Mechanics of Mobility Aid Securement and Restraint on Public Transportation Vehicles

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The Transportation Research Institute at Oregon State University is conducting a research and design project to develop a universal securement system for mobility aids in public transportation vehicles. The research team has embarked on a substantial study to determine the functional, operational, and engineering requirements of a universal securement system. As part of the study the team has developed an understanding of the mechanics of securement. As a result, the mechanics of securement and restraint systems for mobility aids will be explained. The discussion will focus on five generic classes of mobility aids and the characteristics of each class as they pertain to the securement problem. The operating conditions and dynamics of the public transportation vehicles that are relevant to securement and restraint will also be presented. The current technology in securement and restraint systems will be introduced in generic terms. The mobility aids, operating conditions, and securement and restraint systems will be discussed as an integrated system. In conclusion the future of securement and restraint systems will be examined.

There are more than 500 models and styles of mobility aids in use today. Mobility aids commonly used in the adult market will be discussed in five generic classes. These classes cover most aids, but some mobility aids bridge two classes and others are special-purpose devices that fit none of the classes.

MOBILITY AID CLASSES

Manual Wheelchairs

A manual wheelchair consists of two large wheels with two smaller castors in front. In general, the wheelchair frame can be folded. Manual or standard wheelchairs usually have detachable armrests and footrests that permit transfers in and out of the chair.

Sports or Lightweight Wheelchairs

Sport-style wheelchairs are very similar to standard wheelchairs except that they are generally much lighter and have smaller castors in the front and sometimes cambered wheels in the rear. Sports wheelchairs usually have rigid frames and do not fold, but they have quick-release wheels to ease storage. Eliminating the folding feature makes a wheelchair much lighter. Sports chairs often have much shorter wheelbases than standard chairs so they are more maneuverable, and they are stripped down to include the minimum of accessories (such as armrests).

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Electric Wheelchairs

Electric wheelchairs look like standard wheelchairs with large rear wheels and smaller front castors. Electric motors, batteries, and controllers are added to the frame. The large drive wheels are usually much wider and more robust than those on a standard wheelchair frame. There is a tremendous variety of power transmission and control systems for electric wheelchairs, but they are all essentially configured the same.

Powered-Base Wheelchairs

A powered-base wheelchair usually consists of three or four medium-sized wheels. All the motors, batteries, and controllers are underneath the seat on a powered base. Many of the powered bases are modular so that they can be broken down easily into components such as the steering column, batteries, motors and wheels, controller, and seat for transport in a personal vehicle. Powered-base mobility aids are generally robust and heavy for use outdoors and over rough terrain.

Three-Wheeled Scooters

There are many styles and models of three-wheeled scooters, which are generally much lighter and have smaller wheels than powered-base chairs. For models with rear-wheel drive, the batteries and motors are underneath the seat and the steering column is attached to the front wheel. For models with front-wheel drive, the batteries are underneath the seat and the motor and controller are attached to the front drive wheel. Several three-wheeled mobility aids are robust enough to be classified as powered bases.

MOBILITY AID WEIGHT AND CENTER OF GRAVITY

To develop the mechanics of secured mobility aids it is necessary to have information on the weight and centers of gravity of the mobility aid and of the passenger. To find this information for the mobility aid, a small project was undertaken to determine the centers of gravity of several representative models. The horizontal center of gravity was calculated from weight measurements made at each axle of the mobility aid. The vertical center of gravity of standard or sports wheelchairs was found by balancing the chair on its rear wheels; the center

of gravity for battery-powered units was measured by weighing each wheel, then lifting one end of the vehicle 4 in. and reweighing the wheels. A summary of the data is given in Table 1. All values in this table have an error band of ±1 in. (25 mm) and ±2 lb (1 kg). The vertical center of gravity distance is measured from the floor. The horizontal center of gravity distance is measured forward from the center of the rear axle.

