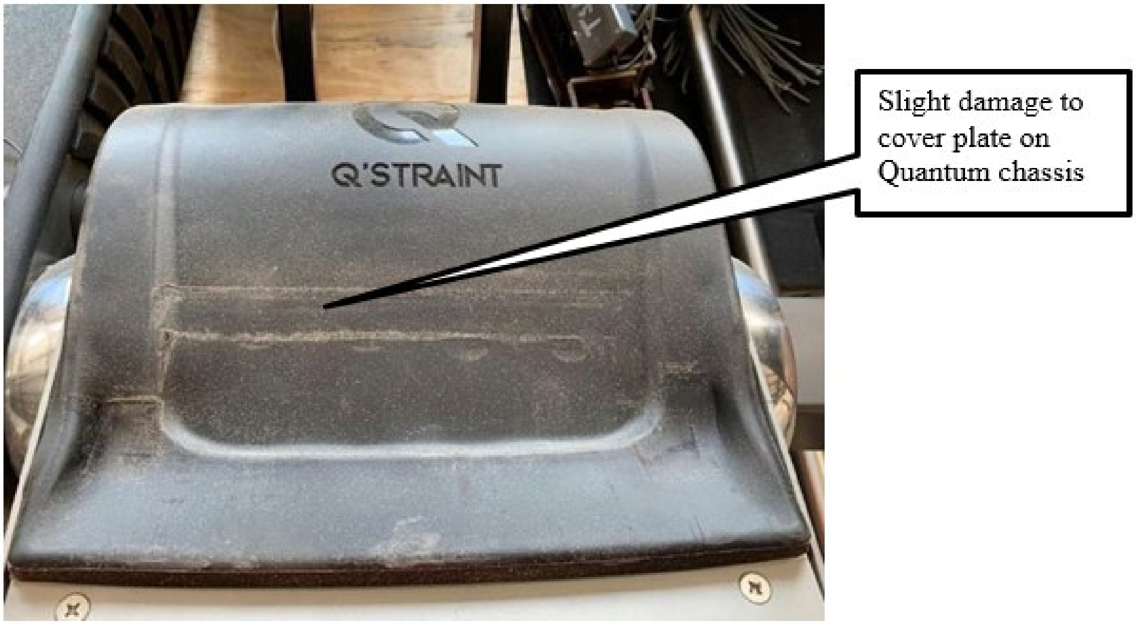
Figure 13. Holes in the left and right side of the full Q'Straint Quantum System backboard

In addition, the SWC in the full Q'Straint Quantum system had a weighted plate that was in contact with the Q'Straint Quantum chassis, as shown in Figure 14. During the impact, this plate provided a point load to the chassis and damaged the cover plate. The damaged chassis covering is shown in Figure 15. Despite the damage noted here, the full Q'Straint Quantum system functioned as intended and was still operational after the test.



Weighted plate on SWC in contact with the Quantum® Chassis

Figure 14. Plate at base of SWC in contact with Quantum chassis



Slight damage to cover plate on Quantum chassis

Figure 15. Slightly damaged cover plate on the Quantum chassis

2.4.2 External Observations

The external camera footage from fixed cameras and drones showed that there was some vertical movement of the locomotive that was transmitted to the trailing railcars in a wave phenomenon. These oscillations were also recorded by the data acquisition system.

2.4.3 Internal Observations

Researchers examined the video footage of the three experiments separately. Observations are discussed below. The vertical displacement "wave" observed in the external video footage was also observed in the internal video footage and reflected in the behavior of the wheelchair, SWCs, and ATDs. The collision dynamics of the impacting locomotives and coupled cars caused the car bodies to bounce vertically on their secondary suspensions, and this in turn induced the ATD's vertical displacement.

