



Proposed test method for and evaluation of wheelchair seating system (WCSS) crashworthiness

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Abstract—Safety of motor vehicle seats is of great importance in providing crash protection to the occupant. An increasing number of wheelchair users use their wheelchairs as motor vehicle seats when traveling. A voluntary standard requires that compliant wheelchairs be dynamically sled impact tested. However, testing to evaluate the crashworthiness of add-on wheelchair seating systems (WCSS) independent of their wheelchair frame is not addressed by this standard. To address this need, this study developed a method to evaluate the crashworthiness of WCSS with independent frames. Federal Motor Vehicle Safety Standards (FMVSS) 207 test protocols, used to test the strength of motor vehicle seats, were modified and used to test the strength of three WCSS. Forward and rearward loads were applied at the WCSS center of gravity (CGSS), and a moment was applied at the uppermost point of the seat back. Each of the three tested WCSS met the strength requirements of FMVSS 207. Wheelchair seat-back stiffness was also investigated and compared to motor vehicle seat-back stiffness.

Key words: *crashworthiness, wheelchair injury prevention, wheelchair seating systems, wheelchair standards, wheelchair testing, wheelchair transportation*

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INTRODUCTION

Substantial research is being done to increase the safety of vehicle seats and to improve their occupant protection features. Manufacturers of automotive seats are now required to perform extensive testing to ensure that production vehicles comply with government crashworthiness and occupant protection regulations as described by Federal Motor Vehicle Safety Standards (FMVSS) (1,2). FMVSS 207, Seating Systems, specifies requirements for static strength of motor vehicle seats and their anchorages. This test protocol is based on inertial loads of the seat during a 20g impact. The FMVSS 207 legislation was instituted in 1968 for passenger cars and extended to include trucks and buses in 1972 (3).

Seating system integrity is key to occupant protection in a crash. Failure of seating system anchorage to the vehicle can lead to excessive occupant excursion, seat impingement on the occupant, and impact with the vehicle interior. Failure of the seat back during frontal impact rebound or rear impact can result in contact with structures in the rear of the vehicle, or, in cases of severe rear impact, ejection of an unrestrained occupant from the vehicle (3,4). FMVSS 207 was intended to evaluate both seat anchorage strength and seat back strength. When using a wheelchair as a vehicle seating system, the need

for structural integrity mirrors that of the originally equipped manufactured (OEM) vehicle seat. Failure of the seating system's anchorage to the wheelchair frame or failure of the seat back will also lead to increased risk of wheelchair user injury. Accordingly, it is appropriate to subject wheelchair seating systems (WCSS) to the same testing described by FMVSS 207 for motor vehicle seats.

The American National Standards Institute/Rehabilitation Engineering Society of North America (ANSI/RESNA)WC/, Volume 1, Section 19—Wheelchairs Used as Seats in Motor Vehicles Standard (WC-19)—which is currently being voted upon for adoption (5), requires that compliant wheelchairs be sled impact tested using a 20 g/30 mph frontal crash pulse. The standard also provides design guidelines for wheelchairs intended for motor vehicle transport and states that the wheelchair seat must be secured so that it does not add to the loads on the occupant during a crash. The wheelchair must also be designed and constructed to provide support for the occupant under impact loading and during occupant rebound, thereby controlling occupant kinematics.

Despite an effort by WC-19 to evaluate wheelchair crashworthiness, the common addition of after-market or customized wheelchair seating systems will invalidate testing and compliance that was performed with a complete wheelchair system that included a different seating system. Therefore, many wheelchairs with add-on seating systems will not have been sled impact tested to evaluate their ability to withstand crash level forces (6). Additionally, WC-19 does not address wheelchair or WCSS performance under rear impact conditions. The newly formed RESNA working group, Seating Devices for Use in Motor Vehicles, was charged with guiding crashworthy seating system design and addressing the crashworthiness of after-market seating systems through development of a new wheelchair seating standard. The outcome of this study is the preliminary development of an ANSI/RESNA seating system standard. Add-on WCSS currently available on the market include those with seat frames independent of the wheelchair frame (**Figure 1a**), and those mounted to the actual wheelchair seat frame (**Figure 1b**). To begin to address WCSS crashworthiness, this study evaluated only seating systems with independent seat frames (**Figure 1a**).

This study tested WCSS according to established FMVSS 571.207 requirements for vehicle seats and attachment hardware (2), in order to minimize the possibility of failure during vehicle impact. The performance requirements of FMVSS 207 are that the vehicle

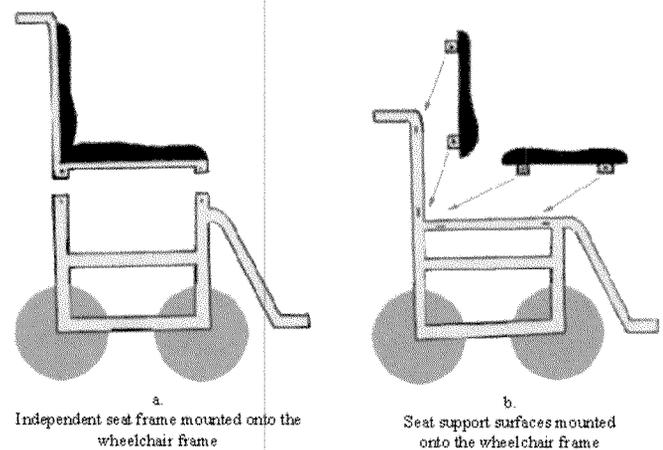


Figure 1.

Add-on seating systems currently available on the market. (a) Independent seat frame; (b) Seat support surfaces.

seat shall withstand the following forces (see **Figures 2 and 3**):

- A force 20 times the weight of the seat applied in a forward, longitudinal direction;
- A force 20 times the weight of the seat applied in a rearward, longitudinal direction;
- A force that produces a 3,300 in-lb rearward moment about the seating reference point, applied to the upper cross-member of the seat back, in a rearward, longitudinal direction.