CHARACTERISTICS OF MOBILITY AID PASSENGERS

Passengers in mobility aids have a wide range of weights and weight distributions. To cover this range, data for 95th-percentile men and 5th-percentile women were studied (*1*,*2*). Lumped mass occupant models were used to determine the center of gravity. The model does not account for atrophy of the lower extremities, asymmetry, or occupant biomechanics that may be unique to paralysis or muscle weakness. Table 2 shows the center-of-gravity measurements for seated 5th-percentile female and 95th-percentile male mobility aid passengers. The horizontal distance is measured from the seat back, and the vertical distance is measured from the bottom of the feet.

OPERATING CONDITIONS

To discuss the mechanics of securement systems, it is necessary to know the conditions in which they must operate. Requirements for securement systems fall into two broad classes: the transfer of forces between the mobility aid and the vehicle carrying it, and the human factors involved in fastening and releasing the system. This discussion focuses on the transfer of forces and the mechanics of the securement systems.

The forces on a mobility aid that might make it move, bend, or break are created by the motions of the vehicle in which

TABLE 1 Summary of Measured Devices

MODEL	TYPE	VERTICAL CG in/(mm)	HORIZONTAL CG in/(mm)	WEIGHT lbs/(kg)
Invacare Rolls 1000	Standard Wheel-chair	12.0 (305)	7.0 (178)	40.0 (18)
Kuschell Champion 3000	Sport Chair	12.0 (305)	5.3 (135)	23.0 (10.4)
Rolls Arrow	Electric Wheelchair	10.0 (254)	6.2 (157)	169.0 (77)
Fortress-Scientific 655FS	Power Base	9.0 (229)	7.5 (190)	209.0 (95)
Fortress-Scientific 2000FS	Scooter	9.0 (229)	8.6 (218)	180.5 (82)
Everest & Jennings Carrette	Scooter	7.5 (190)	9.3 (236)	174.5 (79)
Invacare Tri-Rolls	Scooter	Not Available	8.2 (208)	147.5 (67)
Amigo RWD	Scooter	7.5 (190)	8.2 (208)	129.0 (59)
Average of 4 scooters tested	Scooter	8.0 (203)	8.6 (218)	158.0 (72)

NOTE: CG = center of gravity

TABLE 2 Center-of-Gravity Information for Mobility Aid Passenger

95th Percentile Male Weight	216 pounds	(97.2 kg)
Vertical Distance of Center of Gravity	26 in	(666mm)
Horizontal Distance of Center of Gravity	9 in	(230mm)
5th Percentile Female Weight	102 pounds	(46.0 kg)
Vertical Distance of Center of Gravity	20.5 in	(525mm)
Horizontal Distance of Center of Gravity	7 in	(179mm)

the mobility aid is secured; these forces are generated by accelerations of the vehicle. Accelerations are transformed into forces in accordance with a simplified version of Newton's law:

$$F = m \times A$$

where

F = force,
m = mass, and
A = acceleration.

According to this law, if the mass of the mobility aid and passenger and the amount of acceleration on the vehicle are known, the force on the securement system can be found. The mass of the mobility aid and passenger is equal to the weight in pounds divided by gravity (32.2 ft/sec^2). In SI units the mass of the mobility aid and passenger is given in kilograms.

In the previous section the weights of a sample of mobility aids and representative passengers were itemized; in this section the accelerations that can be expected to put loads on the securement system will be identified. The accelerations are summarized in Figure 1. The rest of the section explains the information in this figure. All values in Figure 1 are given in terms of *g*. Simply explained, if a vehicle containing a 250-lb combination of mobility aid and passenger accelerates at 1 *g*, the force on the securement system will be 250 lb. If it accelerates at 10 *g*, the force will be 2,500 lb.

Essentially, two types of vehicle are used to transport mobility aids: fixed-route vehicles and demand vehicles. Fixed-route vehicles, buses that run on a set schedule and circuit, are generally large (greater than 30,000 lb gross vehicle weight) and have limited acceleration capabilities; they back up rarely, corner slowly, and, except in accident conditions, put low load on the mobility aid or securement system. Demand vehicles, on the other hand, range from common passenger vans to modified truck beds. They are smaller, lighter, and more maneuverable than fixed-route vehicles.