The wheelchair used in Experiment 1 contained pneumatic rear tires and hard front castors. The wheels on the SWCs used in Experiments 2 and 3 were all pneumatic. No wheelchair cushions were used on the WhMD or SWC. The frame of the SWC is completely rigid, in contrast with the wheelchair, which has a flexible fabric seat. The type of tires and the inflation pressures of the pneumatic tires can influence the amount of vertical excursion of the WhMD and SWC. In addition, the rigidity or flexibility of the WhMD and SWC seat, as well as any cushions, can also influence the amount of vertical displacement experienced in a crash. Typical sled and crash tests do not include wheelchair cushions, and no cushions were used in these experiments. The vertical displacement observed reflected the composition of the WhMD, SWC and ATD.

In Experiments 1 and 3, there was unimpeded access to the backboards, as there were no extra backpacks or other equipment strapped to the back of the wheelchair or SWC. In practice, however, it is very common for WhMD users to use wheelchair cushions designed to attenuate vertical forces and provide protection from pressure sores, providing comfort to the occupants. Also, many wheelchair users add backpacks or carriers to the back side of their WhMD. This extra baggage impedes full access to the backboard and increases the distance between the head and the backboard. The effectiveness of the backboard is reduced and there is an increased potential for serious neck and head injuries. WhMD with attached headrests may reduce serious neck and head injury, but some headrest attachment hardware may hit the backboard framework. The crash tests were intentionally designed to not include attached headrests, seat cushions, or extra baggage on the back of the wheelchair or SWC.

Experiment 1: Rear-facing with backboard (no active securement or occupant restraint)

In Experiment 1 (i.e., the unrestrained manual wheelchair against a rear-facing backboard), the ATD moved vertically out of the seat. The video footage from the side view camera shows that at 0.14 minutes, the wheelchair moved back and impacted the backboard followed by very slight compression of the tires before both the wheelchair and ATD moved vertically upward. The ATD rose about 4 inches from the seat of the wheelchair so that the bottom of the ATD was level with the top of the wheelchair tires. The wheelchair lifted about 2 inches off the floor. At 0.20 minutes, both the wheelchair and ATD dropped down vertically. There was vertical oscillation and both the wheelchair and ATD launched vertically once more, but the amplitude was less than half of the initial amplitude. This oscillation behavior was consistent with observations from the external cameras and the results derived from the data acquisition system on the car bodies. The presence of the vertical motion was due to dynamic collision forces imparted by the locomotive and the car bodies bouncing during the impact. The pneumatic tires on the WhMD and SWC may have acted as shock absorbers and influenced secondary vertical movement. Depending on the type of wheelchair cushion, the ATD could exhibit much larger or smaller vertical motion. After 1.00 minute, the ATD settled back into the wheelchair without showing any significant horizontal displacement from the starting point before the crash test.

Since the back of the wheelchair was unimpeded, it made full contact with the backboard. The backboard limited the head and neck movement of the ATD. After the crash event, the feet of the ATD returned to contact the wheelchair footrest. Figure 16 shows a snapshot of the movement experienced by the ATD and the wheelchair during impact during Experiment 1.

