The Application and Safety of Securements and Restraints for Wheelchair Seated Travelers on Public Transit Vehicles.

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Introduction

Individuals with disability can increase their range of mobility by wider access to public transportation. Access to public transportation is particularly limited for those individuals using wheelchairs for their mobility needs. The scheduled, fee for service intra-city transportation of wheelchair users is limited by the lack of easily applied universal wheelchair securement and personal restraint systems.

Securement devices have been used predominantly in licensed transportation vehicles specifically designed or adapted for people with disabilities. The integration of the disabled rider into existing public transportation systems redefines the criteria for securement of wheeled mobility devices. Whereas private vehicles are equipped to accommodate a single wheelchair or a limited variety of wheelchairs, public transit must be equipped to handle nearly the full spectrum of wheeled mobility devices with minimal interference with bus schedules and the services provided to other passengers.

The most common wheelchair securements are classified either as a belt or clamp system. Belt systems are relatively universal due to their flexibility. The confined area on the bus, however, makes access to the floor mounted anchor points very difficult and time consuming even for an experienced able-bodied assistant such as the bus driver. Clamp wheelchair securements are much more convenient, but can be used only with mobility devices that have suitable geometry or appropriate add-on components. These systems were originally designed for use with wheelchairs that have large, spoked rear wheels. Clamping systems that require add-on components to the wheelchairs provide rapid securement at the cost of interfering with the folding of the manual wheelchair or limiting their use to wheelchairs with add-on components. Thus, ideally, wheelchair securements should use light weight brackets, initially flexible to conform to all wheelchair designs and later made rigid for easy attachment to the bus. The brackets should be inexpensively mounted, either permanently or temporarily, without interfering with folding of the wheelchair and the locking mechanism should be installed on the bus.

The literature shows a significant world-wide emphasis on establishing standards related to wheelchair securement. Specifications have been accepted or are being considered in Australia, Sweden, Canada, the U.K., Germany and the U.S.(1,2,3,4,5) A summary of these standards and guidelines are given in Table 1. These standards concentrate on specifying the orientation of the wheelchair in the moving vehicle, the required performance of the securement in a crash event, and the recommended restraint of the occupant.

In general the emphasis of crash testing has been to assure that the wheelchair and occupant are not released within the moving vehicle. Little emphasis has been placed on understanding the dynamics of the crash sequence and the resulting injury to the occupant. Information is also sparse concerning measurement of floor forces, wheelchair and occupant restraint forces, and wheelchair accelerations and displacements. All of these measurements provide information that is needed for an acceptable and effective securement design.

The objective of this paper is to introduce a set of operational requirements for acceptable mobility aid securement and user restraint systems and to demonstrate the effect of some wheelchair and securement related variables on the impact response in a public transit environment. The results will be illustrated using data obtained from impact experiments and user surveys in the course of a cooperative local demonstration project to develop and test a wheelchair securement system

Table 1. Summary of International Standards for Wheelchair Securements

Country	Wheelchair Securement Performance Test	Occupant Restraint Criteria
International-ISO(draft)	Front impact - 20 g's, 48 km/hr.	1. Anchorage points for restraint belts 2. Maximum excursions for front impact
Sweden	Forward pull of 11,240 N	1. Anchorage points for restraint belts 2. Inertial locking lap and torso belts
Germany	Forward pull - 15,960 N Rear pull - 10,640 N	Forward pull - 11,970 N Rear pull - 7,980 N
United Kingdom (Guidelines)	Forward pull - 8,802 N Rear pull - 4,401 N wheelchair motion < 19.8 cm	Forward pull - 1,978 lbs.
Australia	Front impact - 20 g's, 48 km/hr. Side impact - 14 g's, 32 km/hr. Rear impact - 8	1.Anchorage points for restraint belts 2. Lap belt required. 3. Maximum excursions for front impact
Canada (draft)	Front impact - 20 g's, 48 km/hr.	1.Anchorage points for restraint belts 2. Lap belt required. 3. Maximum excursions for front impact
USA-(SAE) (draft)	Front impact - 20 g's, 48 km/hr	1.Anchorage points for restraint belts 2. Maximum excursions for front impact
USA (Legislation)	1. Forward pull- 22,250 N. 2. Wheelchair motion < 5 cm for "normal driving conditions."	Lap and torso belts required