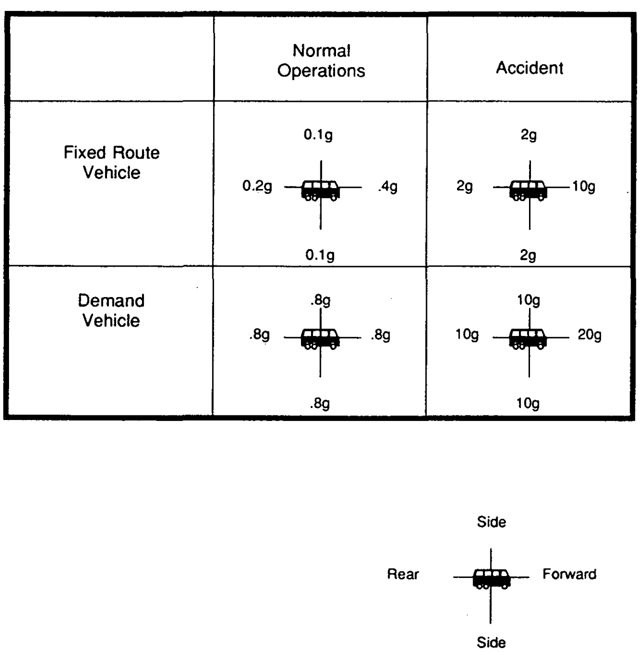

FIGURE 1 Accelerations of vehicles carrying mobility aids (*g* force loads).

Another classification is the operating situation of the vehicle. Specifically, each type of vehicle spends most of its time under normal operating conditions. These include all potential operations in which the vehicle does not hit another object or tip over. Generally, for normal operating conditions, the accelerations of the vehicle are low. Even though most vehicles spend their entire operating lives within the normal operating conditions, accident conditions must also be accounted for. As shown in Figure 1, accident conditions result in much higher accelerations than normal operating conditions.

The last variable in Figure 1 is the direction of the acceleration of the vehicle. Each direction of concern is defined in terms of the direction of the force placed on the securement system:

1. Forward: The securement system holds the mobility aid from moving or pitching forward. This force is caused by the vehicle's braking under normal operating conditions or hitting something head on in accident conditions. Accelerations that cause forward forces are often called decelerations.
2. Sideward: The securement system holds the mobility aid from moving or rocking side to side. This force is caused by the vehicle's turning a corner under normal operating conditions or being hit from the side in accident conditions.
3. Rearward: The securement system holds the mobility aid from moving or pitching backward. This force is caused by the vehicle's accelerating, braking while backing up under normal conditions, or being hit from the rear in accident conditions.

Shown in the figure is the acceleration in each of the major directions for each of the two types of vehicle in each operating situation. The sources for each of the values and the limitations on them are discussed in the following paragraphs.

Fixed-Route Vehicle, Normal Operating Conditions

The values shown are estimates for the accelerations for fixed-route vehicles operating normally. The forward acceleration value of 0.4 *g* is based on standards set for the maximum braking capability of large vehicles. Specifically, according to SAE J992, vehicles of more than 10,000 lb must decelerate at least 3.7 m/sec^2. This is equivalent to 12 ft/sec^2, or 0.4 *g*. According to the U.S. Department of Transportation (DOT), tests have shown that the maximum forward deceleration experienced by a bus is 0.8 to 1.0 *g* (*3*).

The sideward value of 0.2 *g* is an estimate because there are no known standards or measurements for sideward accelerations or forces on restraint systems in fixed-route vehicles. Acceleration measurements for sideward accelerations on large transit buses were between 0.3 and 0.37 *g* for severe operating conditions.

The rearward value of 0.1 *g* is based on the limited acceleration possible with the throttle restrictors used on all buses.

It is possible for a bus to achieve a higher rate by backing up and braking hard, but this condition seldom occurs in normal operating situations.