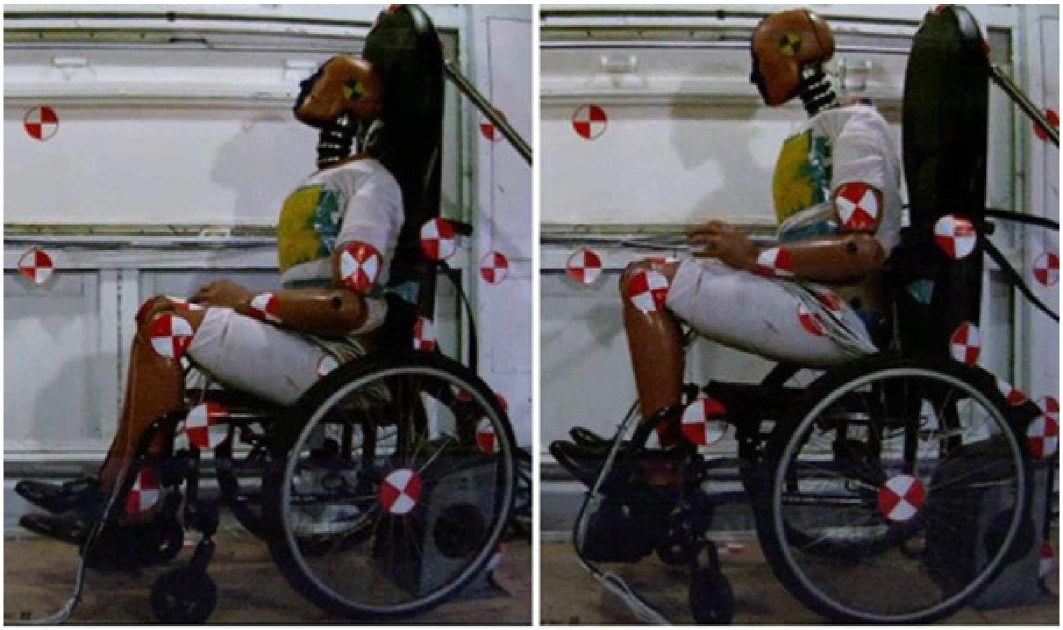
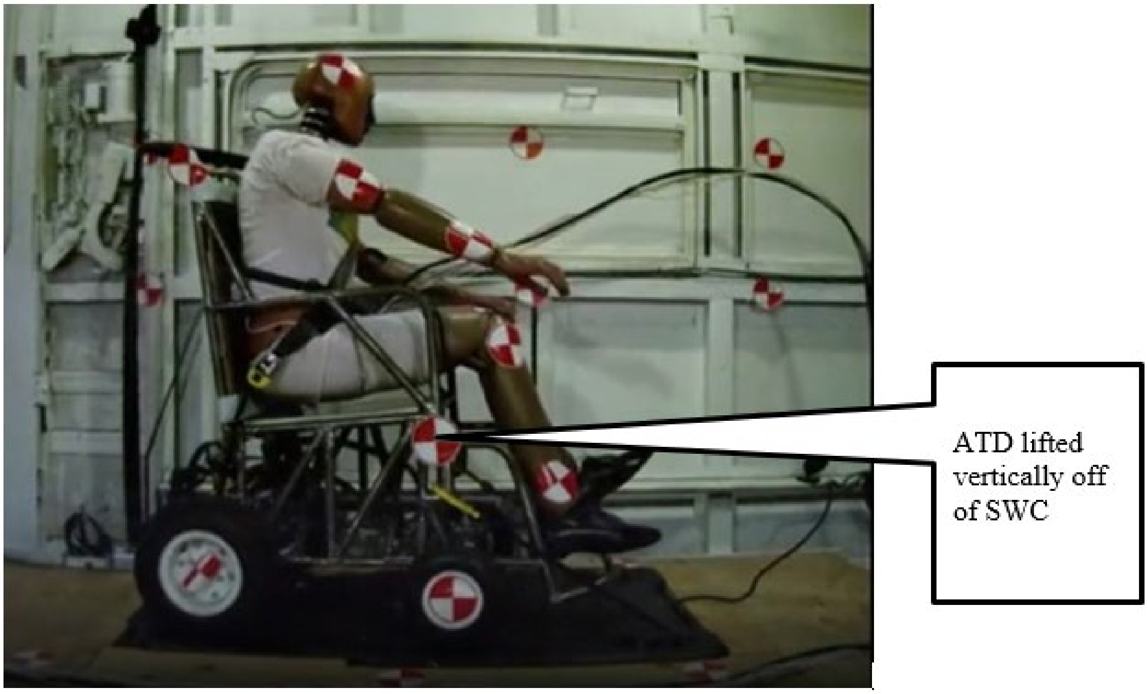


Figure 16. Movement of the ATD rear-facing wheelchair during impact

Experiment 2: Forward-facing with Q'Straint One and three-point occupant restraint

