AN ABSTRACT OF THE THESIS OF

Andrea Mather for the degree of Master of Science in Civil Engineering presented on March 9, 2016.

Title: Wheeled Mobility Devices Performance and Passive Securement Systems

Abstract approved:

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Wheeled mobility devices (WhMD) pose unique safety risks to users while riding public transportation. Unsecured or improperly secured WhMDs create safety concerns for other transit riders and operators. Tests using accelerometers and visual observations were conducted to understand how WhMD orientation and securement in articulated buses, streetcars, and light rail vehicles. These tests used manual wheelchairs and lightweight scooters. The rail study focuses on WhMD orientation. The rail research activity determined that longitudinal and side facing orientation for WhMD performed similarly but due to other on board safety factors longitudinal is the safer option. The bus study focused on the combination of vertical and horizontal roadway curvature and the effect on a rear facing passive containment system. The research determined that the passive rear facing containment system was appropriate when drivers maintained trained operating speed or lower while traversing the complex curvature.

Wheeled Mobility Devices Performance and Passive Securement Systems

by

Andrea Mather

A THESIS

submitted to

Oregon State University

in partial fulfillment of

the requirements for the

degree of

Master of Science

Presented **March 9th 2016**

Commencement June 2016

Master of Science thesis of Andrea Mather presented on March 9, 2016

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Andrea Mather, Author

ACKNOWLEDGEMENTS

The author expresses sincere appreciation to her advisor Dr. Katharine Hunter-Zaworski for all her unwavering support and guidance through professional and personal decisions. The author would like to thank the Graduate School Oregon State University for a scholarship during her research work. In addition, the author would like to thank the School of Civil and Construction Engineering and the Richard and Lilo Smith Fellowship for allowing the author to focus on the research. Furthermore, the author would like to thank the entire committee for their time and patience. The author would also like to thank her amazing parents and family without their love and support this thesis would not be possible. This thesis would not be possible without the support of the transportation cohort at Oregon State University. Through tears and laughs, we support everyone. In conclusion, the author would like to thank all of her non-transportation engineering friends would had to hear about this thesis for two long years and providing a needed balance in her life.

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Chapter 1: Introduction

Public transportation is an integral element of the transportation system in the United States. As cities grow and become increasingly dense, public transportation is becoming a key element of the transportation system. Not every person has the ability to choose from all modes of transportation when making a trip. Many Americans who use wheeled mobility devices (WhMD) are limited to rely on caregivers, paratransit, and public transportation services. If a person chooses to use public transportation there may be additional barriers that include; access to the stop or station, access to the transit vehicle, and securement of the WhMD. The focus of this research is the securement and/or containment of WhMDs on large transit buses, light rail vehicles, and streetcar vehicles.

This document is organized into four chapters including an introduction, two research papers, and a general conclusion. Chapter 1 includes an introduction on public transportation, motivation for the research, and testing. Chapter 2 is the first research paper and focuses on the securement and orientation of WhMDs on light rail and streetcar vehicles. Chapter 3 is the second research paper and focuses on passive securement on large transit buses. Chapter 4 includes the overall conclusions and recommendations from this research.

Background

According to American Public Transportation Association (APTA), public transportation "is transportation by conveyance that provides regular and continuing general or special transportation to the public, but not including school buses, charter or sightseeing service (Fact Book Glossary, 2015)." Terms that are also used to describe public transit are transit, public transit, and mass transit. Public transportation may be referred to by any of these terms. The services are generally funded publicly but not exclusively. The primary object for public transportation is to move people. Public transportation is designed and operated with a spectrum of vehicle and system types. Passenger volume and land use are typically used to make decisions on modes and operation of public transit services.

Transit Usage

The collection of transit ridership data started in the United States in the early 20th century. The decade following World War II saw the highest number transit riders with the highest occurring in 1946 with 23.5 billion trips when car ownership was low (Ridership Report Archives, 2015). For the last fifty years, the mode shift to personal vehicles has occurred. In the period from 1995-2013 transit, ridership in the United States grew by over 37% (Miller, 2015). In 2014, 10.8 billion trips were completed using public transportation that was an increase from 10.7 billion in 2013 and this was the largest number of trips in 58 years (since 1956) (Miller, 2015, Public Transportation Use is Growing, 2014).