Fixed-Route Vehicle, Accident Conditions

The values shown in the figure are estimates for the accelerations for fixed-route vehicles in accident situations. The forward acceleration value of 10 *g* is based on a number of measurements and standards. This has been confirmed by BC Transit tests in which a bus and a van were wrecked in a head-on collision (*4*). The maximum deceleration of the bus was 10 *g* with a duration of about 0.1 sec. The value of 10 *g* has been adopted by some agencies (such as DOT) as a guideline and proposed in other standards by the International Standards Organization (ISO). In some standards and guidelines this is translated into a force on the securement system. Specifically, if the mobility aid and passenger weighed 400 lb, then the force on the securement system would be 4,000 lb (10 × 400) applied horizontally at the center of gravity. This value is given elsewhere (*3*).

The sideward value of 2 *g* was developed through calculations. If a standard-sized car of 1000 kg (2,220 lb) hits a stationary light bus of 10 000 kg (22,000 lb) in the side at 50 km/hr (31 mph), the bus will experience a sideward acceleration of 1.3 *g*. If another bus of the same weight at 17 km/hr (10 mph) hits the first bus from the side, the first bus will experience an acceleration of 2.3 *g*. From these values and a lack of other published data, the value of 2.0 *g* has been selected.

The rearward value of 2 *g* is based on the same assumptions as the sideward situation.

Demand Vehicle, Normal Operating Conditions

The values shown are estimates for the accelerations for demand vehicles operating normally. All values are 0.8 *g* on the basis of the results from tests performed to find the maximum forces and displacements on a scooter restrained by a four-belt system (*5*). The vehicle used in these tests was a standard 1990 Ford chassis with a custom body designed to transport mobility aids. This vehicle was run through a series of tests including maximum acceleration at full throttle, maximum braking, constant radius turns, and swerving maneuvers. The results show that the maximum acceleration that this vehicle can produce without hitting anything or rolling over is about 0.8 *g* in any direction. This value occurs when braking either forward or backward or when swerving or otherwise turning as sharply as possible. Note that the braking performance while backing up is far more severe than the force exerted when accelerating as hard as possible.

Demand Vehicle, Accident Conditions

The values shown are estimates for the accelerations for demand vehicles operating under accident conditions. Most standards and testing of securement devices are based on the forward value of 20 *g* for this case. Experimental data for a van hitting a cement wall at 30 mph (50 km/hr) range to 30 *g* for a very short period (*4*) and to 10 *g* for a van hitting a bus. The value of 10 *g* for both rear and side impacts was based on the latter experimental value and supported by calculations. In effect, if a bus hits a stationary van at 30 mph (50 km/hr), the resulting acceleration on the van will be 10 *g* regardless of direction.

MOBILITY AID SECUREMENT AND RESTRAINT TECHNOLOGY

The discussion on securement and restraint technology will focus on the generic classes of securement systems and restraints and not on specific commercially available systems. It may be possible to draw inferences to specific brands, but this is not the intent. Securement systems refer to the technology used to immobilize the mobility aid. Restraint systems are technologies that restrain the mobility aid passenger from excessive movement.

Belts

Belt securement is generally provided in two-, three-, or four-belt systems; these are often called two-, three-, and four-point securement systems. Two-belt systems are often used on fixed-route bus systems to secure standard, sport, and electric wheelchairs. The mobility aid is backed in against a modesty panel or a flip-up seat and faces forward. The two belts are usually attached to a modesty panel, stanchions, or the floor and reach up from behind and attach to the front uprights of the mobility aid frame. This system is flexible, inexpensive, and adaptable to different models of mobility aids; some mobility aid passengers can attach the system by themselves.

Three-belt systems are similar to the two-belt systems; the third belt is used to attach to the front or cross members of the mobility aid for added stability. One three-belt system that is used on a fixed-route vehicle consists of an additional strap that is mounted on the sidewall of the bus and comes across the platform of a scooter and fastens on the floor. This third strap is often called the scooter strap and is used for scooters and powered-base mobility aids. Passengers are generally unable to fasten three-belt systems unaided.