Experiment 2 evaluated a forward-facing SWC that was secured by the Q'Straint One, while the ATD was restrained by a three-point shoulder strap and lap belt assembly. During the crash test, both the SWC and ATD moved forward in the direction of travel. The ATD slid forward about 3 inches in the seat at 0.09 minutes. Then at 0.12 minutes, the ATD launched 2 inches vertically, and at 0.16 minutes the ATD moved down and backwards. The ATD and SWC settled down at 0.30 minutes. The SWC motion was restricted by the Q'Straint One system to less than 2 inches of movement. All the wheels of the SWC moved less than 1 inch off the ground. The motion of the ATD was restricted by the shoulder strap and lap belt. Figure 17 shows the vertical excursion of the ATD and SWC. In both Figure 17 and Figure 18, the ATD is shown airborne from the SWC. The three-point restraint system prevented both rotation and submarining of the ATD. Figure 18 shows the ATD head whipped backward since there is no headrest on the SWC or backboard to restrict head motion.



ATD lifted vertically off of SWC

Figure 17. The vertical movement of the ATD and the SWC

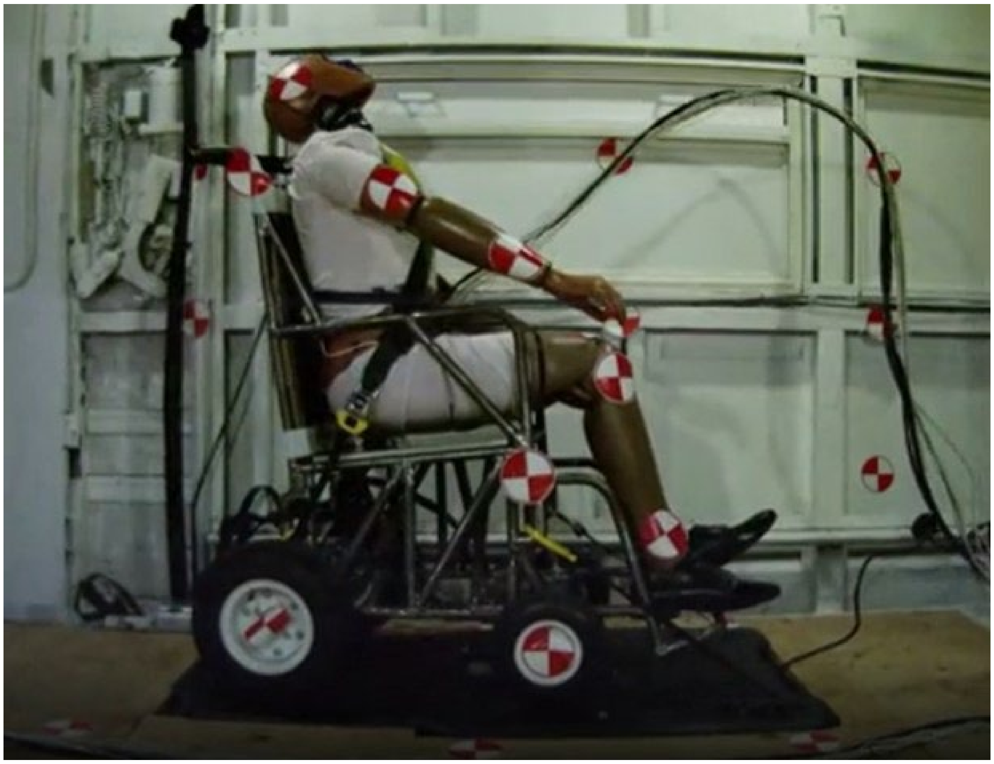


Figure 18. The rear head movement of the ATD and vertical displacement

Experiment 3: Rear-facing Q'Straint Quantum securement and three-point restraint system