The graph in Figure 1 shows the ridership data collected by APTA from 1990-2014 (this data includes all modes of transit) (Ridership Report Archives, 2015). The data shows the overall increase of ridership since the early 1990’s.

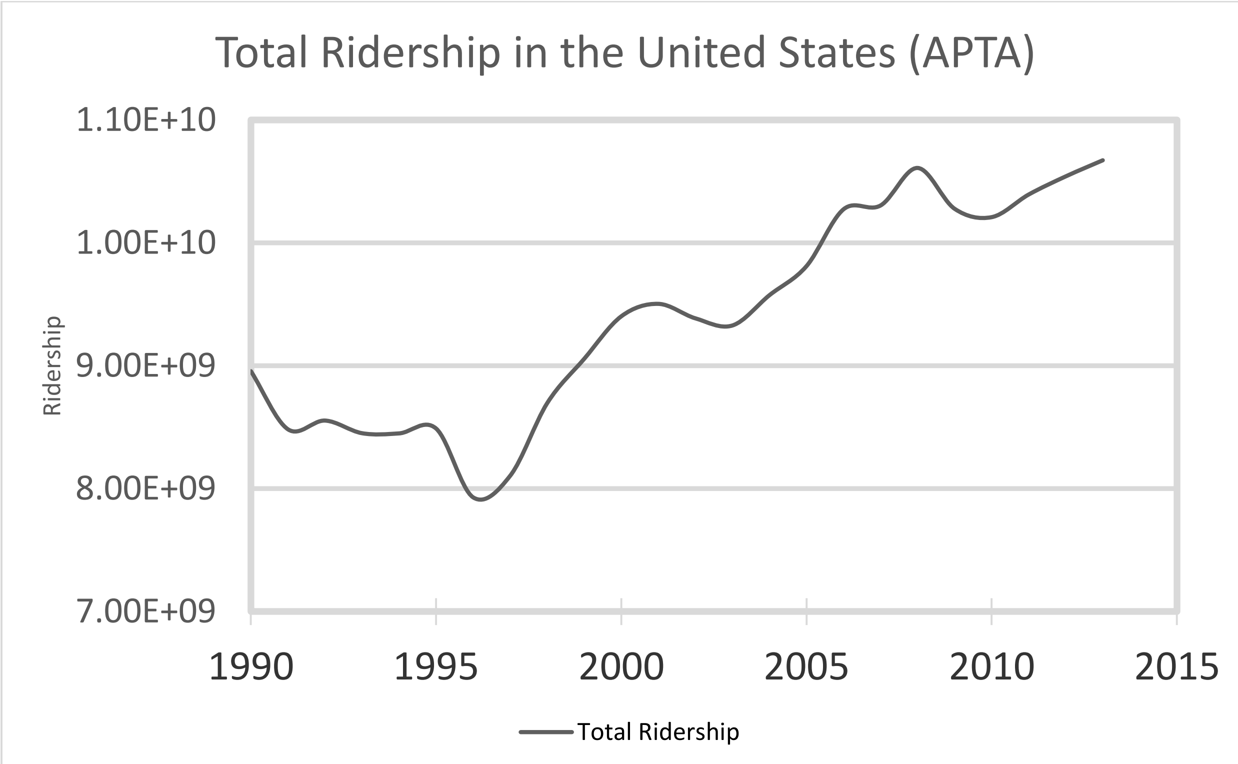

Figure 1 *Ridership data since 1990 (Ridership Report Archives, 2015)*

Another contributing factor to the rate of transit usage is the Millennial Generation and their transportation preferences. This generation (born 1982-2003) is using transit in greater numbers than previous generations. In 2013, APTA released a study about the Millennial Generation and their transportation preferences (APTA, 2013). The study found that Millennials choose the "best" mode of transportation for the trip, and, value living in locations that have many transportation options (APTA, 2013). Ridership is also increasing because of the fluctuation in fuel prices and demographic shifts to urban centers (APTA, 2013).