All loads should be applied within 5 s, held for 5 s and then reduced to 0 within 5 s.

Along with the strength of the WCSS, another aspect requiring investigation is the deflection of the wheelchair seat-back frames when subjected to crash loads. Wainwright (7) concluded that controlled deflection of the occupant's seat back might reduce risk of crash-related injuries. According to another study, done by Warner (8), on the stiffness of motor vehicle seats during impact loads, non-yielding seats can increase occupant rebound during a crash, which can result in an increased risk of occupant injury. Therefore, in addition to assessing WCSS strength, stiffness of WCSS should be evaluated, since this variable could have an effect on occupant safety during motor vehicle impacts.

The application of FMVSS 207 to evaluate the crashworthiness and seat-back stiffness of after-market

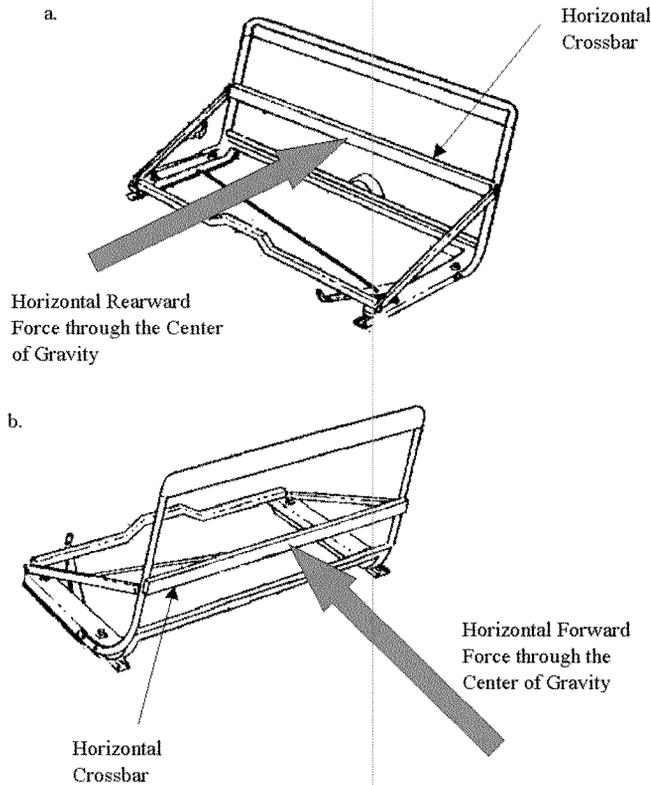


Figure 2. FMVSS 207 forward load (a) and rearward load (b) tests of 20 times the weight of the seat.

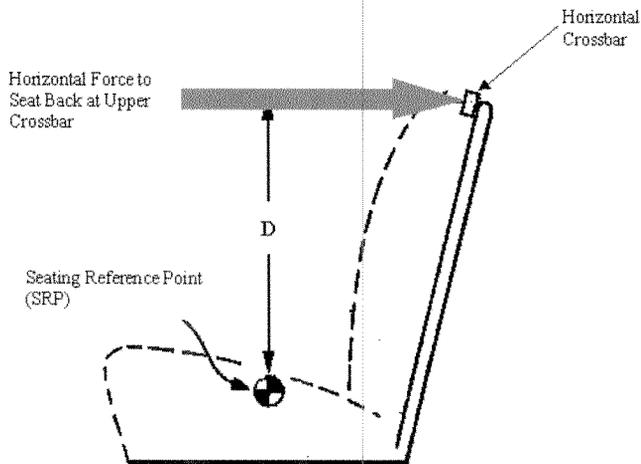


Figure 3. FMVSS 207 3,300 in-lb moment test. D is distance between SRP and horizontal force.

WCSS is a first attempt to evaluate their crash performance, independent of a wheelchair frame. The WCSS complying with a static strength test such as FMVSS 207

will promote improved crash safety for wheelchair occupants traveling in vehicles.

METHODS

Three commercially available, independent frame WCSS were evaluated in this study: Orbit (Invacare, Cleveland, Ohio), a pediatric WCSS; Tarsys (Invacare, Cleveland, Ohio), an adult tilt-and-recline WCSS; and LaBac (LaBac, Lakewood, Colorado), an adult tilt-and-recline WCSS (Figure 4). To our knowledge, only four seating systems that employ frames independent of the wheelchair are currently available on the market.

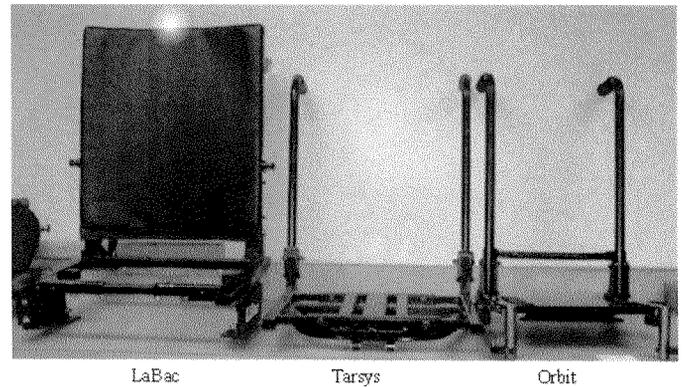


Figure 4. Evaluated wheelchair seating systems (WCSS): LaBac, Tarsys, Orbit.

To conduct the load test according to the guidelines of FMVSS 207 for Seating Systems, a mechanical testing instrument, the Instron Series 4204 (Instron Corporation, Canton, Massachusetts), was used. The Instron is designed to test materials in either compression or tension up to 11,236 lb (50 kN) and consists of a base, a computer-controlled crosshead with a load cell, and a plotter to record data. A rigid, steel test fixture, consisting of a base plate and back plate, was developed and mounted on the Instron. For testing, each WCSS was mounted to this test fixture using the original anchorage hardware of the WCSS.