Methods

Specific operation characteristics needed for an acceptable public transit securement and restraint system were investigated. The project involved wheelchair users, public transit providers, and a panel of experts to establish design parameters, develop design concepts, fabricate prototype systems and evaluate prototypes in sled impact testing and field testing.(6)

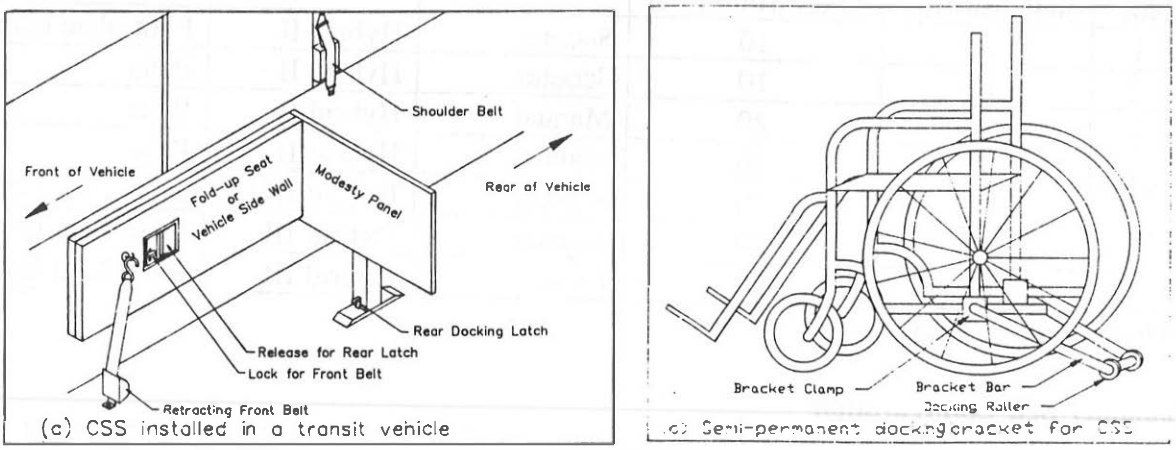
Development of a Prototype System to Satisfy the Local Needs

The prototype securement and restraint system was designed to meet the needs of the wheelchair users and transit systems in Northeast Ohio. The current status of wheelchair travel on public transit was first evaluated with a literature review and surveys of wheelchair users and bus operators. Analysis of this data identified five design objectives. To be widely accepted, a public transit securement system should be user-operable, universal, rapidly applied, crashworthy, and require no permanent addition to the wheelchair. The characteristics of these design objectives are further defined below:

a. User-operable - A person riding in a wheelchair who has average trunk, arm and hand control should be able to secure the wheelchair to the vehicle.
b. Universal - The securement should be easily attached to any type of wheelchair.
c. Rapidly Applied - The wheelchair and occupant should be secured in less than one minute.
d. Crashworthy - Both the wheelchair securement and occupant restraint should be able to withstand a 20 g's, 48 km/hr sled impact or crash test without any loose body formation or indications of life threatening injury.
e. Require no permanent addition to the wheelchair - Securement should be available for the occasional rider and those choosing not to have a permanent attachment on their chair. Any additions to the wheelchair that are needed for securement should be designed so that they can be rapidly attached and removed at the time of travel.

A prototype securement system was then developed to meet these criteria and the needs of the wheelchair traveling populations and transit providers. This prototype system, the Cleveland Securement System, can be used on all wheelchairs and scooters, requires no special adaptations to the mobility aids, exceeds the safety requirements specified by the federal government, and allows many users of mobility aids to secure themselves and their mobility aids in less than two minutes without assistance.

A schematic of the Cleveland Securement System installed in a bus is shown in Figure 1. The basis of the system is the rear docking latch which mates with a bracket extending from the rear of the mobility aid. The bracket can be either semi-permanently attached to the wheelchair, or temporarily attached when transportation is needed. Since temporarily attached brackets may be used, no permanent attachments to the wheelchair are necessary. The semi-permanently attached bracket offers the advantages of quicker securement and increased user independence. The easily accessible retracting front belt secures the front of the mobility aid after it is attached and locked by the user.



