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AUTOMATED MOBILITY AID SECUREMENT

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By
Mark McCarthy, Shawn Watson
T E S Limited
Kanata, Ontario

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16. Abstract

TES Limited was contracted by the Transportation Development Centre (TDC) to analyse the performance and design requirements for automated mobility aid securement in large public transit vehicles since no standards exist that address the specific properties of larger vehicles with respect to the transportation of persons seated in mobility aids.

To clearly define the extent of a Canadian standard for specifying securement performance on large transit vehicles it was necessary to determine whether automated mobility aid securement could be achieved without a positive interlocking device. This became the fundamental objective of the project and was achieved through research, formulation of analytical models and synthesis employing computer simulation techniques.

The project investigation focussed on compartment and impact barrier securement systems. To provide a distinct comparison, the project investigation also analysed fully interlocking type securement systems that positively engage with a component of a wheeled mobility aid. Securement systems utilizing tie-down straps were not thoroughly analysed as they are covered extensively in existing standards and cannot readily be automated.

It was concluded that a non-interlocking securement system is feasible for use on large transit vehicles. Other test data on compartment type securement systems verified that an unrestrained, rearward facing mobility aid placed in a properly designed protective compartment can safely manage the forces associated with normal driving and accident avoidance manoeuvres. Positively interlocking securement of mobility aids should be considered when crash impacts of 10 g or greater are expected.

It is recommended that a standard should be developed to define the requirements for securing mobility aids in large transit vehicles. The standard should consist of performance specifications which include measurements and suggested testing methods for securement performance under normal driving conditions, as well as lateral impact and frontal impact conditions.

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16. Résumé

La compagnie TES Limited s'est vu confier en sous-traitance, par le Centre de développement des transports (CDT), l'analyse des critères de performance et de conception concernant les moyens de retenue automatiques des aides à la mobilité dans les gros véhicules de transport en commun, vu l'absence de normes sur les caractéristiques spécifiques de ces véhicules pour ce qui est du transport des personnes assises dans une aide à la mobilité.

Afin de définir clairement la portée d'une éventuelle norme canadienne qui contiendrait des critères de performance visant les véhicules de transport en commun, il a fallu évaluer la possibilité de réaliser un moyen de retenue automatique sans verrouillage. Cette spécificité est devenue l'objectif fondamental du projet, qu'il a été possible d'atteindre par la recherche, par la formulation de modèles analytiques et par la préparation de synthèses, en faisant appel aux techniques de simulation informatisée.

La recherche était centrée sur les systèmes de retenue de type compartiment et ceux à barrière de protection contre les impacts. Pour avoir une base de référence, les chercheurs se sont également attardés à l'étude des systèmes de retenue avec verrouillage par engagement d'une pièce dans un composant d'une aide à la mobilité sur roues. Les systèmes de retenue par sangles n'ont pas fait l'objet d'études détaillées étant donné qu'ils sont largement couverts par les normes existantes et qu'ils ne peuvent être facilement automatisés.

Il a été conclu qu'un système de retenue sans verrouillage est faisable sur les gros véhicules de transport en commun. D'autres données d'essais portant sur les systèmes de retenue de type compartiment ont permis de vérifier qu'une aide à la mobilité non verrouillée, placée face à l'arrière du véhicule dans un compartiment de protection adéquatement conçu, peut facilement supporter les efforts associés à la conduite normale et aux manoeuvres d'évitement d'accident. On devrait examiner l'emploi de systèmes de retenue avec verrouillage sur les véhicules susceptibles de subir des forces d'impact générant des décélérations de 10 g ou plus.

Il est recommandé d'élaborer une norme visant à définir les exigences en matière de systèmes de retenue des aides à la mobilité dans les gros véhicules de transport en commun. Le projet de norme pourrait comprendre des spécifications de performance assorties de données de mesures et de propositions de méthodes d'essai pour contrôler la performance du système de retenue en conditions de conduite normale et en conditions d'impacts latéral et frontal.

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SUMMARY

The research described in this report was carried out by TES Limited for the Transportation Development Centre (TDC), Transport Canada. The objective of the research project was to establish performance and design requirements for automated mobility aid securement on large transit vehicles which may form the basis for a Canadian wide standard.

The transit industry and passengers alike are in need of a standard to provide the basis for consistent regulations in all Canadian jurisdictions. This standard would also encourage the introduction of full size, accessible buses such as low-floor buses providing greater accessibility to public transportation. In addition, a Canadian wide standard would aid in maintaining compatibility with foreign regulations soon to be implemented. This standard, however, would only apply to vehicles falling within a specific category meeting definite physical and operating specifications.

To clearly define securement performance on large transit vehicles it was necessary to determine whether automated mobility aid securement could be achieved without a positive interlocking device. This became the fundamental objective of the project and was achieved through research, formulation of analytical models and synthesis employing computer simulation techniques.

The project investigation focussed on compartment and impact barrier securement systems as these represent non-interlocking type securement systems. To provide a distinct comparison, the project investigation also analysed fully interlocking type securement systems that positively engage with a component of a wheeled mobility aid. Securement systems utilizing tie-down straps were not thoroughly analysed as they are covered extensively in existing standards and cannot readily be automated.

Through research of current reports, published data, analysis of vehicle test data and computer simulation of securement systems, it was concluded that a non-interlocking securement system is feasible for use on a large transit vehicle. Test data on compartment type securement systems from France and Germany verified that an unrestrained, rearward facing mobility aid placed in a properly designed protective compartment can safely manage the forces associated with normal driving and accident avoidance manoeuvres. It is recommended that positively interlocking securement of mobility aids be considered when crash impacts of 10 g or greater are expected.

The report concludes with the presentation of recommended performance specifications for a compartment type securement system. The specifications encompass the areas of component specifications, recommended information, performance under normal driving conditions, and under frontal, rear and lateral impact conditions.

With sufficient information indicating a non-interlocking securement system is a viable securement option in large transit vehicles, future standards and regulations governing securement performance in large transit vehicles must be flexible enough to allow for their use. Restrictive standards and regulations that dictate the use of specific types of securement systems obstruct the introduction of new technologies and innovative ideas.

SOMMAIRE

Le projet de recherche décrit dans le présent rapport a été réalisé par TES Limited, pour le compte du Centre de développement des transports (CDT) de Transports Canada. La recherche avait pour objectif de définir les critères de conception et de performance concernant les systèmes de retenue des aides à la mobilité dans les gros véhicules de transport en commun, ces critères étant susceptibles de servir de base à l'élaboration d'une norme canadienne.

L'industrie du transport en commun et sa clientèle ont besoin d'une norme qui servira de base à une réglementation uniforme pour toutes les autorités compétentes au Canada. Une telle norme encouragerait également l'adoption d'autobus accessible de dimensions courantes, par exemple les autobus à plancher surbaissé qui facilitent l'accès des personnes. En outre, l'existence d'une norme applicable à la grandeur du Canada contribuerait à maintenir une certaine compatibilité avec la réglementation à la veille d'être adoptée dans d'autres pays. Néanmoins, la norme proposée ne s'appliquerait qu'à une catégorie particulière de véhicules satisfaisant à des conditions définies de construction et d'utilisation.

Pour définir clairement la performance souhaitée des moyens de retenue sur les gros véhicules de transport en commun, il a fallu déterminer s'il était possible d'assurer la retenue automatique de l'aide à la mobilité sans recourir à un dispositif de verrouillage positif. Ce problème est devenu l'objectif fondamental du projet, qu'il a été possible de réaliser par la recherche, par la formulation de modèles d'analyse et par la préparation de documents de synthèse, en faisant appel aux techniques de simulation par ordinateur.

Dans le projet qui est ici décrit, la recherche portait principalement sur les systèmes de retenue utilisant un compartiment ou une barrière de protection contre les impacts étant donné que ces systèmes ne comportent pas de dispositif de verrouillage. Pour avoir une base de référence, les chercheurs ont également étudié les systèmes de retenue à verrouillage par engagement positif d'une pièce dans un composant de l'aide à la mobilité sur roues. Les systèmes de sangles d'arrimage n'ont pas fait l'objet d'une analyse exhaustive étant donné qu'ils sont couverts abondamment par des normes existantes et qu'ils ne peuvent être facilement automatisés.

Après avoir analysé des rapports, des publications, des données d'essais de véhicules et de simulations informatisées de systèmes de retenue, les chercheurs sont arrivés à la conclusion qu'un système de retenue sans verrouillage conçu pour les gros véhicules de transport en

commun était réalisable. Des données d'essais portant sur des systèmes de retenue de type compartiment fabriqués en France et en Allemagne indiquent qu'une aide à la mobilité non retenue faisant face à l'arrière du véhicule et placée dans un compartiment de protection bien conçu peut supporter sans danger les forces associées à la conduite normale et aux manoeuvres d'évitement d'accident. Il est recommandé d'étudier la possibilité d'utiliser des moyens de retenue avec verrouillage des aides à la mobilité, pour les conditions où des collisions peuvent produire des décélérations de 10 g ou plus.

Pour terminer, le rapport présente les recommandations en matière de critères de performance concernant un système de retenue de type compartiment. Ces critères englobent les caractéristiques des composants, les informations recommandées, les performances en conditions de conduite normale et en condition d'impacts avant, arrière et latéral.

Compte tenu de la quantité d'informations dont on dispose confirmant la faisabilité d'un système de retenue sans verrouillage sur les gros véhicules de transport en commun, les normes et la réglementation futures sur la performance des systèmes de retenue dans les gros véhicules de transport en commun doivent être suffisamment souples pour permettre l'utilisation de ces systèmes. Enfin, l'adoption de normes et de règlements restrictifs imposant l'emploi de systèmes spécifiques est un obstacle à l'implantation de nouvelles technologies et de concepts innovateurs.

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1. INTRODUCTION

During the past decade there have been many improvements to transportation services for people with disabilities, and particularly for people in wheelchairs. Paratransit services using small buses, vans and accessible taxis have become generally available and ridership has increased greatly. More recently, accessible large transit buses have been introduced into scheduled service. Some of these buses use a lift to provide access while others are constructed with a low floor and can be accessed by a person in a wheelchair or other mobility aid using a vehicle-mounted ramp.

The transportation of passengers using mobility aids in large transit buses raises several safety and operational concerns for transit operators. The two main safety concerns are:

- Ensuring that the passenger using the mobility aid is at least as safe as any other passenger on the bus; and

- Ensuring that the mobility aid does not injure other passengers during normal operation including violent manoeuvring to avoid an accident or in the event of an accident.

The main operational concerns for the transit operator are:

- The need for the driver to assist with the securement of the mobility aid and restraint of the passenger, if required;

- The loss of seats at the wheelchair position;

- The time delay caused by boarding and securing the mobility aid and passenger; and

- The durability and maintenance concerns of currently used securement systems utilizing belts and straps that are prone to damage and soiling.

Most of these concerns would be addressed through the use of an automated securement system which would allow passengers to secure themselves and their mobility aids, quickly and without the help of the driver or an assistant.

The research described in this report analyses the performance and design specifications for automated mobility aid securement in large public transit vehicles. One aspect of this task was to decide whether mobility aid securement can be achieved without fitting a positive interlock device to the mobility aid, or whether a "universal" interlock fitting must be provided. Another aspect was to define the conditions, in terms of acceleration and velocity change, against which the system must secure the mobility aid.

Existing securement systems were developed primarily for vans and small buses used in paratransit services. These vehicles tend to travel faster than large transit vehicles, and expose their passengers to larger accelerations during normal service. In the event of a collision, the acceleration to which passengers in vans are exposed is greater and rises more rapidly than for passengers in large buses. In severe accidents, the situation for passengers in vans is similar to that for passengers in automobiles, with maximum accelerations of about 25 g, compared with 10 g or less for passengers in larger buses. This is due to the greater mass of a large transit bus in relation to most other vehicles.

The existing Canadian Standard CAN/CSA-D409-92 *Motor Vehicles For the Transportation of Persons with Physical Disabilities* was prepared primarily for vehicles with a gross weight of less than 10 000 kg excluding passenger cars. As well, standard CAN/CSA-Z605-95 *Mobility Aid Securement and Occupant Restraint Systems for Motor Vehicles* applies only to paratransit buses, minibuses, taxis and vans.