The test fixture is bolted to the base of the Instron and various WCSS are anchored to the test fixture (Figure 5). For the purpose of this test, a 2,247 lb (10 kN) load cell was used. Data from the load cell and crosshead movement, such as the maximum displacement and the peak applied loads, are collected and displayed on the

Instron computer. The computer controls the speed with which the load is applied (in/s), the magnitude of the load, and the direction in which the crosshead moves (compression *versus* tension). A Hewlett-Packard 7090A plotting system was used to visualize and plot the force-time history.

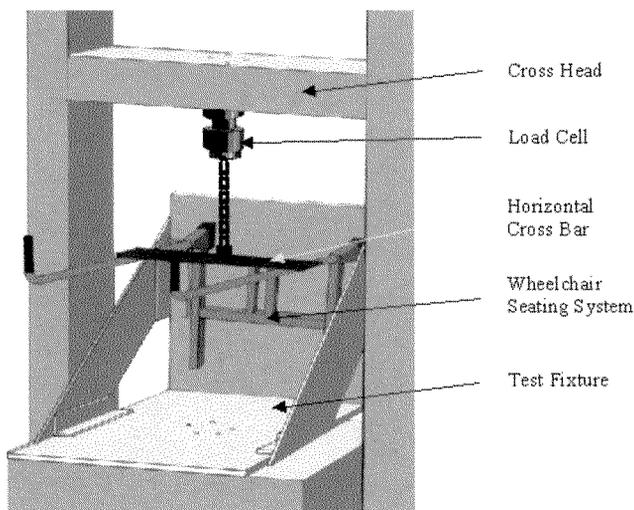


Figure 5.
Test setup on the Instron Series 4204 loading machine.

According to FMVSS 207 (9), loads must be applied at the center of gravity of the seating system (CGSS) and at the uppermost point of the seat-back frame. After determining the CGSS for each system, a customized horizontal crossbar was developed for each WCSS and mounted across each of the seat-back frames to apply loads at the CGSS. The total weight of each WCSS was established and the weight of the horizontal crossbar on the WCSS was subtracted from (forward load) or added to (rearward load) the weight of each WCSS. The total weight of the Orbit WCSS and the Tarsys WCSS excluded the weight of the seating support surfaces, while the total weight of the LaBac WCSS included the seating support surface. For ease in mounting the rigid test fixture bar on the WCSS seat backs, the seat-back support surfaces for the Tarsys WCSS and for the Orbit WCSS were removed during testing.

Table 1 lists the weights and the applied loads of the tested WCSS. To determine the loading needed to establish the 3,300 in-lb moment about the CGSS, the moment arm (distance) from CGSS to the uppermost point of the seat back was measured and recorded in **Table 1**. The

loads in **Table 1** were the actual loads applied to the WCSS, and were higher than required by FMVSS 207 due to the overshooting of the maximum load settings by the Instron.

Table 1.

Parameter	Tarsys	Orbit	LaBac
Weight Seating System (lb)	24.5	7.75	38.6
Forward load (lb)	500	151	812
Rearward load (lb)	499	170.5	772
Distance from CGSS to upper crossbar of the seat back (in)	15	16	15
Load applied to generate 3,300 in-lb moment about the CGSS(lb)	233.5	222.5	225

The FMVSS 207 protocol was adapted to test the WCSS. **Figure 6** shows the directions and locations of the forward load, rearward load, and the moment applied to each WCSS. All loads were applied within a, 0- to 50-lb tolerance range according to the FMVSS 207 protocol for motor vehicle seats.

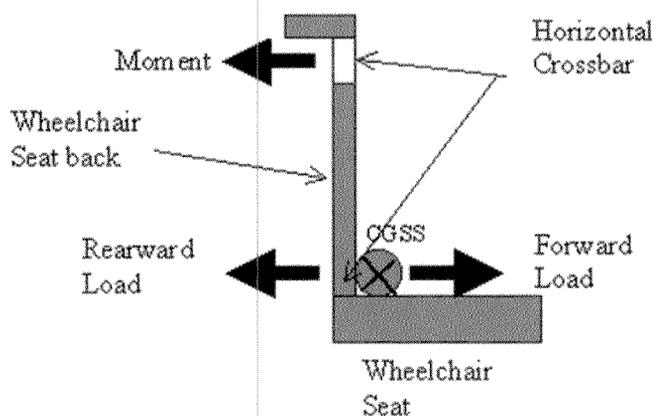


Figure 6.
Schematic view of the direction and location of the forward load, rearward load, and the moment applied to the WCSS.

- First, the forward load was applied to the horizontal crossbar through the CGSS of the WCSS. As shown in **Figure 7a**, the CGSS aligned with the load cell of the Instron, and the crosshead moved downward, applying the load to the horizontal crossbar.
- Second, the rearward load was applied to the crossbar through the CGSS. Special interface hardware, (A in **Figure 7b**) and an S-shaped hook (B in **Figure 7b**) were

used to connect the horizontal crossbar to the load cell. The crosshead of the Instron moved upward to apply the load.

- Third, the 3,300 in-lb seat-back moment was applied about the CGSS (Figure 7c) by applying a rearward load to the horizontal cross bar attached to the seat back uppermost location.