(c) CSS installed in a transit vehicle

(c) Semi-permanent docking bracket for CSS

Figure 1. Cleveland Securement System

Occupant restraints are provided by the Cleveland Securement System, though their use is not required by the laws of the Americans with Disabilities Act. The lap belts are attached to the brackets so that crash loads are transmitted through the securement system to the vehicle structure. An inertial locking shoulder belt is mounted to the wall of the vehicle, and fastens to a second buckle on the lap belt.

Field testing was performed to evaluate the system's acceptability by the drivers and wheelchair users. The securement and restraint system was installed on two paratransit and two fixed route buses in Akron, Cleveland and Lake County, Ohio. Selected wheelchair users were accompanied and supervised on the first test run. The ride lasted 20 to 30 minutes, covered 4 to 7 miles of typical inner city streets and interstate highways, and contained many right and left turns, stops and starts. The users then continued to use the system in normal service and evaluated its operation by answering a questionnaire. The vehicle operators also participated in the testing and assessed the influence of the securement system's operation on the transporting of the wheelchair users.

Sled Impact Testing

Sled impact testing was performed at the Transportation Research Center in Ohio to evaluate the crash worthy behavior of different securement and restraint designs. To gain an overall understanding of the dynamic performance of the systems, variations in mobility aid securement and restraint systems, were tested. More than one variable was investigated in each test to maximize the cost effectiveness of the test protocol. Different impact magnitudes and test dummy designs were also used to characterize the dynamic performance of the securement systems. Initial tests were conducted with commercial securement systems to gather control data on the behavior of existing devices. Later tests evaluated the prototype configuration of the Cleveland Securement System. The test matrix below (Table 2) indicates a list of primary variables. For each test, a mobility aid was secured to the test sled, and an anthropomorphic test dummy was restrained in the wheelchair by lap and shoulder belts. Data was collected from on board instrumentation and high speed motion pictures using four synchronized cameras.

Table 2. Sled impact test matrix

Test No.	*Shoulder Belt Config.	Impact Magnitude (g's)	Mobility Aid	Test Dummy	Securement System
1	A	10	Scooter	Hybrid II	Foot plate clamp
2	B	10	Scooter	Hybrid II	Belts
3	B	20	Manual	Hybrid II	Belts
4	B	20	Manual	Hybrid II	Belts
5	C	20	Scooter	Hybrid III	Bracket and clamp
6	C	20	Scooter	Hybrid III	Rear Steel Cables
7	C	20	Power	Hybrid III	Rear Steel Cables

*Defined in the Text

Shoulder Belt Configuration

Three different shoulder belt configurations were used. In all tests, the lower end of the shoulder belt connected to the lap belt near the hip. In test 1 (Configuration A), the shoulder belt anchorage height was 90 cm above the test platform and in an unusual midline location directly behind the wheelchair and test dummy. This location was selected to better restrain the test dummy in a scooter at a readily available anchorage location on the test sled. In tests 2, 3, and 4 (Configuration B), a nylon, adjustable length belt was mounted to the simulated vehicle wall also 90 cm above the test platform and now 60 cm laterally from the mid-line of the wheelchair and test dummy. This anchor location reproduced the shoulder belt position in the transit vehicles of the collaborating transit system involved in the local demonstration project. The belt was adjusted to minimize the slack prior to each test.

In tests 5, 6 and 7 (Configuration C), automotive polyester shoulder belts with inertial locking retractors were again mounted 60 cm laterally from the wheelchair mid-line, but the D-Ring for the belt was now mounted 180 cm above the simulated vehicle floor. This location was selected because it represents a mounting position above the windows of the fixed-route bus. This configuration placed the shoulder belt diagonally across the dummy's torso from the pelvis and over the mid length of the clavicle.

Impact Magnitude

Frontal impact conditions were selected to adequately test the securement systems but the early tests on scooters were performed at a lower impact magnitude in an attempt to spare the mechanical integrity of the scooters. Tests 1 and 2 used an impact of 10 g's and 32 km/hr., with a pulse duration of 130 msec. In the latter experiments (tests 3 and 4) and in the prototype evaluations (tests 5, 6 and 7) simulated impacts of 20 g's, and 48 km/hr., with a 100 msec duration were used. This level of impact test matches specifications in the draft ISO, SAE and Canadian standards shown in Table 1.