Experiment 3 evaluated a rear-facing SWC that was secured by the Q'Straint Quantum with the ATD restrained by a three-point restraint system consisting of a shoulder strap and lap belt. At 0.07 minutes, the SWC moved rearward toward the backboard and the SWC rotated with the front wheels lifting about 2 inches off the ground and rotating around the rear wheels held in place by the Q'Straint Quantum securement system. In this impact test, a vertical component of acceleration was observed. In Figure 19, the Q'Straint Quantum is shown moving toward the backboard and launching vertically upward; at 0.15 minutes, it reached the maximum vertical excursion of 6 inches above the SWC. Figure 19 shows the surrogate chair lifting off the floor of the carbody, although it is still firmly held by the Q'Straint Quantum system against the backboard. The vertical ATD motion was not unexpected, although vertical carbody motion and subsequent vertical occupant motion have been observed in accident investigations [9] and full-scale train-to-train tests [10]. Upon impact, the cars pitched down at the leading end and pitched up at the trailing end, which can cause forward-facing occupants and ATDs to be launched over the top of adjacent seat backs, especially when seats are in the open-bay configuration. Vertical carbody motion tends to be greater in the last car in a consist, since there is no car coupled behind it to restrict the vertical motion of the trailing end. Therefore, the vertical motion in this experiment was more extreme because it was located at the trailing end of the last car in the consist. Figure 19 and Figure 20 show the vertical motion of the ATD. The ATD dropped back down onto the surrogate seat and there was a very small secondary vertical movement.

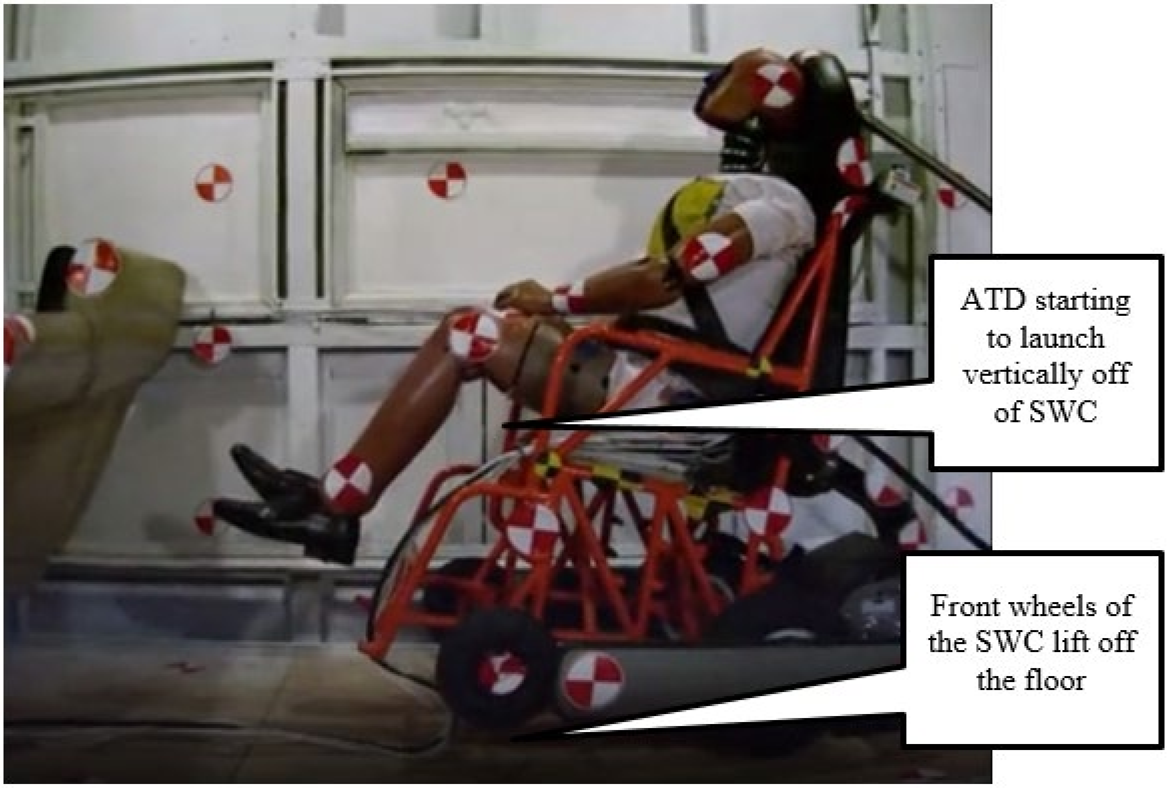


Figure 19. The Q'Straint Quantum is moving toward the backboard and is also launching vertically