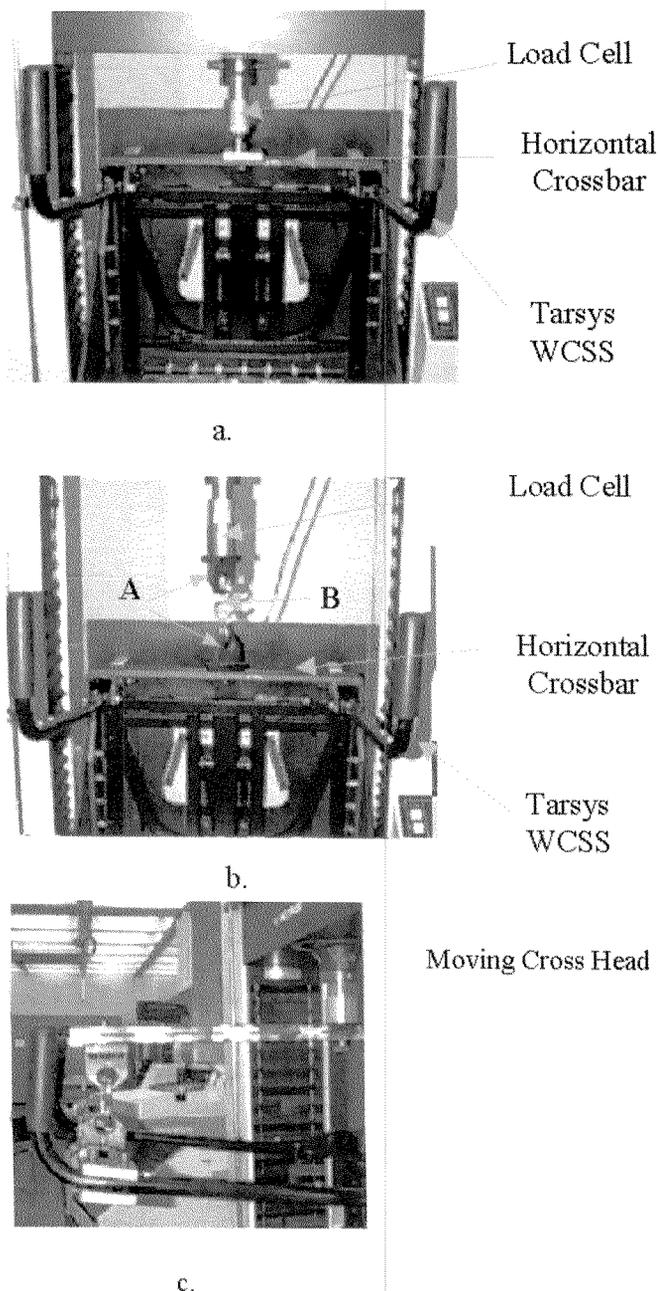


Figure 7.

Test setup to apply the (a) forward load, (b) rearward load, and (c) moment. A is interface hardware; B is an S-shaped hook.

The load cycle for all three tests was as follows (tolerance, ± 0.5 s):

1. Apply each load within 5 s
2. Hold each load for 5 s
3. Reduce each load within 5 s.

Before applying the maximum required load on each WCSS, an initial load (5 percent of the maximum) was applied to the WCSS to determine the required speed of the crosshead to achieve the desired rate of loading.

After the WCSS was mounted on the test fixture, and the horizontal crossbar mounted to the crosshead, the desired peak loads and crosshead speed were set through the Instron controller. Before loading the WCSS, the seat-back angle was measured with a SmartTool digital inclinometer (Macklanburg Duncan, Charlotte, NC) with an accuracy of 0.1° . The deflection angle was measured at the peak load. After the load on the WCSS was reduced to zero, the final (permanent) deflection angle was measured.

Figure 8 shows a schematic view of this deflection angle, measured for: 1) forward load, 2) rearward load, and 3) moment tests. Data collection included the peak load, load-time history, and the excursion of the crosshead. Each test was recorded on videotape. Pictures were taken at the start of each test, at the time of the peak applied load, and after the load was withdrawn.

RESULTS

Table 2 summarizes the results of testing and shows the seat-back deflections, the peak applied loads, the applied moments, and the maximum permanent seat-back deflections of the three WCSS. Each of the tested WCSS met the FMVSS 207 criteria, which are to meet the loading requirements without failure of the seating systems or anchorages.

Force-time histories of the WCSS during forward load, rearward load, and moment tests are shown, respectively, in Figures 9, 10 and 11. Due to the limited Instron crosshead speed of 20 in/s, the required time of 5 s to load the WCSS could not be established for the moment test of the Orbit WCSS. Instead, 10 s was needed for the crosshead to reach the target load.

During forward loading of the seat back, the LaBac WCSS had the largest peak deflection, 3.5° (0.7 in). For the rearward load test, the LaBac WCSS had the largest peak