Mobility Aid

Standard manual, folding wheelchairs with sling seats were used in tests 3 and 4. Tests 1 and 2 used three-wheel scooters from two different manufacturers. To reduce the variability between the securement evaluation tests, and to minimize the expense of wheelchairs for testing, a three-wheel scooter and power chair were reinforced to withstand multiple 20 g loads in tests 5, 6 and 7. Battery masses were simulated by similar weight and size lead filled wooden boxes with the original unmodified fastener mechanisms holding them in place.

Test Dummies

Fiftieth percentile male Hybrid II (tests 1, 2, 3 and 4) and Hybrid III (tests 5, 6 and 7) test dummies were used to apply the anthropomorphic load distribution to the restraint systems and wheelchairs. Instrumentation in the dummies provided data on the accelerations of the occupants head, chest, and hip. In the latter tests the Hybrid III dummy was used to provide data on chest deflection.

Securement and Restraint Systems

A commercial securement system was modified for improved strength in test 1, and clamped the scooter across the foot board to the simulated vehicle floor. A nylon passenger lap belt was anchored to the vehicle floor. A commercial, four point belt securement system was used in tests 2, 3 and 4. Each securement belt was anchored to the floor of the test sled in the geometry used by the collaborating local transit system. A passenger lap belt was connected to each rear securement belt near its point of attachment to the mobility aid. In test 2, the two rear belts were fastened around the large diameter seat post of the scooter and the two front belts were attached low on the steering tiller. In test 3 and 4 the belts were attached to the frame of the manual wheelchairs near each wheel.

Prototype securement systems were used in tests 5, 6 and 7. In test 5, a steel bracket was attached to the mobility aid, and engaged a latch mounted to the vehicle floor. This, the first prototype of the Cleveland Securement System, was described earlier. Lap belts were mounted to the bracket near its attachment point to the mobility aid. In tests 6 and 7, steel cables were used as rear securements and were anchored to the test buck 20 cm above the floor. The cables extended horizontally and hooked around the frame of the wheelchair near the rear wheels or around the large seat post of the scooter. Automotive passenger lap belts with locking retractors were mounted 30 cm above the vehicle floor

Data Collection

Data from on board instrumentation directly measured the variables listed in Table 3 below. The data was digitally recorded at 8000 Hz for 440 msec., beginning 10 msec prior to the initiation of the simulated impact acceleration pulse. The recorded data was available both as a hard copy analog output as a function of time, and as digital data stored on computer diskettes.

Table 3. Measured mobility aid and occupant response data from sled testing

Occupant
- Head Acceleration (3 axes)
- Chest Acceleration (3 axes)
- Hip Acceleration (3 axes)
- Chest Compression (Hybrid III)

Occupant Restraint
- Shoulder Belt Force
- Lap Belt Force
- Shoulder Belt Elongation
- Lap Belt Elongation
- Shoulder Belt "Pay-Out"

Mobility Aid
- Acceleration (3 axes)
- Floor Contact Forces (3 axes)

Mobility Aid Securements
- Rear Restraint Forces
- Front Restraint Forces
- Front Restraint Elongation

The floor loads were measured with triaxial load cells mounted under each wheel of the mobility device. Each belt, used either as a wheelchair securement or personal restraint, was instrumented with clip-on load cells to record belt tensions. The belts were also marked to determine the maximum elongation and payout from the retractors.

High speed color films were recorded from 4 viewing positions. Each test had cameras mounted on either side of the test sled, one overhead and either a frontal or rear view. All cameras recorded the crash at 1000 frames per second from approximately 100 msec prior to the crash impulse to 1 second after the impact. The cameras were mounted rigidly to the test sled with standard fixturing used at the Transportation Research Center. The kinematic analysis of the occupant response was based on these motion picture films.

The data from the high speed films were captured using FrameGrabber software to digitally store images of key frames. Frames were analyzed at 0, 50, 70, 90, 100, 110, 120,130, 140, 150, 170, 190, 210, 250, 300, and 350 msec after the initiation of the crash impulse. For each frame, the position of the dummy's head, chest, hip, knee, and ankle were identified relative to the test sled. The motion of the mobility aid at the rear axle was also measured. Customized software was developed to scale the data and calculate displacements and joint flexion angles. The kinematic data from this analysis is given in Table 4.