Four-belt systems consist of two belts that attach to the front of the mobility aid and two belts that come up from behind and attach at the rear uprights of the wheelchair frame. In general, the mobility aid faces forward but it does not back in against a flip-up seat or modesty panel. These systems are generally found on demand-responsive vehicles and fasten to tracks or plates on the floor or side of a vehicle. Four-belt systems cannot be attached independently by the passenger.

Wheelclamps and Belts

Many fixed-route transit agencies provide wheelclamps and belts. Wheelclamp systems usually also have one or two additional belts. The belt secures the mobility aid on the opposite side of the wheelclamp. The orientation of the belts

with respect to the side and stanchion of the vehicle usually depends on the orientation of the flip-up passenger seat in the transit vehicle. If the flip-up seat faces forward, then the belt or belts pull up from under the seat. On flip-up seats that face the side, the belt pulls out from the side of the vehicle and attaches to the front of the mobility aid.

The wheelclamp is on either the aisle side or the outside of the transit vehicle. Aisle-side placement permits the extra belts to function better but may pose a tripping hazard. Many newer models of wheelclamps accommodate both narrow and wide wheelchair wheels. Observations of these systems in service indicate that they are installed in many different configurations and often the passenger uses only the wheelclamp, even when instructions say that the belt must also be used for securement. Only the wheelclamp is used because it can be easily engaged without the help of others. When the wheelclamp is used alone it becomes a one-point securement system, which is unbalanced and asymmetrical and consequently puts unequal loading on a mobility aid frame.

Lockdown Systems

Lockdown securement systems are almost exclusively used by mobility aid passengers who drive their own vehicles. In general, lockdown systems require the attachment of additional hardware to the mobility aid frame and vehicle. Often the additional hardware is attached underneath the mobility aid, so it decreases the clearance underneath the mobility aid, which can be a problem. The advantage of this technology is that mobility aid passengers can use it independently, quickly, and easily. Lockdown systems provide fast, convenient, and independent securement. In most lockdown systems, the attachment mechanism acts through the center of gravity of the mobility aid.

Restraint Systems

Restraint systems are used to restrain the mobility aid passenger. They can be classified in terms of the number of belts or points of restraint: generally there are two-, three-, or four-point restraint systems. The use of restraint systems for fixed-route vehicles is usually voluntary, but passenger restraint systems are nearly always required for demand-responsive vehicles. There is controversy over whether the restraint system should be attached to the mobility aid, the vehicle, or the securement system. In the proposed standards ISO and SAE have taken the position that the restraint system must be attached to the transit vehicle. Typically, the mobility aid is not strong enough to take the restraint loads, but the mobility aid must be secured enough itself to avoid pinning or loading the occupant in a crash. The rationale behind placing the restraint system on the mobility aid is that the mobility aid passenger would not be pinned between the restraint and the mobility aid if there was relative movement between the mobility aid and the securement system. However, attaching the restraint system to the securement system or off the mobility aid would permit more options for personal restraint.

Two-point restraint consists of a lap belt that is attached either directly to the mobility aid or securement system or directly to the transit vehicle. The lap belt restrains the pelvis but does not prevent the torso from rotating. One of the major problems with two-point restraint is the routing of the belt given the design of the mobility aid.

Three-point restraint combines a lap belt and shoulder strap. In general, a three-point restraint system is attached directly to the securement system or the transit vehicle. A three-point system provides restraint to the pelvis and limits rotation of the torso.

Four-point restraint consists of a lap belt and shoulder harness and provides the highest level of restraint. The lap belt restrains the pelvis, and the shoulder harness provides symmetric restraint to the upper torso and prevents rotation and torsion. Four-point restraint systems are often provided with optional head restraint systems. Head restraint is a different issue, one related to back support.

MECHANICS OF SECUREMENT SYSTEMS

In this section the capabilities of the different types of securement system will be discussed. The discussion will cover the general characteristics of each system and its specific operation with the five classes of mobility aids. No matter which securement system is used, it must provide forces sufficient to hold the mobility aid in all three directions: forward, sideward, and rearward. It must also keep the mobility aid from rotating about any axis: tipping forward, rearward, or sideward, or pivoting about the vertical axis.