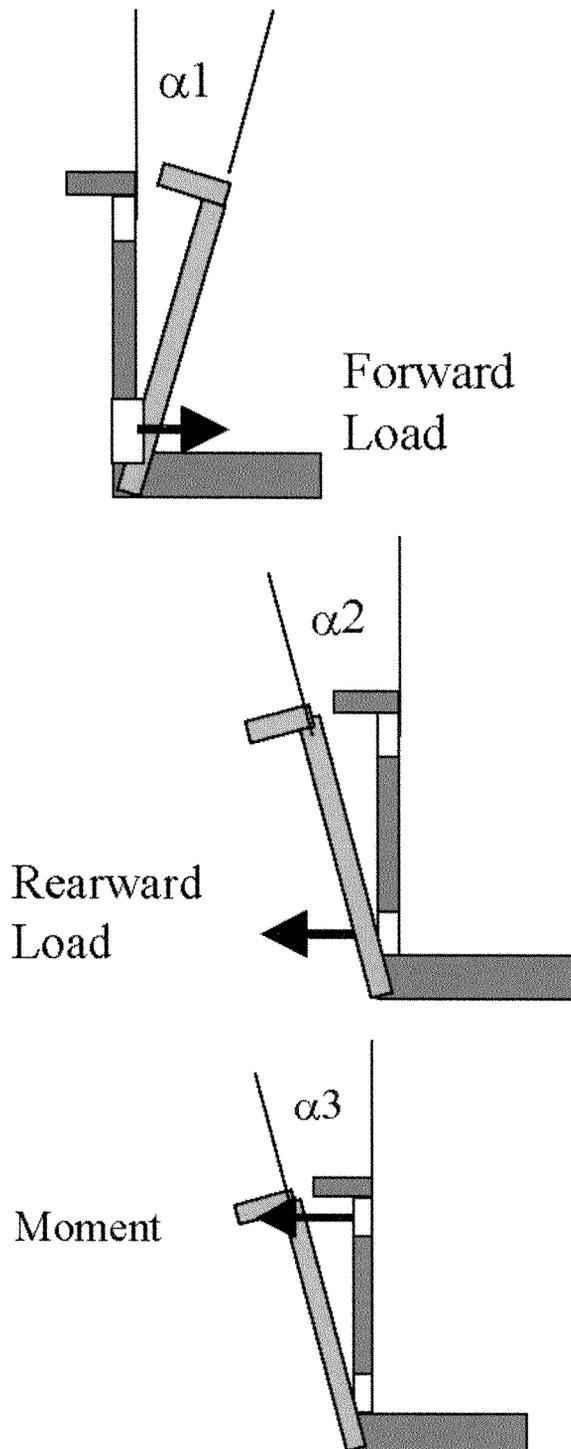


Figure 8. Deflection angle (α) measurements for the (a) forward load, (b) rearward load, and (c) moment tests.

deflection of 3.5° (0.6 in). The Tarsys WCSS showed the smallest peak deflection for both forward and rearward load testing. Among the three WCSS, the Orbit seat back

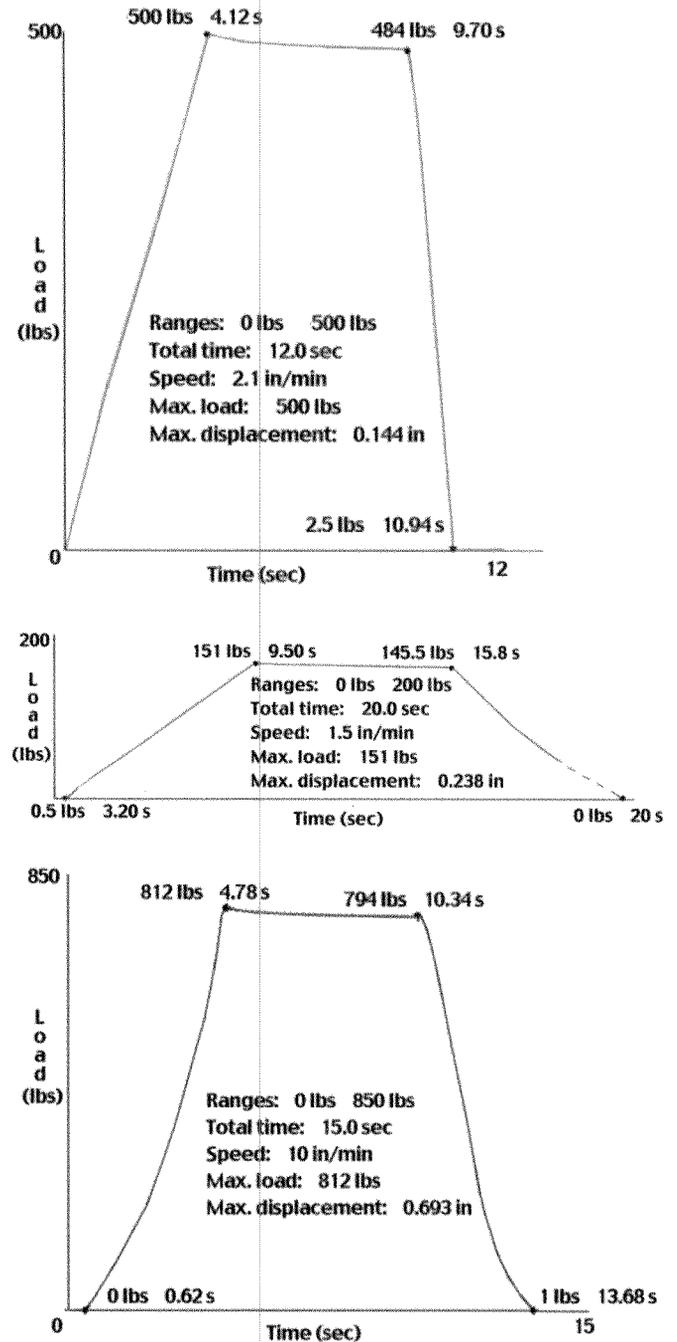


Figure 9. Force-time history for forward load test of the (a) Tarsys, (b) Orbit, and (c) LaBac WCSS.

showed the largest deflection during the moment test, 8.8° (3.4 in). The Tarsys and the LaBac WCSS showed a permanent deflection of 1.2° and 1.0° , respectively. Compared to these two seating systems, the Orbit WCSS showed a very small permanent deflection of 0.1° . The small perma-

Table 2.