Table 4. Kinematic data calculated from high speed films

Displacements	Velocity	Joint Flexion	Joint Angular Velocity
Head Chest Hip	Hip	Hip	Head
Knee Ankle		Neck	Torso

Results

Development of a Prototype System to Satisfy Local Needs

The evaluation of the Cleveland Securement System showed that securement systems can be designed to overcome many of the difficulties present in the public transportation of individuals using mobility aids. The wheelchair users were pleased with the performance of the Cleveland Securement System. They felt that the system offered better stability during the test ride than the system they normally use. They were satisfied with the docking procedure and were happy with the lap and shoulder belt arrangements. The independence of the system was cited for its quickness of attachment and release of the wheelchair from the transit vehicle.

Positioning the mobility aid for docking is the most difficult stage of the securement process with the Cleveland Securement System, but it was handled well by the users. They were all able to align their wheelchairs and engage the securement bracket with the docking latch. The unassisted maneuver required less than five tries on the first exposure to the system. With experience, docking was generally achieved on the first approach.

The front securement belt and the passenger shoulder belt interfaced easily with the rider and mobility aid. During on the road driving maneuvers, each rider commented enthusiastically about the feeling of stability and the lack of movement of the mobility aid. After the test run, the release from the system was achieved in less than one minute without difficulties by the wheelchair travelers.

Sled Impact Testing

Kinematic Sequence

A consistent sequence of events characterized the response of a wheelchair seated test dummy during a simulated crash when lap and shoulder belts were used. The sequence illustrated in Figure 2 describes the dummy's response when seated in manual wheelchairs, powered wheelchairs and three wheeled scooters during 10 g and 20 g crashes. Representative data collected from the motion pictures and instrumentation on the dummy and the acceleration platform were used to describe the occupant kinematics.

Collectively this data is used to divide dummy motion into three phases defined by the movements of the hip, neck and the back. During the first 70 to 140 msec after impact, the dummy moved forward with joint angles remaining relatively constant in the initial sitting posture. The end of this phase was defined by the maximum forward hip motion. In all the tests, the maximum hip acceleration was approximately twice the magnitude of the maximum sled acceleration (Table 5). This amplification of acceleration was thought to be a product of the elasticity of the occupant restraint, and the wheelchair seat.

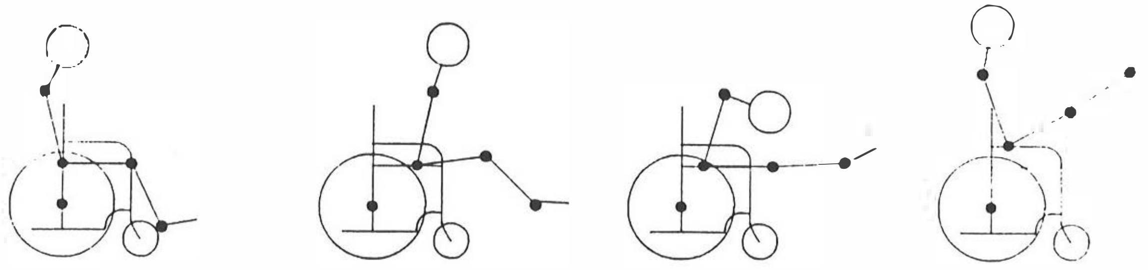


Figure 2. Kinematic Sequence
The kinematic response to a frontal impact of a wheelchair occupant restrained with a lap and shoulder belt.

In the next phase, once the hip motion was slowed by the pelvic restraint, the trunk, head, thighs and shins rotated forward. The maximum forward displacement of the head, chest and legs occurred at this time. The inclined foot support on three wheeled scooters resisted rotation of the legs and prevented excessive leg rise. Peak head and chest accelerations, achieved during this phase indicate the potential for serious flexion injury to the wheelchair occupant. The anchor location of the shoulder belt significantly affected the forward chest motion and the duration of this phase. The forward rotation phase typically lasted from 80 to 120 msec with low shoulder belt configurations and 20 to 50 msec with high mounted shoulder belts.

In the third phase, following maximum flexion, the dummy rebounded toward the initial seated position and beyond. The movements were much slower and the accelerations less significant during this phase. The rotational inertia of the dummy continued the motion beyond contact with the seat. In some instances, the neck was overextended in a whip-lash motion indicating the potential for extension injury to the cervical spine.