Since no standards exist that address the specific properties of larger vehicles with respect to the transportation of persons seated in mobility aids, there is a need for a Canadian standard for the securement of wheeled mobility aids on large transit buses (Ref. 1). Such a standard, and the development of an automated securement system, is made urgent by the introduction of increasing numbers of low-floor large transit buses. European experience suggests that these will attract passengers using wheeled mobility aids, though not initially in large numbers. Nevertheless, the introductory period is the time to familiarize passengers with a securement system that will continue to be effective when the number of passengers in wheeled mobility aids increases.

Since the late 1980s, European practice in low-floor buses has required passengers in wheelchairs to travel facing rearward, unrestrained but supported by a soft bulkhead. This is recommended by the European Community COST Project 322, Low-floor Buses (Dejeammes, 1996). Tests using anthropomorphic dummies in wheelchairs in buses have demonstrated the safety of this approach (Refs. 2 and 3). The U.S. Americans with Disabilities Act (ADA) (Ref. 4) allows passengers in wheelchairs to travel facing either forward or rearward, but requires wheelchairs and other wheeled mobility aids to be secured. Equipment has to be available to restrain the occupant, but its use is not mandatory. In practice, wheelchair securement systems in the U.S. are almost always manually applied using four adjustable straps.

Trials of low-floor buses in Victoria, British Columbia followed the U.S. approach, using four-strap securement systems for forward-facing mobility aids, later followed by a two-strap system with a rear support bar. Low-floor buses with a European-style safe compartment for passengers in unsecured wheelchairs are being introduced by Société de Transport de la Communauté Urbaine de Montréal, Kitchener and Hamilton Transit in Ontario and other transit operators in Quebec.

1.1 Project Objectives

The research described in this report was carried out by T E S Limited for the Transportation Development Centre (TDC), Transport Canada. The objective of the research project was to establish performance and design requirements for an automated mobility aid securement.

To clearly define the extent of a Canadian standard for specifying securement performance on large transit vehicles it was necessary to determine whether automated mobility aid securement could be achieved without a positive interlocking device. This became the fundamental objective of the project and was achieved through research, formulation of analytical models and synthesis employing computer simulation techniques.

The project investigation focused on compartment and impact barrier securement systems as these represent the furthest extreme of non-interlocking type securement systems. To provide a distinct comparison, the project investigation also analysed fully interlocking type securement systems that positively engage with a component of a wheeled mobility aid. Securement systems utilizing tie-down straps were not thoroughly analysed as they are covered extensively in existing standards and cannot readily be automated.

1.2 Project Tasks

To determine the performance and design specifications for wheeled mobility aids in large public transit vehicles, the following tasks were accomplished:

1) Establishment of Securement Performance Requirements - A cross section of larger urban transit systems and provincial legislators across the country were contacted to establish the range of current securement performance requirements. The research not only focused on establishing current requirements, but investigated the experiences with the current requirements and the opinions and suggestions offered for the future. The database was then used to determine whether or not consensus may be possible to establish common securement performance requirements or a general trend of approaches to the problem.

User groups were not directly involved as it was assumed that their opinions have already, to a large extent, shaped the perceptions, opinions and practical approaches of operators and legislators to the problem.

2) Development of a Database of Mobility Aid Designs - Initial research was required to obtain as much information on different types of mobility aids sold in Canada as possible. Manufacturer brochures, information gathered through rehabilitation centres and other sources enabled conclusions to be drawn from the various mobility aid designs which require accommodation by a securement system. This resulted in the definition of three representative generic mobility aid models.

3) Generation of Performance and Design Specifications - The two databases were then analysed. Most current legislations and/or practical implementations fell within a narrow band of requirements. The band of requirements was applied to the various generic mobility aids for analysis. This analysis included the calculation of forces impacting on the generic mobility aids within the band of requirements and the application of computer modelling to simulate the forces and stresses at various points of the generic mobility

aids. This process formed the basis for determining the specifications. It was also possible to state whether the basic idea of securing a mobility aid without positively interfacing with it is possible.

It must be assumed that there will be some operators and legislators who are not interested in a country-wide consensus. However, it is the goal to achieve a consensus which the majority of operators and legislators can accept. Although this approach does not involve the creation of a national standard it is likely that the mere existence of a workable set of specifications established through the federally operating TDC will cause operators to align their procedures and requirements across the country.

The following list summarizes the requirements suggested for the development of performance specifications:

- A totally unrestrained mobility aid facing forward or rearward;

- A mobility aid secured for normal vehicle operation including emergency stops and evasive manoeuvres in which the vehicle acceleration does not exceed 1 g;

- A mobility aid secured for crash accelerations based on measurements of large bus collisions which did not exceed 5 g; and

- A mobility aid secured for crash accelerations based on the U.S. ADA standard stipulating accelerations of 10g.

The different requirements determine the possible technical options to securement and to the design of automated securement systems.

While the safety of the occupants of mobility aids and other travellers is paramount, it is also important to consider the ease of use of securement systems, their maintenance and their applicability to a wide range of commonly used mobility aids (Ref. 5).

2. AUTOMATED MOBILITY AID SECUREMENT

Many of the difficulties associated with mobility aid securement can be resolved with the use of an automated securement system. An automated securement system refers to a securement system that does not require the aid of any assisting personnel. Assisting personnel may include a companion of the mobility aid occupant, or the vehicle driver. There are essentially two types of automated securement systems: systems which utilize additional hardware that positively interlocks with the mobility aid, and systems that constrain the motion of the mobility aid without directly attaching to the mobility aid or interlocking with a device mounted on the mobility aid.

Positively interlocking securement systems are generally classified as tie-down, wheel clamp, lockdown and docking type securement. Of these, only lockdown and docking type securement systems are readily automated (Ref. 6).

Tie-down systems and wheel clamp systems typically do not require modifications to the mobility aid as these securement systems attach to existing frame members and wheels. However, positively interlocking lockdown and docking systems inherently require some modification of the mobility aid as these systems use a standardized point of connection on the mobility aid (Ref. 6). Most of these systems are considered fully constrained securement as the mobility aid is prevented from translating or rotating in any direction.

Non-interlocking securement systems like the deployed bristles system developed by Baylor College of Medicine (Ref. 7), deployed side air bags, move-in-place (Ref. 8) and compartment style securement systems do not utilize a standardized point of connection on the mobility aid. These systems can be considered to be partially constrained securement where the mobility aid is fully constrained to a determined level of force, yet some restricted movement may occur beyond this level of force. The adopted level of force is typically associated with the estimated forces imposed by normal driving manoeuvres and accident avoidance manoeuvres.

2.1 Passenger Concerns

Mobility aid users travelling on public transit have voiced many concerns about current mobility aid securement systems. These concerns range from motion sickness, resulting from the orientation in the vehicle, to personal independence. The securement system is required to accommodate the desires of mobility aid users while still providing safe, stable and comfortable securement of their mobility aids.

One of the most significant concerns of disabled persons is the invasion of personal privacy. Respecting the personal privacy of transit passengers requires a securement system that minimizes intrusion into the space immediately surrounding the occupant (Ref. 7). Any securement points must be positioned so that they are accessible by an assistant without close physical contact with the body of the occupant. With limited access, operators are frequently required to lean over the passenger during the securement process. This places the operator in an awkward position and often intrudes in the personal space of the occupant.

Other concerns include the level of independence desired by most bus passengers. Persons using mobility aids desire the same level of independence afforded to ambulatory passengers. Independence is decreased when special procedures related specifically to mobility aid users are necessary to ensure adequate mobility aid securement. This would include assistance provided by a vehicle operator. Most passengers are willing to assume the same level of risk that is acceptable to ambulatory passengers in order to maintain a high level of independence. At the time of a crash, persons in mobility aids may be at greater risk than others, because, depending on its size and type, their mobility aid may increase their excursion distance. In addition, unsecured mobility aids place other passengers' safety at risk.

2.2 Driver/Vehicle Operator Concerns

A large portion of drivers and operators are opposed to securement systems that require operator assistance because of the added responsibility that is placed on them. Similar to passenger concerns, the vehicle operator should not be required to intrude in the personal space of the mobility aid occupant. Securement points should be accessible and in a location that does not place the operator in an uncomfortable position. Other concerns include the twisting and bending motions imposed on drivers and operators during the securement procedure.

In addition, large transit vehicles are fixed route vehicles that board passengers at specified stops at scheduled times. Securement requiring assistance increases boarding times and reduces overall scheduling efficiency. This will present an ever increasing problem for transit system operators as the quantity of passengers using mobility aids gradually increases.

2.3 Interlocking vs. Non-Interlocking Securement

Non-interlocking securement systems possess many advantages over positively interlocking securement systems. The primary advantage is the relative ease with which the system may be automated or the complete lack of automation required. Non-interlocking systems such as the deployed bristles system (Ref. 7) are readily automated because less accuracy in positioning is required. Better still, compartment type securement systems rarely require automation of securement components. This type of passive securement is a form of automated securement as it does not require the aid of assisting personnel such as the vehicle driver. Devices forming part of this system may or may not be actually automated since most compartment systems do not utilize moving parts.

Automation or the lack of requirement for automation in a passive system correspondingly reduces securement time and effort. In addition, the ability to adapt to different mobility aids is greatly improved and there are no modifications required to the mobility aid. A non-interlocking securement also eliminates life expectancy concerns associated with fatigue loading of the mobility aid frame, a problem associated with positively interlocking systems.

3. SECUREMENT PERFORMANCE REQUIREMENTS

3.1 Research Approach

The research approach consisted of gathering relevant information through published sources of data and gathering opinions and experiences through discussions with provincial legislators, transit authorities, experts and consultants in the field of mobility aid securement.

The literature search uncovered several documents discussing various aspects of mobility aid securement. The topic of these documents ranged from reports on actual dynamic testing of securement systems to theoretical analysis of kinematic motion of the mobility aid occupant. Discussions with various public transit authorities provided some varied opinions, but most acknowledged similar fundamental concerns. Discussions with persons experienced in the field of mobility aid securement revealed many of the obstacles and difficulties that have surfaced in attempting to legislate mobility aid securement.

3.2 Research of Existing Mobility Aids

Research of existing wheeled mobility aids in common use resulted in a large database of different mobility aid designs. The database was organized in a similar manner to that used by the University of Pittsburgh (Ref. 9) and the following families of mobility aids were established: conventional manual wheelchairs, conventional powered wheelchairs, manual sport wheelchairs, power base mobility aids, three- or four-wheeled scooters, and manual strollers.

Conventional manual and powered wheelchairs are the most commonly used wheeled mobility aids. These are very similar in construction, typically utilizing a frame structure with two large rear wheels and two smaller front casters. Powered wheelchairs incorporate batteries and electric motors which drive the larger rear wheels. Manual sport wheelchairs also employ large rear wheels and front casters, but use a rigid lightweight frame with a much shorter wheel base.

Scooters and power base mobility aids appear similar and are differentiated by the use of a tiller steering mechanism on the scooter designs. Power bases also incorporate three or four larger wheels and often weigh more than a scooter.

In addition to mobility aid information obtained from manufacturers, mobility aid characteristics were obtained from a mobility aid database report produced by the University of Pittsburgh (Ref. 9). This report provided information on seating, wheel size, frame size, weight and centre of gravity characteristics from a large database of current mobility aid manufacturers.

Our analysis focused on conventional manual and powered wheelchairs and three-wheeled scooters, as these represent an extensive range of the different mobility aids in common use.

3.2.1 Structural Concerns

Many of the reports referred to concern over the inherent structural weaknesses in current mobility aid design (Refs. 10 and 11). Recently, mobility aids, specifically wheelchairs, have been progressing towards lighter, more agile designs. This appears to be driven primarily by the demands of mobility aid users. Persons using mobility aids desire lighter mobility aids which increase their mobility allowing them to travel faster and over longer distances with less effort. This proliferation of progressive mobility aids will continue with ever increasing variations in design and material choices. Therefore, although efforts are being made to increase the structural strength of mobility aids for transport in vehicles, greater strength is typically achieved with the use of either heavier materials or expensive, exotic materials.