The motion settled down by 0.3 minutes and the ATD was sitting in the SWC almost at the same location as it started. The overhead interior video footage did not show any rotation or pivoting of the ATD, and there was no submarining under the lap belt. Both the Q'Straint Quantum securement system and the lap and shoulder belts all met their design parameters.

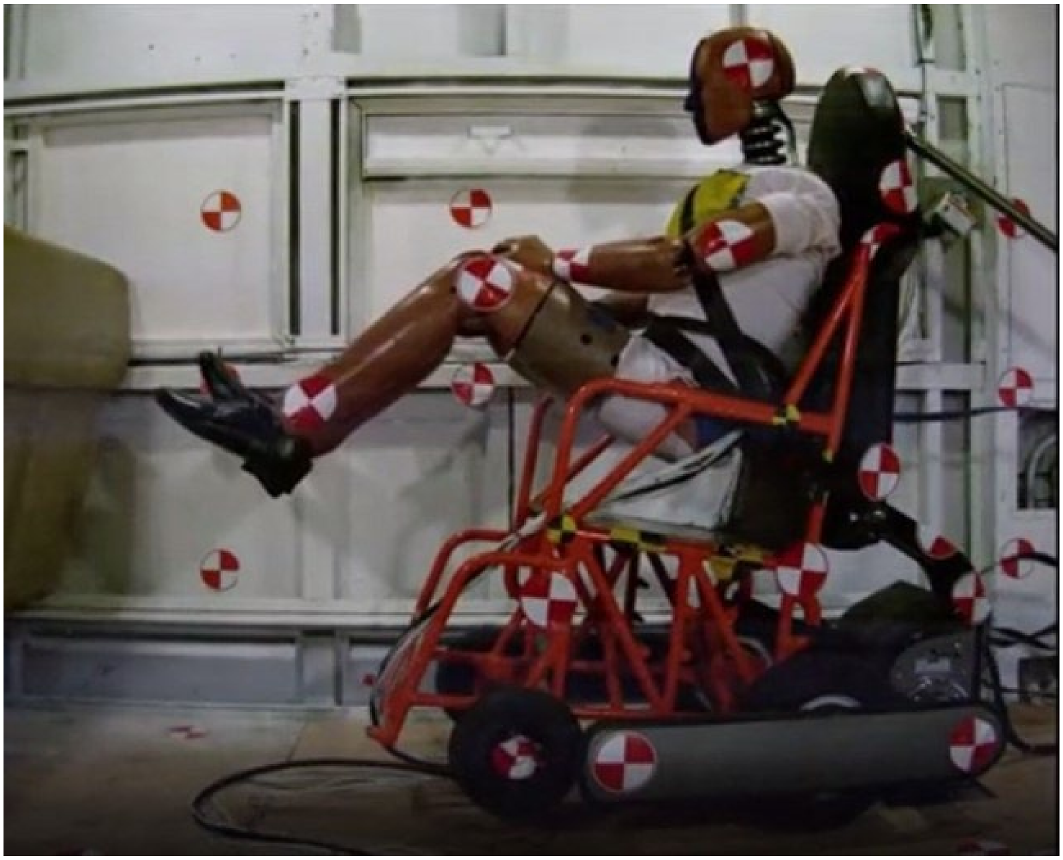


Figure 20. The largest vertical excursion of the ATD observed

3. Results

The research team analyzed the results of the three experiments and the train-to-train impact test to determine if securement and restraint systems used on public transit buses would provide adequate protection of passengers in WhMD on board passenger trains.