Table 5 Comparison of sled and pelvis accelerations

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
Sled Acceleration (g's)	10	10	20	20	20	20	20
Pelvis Acceleration (g's)	21	22	45	42	49	42	48

Effect of Mobility Aid Design

The influence of mobility aid type on dummy kinematics was investigated in tests 5, 6, and 7. The maximum acceleration and the time to maximum acceleration for different body segments were used to describe the kinematics (Table 6). The area under the acceleration vs. time plots was calculated to indicate the energy transmitted to the occupant. The shape of the acceleration vs. time curves were highly repeatable between all three tests (Figure 3). No significant differences were seen in upper body accelerations, the times to reach maximum accelerations, and the transmitted energy on comparison of the three wheeled scooter and the battery powered wheelchair. For both mobility aids, the body restraints amplified the impulse load on the pelvis to approximately twice the input acceleration and amplified the load on the head to approximately three times the input load levels.

Table 6 **Occupant Kinematics for Different Mobility Aid Designs** (mean ± standard dev.)

	Scooter (Test 5,6)	Power (Test 7)
Peak Resultant Acceleration (g's)		
Head	64.5 ± 2.1	75.0
Chest	37.0 ± 1.4	36.4
Pelvis	45.5 ± 4.9	48.0
Time to Peak Accelerations (msec.)		
Head	100 ± 6.4	110
Chest	81 ± 6.4	75
Pelvis	71 ± 2.1	76
Area under Resultant Acc. vs. Time (m/sec)		
Head	51.8 ± 3.7	68.0
Chest	21.8 ± .4	21.6
Pelvis	22.4 ± 2.1	22.3

Discussion

Development of a Prototype System to Satisfy Local Needs

The results of the field testing and sled impact testing of the Cleveland Securement System demonstrated that a safe and rapidly applied securement and restraint system can be developed that is acceptable to both wheelchair users and transit vehicle operators. This was accomplished by developing the auto-engage concept so that it is useable with all mobility aids without requiring the permanent use of add-on components. The operational benefits of auto-engage systems for public transit use shown in this project are being increasingly recognized by industry and they are beginning to appear in the market place.

Sled Impact Testing

The complex, multi variable nature of the sled impact tests with numerous securement, restraint, and mobility aid designs required extensive use and correlation of the high speed multi view cinematography and the sampled transducer data. The analysis, however, was possible because of the synchronization of the transducer outputs and the motion pictures. During this analysis several important observations were made and aided the understanding of securement and restraint performance.

Lap Belt Position

In test 3, the lap belt was routed through the wheelchair arm rest. This configuration allowed the belt to be located on the pelvis of the test dummy, but the arm rest prevented the lap belt from applying a downward force to the pelvis during impact. The lack of downward force allowed the dummy's pelvis to translate below the belt and submarining was observed. Consequently a forward hip displacement of 43 cm was measured which was significantly larger than the 30 cm excursion measured when the lap belt was routed under the arm rests in the similar test 4. Such submarining is recognized to cause abdominal and back injury. This result is important because the location of the belt tested here is less intrusive and more accessible, allowing for faster application. These advantages make it likely to be used by vehicle operators or wheelchair users who are unaware of the increased risk of injury.

Shoulder Belt Induced Torso Rotation

Using shoulder belt configuration B with a manual wheelchair in tests 3 and 4, the shoulder belt was observed to clearly restrain the shoulder on the wall side of the vehicle, but produced no resistance to forward rotation of the aisle side shoulder. The unrestrained shoulder continued moving forward after the hip reached its maximum forward excursion. This forward motion of the aisle side shoulder resulted from the absence of belt restriction and caused the head to simultaneously twist and flex toward the wall, likely producing neck injury.