Additional strength concerns arise when analysing three-wheeled scooter-type mobility aids and to a certain extent power base mobility aids. The scooter design does not include side frames and cross braces which would aid in the protection of the occupant. With a narrower wheel track width and longer wheel base length, and typically three rather than four wheels, the scooter design is inherently less stable than a wheelchair. In addition, the tiller steering control is placed in front of the occupant within the Frontal Clear Zone (as specified by Society of Automotive Engineers (SAE) recommendations) where the occupant will impact the tiller control when accelerated towards it (Ref. 12).

3.3 Research of Low-floor Bus Technology

A report produced for the Ontario Ministry of Transportation by Delcan Corporation (Ref. 13), provides an abundance of information on low-floor bus technology supplied by bus manufacturers. Low-floor buses were also researched and analysed to determine the characteristics of these vehicles in crash impact scenarios and characteristics under normal operating conditions.

Fundamental low-floor bus characteristics were reported to be a reduced centre of gravity height due to the lowered floor and floor structure, and integral construction (Ref. 13). The lower centre of gravity improves the overall stability of the vehicle and the integral construction provides an overall improvement of crash worthiness. Other characteristics included vehicle length, passenger capacity and an intended use for transport of a greater range of the general public.

3.4 Research of Existing Securement Systems

Research of existing securement systems revealed two mobility aid securement systems that were of primary interest. These included the tie-down securement system currently in use by BC Transit in British Columbia and the compartmental type securement design in use by Kitchener Transit in Ontario.

BC Transit currently uses a two-strap system for wheelchairs and similar mobility aids and a three-strap system for scooters and power base mobility aids on their low-floor buses. The straps secure the mobility aid to the vehicle floor and against a support bar. The support bar which is angled at 15 degrees towards the longitudinal centreline of the vehicle, positions the mobility aid facing forward angled slightly towards the aisle. This position is used to provide ease of entry and exit past side-facing seats in the flipped up position. A scooter is secured in a similar fashion with an additional third strap over the front portion of the scooter body. The components of this system have been selected to withstand a minimum 10 g frontal impact. An occupant restraint belt is provided and is optional whereas securement of the mobility aid is mandatory.

This securement system requires the assistance of the vehicle operator as the tie-down hardware is generally inaccessible from a seated position in a mobility aid. BC Transit has experienced positive feedback from users of the securement system, as many of the passengers have become familiar with similar hardware used on BC Transit's paratransit service. The passengers have also grown accustomed to the assistance provided by the vehicle operators. Operators indicated that time delays were minimized with persons familiar with the securement system; however, in some cases drivers were reluctant to provide assistance since additional training was required and the drivers would assume a greater level of responsibility relative to other passengers.

Kitchener Transit's experience in transporting mobility aids has indicated most mobility aid users won't utilize tie-down straps when their use is optional. In light of this experience, Kitchener Transit has recently purchased a large quantity of low-floor buses equipped with two rear-facing compartment type securement systems. These compartment securement systems use flip-up seats to create the compartment area thereby maximizing ambulatory seating. With the seats in the flipped up position, the rear of the mobility aid is positioned against a padded impact barrier. A stanchion is located on the aisle side of the compartment to prevent tipping of the mobility aid and to provide a hand hold for the occupant. A second hand hold, located on the wall side of the compartment, is revealed when the seats are flipped up.

Similarly, Société de Transport de la Communauté Urbaine de Montréal will shortly introduce low-floor buses equipped with one compartment type securement system. The majority of Canadian public transit systems are currently using wheel clamp or lock systems in combination with tie-down straps. Most transit systems which employ tie-down type securement systems also provide an occupant restraint system to be used at the occupant's discretion. The securement of the mobility aid is typically mandatory and assistance is provided where required.

3.5 Research of Existing Standards and Regulations

A search of existing standards identified several standards either currently in use, awaiting implementation or in the stages of being finalized. The standards review focused on the Canadian Standards Association documents CAN/CSA-Z605-95, *Mobility Aid Securement and Occupant Restraint Systems for Motor Vehicles* (Ref. 14) and CAN/CSA-D409-92, *Motor Vehicles for the Transportation of Persons with Physical Disabilities* (Ref. 15). Included in the review was the ANSI/RESNA Subcommittee on Wheelchairs and Transportation (SOWHAT) working document WC/19 *Standard for Wheelchairs Used as Seats in Motor Vehicles* (Ref. 16). In addition, results produced by The Cleveland Clinic Foundation (Ref. 8) were reviewed which included an analysis of the following in-process standards: Society of Automotive Engineers document J2249 *Wheelchair Tiedown and Occupant Restraint Systems for Use in Motor Vehicles* (Ref. 17), and the International Organization for Standardization (ISO) document 10542 *Wheelchair Tiedown and Occupant Restraint Systems for Motor Vehicles* (Ref. 18).

The primary regulations reviewed during the research phase were the U.S. ADA (Ref. 4) and Ontario's Regulation 629 (Ref. 13). As well, the review evaluated results of various independent reviews of regulations established in Australia, France, United Kingdom, Germany, Denmark, and Sweden (Refs. 2, 3 and 8).

3.5.1 Canadian Standards Association CAN/CSA-D409-92

The standard CAN/CSA-D409-92, specifies the design and manufacture of the transporting vehicle, as well as associated lifts and ramps. It applies to motor vehicles other than passenger cars, but was prepared primarily for vehicles with a gross vehicle weight rating (GVWR) of less than 10 000 kg (20 000 lb) which would exclude most large public transit vehicles. However, the standard does distinguish between vehicles above and below the 10 000 kg rating and includes design requirements that specifically apply to vehicles with a GVWR greater than 10 000 kg. The specifications that pertain specifically to mobility aid securement apply to all vehicles with no weight distinction.

According to the report produced for the Ontario Ministry of Transportation by Delcan Corporation (Ref. 13), this 10 000 kg (20 000 lb) weight dividing line was established to modify the standard from its original intent of specifying requirements for vehicles used in paratransit services. The weight distinction was based on Canadian and U.S. motor vehicle standards and crash tests which indicate there is a substantially lower risk of injury to passengers travelling in large transit vehicles. This resulted in the exclusion of large transit buses from certain requirements and the inclusion of a preliminary statement confining the initial intent of the standard to vehicles with a GVWR of less than 10 000 kg (20 000 lb).

3.5.2 Canadian Standards Association CAN/CSA-Z605-95

The standard CAN/CSA-Z605-95 specifies design requirements, test procedures and performance requirements for mobility aid securement and occupant restraint systems used in public transportation vehicles not exceeding 7 000 kg (15 000 lb) gross vehicle weight rating. This standard specifically applies to mobility aid securement systems which employ a four point, belt type tie-down arrangement. Although this standard includes tie-down securement systems with and without modifications to the mobility aid, it disregards securement systems utilizing any other type of securement. The standard specifically excludes large transit vehicles as it applies only to para-transit buses, minibuses, taxis and vans.

3.5.3 Other Standards/Regulations

Similarly, other standards and regulations focus on securing mobility aids in the event of a severe impact in lighter, smaller vehicles. These include SAE and ISO standards which are currently in review and specify requirements for securement up to a 20 g impact focusing primarily on four point tie-down securement systems. The Rehabilitation Engineering and Assistive Technology Society of North America (RESNA) is currently working together with other organizations to generate standards for transportable wheelchairs which focus on tie-down securement systems.

3.5.4 Additional Information

Additional information was available in the form of test results and recommended securement guidelines presented in numerous reports and excerpts from journals and conference proceedings. Approximately 40 documents on the subject of mobility aid securement were reviewed. A complete listing of the referenced documents is presented in Appendix C.

Some further views and opinions were presented and noted at the *4th Annual Conference on Mobility Aids and Public Transport, Docking Type Securement Systems*, held at the University of Victoria, Victoria, B.C., June 19, 1996. The conference was an open forum of informative discussions concerning the prominent issues surrounding mobility aid securement. The conference discussions focused on the topics of CSA standards applicability, engineering aspects of mobility aid securement, docking type securement and social issues surrounding mobility aid securement. Information obtained from the conference was incorporated into the relevant sections of this report.

3.6 Wheeled Mobility Aid Securement

Forces are exerted on a mobility aid when the transporting vehicle is accelerated or decelerated or the direction of travel is altered. Moderate changes in speed and direction most often occur as a result of normal driving manoeuvres; however, larger accelerations in any direction can occur as a result of a crash impact. A mobility aid securement system must fully constrain or limit the motion of a mobility aid under this range of applied forces to protect the occupant and other passengers from injury.

To accomplish full securement, the securement system must provide restraining forces in all three physical dimensions: laterally across the vehicle, lengthwise from vehicle front to rear, and vertically. In addition, the securement system must resist any moments applied to the mobility aid which would cause it to rotate about one of these three axes (Ref. 11).

For the purpose of analysis, this range of applied forces has been divided into two categories which include the forces/accelerations resulting from normal driving and accident avoidance manoeuvres, and those resulting from crash impact.

3.6.1 Dynamics of Wheeled Mobility Aid Securement

The dynamics of mobility aid securement describes the motion of the combined mobility aid/occupant configuration allowed by the securement system under the application of external forces. The extent and direction of this motion is strongly affected by the combined centre of gravity location of the mobility aid/occupant configuration.

Conventional manual wheelchairs typically have a combined centre of gravity location in front of the occupant approximately at mid height. In contrast, conventional powered wheelchairs have a lower combined centre of gravity. This lower centre of gravity improves the unrestrained stability of the chair when acted upon by external forces. Scooters and power base designs, however, typically position the occupant higher resulting in a higher combined centre of gravity. With the addition of a narrower wheel base, the scooter type mobility aids have a greater potential to tip over with the application of external forces (Ref. 11).

Examining the occupant and mobility aid as separate bodies with individual centre of gravity locations provides further insight into mobility aid responses to applied external forces. In the absence of restraining forces and with the centre of gravity of the occupant positioned above the wheelchair centre of gravity, the application of forward and rearward forces caused by accelerating the occupant will tend to pitch the wheelchair forward or rearward. Since the forward wheels are positioned ahead of the wheelchair centre of gravity, they will provide opposing forces to the forward applied external forces thereby improving the stability of the wheelchair. In the rearward direction, opposing forces are also contributed by the rear wheels, however, since the wheelchair centre of gravity is much closer to the rear wheels, the opposing forces are smaller, allowing the chair to roll more easily about its rear axle. Forces applied in the lateral direction above the centre of gravity will tend to tip the wheelchair over on its side. The wheelchair wheels can provide only limited opposing forces in the lateral direction, once again due to the close location of the wheels relative to the centre of gravity.

The most thorough and accurate analysis of securement system dynamics and occupant/mobility aid motion is provided through dynamic testing of the combined system. The above analysis is only illustrative as it neglects the dynamic behaviour of the occupant and mobility aid under the application of external forces. As the combined system is accelerated, the occupant will move in the direction of the applied forces continually changing the location of the combined centre of gravity. In addition to moving in the direction of the applied forces, the occupant will also exhibit rebound motions after the body of the occupant has reached full extension. Combined with the inherent flexibility and compliance of the mobility aid, the motion and direction of the mobility aid under the action of external forces will be considerably affected (Ref. 19).

3.6.2 Wheeled Mobility Aid Location

The magnitude of forces exerted on the mobility aid are related to the location of the mobility aid in the vehicle. Extreme forward and rearward locations tend to produce greater forward, rearward and lateral accelerations in certain types of crash impacts and during normal driving manoeuvres (Ref. 8). Since the centre of the vehicle will generally experience the least accelerations, it is preferable to secure mobility aids in a central location in the vehicle.

3.6.3 Wheeled Mobility Aid Orientation

As well as being dependent on the requirements of the securement system, the orientation of the mobility aid is affected by considerations of passenger safety, human factors and vehicle layout including seating arrangements. Passenger safety is paramount and must address not only the securement of the mobility aid, but also the emergency evacuation of all passengers. As well, the designated passenger orientation must provide clear accessibility to the securement system and related components to allow for ease of use.