Seating System	Forward Load				Rearward Load			Moment Upper Seat Back			Permanent Seat Back Deflect. (deg)
	Weight (lb)	Peak Load (lb)	Peak Ext. (in)	Peak Ext. (deg)	Peak Load (lb)	Peak Ext. (in)	Peak Ext. (deg)	Applied Load (lb)	Peak Ext. (lb)	Peak Ext. (deg)	
Tarsys	24.5	500	0.1	0.9°	505	0.2	0.3°	233.5	1.6	2.0	1.2°
Orbit	7.75	151	0.2	1.1°	170.5	0.4	2.7°	222.5	3.4	8.8°	0.1°
LaBac	38.6	812	0.7	3.5°	772	0.6	3.5°	225	1.9	4.0°	1.0°

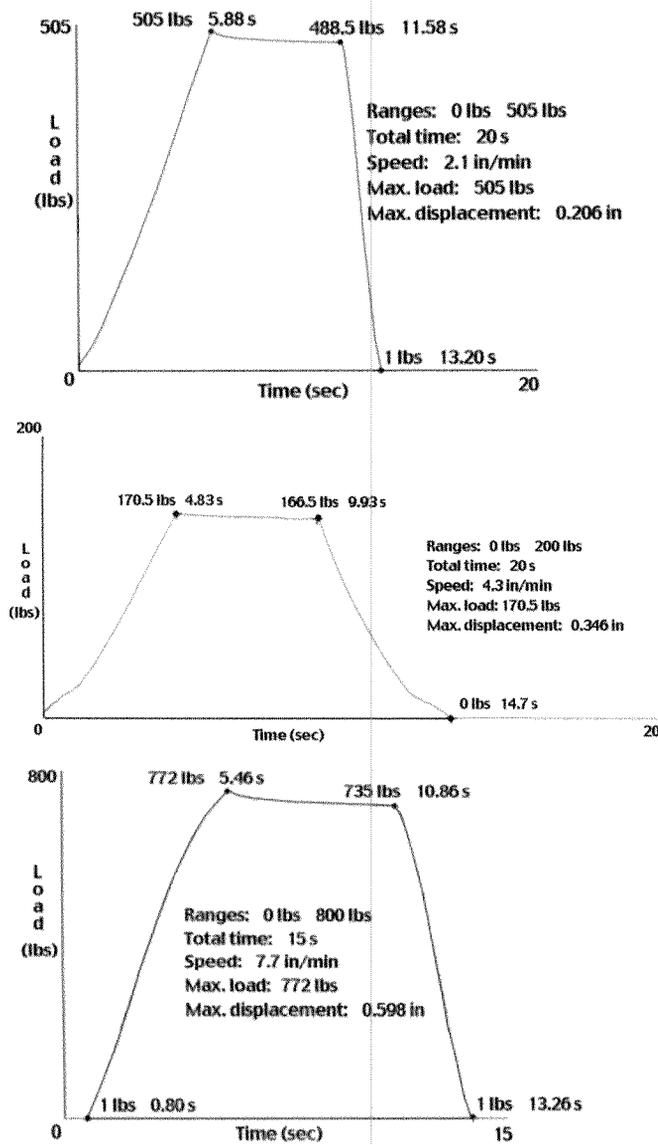


Figure 10. Force-time history for rearward load test of the (a) Tarsys, (b) Orbit, and (c) LaBac WCSS.

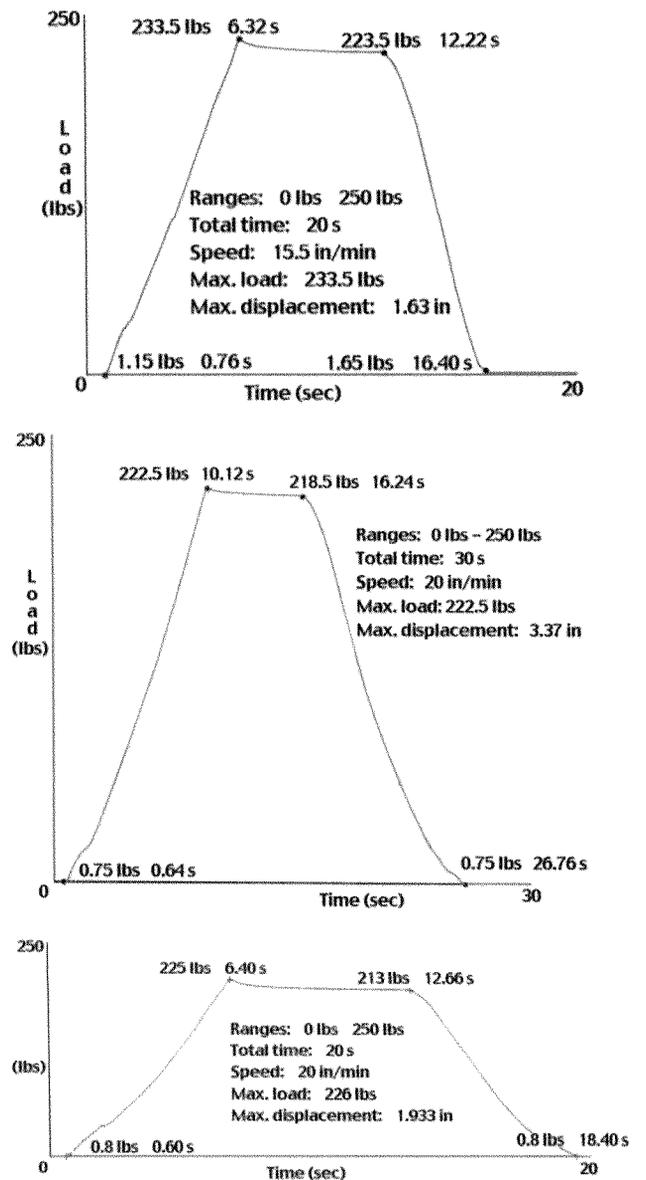


Figure 11. Force-time history for moment test of the (a) Tarsys, (b) Orbit, and (c) LaBac WCSS.

ment deformations of the tested WCSS show that these systems absorbed minimal energy during application of forces and moments on the seat backs.

Seat-back stiffness values of the three WCSS were calculated using two methods, to facilitate comparison with motor vehicle seat-back stiffness values:

- Dividing the load associated with the applied moment to the upper seat back by the horizontal excursion of the upper most point of the seat back (lb/in); and
- Dividing the moment applied to the seat back by the seat back angular rotation (in-lb/°).