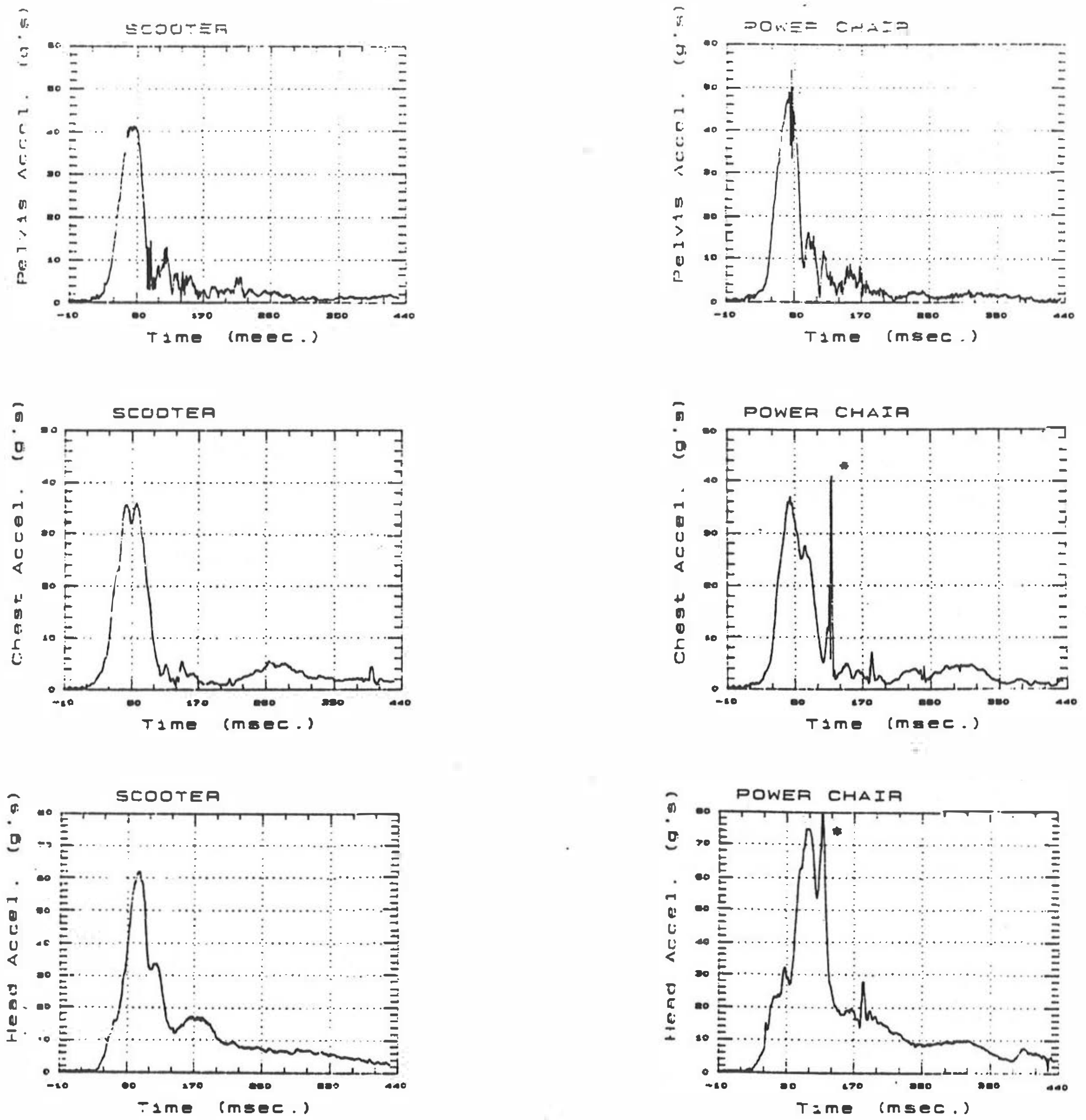


Figure 3. Acceleration vs. Time after Impact
Resultant acceleration data for the pelvis, chest, and head of the wheelchair occupant seated in a scooter and powered wheelchair during a 20 g., 48 km/hr sled test. The second acceleration peaks (indicated by the *) are thought to be caused by a rib fracture in the test dummy. No secondary impact was observed on the high speed films when the failure occurred.

Variable Seat Height

The seat of the three wheel scooter was approximately 12 cm higher from the floor than the manual wheelchair seat. Using shoulder belt configuration B with a scooter, the shoulder belt anchor in test 2 was therefore only 35 cm above the seat, and the shoulder belt slipped off the shoulder on impact, allowing the torso to rotate forward without twisting. Thus, since the torso was essentially unrestrained, the hip continued to flex until the chest of the dummy impacted the tiller. Within 20 msec of this tiller impact, the dummy experienced maximum hip flexion, chest acceleration, neck flexion, and head acceleration. The maximum head and chest accelerations (35 and 36 g's respectively) were more than twice as large as in test 1, (13 and 17 g's respectively) when no tiller impact occurred. Although the tiller impact complicated the analysis, the effect of seat height variation on shoulder belt slippage is clear. This is indicative of major changes in body kinematics related to seat position relative to the shoulder belt anchor location.