The securement systems shown in Figure 2 will be used to illustrate and assist with the discussion of the mechanics of securement. The figure shows four belt configurations for illustrative purposes. Specific systems will be discussed later. The examples will be for the forward forces only, when the vehicle is decelerating.

Assume that Belts A and C are being used. The passenger is restrained with a lap belt to the mobility aid, and the mobility aid is secured with a two-belt system to the floor of the vehicle. In a deceleration, the forward force on the passenger, which is centered on his or her center of gravity, pulls on Belt C. This force is transferred to the mobility aid, and thus the force on Belt A is for both the mobility aid and passenger. Because the center of gravity for the combination is above the line between the point at which Belt A attaches to the mobility aid and where it attaches to the floor, the mobility aid and passenger will tend to tip forward, making the securement system ineffective. If the passenger is unrestrained, the force on Belt A will only be that to secure the mobility aid and the passenger will fly forward out of the mobility aid during the deceleration. If the mobility aid's center of gravity is on or only slightly above Belt A, the mobility aid will have little tendency to tip.

For the second example, assume that Belt B is used instead of Belt A. Now the center of gravity is always below the line of the belt; therefore, during a deceleration the mobility aids will tend to tip back, whether the passenger is belted in or not.

If Belt D is used to both restrain the passenger and secure the mobility aid, then for deceleration, the force on the mobility aid is transferred through the passenger to be carried by Belt D. This situation can crush the passenger.

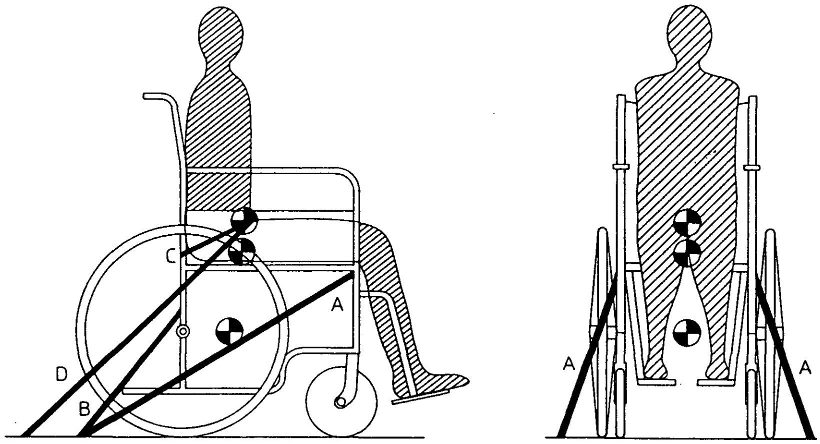

FIGURE 2 Generalized securement system.

If Belts A and D are used together, and both belts work as designed, it is assumed that Belt D carries the force on the passenger and Belt A carries the force on the mobility aid only. However, if Belt A is loose, fails, or is improperly placed, then the same situation as with only Belt D occurs.

Note that the examples focused only on forward forces and rotations that tip the mobility aid either forward or backward. The same types of motion can also occur to the side.

The discussion on the mechanics of the different securement systems will focus on describing the forces on the mobility aid and the occupant and ways the securement systems counteract those forces that result from accelerations that occur under normal and accident conditions. Each section will describe the forces that the securement systems put on the mobility aid. To secure the mobility aid adequately, the securement system must limit translation in three directions and rotation about three axes, during forward, rearward, and sideward acceleration under normal and accident conditions.

Note that securement during accident conditions is only as good as the structural integrity of the mobility aid itself. Most mobility aids were not designed to be secured and may fail under heavy loads. A few manufacturers have begun to take accident loadings into account when designing mobility aids.

Belt Securement Systems

In a two-belt system it is assumed that the belts are attached to the front portion of the mobility aid frame (Belt A in Figure 2). To limit translation and rotation of the mobility aid from side to side, the line of the belts should pass out to the side of the mobility aid as shown in Figure 2 (*right*).