The bulk of the information obtained on passenger orientation on transit vehicles is based on research of accident statistics, passenger biomechanics and dynamic characteristics of the transit vehicle. A review of existing data on large transit vehicle accidents indicates that a greater percentage of accidents involve frontal impacts. Lateral and rear impacts appear to occur less often and result in far reduced levels of acceleration. However, according to a report produced for Project Action by ECRI (Ref. 20), there is insufficient data to indicate the orientation of a mobility aid should be based solely on the frequency of accidents occurring in any one direction.

3.6.3.1 *Forward/rearward facing orientations*

Many mobility aid users have expressed concern over orientations which specifically position them facing rearward as they often face other passengers or may experience motion sickness. Forward facing orientations allow the mobility aid occupant to face the direction of vehicle travel. This provides forward visibility for the rider and is the most common seating position in vehicles in North America. In addition, mobility aid occupants do not want to be segregated by being required to face a direction different from that of other passengers.

However, the results of accident research and testing simulating frontal crashes has established that a rear facing orientation with a padded head and back support will provide superior protection to the mobility aid occupant in a frontal impact (Refs. 20, 21 and 22). The strong opposition to rearward facing orientations may be eased with consideration of the added benefits provided by facing this direction. In addition to an increased level of protection, a creative arrangement of seats in the transit vehicle may be able to overcome any awkwardness or segregation experienced as a result of facing rearward. There also does not appear to be conclusive data indicating the motion sickness associated with a rear facing position is a predominant concern. Experiences in Europe indicate that motion sickness is not a factor in short urban journeys (Refs. 2 and 3).

3.6.3.2 *Angled orientations*

Many studies have indicated angled orientations of the mobility aid should be avoided until further extensive research can be conducted. Angled orientations exert greater forces on the mobility aid and occupant in the lateral direction. As discussed, mobility aids are inherently unstable in the lateral direction. In addition, current occupant restraints consist of lap and torso belts similar to those required in personal automobiles. These restraints are designed to retain an occupant in frontal collisions and provide limited lateral restraint. Without proper restraints the body of the occupant will experience greater displacements in the lateral direction increasing the potential for injury. The human body can only withstand limited excursions in the lateral direction prior to incurring injury (Ref. 20).

This potential for injury resulting from forces exerted in the lateral direction strongly supports the opposition to angled orientations. Even the accelerations experienced during normal driving manoeuvres are capable of producing forces great enough to cause injury. Seating layouts with angled orientations often reduce the amount of aisle width and can potentially interfere with the entry and exit of other passengers.

3.6.4 Occupant Restraint Systems

Although a heightened concern of most disabled persons is the desire to be treated in the same way as other passengers, some precautionary measures such as occupant restraints may be a necessary element of a securement system. Ambulatory passengers typically have the ability to restrain themselves against the forces generated by normal driving manoeuvres in contrast to the wide range of muscular control of persons with disabilities. These forces are generated by accelerations of up to 0.3 g, forceful enough to eject a non-responsive passenger from their seat (Ref. 13), possibly incurring injuries. In addition, persons with disabilities may have greater potential to sustain injuries from light impacts caused by normal driving manoeuvres. Occupant restraint systems are typically not automated and fastening is normally left to the mobility aid occupant. As is the current practice of many transit operations, occupant restraint systems should be, as a minimum, offered to wheeled mobility aid users.

3.7 Securement Restraining Forces

Current accident information (Ref. 13) indicates the number of injuries involving crash impacts is an almost negligible percentage of the total accidents involving large transit vehicles. In addition, a very low percentage (0.3%) of all transit vehicle accidents in Canada were considered serious events (Ref. 13). However, a larger percentage of accidents involving persons using mobility aids appears to involve the misuse of securement and restraint systems. These accidents typically occur during entry or exit of the passenger or during normal driving conditions. This information demonstrates that a greater emphasis should be placed on securement performance during normal driving conditions (Ref. 8).

3.7.1 Securement for Normal Driving Conditions

Normal driving conditions of large transit vehicles include emergency braking, maximum forward acceleration, cornering and lane changing manoeuvres. Forward acceleration of the transit vehicle produces movement of the mobility aid primarily in the rearward direction and braking deceleration of the vehicle produces movement primarily in the forward direction. Cornering and lane changing manoeuvres produce forces of a combined nature with components in the forward, rearward and lateral direction. Securement of mobility aids under these normal operating conditions protects the mobility aid and occupant from excessive movement, but does not necessarily provide full protection under crash impact forces. The comfort of the mobility aid user should also be considered as tests have indicated even small cyclical movements of the mobility aid of up to 16 mm (5/8 in.), can make travel uncomfortable for a disabled passenger (Ref. 7).

A review of the test data available on vehicle accelerations that occurred during normal driving manoeuvres indicates medium and large sized transit vehicles are capable of maximum forward accelerations of 2.4 m/sec^2 (0.25 g) (Ref. 23). Another report by Oregon State University (Ref. 11) has adopted maximum vehicle accelerations during normal driving manoeuvres as 0.40 g forward acceleration, 0.20 g sideward acceleration, and 0.10 g maximum rearward acceleration. German acceleration measurements of a low-floor bus (Ref. 2) suggest 0.30 g rearward acceleration during forward acceleration of the vehicle, 0.45 g forward acceleration during braking and 0.35 lateral acceleration during manoeuvring.

The Ontario Ministry of Transportation conducted testing that indicates an occupied mobility aid with brakes applied will move with an applied acceleration of 2.9 m/sec^2 (0.29 g) (Ref. 13). Similarly, testing of wheeled mobility aids on flat surfaces indicates that sliding of an occupied standard manual wheelchair occurred at accelerations as low as 1.8 m/sec^2 (0.18 g) (Ref. 23).

3.7.2 Securement for Crash Impact Protection

Generally, not all mobility aids can be safely secured for crash impact conditions while occupied. Securement systems required to meet the level of securement experienced in a crash impact would only be effective if the mobility aid was designed to meet the same level of impact. Therefore, standards or regulations imposing crash impact securement requirements on transit vehicles should as a minimum require the mobility aid to meet these same requirements. This is the direction taken by the Canadian Standards Association in the development of the standard CAN/CSA-Z604-95, *Transportable*

Mobility Aids for Occupancy in Moving Vehicles for mobility aids transported in vehicles not exceeding 7 000 kg (15 000 lb) GVWR. This standard is referenced by CAN/CSA-D409-92, *Motor Vehicles for the Transportation of Persons with Physical Disabilities* that requires a wheeled mobility aid to meet certain construction and crash worthiness criteria.

There is also some inconsistency in the levels of crash impact protection suggested by various standards and regulations. This inconsistency arises from the grouping of transit vehicles into one category. Based on research and tests conducted, fixed route vehicles weighing 10 000 kg (20 000 lb) or greater, require a lower level of impact protection (Ref. 24). Actual crash testing performed by BC Transit has indicated that large transit vehicles experience decelerations well below 10 g. In comparison, CSA standards dictate mobility aid securement systems are to be crash impact tested to 20 g because the standards refer to the securement of mobility aids in vehicles not exceeding 7000 kg GVWR and therefore require a higher level of impact protection.

4. PERFORMANCE AND DESIGN SPECIFICATIONS

A comparison of the accelerations produced by large transit vehicles under normal operating conditions and the accelerations required to move an unsecured mobility aid indicates that securement is possible with non-interlocking frictional methods, the simplest of which is the compartment or barrier type securement system. Therefore, performance and design specifications for positively interlocking securement systems were not further developed.

4.1 Compartment Type Securement Systems

In a compartment securement system, compliant impact barriers or bulkheads are used to restrict the motion of the mobility aid and occupant. Bulkheads are usually located in the front of the compartment and impact barriers are located in the rear and on the sides of the mobility aid.

The forward bulkhead is in place to restrict the mobility aid and occupant to decelerate at the same rate as the vehicle over an extended period of time. The bulkhead and the position of the mobility aid against the bulkhead will prevent the mobility aid from accelerating through a distance and impacting the barrier. An impact sharply increases the amount of force experienced by the mobility aid and occupant as the time interval for deceleration is significantly reduced, thus increasing the level of deceleration.

The rear impact barrier, on the other hand, faces the passenger and must be placed further away from the mobility aid to provide additional space for entry into and exit from the compartment. With the brakes of the mobility aid fully applied, restraining forces generated by friction between the mobility aid tires and the floor of the vehicle are present to prevent movement of the mobility aid under most conditions. However, forward accelerations of the vehicle may exceed these frictional restraining forces and cause the mobility aid to move rearward and impact the rear barrier. This impact is much more manageable than for a frontal impact of the vehicle, because the acceleration levels are much lower.

One method to reduce the potential for impact with the rear impact barrier is to increase the frictional forces restraining the rearward motion of the mobility aid. The frictional forces restraining the mobility aid are proportional to the combined weight of the mobility aid and occupant, and the coefficient of friction provided by the interaction of the vehicle floor and the wheels of the mobility aid. This coefficient of friction can be increased to provide greater restraining forces by changing the material properties on the compartment floor. CAN/CSA-D409-92 specifies a minimum coefficient of static friction of flooring material of 0.5 under wet and dry conditions when tested in accordance with ASTM Standard D2047. This would be sufficient to prevent a mobility aid from moving excessively during normal driving manoeuvres.

As with any securement system, an area of concern in compartment securement is the magnification of the applied accelerations as the occupant and mobility aid do not experience the same accelerations. Studies have shown that the occupant can experience sharply increased accelerations compared with those of the vehicle and mobility aid (Ref. 10). This is explained by examining the stiffness of the human body relative to the mobility aid. A non-responsive human body restrained by a typical lap belt is very compliant to input forces. The very low stiffness of the occupant's body compared with the relatively stiff mobility aid tends to cause very large excursions of the upper torso possibly resulting in occupant injury (Ref. 21). This magnifying effect can be significantly reduced by securing the mobility aid in the rearward facing direction. In this orientation, the occupant is supported by the chair back of the mobility aid with very minimal excursion, thereby limiting the impact forces experienced. As the mobility aid impacts the compliant surface of the impact barrier, the majority of the energy of impact can be absorbed and dissipated. This will reduce any rebound forces which may cause the occupant to pitch forward in the mobility aid (towards the rear of the vehicle). Restraining the occupant in the mobility aid may also be a necessary requirement.

4.1.1 Current Testing Results

The most comprehensive testing studies on compartment securement systems have been conducted by several European communities. Two reports contain extensive research on unrestrained compartmental and impact barrier mobility aid securement.

A report produced by Studiengesellschaft für unterirdische Verkehrsanlagen e.V. (STUVA) for the German Ministry of Transport (Ref. 2) concluded that an unrestrained wheelchair can safely absorb the forces generated by fairly high acceleration values associated with the sharp cornering and emergency braking manoeuvres of large transit buses. The report states the wheelchair must be rear facing and properly positioned against a sufficiently wide retaining panel which supports the full surface of the rear of the wheelchair. The report also states braking of all four of the wheelchair wheels would greatly improve the ability of the wheelchair to remain in position.

A second report produced for the Institut National de Recherche sur les Transports et leur Sécurité of France (Ref. 3) suggests the rearward facing position provides acceptable securement of the mobility aid when unrestrained. The report also recommends the back of the wheelchair must be placed against a resistant wall with lateral supports on either side. Some tipping of the wheelchair was observed during testing and the side supports are necessary to provide lateral restraining forces.

Both reports conducted in-situ tests with conventional electric and manual wheelchairs on low-floor buses. Both reports also concluded the heavier conventional electric wheelchairs have the greatest stability and resist slipping on the vehicle floor to a greater extent than conventional manual wheelchairs. This is explained by the reduced downward force exerted by the lighter manual wheelchair which effectively reduces the magnitude of the frictional restraining forces. Both reports focus only on wheelchairs and exclude scooter and power base mobility aids which are prevalent in North America.

4.1.2 Compartment Securement Crash Impact Protection

A compartment design with the mobility aid facing rearward will provide securement force in the forward direction for crash impact protection; however, securement force in the rearward and lateral directions is only provided by the frictional forces generated between the mobility aid tires and the floor. If the frictional forces restraining the mobility aid are exceeded as imposed by a crash impact, the mobility aid will move and impact the nearest object. Padded side and rear impact barriers are required to be able to absorb and dissipate the energy resulting from the impact in order to reduce the potential for occupant injury. The optimum barrier will require generous damping properties to minimize any rebound effect. In addition to being effective, the material must be durable and low cost.