Shoulder Belt Slack

The shoulder belt configuration in tests 5,6 and 7 had a major affect on the neck kinematics. The longer belt length and slack in the retractor allowed the shoulder to move forward for the first 70 to 90 msec. At this time, the hip flexion was abruptly stopped and reversed. Because the shoulder belt crossed the center of the chest, the torso and neck were not twisted as much as in the previous tests 3 and 4. The rapid reversal in chest acceleration produced a dramatic neck flexion of approximately 95 degrees, far exceeding the safe flexion angle of 60 degrees. (7,8,9)

Lateral Distance of Shoulder Belt Anchorage

In all tests where the shoulder belt was anchored 60 cm. laterally to the wheelchair mid-line, the rebound of the dummy was directed toward the wall of the vehicle, indicating the potential for injury and the need to consider padding the vehicle wall in the wheelchair bay.

Conclusions

The work reported here has shown that the difficulties encountered when mobility aid users travel on public transit can be overcome when the problems and needs of the user groups are identified, and analytical solutions implemented.

The limited sled testing has shown that the sequence of kinematic motions of the dummy seated in a wheelchair is consistent for different types of mobility aids and impact magnitudes. The restraint geometry, however, was found to have a significant affect on the occupant's kinematics.

Proper positioning of the passenger lap belts was shown to control the hip motion. Although the lap belt positioning over the arm rests demonstrated considerable operational advantages the risk of the occupant submarining and resulting injuries exceeded the benefits and indicated the need for better design.

Variations in the locations of shoulder belt anchor locations were shown to have numerous effects on the occupant response. Potential injury resulting from the shoulder belt configurations were shown to be neck extension, combined neck flexion and rotation, chest impact with the scooter steering tiller, and rebound into the vehicle wall.

The effect of shoulder belt anchorage location on wheelchair occupant kinematics is important because in public transit vehicles, the vehicle construction (window locations, shell design, fold-up seats) and service needs limit the acceptable locations that offer the structural integrity needed to withstand the forces applied by the shoulder belt. The variations in wheelchair design and positioning further complicate the problem. Understanding the relationship between the anchor location and the response of the wheelchair users under impact conditions is essential for producing a high level of protection.

The variables discussed in this work need to be further investigated so that vehicles, mobility aids and securement and restraint systems can be designed for optimal protection of the wheelchair traveler and the public transit passengers.

References

1. Dalrymple GD, Hsia, H, Wheelchair and Occupant Restraint on School Buses, National Highway and Traffic Safety Administration, Washington, DC, May 1990
2. ISO Working Document 10542, Wheelchair and Occupant Restraint Systems for Use in Motor Vehicles, March 1993
3. Standards Association of Australia, Wheelchair Occupant Restraint Assemblies for Motor Vehicles, Australian Standard 2942 - 1987, North Sydney, N.S.W.
4. SAE Working Document 4-93, Wheelchair and Occupant Restraint Systems for Use in Motor Vehicles, Aug. 1993
5. Department of Transportation, 49 CFR, Part 38: Americans with Disabilities Act (ADA): Accessibility Specifications for Transportation Vehicles, Sept. 6, 1991
6. Reger SI, Adams TC, Comparative Field Testing of the Cleveland Securement System, *Project Action Final Report - 1993*, Project ACTION, Washington DC, 1993
7. Kallieris D, Mattern R, Miltner E, Schmidt G, Stein K, Considerations for a Neck Injury Criteria, 1991
8. Laberge-Nadeau, Xiang-Tong T, Maag U, Neck Injuries Amongst Motor Vehicle Occupants Involved in a Collision, AAA Foundation for Traffic Safety, Washington, DC, April 1993
9. Huelke DF, Anatomy of the Human Cervical Spine and Associated Structures, SAE paper No. 790130, Society of Automotive Engineers, Warrendale, PA, 1979

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