3.1 Securement Experiment Test Results

The train-to-train impact occurred at 24.3 mph. The two wheelchair securement and occupant restraint systems used in the experiments maintained their structural integrity and remained attached to the carbodies during the tests. At the end of the tests, the ATDs were all seated in the wheelchair or SWC. All the wheelchairs and ATDs remained compartmentalized in each of the three experiments. The injury values measured by the H3-50Ms met the performance requirements specified in the APTA seat and table standards [6], [7].

All injury values were well below the performance limits. The values are listed in Table 1 in terms of percent of the performance limit, so that values less than 100 percent meet the following APTA requirements [2], [3]:

- Head injury criteria (HIC15) must not exceed 700
- Neck axial tension (Fz) must not exceed 938 lbf (4170 N)
- Neck axial compression (Fz) must not exceed 899 lbf (4000 N)
- Neck injury criteria (Nij) must not exceed 1.0
- Chest deceleration must not exceed 60 g over a 3 ms clip
- Axial femur load must not exceed 2250 lb (10,000 N)

Table 1 summarizes the injury performance for each occupant experiment, as reported in Research Results No. RR 22-27 published by FRA in September 2022 [3]. All the test results show that the test crash was survivable and that the injuries were limited in severity.

Table 1. Injury Criteria for Occupant Experiments

Injury Criteria	**Data**						**Limit**
Experiment Number	1		2		3		
Direction	Rear-facing		Forward-facing		Rear-facing		
Restrained	No		Yes		Yes		
HIC15	21	(3%)	32	(5%)	17	(2%)	700
Neck Tension (kN)	0.49	(12%)	0.82	(20%)	0.32	(8%)	4.17kN
Neck Compression (kN)	0.25	(6%)	0.28	(7%)	0.97	(24%)	4kN
Neck Injury Criteria (Nij)	0.15	(15%)	0.26	(26%)	0.26	(26%)	1
Chest Acceleration 3 ms (g)	11	(18%)	16	(26%)	21	(35%)	60g
Chest Compression (mm)	20[†]	(32%)	20	(31%)	6	(9%)	63mm
Left Femur Compression (kN)	0.40	(4%)	0.39	(4%)	1.02	(10%)	10kN
Right Femur Compression (kN)	0.59	(6%)	0.43	(4%)	0.92	(9%)	10kN

[†] Spike in chest compression due to signal noise

4. Discussion

Results showed that the WhMD securement and two passenger restraint systems tested prevented serious injuries of the ATDs.

The focus of the experiments was to evaluate protection provided by WhMD securement and occupant restraint systems in the large wheelchair maneuvering space on passenger trains where there is a lack of passenger compartmentalization for WhMD passengers. Passengers who use WhMDs need extra space to maneuver into and out of the accessible space. FRA recommended a larger accessible space on board railcars (i.e., a space of 59 by 30 inches). The setup for Experiments 1 and 3 was rear-facing and both used a backboard. It was clear from observations of the video and the test data that unimpeded space behind the mobility device permitted the backboard to provide some head support. Any additional space between the backboard and the back of the WhMDs increased the likelihood of serious injury. There is a need for additional research and development of improved head and neck protection systems to be incorporated into the backboard to reduce the travel distance of the head and neck during a crash situation. In addition, there is a need to understand the performance of the securement systems in a situation where the back of the WhMD may not be able to directly contact the backboard. For example, many people have additional baggage on the back of their WhMD, and there are many powered wheelchairs with batteries and other equipment that occupies the area between the rear wheels. Since trains travel in two directions, two backboards for rear-facing orientation should be considered, and the backboard should also be modified if possible to permit the WhMD to be placed adjacent to the backboard to reduce the distance between the head of the passenger and the backboard.