Table 3 shows the stiffness values of the three tested WCSS. According to these results, the Orbit seating system showed the lowest and the Tarsys showed the highest stiffness.

Table 3.

WCSS	Stiffness (in-lb/deg) (rotation based)	Stiffness (lb/in) (deflection based)
Tarsys	1650	146
Orbit	375	65
LaBac	825	119
NHTSA (11) motor vehicle seats	576±249 (avg) (min 216/max 1191)	
Warner (8) motor vehicle seats		135 (avg) (min 40/max 606)

DISCUSSION

FMVSS 207 criteria have influenced vehicle seat design. Over time, two contradictory philosophies in seat-back design have prevailed:

1. Seat backs should both controllably yield and absorb energy to provide improved occupant "ride-down," and
2. Seat backs should be stiff so that they prevent occupant impact with interior structures in the rear of the vehicle and/or ejection from the rear of the vehicle.

The contradiction indicates that further investigation of optimal seat-back stiffness is required. The majority of testing and modeling efforts, however, indicate that controlled, yielding seat backs may be more effective in reducing rear impact injury risk. Accident injury statistics also confirm the advantages of seat backs designed to

yield controllably (8,10). This design factor should also be addressed in the development of WCSS intended to serve as vehicle seats. As a preliminary step toward quantification of WCSS design parameters, our study evaluated the stiffness of seat backs and compared these values to those of motor vehicle seat backs.

The FMVSS 207 test protocol has existed for roughly 30 years, but not without objection. For example, it is generally acknowledged that testing loads are not adequate to reflect the strength needed to prevent seat-back failure in a severe rear impact. A petition submitted by Saczalski to the National Highway and Traffic Safety Administration (NHTSA) in 1989 (4), seeks to: 1) increase the FMVSS 207 applied moment from 3,300 in-lb to 50,000 in-lb; 2) add a rearward seat-back deflection limit of 40°; and 3) base seat-back strength requirements upon loading associated with the upper torso weight of a 95th-percentile male occupant in a 30 g impact. The primary rationale behind the petition is that the seat-back loading required by the FMVSS 207 test protocol includes only inertia effects of the seat back, but fails to account for forces applied to the seat back by the occupant. To address open petitions, NHTSA is in the process of conducting a comprehensive research plan consisting of computer modeling analysis and testing of existing seating systems, and development of an advanced integrated safety seat that will guide future modifications to FMVSS 207 (11).

A 1997 NHTSA study analyzed injury types and incidence rates associated with seat-back collapse in rear impact crashes (3). Data for the study were extracted from the National Accident Sampling System (NASS) and focused on seat backs that collapsed in a rearward direction during vehicle rear impact. As might be expected, it was found that motor vehicle seat-back failure occurred more frequently during rear impacts with higher changes in velocity. When all severity levels of impact were considered, whiplash (American Medical Association Abbreviated Injury Scale [AIS] level 1 injury) occurred more frequently when seat backs maintained their upright position, but more severe injuries (AIS levels 2–6) occurred more often when seat backs collapsed rearward.

This same study also evaluated injury cost associated with a collapsed seat as compared to a seat that remained upright during rear impact. It was determined that the total injury cost across all impact severities (10–54 km/hr) is 2.83 times higher for seats that col-

lapsed in rear impact scenarios. This study further emphasizes the importance of structural integrity of the seat-to-back structure during rear impact. This factor is just as important when using a wheelchair as a motor vehicle seat, but has received only minimal attention to date. Clearly, additional rear impact performance data related to the integrity of the wheelchair seat-to-back must be sought.

Our study results indicated that all evaluated WCSS are capable of withstanding FMVSS 207 loading requirements without failure. These results suggest that the tested WCSS will at least provide a reasonable level of safety during rear impact or rebound. However, it should be noted that in following FMVSS 207 protocols, test loading did not account for that associated with the occupant loading of the seat back. As suggested by the Saczalski petition to FMVSS 207 (4), loading levels should include both the inertial effects of the seat and the occupant load applied to the seat back.

A study conducted by Warner (8) tested the strength, stiffness, and energy absorption of motor vehicle seats. His study concluded that rigid seat backs have the potential to increase injury exposure in real world impacts due to three major concerns: 1) ramping; 2) rebound; and 3) out-of-position occupants. Ramping describes the motion of an occupant sliding upward along the seat back in a severe rear impact. Under these circumstances, rigid seats have the potential of exposing unrestrained occupants to impacts with the roof structure, leading to head and neck injuries. Second, non-yielding seats can increase occupant rebound because most of the seat deflection will represent elastic energy, which will be returned to occupants in the form of rebound velocity. Third, rigid seats are potentially dangerous to occupants not in the normal seated position, and especially for unrestrained occupants.

A majority of rear-impacted vehicles experience pre-impact changes in momentum, which could cause occupants to be out of a normal position upon impact. Occupant contact with a yielding, energy-absorbing seat is expected to reduce out-of-position impact effects. If use of yielding motor vehicle seats has lower risk of occupant injury than rigid seats (during rear impacts), then wheelchairs with controlled, yielding seat backs could also provide better crash protection to wheelchair occupants than rigid wheelchair seat backs. The WCSS designs must begin to address such issues when they are intended for motor vehicle transport.

A study done by Wainwright (7) conducted FMVSS 207 static testing and FMVSS 208 frontal barrier testing

on a proposed integrated seating system design. During the design process, they found that a seat structure that is too stiff and has no energy absorption could result in both unwanted rebound and in higher occupant loads. After several sled tests, they found that an angle of 12° permanent seat-back deformation reduced the unwanted load and rebound on the occupant. This study also illustrated the need for controlled, non-elastic yielding of the seat back to optimize occupant protection. The WCSS designers must also consider such approaches to enhance wheelchair-occupant protection in a crash.