Assuming that a mobility is backed against a flip-up seat, a two-belt securement system can secure a mobility aid in the forward and rearward directions and limit sideward movement. It is recommended that the belts pass down toward the floor at an angle of between 60 and 45 degrees and pass out to the side at about 15 to 30 degrees (Canadian Standards Association Z605; draft).

One of the major problems with two-belt systems is finding appropriate attachment locations on the powered-base and scooter-style mobility aids for the two belts that also meet the recommendation for angles and secure attachment points.

A three-belt securement system is a two-belt securement system with an extra strap that is provided to prevent scooters and powered-base mobility aids from tipping over sideways. A three-belt system often consists of a two-belt system with an added scooter strap. The scooter strap is mounted on the interior sidewall of the bus; it comes across the platform of a scooter and fits into a fastener on the floor of the bus. The two-belt system prevents translations and rotations that were discussed earlier, and the extra strap limits sideward motion and tipping to the side.

A four-belt securement system provides the best level of securement. Four-belt securement systems restrict translation forward, rearward, and sideward and rotation about the three perpendicular axes. It is important that the belts pass down toward the floor at about 45 degrees and pass out to the side at about 30 degrees. These angles are suggested so that there is a sufficient horizontal component to counteract forward, rearward, and sideward forces. The two belts attached at the front of the mobility aid pull forward and counteract the forces induced by rearward acceleration. If all four belts are attached at an angle to the side, they will counteract the forces induced by side-to-side acceleration.

Four-point securement systems have problems attaching to the powered-base or scooter-style mobility aids because there are not enough attachment locations to provide balanced restraining forces. Two manufacturers of mobility aids are now providing dedicated attachment points on some of the new models. One of the manufacturers provides an accessory kit to modify a mobility aid so that a securement system can attach. These modifications are designed for four-point belt securement systems.

Wheelclamp Securement Systems

A wheelclamp restricts forward, backward, and sideward movement but does not prevent rotation. Therefore, the wheelclamp must be used with one or more belts. During rapid acceleration and deceleration, a wheelclamp will not

prevent a mobility aid from rotating, and because it is attached to only one wheel, there may be significant structural damage to the mobility aid.

A wheelclamp-and-belt combination provides two-point restraint: the wheelclamp prevents translational movement, and the extra belt limits rotation. One of the major problems of using a single belt with a wheelclamp is the unequal loading on the mobility aid frame. Rotation about the main wheels and movement from side to side is dependent on the configuration of the wheelclamp-belt combination. If two belts are used with a wheelclamp, the loading is more symmetrical and there will be less side-to-side movement or rotation.

Lockdown Securement Systems

The lockdown securement systems that have been studied are designed for use in personal vehicles. They require hardware on the mobility aids and on the vehicle. The interface of these two acts much like a trailer hitch and transmits forces like the belt systems do. Usually the interface is below the mobility aid, directly below the center of gravity. During deceleration the lockdown not only takes the force generated forward but counteracts tipping by holding down the center of the mobility aid. The same is true for forces in the other directions.

SUMMARY AND FUTURE NEEDS

The basic mechanics of mobility aid securement have been discussed. Current securement systems are adequate for normal operations but leave much to be desired. Most are hard to engage and time-consuming to attach, and only the four-belt and lockdown systems can be secured adequately in all directions. Most mobility aids are not designed to be secured or to survive an accident situation. In an ideal world all mobility aids would be transportable, and all securement systems would be easy to use and connect to all mobility aids. To reach this ideal,

1. Realistic standards based on real numbers for accelerations supported from accident data are needed. For example, the frequency of an accident of a particular magnitude of acceleration may be so small that the proposed standards are unrealistic.
2. Mobility aids must be designed to be transportable. They must have the structural integrity to withstand normal operations and accident situations, and they must be designed to be securable.
3. Universal securement systems must be developed. They must connect to all common types of mobility aids and be easy and quick to use.
4. The rehabilitation and transportation communities must be educated about what constitutes safe securement.

SAE, ISO, and the Canadian Standards Association are working on standards that will address the need for realistic standards and transportable mobility aids.

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