The orientation in Experiment 2 was forward-facing. There were no head restraints on the SWC nor on the securement system. The ATD showed whiplash behavior, although the test results met the accepted injuring criteria standards. Since passenger train movement is in two directions, it is not known if a backboard placed with the Q'Straint One would have been effective in reducing the whiplash of the ATD traveling in the opposite direction than tested. Experiments 1 and 3 tested the theoretical rear-facing orientation and demonstrated that the backboard was effective. Head supports attached directly to the WhMD should provide some protection. There is a need to conduct further research to verify the effectiveness of headrests that are attached in rear-facing securement systems during crashes. For people who use folding wheelchairs, the permanent attachment of a headrest is much more complicated and may be impractical.

The vertical motion of the locomotive and carbodies during the crash was reflected in the vertical excursion of surrogate and manual wheelchairs. All three devices had pneumatic tires which may have augmented some of the vertical displacement and the amplitude of the secondary oscillations. No wheelchair cushions were used on any of the test SWC or wheelchairs. Some types of wheelchair cushion would in some circumstances increase the degree of the vertical motion of the ATDs. For Experiment 1, there was no occupant restraint system, and while the ATD did exhibit vertical displacement, the ATD ended up in the wheelchair seat. In Experiments 2 and 3, the ATDs were restrained with three-point restraint systems that controlled some of the vertical displacement. The ATD in Experiment 3, the Q'Straint Quantum system showed the largest amount of vertical displacement, but this is attributable to the location of the securement system in the trailing vehicle and the amount of vertical displacement of the carbody itself. At the end of the test, all the ATDs were seated in the SWC.

There is a need for at least 59 inches of clear maneuvering space for WhMDs on board passenger railcars. The crash test results showed that the rear-facing securement system with a backboard provided sufficient occupant protection in the 23.4 mph crash test. Compartmentalization strategies for WhMD users should take into account that passenger trains move in both directions along longitudinal tracks. Some people cannot travel facing the rear of the train. There may be configurations and user preferences where forward-facing orientation would be desired and other securement systems such as a four point tie down should be considered.

The rear-facing backboard system is the simplest compartmentalization system tested that met all the injury criteria. The rear-facing backboard can be used independently by the WhMD users and does not require any additional assistance from trained train crew.

Further research, design, and testing of the backboard is needed to provide improved head and neck protection and to accommodate WhMD that have equipment or luggage on the rear of the mobility device. Further study is needed for forward-facing securement systems that also meet the operational needs of passenger rail.

5. Conclusion

The experiments performed during the train-to-train crash test results showed that “off the shelf” securement systems designed and tested for bus transit provided adequate protection of ATD seated in SWC or WhMD on board passenger railcars. The team used ATD measurements to calculate injury criteria for the head, chest, neck, and femurs; all measurements were well below the requirements specified in industry safety standards for passenger seats and tables. All the securement and restraint systems limited the motion of the manual wheelchair and SWCs. The three-point restraint systems reduced the displacement of the ATDs. No wheelchair cushions were used in the test and there was clear space behind the manual wheelchair. There was a lower plate on the SWC that did impact the Quantum mechanism, but it was still operable after the test.

The team found the rear-facing backboard to be the simplest securement system that met all the injury criteria. The rear-facing backboard can be used completely independently and does not require any additional assistance from trained passenger train crew. However, the backboard itself requires further research, design, and testing to accommodate wheeled mobility devices with luggage or equipment on the back of the device. Additional research is needed on a forward-facing securement and restraint system that meets the needs of both passengers and train crews.

6. References

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Abbreviations and Acronyms

ACRONYM	**DEFINITION**
APTA	America Public Transportation Association
ATD	Anthropomorphic Test Device
CEM	Crash Energy Management
FRA	Federal Railroad Administration
H3-50M	Hybrid III 50th percentile male
HD	High Definition
HS	High Speed
OSU	Oregon State University
PRIIA	Passenger Rail Investment and Improvement Act of 2008
RESNA	Rehabilitation Engineering Society of North America
RVAAC	Rail Vehicle Accessibility Advisory Committee (US Access Board)
SIV	Secondary Impact Velocity
SWC	Surrogate wheelchair
TTC	Transportation Technology Center
Volpe Center	Volpe National Transportation Systems Center
WhMD	Wheeled Mobility Device