As shown in **Table 2**, all WCSS had only minimal permanent seat-back deformation. The Orbit WCSS had the smallest deformation (0.1°) and the Tarsys WCSS had the largest deformation (1.2°), which is still quite small. The low permanent deformation values indicate that little energy was absorbed by the WCSS during loading. Such performance characteristics may cause excessive rebound due to the energy transfer from the motor vehicle directly to the wheelchair-seated occupant. As indicated by previous motor vehicle seat studies, this direct transfer of energy to the occupant can also produce higher (unwanted) occupant loads.

As part of the NHTSA research plan to define guidelines for modification to FMVSS 207, a study was conducted to evaluate the moment-deflection characteristics of motor vehicle seats backs (11). Twenty-five different seats were tested using the FMVSS 207 moment test protocol. Average yield strength of the seat backs was found to be 6814±1878 in-lb, while average ultimate strength was found to be 11266±3275 in-lb. The average angular rotation from initial position at the FMVSS 207 moment limit (3,300 in-lb) was found to be 8.7°. The average stiffness of the seat backs was 576±249 in-lb/°. The maximum stiffness was found to be 1,191 in-lb/° and the minimum stiffness was 216 in-lb/°. Using the same approach to determine stiffness of the WCSS, we find the following stiffness values: 375 in-lb/° (Orbit), 1,650 in-lb/° (Tarsys) and 825 in-lb/° (LaBac). Both adult WCSS (Tarsys and LaBac) exceed the average stiffness of NHTSA-evaluated auto seat backs (576 in-lb/°). The pediatric WCSS (Orbit) stiffness is lower than the auto seat-back average. Adult WCSS (Tarsys and LaBac) seat back rotation (2.0° and 4.0°, respectively) at the FMVSS moment limit were lower than the average motor vehicle seat-back rotation (8.7°) at the same moment. The pediatric WCSS seat-back rotation (Orbit, 8.8°) was near the motor vehicle seat back average of 8.7°. These comparative findings would suggest that adult, independent frame

WCSS have stiffer seat backs than the average motor vehicle seat back.

Our findings on WCSS seat-back stiffness can also be compared to an earlier study conducted by Warner (8). In this study, 61 motor vehicle seats were evaluated under static loading conditions. The average stiffness was 135 lb/in, with a maximum of 606 lb/in and a minimum of 40 lb/in. These values were calculated using the load associated with the 3,300 in-lb moment test (approximately 235 lb) and the rearward deflection of the seat back measured at the point of load application. It is important to note that Warner applied the load to the seat back at 14 in above the seated reference plane (ASRP), whereas our moments were applied at 19.25 in ASRP for the Orbit, 15.75 in ASRP for the Tarsys and 18.25 in ASRP for the LaBac. Although our loads were applied higher on the seat backs, the Tarsys WCSS seat back appeared stiffer than the average Warner-evaluated motor vehicle seat back (see **Table 3**). The LaBac WCSS stiffness is close to the average Warner value and the Orbit (pediatric WCSS) appears less stiff than the average Warner seat-back stiffness. Without applying our loads at the same point as Warner, we can only make approximate comparisons between our seat-back stiffness values and those determined by Warner.

These comparisons to motor vehicle seats are similar to the comparisons done with more recent NHTSA-evaluated seat-back stiffnesses, described above. Such findings suggest that the evaluated adult WCSS are not yielding in their designs, and may, in fact, be more rigid than desired in a crash. Wheelchair occupants may be subjected to increased loading transmitted from the vehicle and seating system during rear impact or rebound. Although the tested WCSS appear to have adequate strength, designs that introduce controlled energy absorption through permanent deformation could improve wheelchair-occupant crash safety.

CONCLUSION

Our study used a modified FMVSS 207 test method to evaluate the crashworthiness of independent frame WCSS. All three tested WCSS met FMVSS 207 test criteria and were able to withstand the maximum required loads without significant deformation or failure. The test methods used in this study provide a preliminary means for assessing WCSS performance under rear impact and rebound conditions (conditions that have not been con-

sidered in wheelchair transportation standards thus far). This low-cost static load test does not imply a crash-proof WCSS, but functions as a first step toward evaluating add-on seating systems and attachment hardware for safe use on wheelchairs used as motor vehicle seats. Sled testing costs to evaluate all possible combinations of wheelchair bases and add-on seating systems could be excessive and cost prohibitive.

Because stiffness and energy absorption of motor vehicle seat backs have been shown to have an impact on the risk of injury in a crash, our study also evaluated these WCSS characteristics. The tested adult wheelchair seat backs (Tarsys and LaBac) were found to have stiffnesses that exceed the average stiffness of motor vehicle seats, while the pediatric WCSS (Orbit) stiffness was slightly less than the average motor vehicle seat. During loading, evaluated WCSS were found to absorb little or no energy, as evidenced by minimal permanent deformation. Both stiffness and energy-absorbing characteristics must be considered in future transport WCSS designs to optimize user crash protection.

To date, very little has been done to assess the crashworthiness of add-on WCSS. ANSI/RESNA WC/Volume 1, Section 19, a voluntary standard to evaluate the entire wheelchair system under frontal impact conditions, is accepted with a two-year phase-in period starting April 2000. However, this standard does not assess all possible add-on seating options, nor does it evaluate wheelchair/seating system performance under rear impact conditions. The modified FMVSS 207 test protocol used in this study can provide an initial crashworthy evaluation of add-on WCSS under rear impact and rebound conditions. Future testing efforts should load WCSS to failure to determine their actual strength. Also, those seating systems that mount support surfaces directly to the wheelchair frame should be evaluated following the same test protocol. The authors acknowledge the fact that, when time and funds allow it, a dynamic test should be conducted to evaluate the crashworthiness of add-on wheelchair seating systems.

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