A number of materials are available to provide the required damping properties and energy dissipation. These include elastomers and polymers which use displacements of compressible material to absorb energy. Less commonly used viscous damping is another method which absorbs energy by the shearing of a liquid. Both can be incorporated into the form of a barrier which will absorb energy and dissipate it in a controlled manner, thereby reducing the forces exerted on a mobility aid occupant. This will in turn reduce damage to the mobility aid while effectively restraining the mobility aid to protect other passengers from its uncontrolled movement.

4.2 Computer Simulation of Mobility Aid Securement

Computer simulation of normal driving and crash impact scenarios was performed to provide further insight into the forces and resulting stresses involved in various forms of mobility aid securement. This allowed a direct comparison of the stresses produced in mobility aids as a result of the securement system. The simulation also allowed observation of the predicted behaviour of the mobility aid and securement system to externally applied dynamic forces. Combined, this information provided analytical verification of a securement system which does not positively interlock with the mobility aid.

The computer simulation involved subjecting two generic mathematical models to the time varying ground based accelerations associated with both normal driving and crash impact scenarios. A complete geometric model of a conventional powered wheelchair and a three-wheeled scooter were generated. As well, boundary conditions were applied relative to the type of securement system being modeled. The model with boundary conditions was then processed to produce modal frequency information, predicted displacement behaviour and dynamic stress outputs.

4.2.1 Simulation Approach

The simulation results were produced by simulating the exposure of the two mobility aid models to various impact scenarios. The impacts were simulated by a time-varying ground-based acceleration function of a trapezoidal shape (Ref. 25). With a constantslope rise and decay and a central dwell period, this force function estimates the impact pulse experienced during a collision.

The simulations were first performed with the models in a forward orientation with the scooter secured by a simulated lockdown type securement and the wheelchair by a wheel clamp type securement. This provided some validation of the models and a basis to compare other results. The next simulations were performed with the models in a rearward orientation positioned against the forward bulkhead of a compartment type securement system.

In addition, simulations were performed with flexible restraints imitating a platform suspended by flexible shock isolators. These simulations were performed to investigate the feasibility of isolating a section of the vehicle floor to reduce the magnitude of the input accelerations and resulting forces. Refer to Appendix A for a complete listing of the computer simulation input loads and constraint conditions.

4.2.1.1 *Conventional powered wheelchair model*

The conventional powered wheelchair was modeled from a generic powered wheelchair incorporating many standard features. The model incorporated a steel frame with an attached seat, front and rear wheels constructed of aluminum, and batteries modeled as homogeneous masses located below the seat structure. Similarly, two electric gear motors were modeled as homogeneous masses on either side of the frame. The overall centre of gravity of the wheelchair was located based on measurements presented in the University of Pittsburgh database report (Ref. 9). Further wheelchair model characteristics are presented in Appendix B.

4.2.1.2 *Three-wheeled scooter model*

The mathematical model of the scooter represented a generic three-wheeled scooter with a tiller steering mechanism. The model incorporated an elevated seat with a vertical seat post. The base was modeled as a steel frame with a fibreglass shell. Batteries were modeled as homogeneous masses located under the seat, and the properties of rubber wheels were incorporated to model the larger, more compliant wheels of a scooter. Once again, the centre of gravity was located based on measurements presented in the University of Pittsburgh database report (Ref. 9). Refer to Appendix B for further scooter model characteristics.

4.2.1.3 *Anthropometric human model*

In addition to the two mobility aid models, a mathematical model of an anthropometric dummy was constructed. To simplify the modelling process, the head, upper torso, pelvis and legs were modeled as three homogeneous bodies while low elasticity neck and spine members were used to connect these elements together. The rigid portions of the body closely approximate the human body in size, form, total weight and weight distribution, while modelling the thoracic and lumbar areas permitted simulation of the excursions and stresses in the thoracic and lumbar areas (Ref. 26). These are the two areas where maximum excursions occur when an occupant is exposed to vehicle accelerations. The human model was based on a large male weighing 110 kg (242 lb) to approximate worst case conditions. Refer to Appendix B for further human model characteristics.

In the simulation process, the human model was merged with the corresponding mobility aid model to form a realistic representation of an occupied mobility aid. The human model was fully connected to the mobility aid model through the seat/buttock area simulating a lap belt occupant restraint.

4.2.2 Simulation Results

The results of the simulations illustrate dramatically different behaviours between the two models in both forward and rearward orientations. In most securement scenarios, the wheelchair model experienced moderate stresses up to the maximum 10 g input. The scooter model, however, experienced failure in the seat post at force inputs as low as 5 g even though the seat post was modeled as heavy gauge structural steel. The human model response to the input forces was similar in both mobility aid models.

Wheel lock securement simulations of the wheelchair indicate maximum stresses will be located in the wheels with all wheels experiencing roughly the same amount of stress based on the securement of all four wheels. Large deformation of the wheels and high stress levels occurred at a 10 g acceleration level with the wheels rigidly constrained, indicating the failure of the wheel structure. The stiffness of the human model was also varied to assess the effect of the occupant restraint. The results indicate a more effective restraint that restricts excessive motion of the occupant will create slightly higher peak stresses in the wheelchair.

The flexibility of the wheel lock constraints was varied to simulate the effect of a shock isolated platform concept as previously discussed. The elastic constraints significantly reduced the level of stress observed in the wheel structure. These results indicate a platform suspended by shock isolators may reduce the level of force transmitted to a secured wheelchair with application to wheels secured through the use of wheel locks or simple friction as in a compartment type securement system.

Compartment type securement simulations of the wheelchair model indicate the wheelchair will experience maximum stress in the frame members when decelerated against a relatively stiff wall structure. This stress slowly diminishes as it is distributed to other frame members which did not directly contact the bulkhead. Failure was not observed up to the maximum 10 g impact.

The results of the scooter simulations indicate maximum stresses will be localized in the attachment point between the main frame and the seat post and failure will occur below a 5 g impact. Unfortunately, accurate simulation of the stresses in the seat back of either model was not possible within the scope of the simulation program. This is an area that should be explored further as some information indicates that rear facing seats will experience greater bending moments during frontal impacts (Ref. 26). Refer to Appendix A for a complete listing of simulation results relative to input load and constraint conditions.

In addition to obtaining the stresses resulting from various securement methods, Appendix B illustrates the relative displacement amplitudes associated with the first six modal frequencies. These relative displacements demonstrate the mode shapes of the anthropometric human model and mobility aid and indicate what effects the occupant and occupant restraint will have on the securement system.

5. RECOMMENDED PERFORMANCE SPECIFICATIONS

The following recommended performance specifications have been compiled from an analysis of the mobility aid database, mobility aid securement database and computer simulation results. In addition to performance specifications, component specifications and recommended displayed information guidelines have been included to provide a minimum level of operational performance.

The level of clarity and explanation provided in the Cleveland Clinic Foundation report entitled "Wheelchair Securement and Passenger Restraint for Public Transit" (Ref. 8) was adopted for the format of this section of the report. Information presented from referenced source documents has been slightly altered to remain consistent with the terminology of the remainder of the report. The following superscript identifiers represent the various source documents:

[CCF] Cleveland Clinic Foundation, Department of Rehabilitation Medicine and Invacare Corporation, "Wheelchair Securement and Passenger Restraint for Public Transit" (Ref. 8);

[CS] A requirement developed from results of computer simulations;

[CSA] A requirement adopted from the Canadian Standards Association standards Z605-95 and D409-92 (Ref. 14 and 15);

[FMVS] A requirement adopted from the U.S. Federal Motor Vehicle Safety Standards (Ref. 27);

[LSCO] A requirement adopted from the Institut National de Recherche sur les Transports et leur Sécurité (Ref. 3);

[MVSA] A requirement adopted from the Canadian Motor Vehicle Safety Act, Canadian Motor Vehicle Safety Standards (Ref. 28);

[N] No existing reference has been utilized;

[STVA] A requirement adopted from STUVA (Ref. 2).

5.1 Component Specifications

- The mobility aid must be rear facing and properly positioned against a sufficiently wide bulkhead or retaining panel which supports the full surface of the rear of the mobility aid. [CCF]The centreline of the mobility aid should be positioned 419 mm (16.5 inches) from the vehicle interior next to the mobility aid and at least 343 mm (13.5 inches) from the aisle.

  Rationale: [STVA]A rear facing orientation has been shown to be the safest position for a mobility aid in a compartment type securement. [CCF]This lateral location is based on a wide wheelchair 686 mm (27 inches), positioning it completely within the minimum width wheelchair bay of 762 mm (30 inches) wide allowing at least 76 mm (3 inches) of clearance to the interior side.

- The forward bulkhead that the rear of the mobility aid rests against should measure a minimum 838 mm (33 inches) in width and 1219 mm (48 inches) in height.

  Rationale: [CCF]The bulkhead should support the full surface of the rear of the mobility aid based on a wide wheelchair 686 mm (27 inches) and a maximum height of 965 mm (38 inches) (Ref. 9) plus some contingency for variations in mobility aid designs.

- [LSCO]Some form of lateral support should be provided on either side of the correctly positioned mobility aid.

  Rationale: [LSCO]Lateral supports are required to secure the mobility aid laterally minimizing any lateral movement of the mobility aid and occupant under both normal driving conditions and crash impact conditions.

- [CSA]The flooring in the compartment should meet a minimum coefficient of static friction of flooring material of 0.5 under wet and dry conditions when tested in accordance with ASTM Standard D2047.

Rationale: [N]A minimum coefficient of static friction will minimize movement of the mobility aid under normal driving conditions with the brakes of the mobility aid fully applied.

- For design and testing purposes [LSCO]the mobility aid weight should be 65 kg (143 lb) which is the weight of an average powered wheelchair (Ref. 9) representing a heavy mobility aid. The occupant weight should be that of a 50th percentile male.

  Rationale: [N]An average wheelchair was chosen based on the distribution of mobility aids in use and the heavier weight of powered wheelchairs. Occupant weight based on a 50th percentile male is consistent with CMVSS specifications (Ref. 28).

5.2 Recommended Information

- [STVA]Information posted in the compartment bay in clear view of the secured, occupied mobility aid should state that the brakes of the mobility aid wheels should be fully applied for greater safety.

  Rationale: [STVA]The brakes of the mobility aid should be fully applied at all times during vehicle movement to minimize unwanted motion of the mobility aid during travel and the risk of injury due to impact with surrounding surfaces.

- [CCF]Instructions should be provided which clearly state the steps necessary to position and secure the mobility aid. Components that are referenced in the instructions must be easily identified through labelling, size, geometry, colour or other means. [N]The instructions should be posted, where upon entering the compartment, the occupant of a mobility aid can readily read them.

  Rationale: [CCF]In many instances, the driver and mobility aid occupant may use the securement system infrequently and posted instructions will reduce the possibility of incorrectly positioning or securing the mobility aid. Clear instructions will also reduce the amount of time for securement and avoid confusion.

- [CCF]All passengers utilizing mobility aids, vehicle drivers and other personnel who will assist in applying the securement system should receive training.

  Rationale: [CCF]Any individual who is involved with the securement system should thoroughly understand how it operates and should be trained in the securement of different types of mobility aids. Different mobility aids may require different procedures or attention to specific areas of concern that will improve the safety of the passenger.

5.3 Performance Under Normal Driving Conditions

- [CCF]The secured mobility aid should move no more than 51 mm (2.0 inches) in any direction, measured at points of contact with the floor, when the following normal driving accelerations are applied to the combined centre of gravity of the occupied mobility aid:

  Forward Applied Acceleration: 0.50 g
  Rearward Applied Acceleration: 0.35 g
  Lateral Applied Acceleration: 0.35 g

  Limiting the motion to as little as possible should be a design objective. Greater motion may be experienced at points above the floor.

  Rationale: [CCF]The load level is based on driving accelerations of 0.35 g that could be attained while driving in traffic. CSA standards refer to the motion of the mobility aid at points of contact with the floor. The ADA specifies 2.0 inches of motion during normal operating conditions. [FMVS]OEM seats must have no motion even under crash situations and less than 1.0 inch of motion has been shown to be achievable. More stringent requirements are not suggested here to allow manufacturers and designers more opportunities to address other aspects of securement.

- [CCF]Any part of the mobility aid originally in contact with the floor should remain in contact with the floor.

  Rationale: [CCF]Mobility aid users are very sensitive to tipping of the mobility aid and loss of floor contact produces the sensation of insecurity and loss of control.

5.4 Performance Under Rear and Lateral Impact Conditions

- [CCF]The mobility aid should not move more than 76 mm (3.0 inches), measured at any point of contact with the floor, when a static lateral force equivalent to 5.0 g multiplied by the occupied mobility aid weight is applied to the combined centre of gravity of the occupied mobility aid.

  Rationale: [CCF]The FMVSS specifications allow 2.0 inches of movement for loading equal to the weight of the wheelchair. The ISO guidelines allow for 200 mm (7.9 inches) of movement under a 20 g load. Interpolating between these values results in an acceptable movement of 76 mm (3.0 inches) for a 5 g load. [N]The mobility aid should be limited in lateral direction motion for the safety of other passengers.

- [CCF]Upon release of a test load or termination of the lateral or rear impact, the mobility aid should return to an upright, rearward facing position.

  Rationale: [CCF]If the securement system limits tipping of the mobility aid such that the mobility aid is still stable under loading conditions, then the combined centre of gravity will remain above the mobility aid base and the mobility aid will return to an upright position.

5.5 Performance Under Frontal Impact Conditions

- [CCF]Forward or rearward movement of an occupied mobility aid should be limited to 200 mm (7.9 inches) when a static frontal force equivalent to 10 g multiplied by the occupied mobility aid weight is applied to the combined centre of gravity of the occupied mobility aid. [CCF]Movement in lateral or rear directions should be limited to 76 mm (3.0 inches) or less.

  Rationale: [CCF]The 200 mm (7.9 inches) is adopted from the SAE draft standards and is thought to be obtainable with most existing systems. To prevent secondary impact with barriers in front of the mobility aid and to prevent the mobility aid from applying a load to the occupant, the forward movement should be kept as small as possible.

- [CS]The forward bulkhead should be designed to withstand the static impact force developed from a 10 g acceleration of an occupied mobility aid with an average weight of 110 kg (243 lb) and an occupant weight equivalent to a 50th percentile male.

  Rationale: [N]Research data (Ref. 13) indicates large transit vehicles may experience decelerations of up to 10 g in head-on collisions or when impacting a fixed barrier, therefore, the forward bulkhead must be able to withstand the full impact force of an occupied mobility aid.

- [MVSA]Any impact barrier, bulkhead or any other non-glazed surface of the interior of the compartment that is capable of being contacted by the head, pelvis or other part of the body should be constructed of energy absorbing material that, as a minimum, collapses to within 32 mm (1.25 inches) of a rigid panel surface without permitting contact with any rigid material. The material must also possess generous damping properties to dissipate the absorbed energy and limit rebound effects.

  Rationale: [N]Surfaces surrounding the occupied mobility aid must be able to absorb and dissipate the energy of impact to minimize injury to the occupant in any condition and damage to the mobility aid in normal driving conditions.

- [CCF]No component of the securement system will break loose.

  Rationale: [CCF]Any loose component could become a projectile that puts all vehicle passengers at risk.

6. SUMMARY OF FINDINGS

A standard or set of guidelines stating essential performance specifications is required to specify vehicle safety features necessary for accommodating persons with disabilities in transit buses without compromising the safety of other passengers. With sufficient information indicating a non-interlocking securement system is a viable securement option in large transit vehicles, the standards and regulations governing securement performance in these vehicles must be flexible enough to allow for their use. Restrictive standards and regulations that dictate the use of specific types of securement systems obstruct the introduction of new technologies and innovative ideas.

To avoid restrictive regulations, the performance of a securement system should be stated in the form of general guidelines and performance specifications. An excellent example of generalized guidelines is contained in a report produced for the U.S. Federal Transit Administration under the Transit Cooperative Research Program (Ref. 8). This comprehensive set of guidelines details general guidelines such as presentation of information, training, mobility aid location, operation and maintenance requirements as well as full performance specifications.

After completion of a comprehensive set of guidelines, they must be implemented across Canada as a standard for large transit vehicles. The transit industry and passengers alike are in need of a specification to provide the basis for consistent regulations in all Canadian jurisdictions. This standard would also encourage the introduction of full size, accessible buses such as low-floor buses providing greater accessibility to public transportation. In addition, a Canadian wide standard would aid in maintaining compatibility with foreign regulations soon to be implemented. This standard, however, would only apply to vehicles falling within a specific category meeting definite physical and operating specifications. These vehicle specifications also need to be clearly defined and incorporated within the guidelines.

The following section of the report provides an outline of the key findings of this study on automated mobility aid securement. These findings are listed in their order of appearance.

Transit Authorities Contacted

- The majority of transit providers contacted expressed the need for a standard which specifically addresses large transit vehicles. Many transit providers expressed concerns over liability issues and would prefer a standard or some form of direction indicating what form of securement is safe and effective.

Securement Force Levels

- From the information obtained, there is a general consensus that large transit vehicles will exert lower levels of force on the mobility aid and occupant in both normal driving and crash impact scenarios than what is currently recommended in existing standards;

- Actual crash testing has indicated that large transit vehicles experience decelerations well below 10 g;

- Accident information demonstrates that a greater emphasis should be placed on securement performance during normal driving conditions;

- The CSA standards CAN/CSA-Z604-95, Transportable Mobility Aids for Occupancy in Moving Vehicles, CAN/CSA-Z605-95, Mobility Aid Securement and Occupant Restraint Systems for Motor Vehicles and CAN/CSA-D409-92, Motor Vehicles for the Transportation of Persons with Physical Disabilities are not directly applicable to large transit vehicles due primarily to vehicle weight restrictions.

Wheeled Mobility Aid Location/Orientation

- A mobility aid secured in a central location in a large transit vehicle will typically experience the least accelerations during normal driving manoeuvres and a crash impact;

- Frontal impacts tend to produce larger accelerations requiring greater protection of the occupant in this direction. Dynamic testing simulating frontal crashes has established the safest orientation is rearward facing (relative to the vehicle) combined with a padded head and back support;

- The combined wheelchair and occupant system is most stable when external forces are applied in the forward direction (relative to the wheelchair) and is most unstable when forces are applied in the lateral and rearward directions (relative to the wheelchair). Scooter type mobility aids are more unstable than wheelchairs due to a higher combined centre of gravity, narrower wheel track and shorter wheelbase;

- For effective securement, a compartment securement system should position the mobility aid in the rear facing direction (relative to the vehicle) in such a manner as to reduce any awkwardness presented by this position.

Mobility Aid Securement System Design

- Automated securement systems can eliminate the vast majority of difficulties currently surrounding the securement of mobility aids on public transit vehicles;

- Non-interlocking type securement systems can readily be automated mainly due to a reduction in the level of accuracy required when positioning the mobility aid. This also minimizes securement time and effort and eliminates the need for mobility aid modifications;

- Positive interlocking securement should be considered for securement beyond 10 g crash impact conditions;

- A comparison of the accelerations produced by large transit vehicles under normal operating conditions and the accelerations required to move an unrestrained mobility aid indicate that securement is possible with devices that utilize only friction;

- A compartment type securement system must be equipped with head and back supports to avoid excessive movement of the occupant during deceleration and impact absorbing/damping materials should be applied to likely areas of impact;

- A compartment securement system must include some form of lateral support to resist lateral forces experienced during normal driving manoeuvres;

- A compartment securement system may require driver training to emphasize the consequences of erratic driving;

- The performance of scooter type mobility aids in compartment type securement systems can only be assumed since actual test results of the braking capabilities of scooters and power base mobility aids were not available;

- Although compartment type securement is a viable option, it can only provide safe securement to a certain level of impact. To protect the mobility aid occupant against greater levels of impact, new innovative approaches to automated securement need to be addressed. These may include some current technologies such as automatically deployed air bags, automatically deployed bristles and Move-In-Place (MIP) securement systems.

Computer Simulation Results

- In general, the wheelchair model experienced moderate stresses up to the maximum 10 g acceleration input in most securement scenarios;

- Flexible constraints simulating shock isolators significantly reduced the level of stress observed in the wheelchair model;

- Compartment type securement simulations of the wheelchair model indicate the wheelchair will experience maximum stress in the frame members that contact a rigid bulkhead and may not fail up to the maximum 10 g impact;

- The results of the scooter simulations indicate maximum stresses will be localized in the attachment point between the main frame and the seat post and failure may occur below a 5 g impact in all securement scenarios.

7. CONCLUSIONS

Through research of current reports, published data, analysis of vehicle test data and computer simulation of securement systems, it can be concluded that a non-interlocking securement system is feasible for use on a large transit vehicle.

Actual test data on compartment type securement systems verified that an unrestrained, rearward facing mobility aid placed in a properly designed protective compartment can safely manage the forces associated with normal driving and accident avoidance manoeuvres.

Positively interlocking securement of mobility aids should be considered when crash impacts of 10 g or greater are expected.

8. RECOMMENDATIONS

8.1 Standard/Guideline Development

It is recommended that a standard be developed to define the requirements for securing mobility aids in large transit vehicles. The standard should consist of performance specifications which include measurements of performance and suggested testing methods for securement performance under normal driving conditions, as well as lateral impact and frontal impact conditions.

8.2 Monitor Kitchener Experience

It is recommended that Kitchener Transit and similar transit operations introducing innovative securement solutions should be closely monitored to gauge the acceptance of these systems by transit passengers. The foremost sources of information are the transit passengers that utilize a securement system on a regular basis. Undoubtedly, refinements of new securement systems will occur during usage and these refinements can be incorporated within the developed guidelines.

8.3 Investigate Scooter Performance

It is recommended that more information be obtained on the behaviour of scooters and similar mobility aids in both normal driving and crash impact situations. This may require actual performance testing of scooters and power base type mobility aids. A report produced for the U.S. Department of Transportation (Ref. 12) illustrates many of the problems associated with the securement of scooters, but focuses on positive interlocking securement systems. It is difficult to assess the behaviour of scooter type mobility aids secured in a compartment securement system without sufficient information on braking capabilities. The effectiveness of this type of securement system depends entirely on the braking system of the mobility aid.

8.4 Further Investigation into Automated Securement

It is recommended that the application of compartment type securement systems be further assessed with actual dynamic testing. The introduction of shock isolators, for example, may be a simple and inexpensive addition to the compartment design which will reduce the level of force input to the mobility aid and occupant. As well, to minimize occupant injury, the energy absorption characteristics and strategic location of impact barriers need to be carefully considered during testing and documented for inclusion within the appropriate guidelines.

APPENDIX A

COMPUTER SIMULATION RESULTS

Table 1: Computer Simulation Results
Conventional Powered Wheelchair Model with Anthropometric Human Model

Mobility Aid Model and Load Case	Ground Based Acceleration Input	Mobility Aid Model Stress (Maximum)	Displacement of Mobility Aid and Human Model Excursion
Wheelchair Model Load Case 1	10 g	192 191 psi ($1.33x10^6$ kPa)	Maximum human model excursion: 7.7 ins. (196 mm) Maximum wheelchair displacement: 0.58 ins. (14.7 mm) (wheel failure)
Wheelchair Model Load Case 2	10 g	16 820 psi (115 971 kPa)	Maximum human model excursion: 3.18 ins. (80.8 mm) Maximum wheelchair displacement: 0.50 ins. (12.7 mm)
Wheelchair Model Load Case 3	10 g	16 836 psi (116 081 kPa)	Maximum human model excursion: 3.20 ins. (81.3 mm) Maximum wheelchair displacement: 0.53 ins. (13.5 mm)
Wheelchair Model Load Case 4	10 g	19 490 psi (134 380 kPa)	Maximum human model excursion: 0.46 ins. (11.7 mm) Maximum wheelchair displacement: 0.53 ins. (13.5 mm)

Note 1: The following conditions apply to the respective load cases:

Wheelchair Model Load Case 1:
- Wheel lock type securement system securing all four wheels
- Rigid constraints (zero degree of freedom boundary conditions)
- Normal human model with typical anthropometric conditions

Wheelchair Model Load Case 2:
- Wheel lock type securement system securing all four wheels
- Flexible Constraints (x:650 lb/in, y:5 000 lb/in, z:650 lb/in)
- Normal human model with typical anthropometric conditions

Wheelchair Model Load Case 3:
- Wheel lock type securement system securing all four wheels
- Flexible Constraints (x:650 lb/in, y:5 000 lb/in, z:650 lb/in)
- Partially stiffened human model

Wheelchair Model Load Case 4:
- Wheel lock type securement system securing all four wheels
- Flexible Constraints (x:650 lb/in, y:5 000 lb/in, z:650 lb/in)
- Fully stiffened human model

Note 2: All simulations were conducted with a trapezoidal acceleration input pulse with the following specifications:

Rise Time: 0.03 sec
Fall Time: 0.03 sec
Dwell Time: 0.02 sec

Table 2. Computer Simulation Results
Three Wheeled Scooter Model with Anthropometric Human Model

Mobility Aid Model and Load Case (Note 1)	Ground Based Acceleration Input (Note 2)	Mobility Aid Model Stress (Maximum)	Displacement of Mobility Aid and Human Model Excursion
Scooter Model Load Case 1	10 g	106 050 psi (731 194 kPa)	Maximum human model excursion: 23.4 ins. (594 mm) Maximum scooter displacement: negligible (seat post failure)
Scooter Model Load Case 2	2 g	9 673 psi (66 693 kPa)	Maximum human model excursion: 0.80 ins. (20.3 mm) Maximum scooter displacement: negligible
Scooter Model Load Case 3	5 g	56 059 psi (386 516 kPa)	Maximum human model excursion: 17.4 ins. (442 mm) Maximum scooter displacement: 2.9 ins. (73.7 mm) (moderate seat post deformation
Scooter Model Load Case 4	10 g	88 602 psi (610 893 kPa)	Maximum human model excursion: 35.1 ins. (892 mm) Maximum scooter displacement: 5.9 ins. (148 mm) (large seat post deformation)

Note 1: The following conditions apply to the respective load cases:

Scooter Model Load Case 1:
- Frame lock down type securement system utilizing front and rear securement points
- Rigid constraints (zero degree of freedom boundary conditions)
- Normal human model with anthropometric conditions

Scooter Model Load Case 2:
- Compartment securement type securement system
- Unrestrained mobility aid in contact with impact with barrier/bulkhead
- Normal human model with anthropometric conditions

Scooter Model Load Case 3:
- Compartment type securement system
- Unrestrained mobility aid in contact with impact with barrier/bulkhead
- Normal human model with anthropometric conditions

Scooter Model Load Case 4:
- Compartment type securement system
- Unrestrained mobility aid in contact with impact with barrier/bulkhead
- Normal human model with anthropometric conditions

Note 2: All simulations were conducted with a trapezoidal acceleration input pulse with the following specifications:

Rise Time: 0.03 sec
Fall Time: 0.03 sec
Dwell Time: 0.02 sec

APPENDIX B

COMPUTER SIMULATION MODEL DATA

Mobility Aid Computer Simulation

Anthropometric Human Model Data:
(see Figure 1 for reference point location and reference axis orientation)

Anthropometric Model Weight: 242 lb

Centre of Gravity Location:	X-direction:	10.5 ins.
	Y-direction:	12.8 ins.
	Z-direction:	9.0 ins.

Mass Moment of Inertia:	Ixx: 251.2 ins^4
	Iyy: 164.5 ins^4
	Izz: 282.7 ins^4

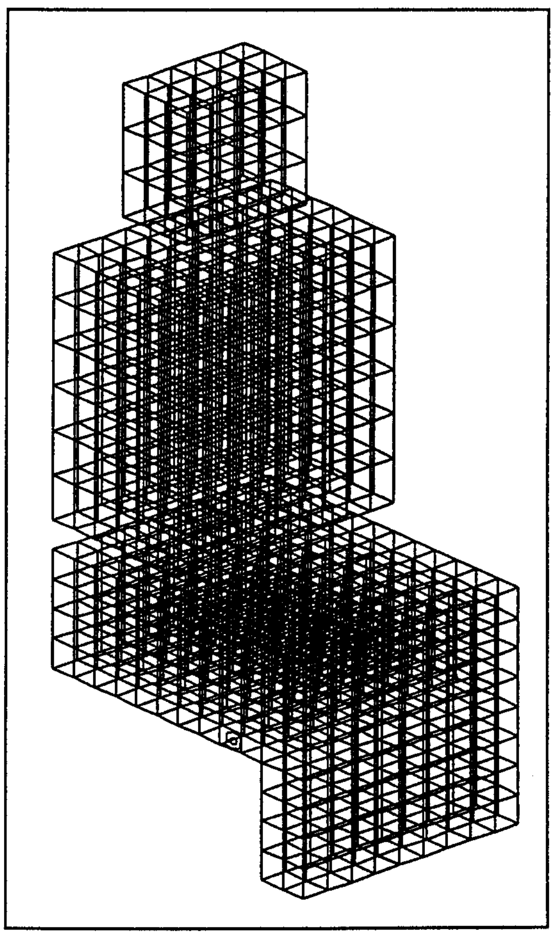

Figure 1: Anthropometric Human Model

Anthropometric Human Model Modal Analysis Results:

Table 1. Anthropometric Human Model Modal Analysis Results

MODE NUMBER	FREQUENCY (r/s)	FREQUENCY (Hz)
1	6.06	0.96
2	6.17	0.98
3	18.45	2.94
4	19.62	3.12
5	20.68	3.29
6	26.81	4.27

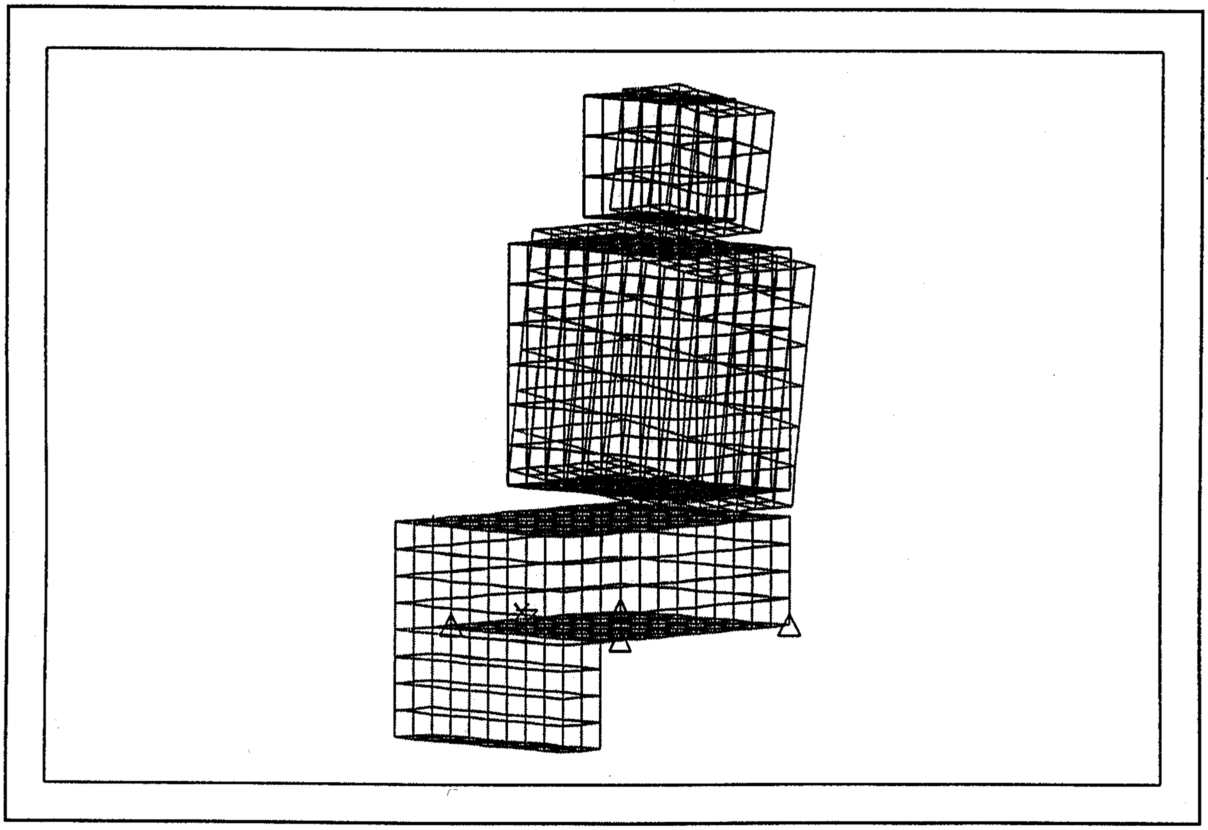

**Figure 2: Anthropometric Human Model, Sample Modal Analysis Result
Mode 1: 0.41 Hz**

Powered Conventional Wheelchair Model Data:
(see Figure 3 for reference point location and reference axis orientation)

Wheelchair Model Weight:	131 lb	
Centre of Gravity Location:	X-direction:	17.8 ins.
	Y-direction:	-2.7 ins.
	Z-direction:	9.0 ins.
Mass Moment of Inertia:	Ixx:	63.7 ins^4
	Iyy:	17.3 ins^4
	Izz:	126.9 ins^4

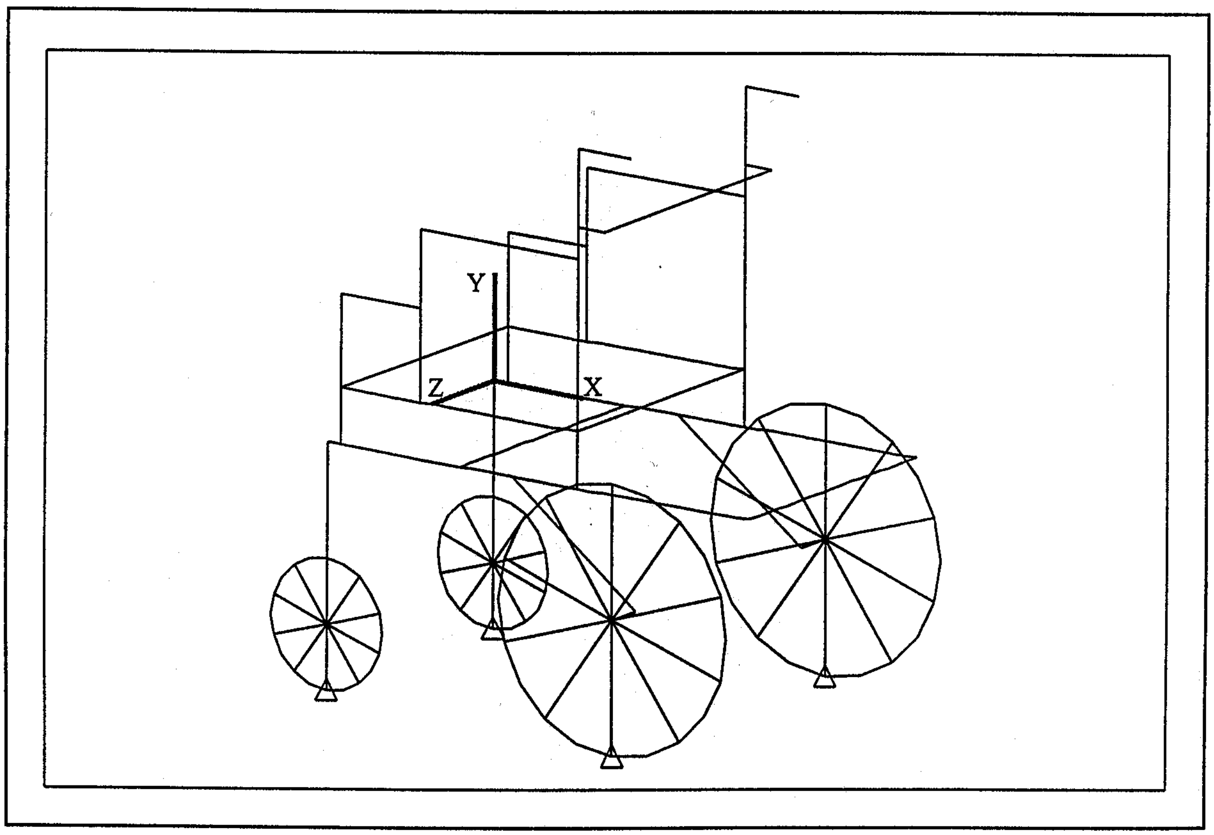

Figure 3: Conventional Powered Wheelchair Model

Combined Wheelchair/Anthropometric Model Modal Analysis Results:

Table 2. Combined Wheelchair/Anthropometric Model Modal Analysis Results

MODE NUMBER	FREQUENCY (r/s)	FREQUENCY (Hz)
1	6.22	0.99
2	6.29	1.00
3	18.53	2.95
4	19.82	3.12
5	20.86	3.22
6	26.85	4.27

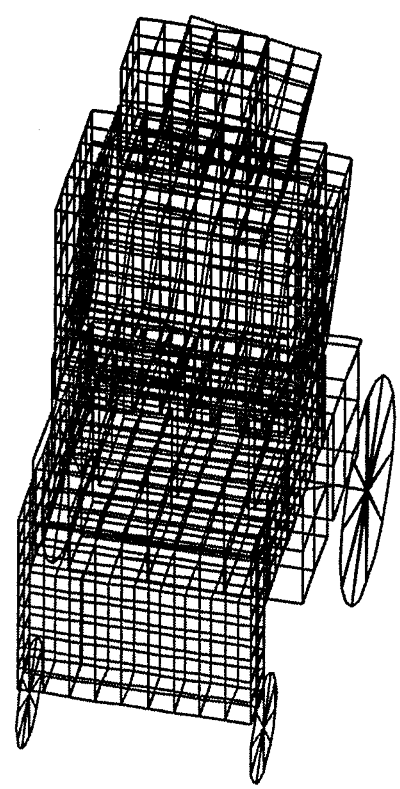

Figure 4: **Conventional Powered Wheelchair Model, Sample Modal Analysis Result Mode 1: 0.99 Hz**

Three-wheeled Scooter Model Data:
(see Figure 5 for reference point location and reference axis orientation)

Three-wheeled Scooter Model Weight: 118 lb

Centre of Gravity Location:	X-direction: 27.4 ins.	
	Y-direction: 4.0 ins.	
	Z-direction: 11.8 ins.	
Mass Moment of Inertia:	Ixx: 79.5 ins^4	
	Iyy: 342.7 ins^4	
	Izz: 311.5 ins^4	

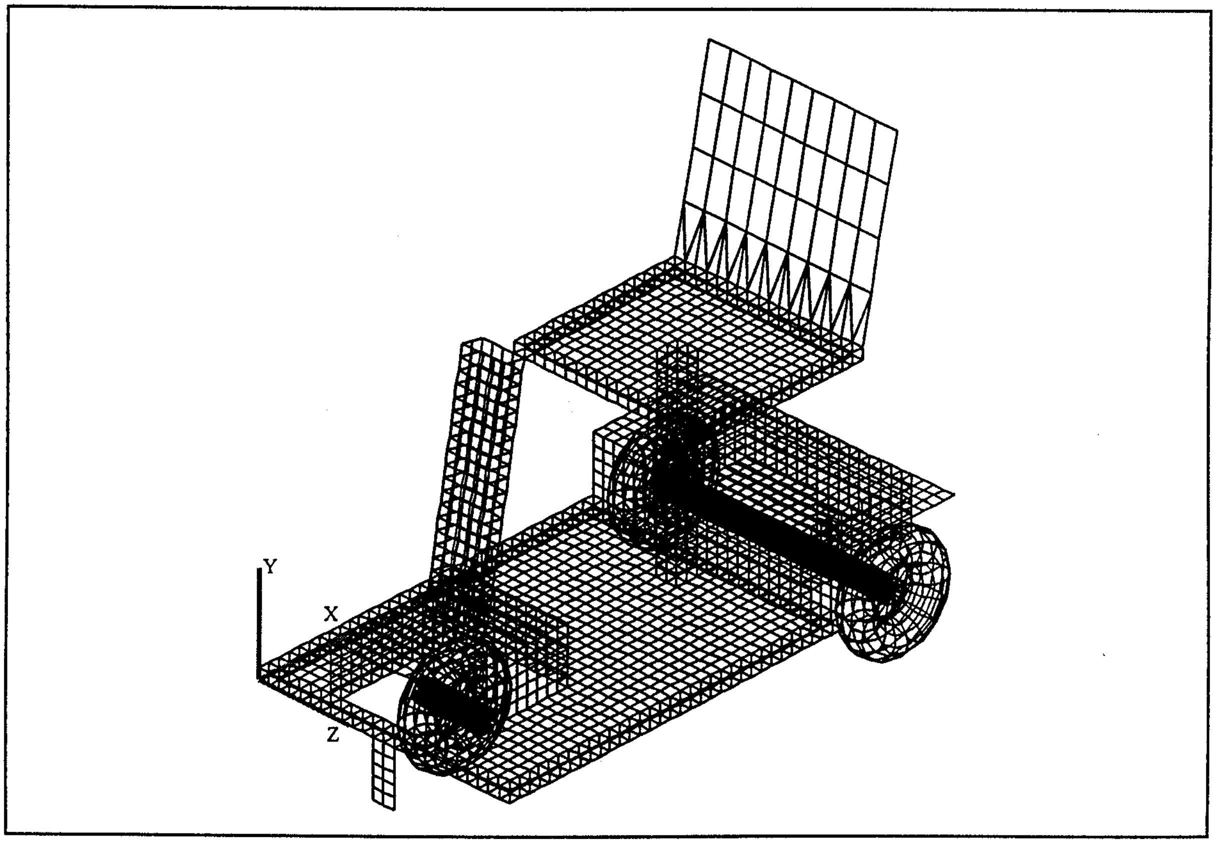

Figure 5: Three-wheeled Scooter Model

Combined Scooter/Anthropometric Human Model Modal Analysis Results:

Table 3. Combined Scooter/Anthropometric Human Model Modal Analysis Results

MODE NUMBER	FREQUENCY (r/s)	FREQUENCY (Hz)
1	4.93	0.78
2	5.01	0.80
3	14.91	2.37
4	15.00	2.39
5	19.12	3.04
6	22.22	3.54

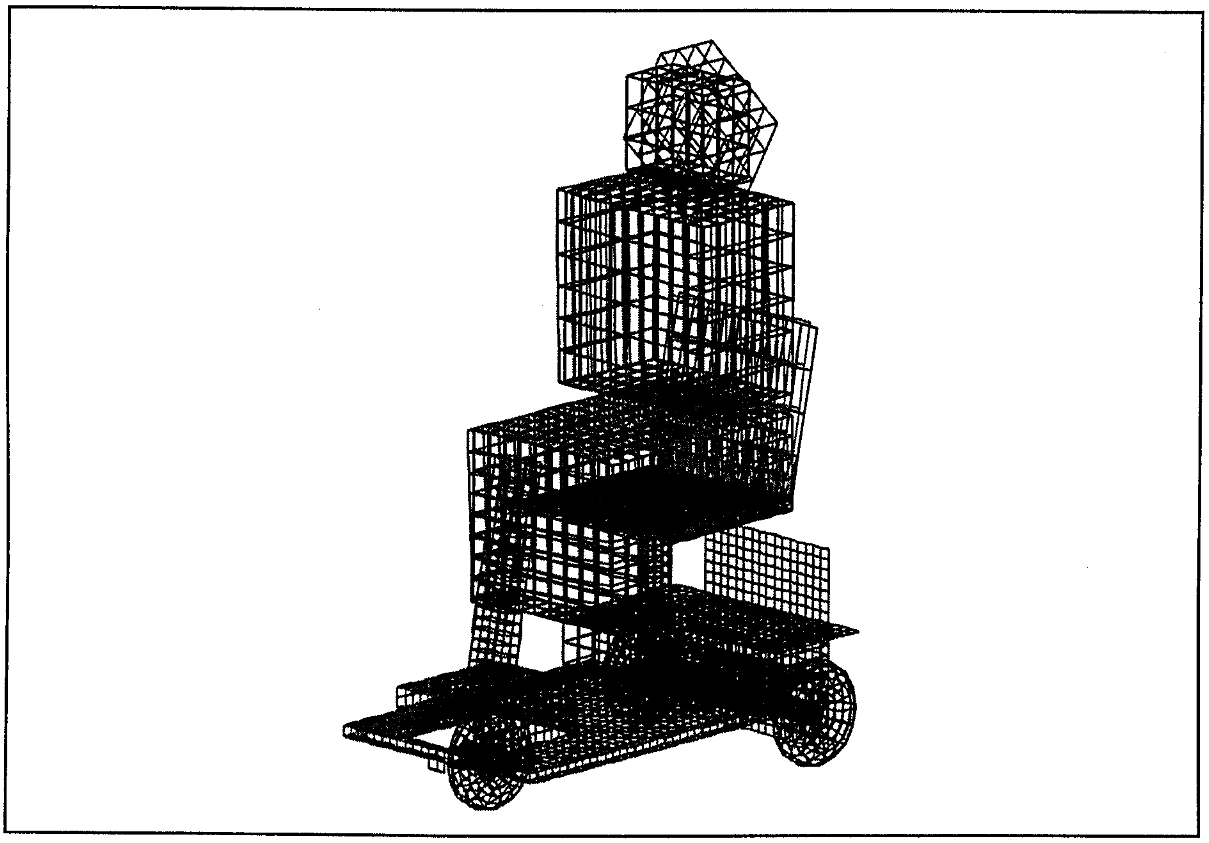

Figure 6: Scooter Model, Sample Modal Analysis Result
Mode 4: 2.69 Hz

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Fredericton, New Brunswick, Canada
F. Hawkins, Operations Supervisor
(506) 454-6287

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F. Henderson, Director of Transportation
(506) 658-4710

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St. John's, Newfoundland, Canada
W. Thistle, General Manager
(709) 570-2130

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Community Services Dept., City of Sudbury
Sudbury, Ontario, Canada
G. Valinquette, General Manager
(705) 675-3333

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Department of Administration and Transit
Kitchener, Ontario, Canada
W. Beck
(519) 741-2560

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Thunder Bay, Ontario, Canada
A. J. Grant, Transit Manager
(807) 684-2188

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Ajax, Ontario, Canada
T. Barnett, Director of Transit
(905) 427-5710

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City of Barrie
Barrie, Ontario, Canada
G. Kaveckas
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Brampton, Ontario, Canada
G. Marshall, Director of Transit
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11 Brantford Transit
Brantford, Ontario, Canada
R. Pain, Supervisor of Motor Vehicles
(519) 753-7391

12 Burlington Transit
City of Burlington, Transit & Traffic Dept.
Burlington, Ontario, Canada
V. Mauceri, Director of Transit and Traffic
(905) 335-7763

13 Cambridge Transit
Community Services Dept., Corporation of City of Cambridge
Cambridge, Ontario, Canada
G. Stockford, Transit Manager
(519) 740-4633

14 Cornwall Transit
Cornwall, Ontario, Canada
S. Goodwin, Transit Manager
(613) 930-2636

15 GO Transit
Toronto, Ontario, Canada
R. McKenzie
(416) 638-7411

16 Guelph Transit
Guelph, Ontario, Canada
R. W. Coghill, General Manager
(519) 822-1811

17 Edmonton Transit
Edmonton, Alberta, Canada
D. Nowicki, Director of Custom Transportation Services
(403) 496-4553

18 BC Transit
Victoria, British Columbia, Canada
A. Little
(604) 385-2551

PROVINCIAL LEGISLATORS CONTACTED

1 Halifax, Nova Scotia
Public Utility Board,
Public Passenger Division
(902) 424-4448

2 Fredericton, New Brunswick
Public Transit Policy Branch
(506) 453-2802

3 Newfoundland
Work Services and Transportation
(709) 729-2519

4 Ontario, Ministry of Transportation
Downsview, Ontario
(416) 235-4013