The use of wheelchairs and other WhMDs has also increased in recent years. During the years from 2005 to 2010, a 12.5% increase in wheelchair use occurred in the United State for people over the age of 15 (Brault 2008, Brault 2012). Looking at future trend analysis shows that an approximant 5% growth of WhMD is predicted (LaPlante and Kaya, 2010). The combination of increasing overall transit and WhMD usage creates the growing need to use space onboard transit vehicles as efficiently as possible.

Transit Users

The consumers of transit can be broken into two distinctive groups: choice riders and non-choice riders. Choice riders have to ability to use other modes of transportation but choose to ride transit. This choice may by driven by cost of other modes and the ability to save money, travel time and reliability, stress reduction during commuting at peak hours, environmental concerns with private vehicles and many others (TCRP 165, 2013). A large group of choice riders is commuters using transit during peak hours to travel from home to work. These riders are reflected in large metro areas and the design of the transit systems is to provide service from the suburban areas to the central business districts or downtowns. For example, in Portland, Oregon, each of the lines in the MAX light rail transit system connects a suburban area to the downtown area. If the primary goal of the transit system is to reduce future peak hour trips on major arterials, then choice riders are the target rider group (TCRP 165, 2013).

Non-choice or transit dependent riders do not have the ability to use another mode of transportation independently. These riders are dependent on transit for several reasons including but not limited to: age, mental limitations, physical limitation, or financial limitations (TCRP 165, 2013). Choice riders may use transit for some or all of their trips. For example, a person may walk or bike for short trips and use transit for long trips. Others use transit for nearly all trips. Typically, transit dependent riders are smaller transit agencies' principle rider (TCRP 165, 2013). The research completed in Chapters 2 and 3 focuses on non-choice riders. Typically, people who use WhMDs fall into the non-choice rider category.

Project Goals

The overall goal of the project, described in this report, is to analyze securement systems on transit vehicles using acceleration data and visual observations. The goal for the rail transit subproject is to study the orientation of the WhMD within the area assigned to WhMDs, and to make recommendations to the rail transit provider. The goal for the large articulated transit bus subproject is to analysis the passive containment system during extreme cornering and curvature.

Study Scope and Limitations

The available resources of the cooperating transit agencies set the scope of the studies reported in this thesis. The study reported in Chapter 2 was motivated by TriMet and included testing of their new vehicles and test track. The researchers had limited time with the vehicles and agency personnel and focused primary on braking conditions. Lane Transit District (LTD) provided the motivation for the research in Chapter 3. This research focuses on large transit buses and the use of rear facing passive containment systems for WhMDs. The availability of vehicles, and staff time limited the scope of the research. Only one securement system, one bus type, and two WhMDs were used in the testing. Crash testing was not included in any of the testing and all testing had to be performed in safe conditions.

Contributions

This research highlights the contributions made by each paper. The contributions made by the research in Chapter 2 is the first to document the relationship between WhMD orientation and brake testing on light rail and streetcar vehicles. This testing confirmed the assumption that the securement of WhMD is not required on these rail transit vehicles and created starting point for additional research on side facing orientation for WhMDs. The research reported in Chapter 3 adds to the knowledge on the use of rear facing passive containment systems on large transit buses. Prior research had been conducted on small transit vehicles and the securement of WhMDs but very limited research has been performed on large transit buses and the use of passive containment systems. Specify the contributions included the recommendation for the continued use of passive rear facing containment systems on large transit buses and additional research into the relationship of driver behavior and acceleration.

Transit System Types

There are many different types of public transportation agencies in the United States. There are two main categories of transit services: rubber tire (buses) and steel tire (trains). Each type of public transportation service type will serve the community in a different way. A highly urbanized area with a strong concentration of jobs in a downtown or central business district will likely be best served by a commuter rail, heavy rail, and/or light rail system. These systems have the capacity to service the largest number of people during peak periods however they also have large capital costs (TCRP 165, 2013). A smaller populated area may use a fixed route bus service. This has the ability to serve a large area without having the large capital costs. Many transit agencies operate a mix of service types. For example, in the Portland, Oregon metropolitan area, the transit agency TriMet operates commuter rail, light rail, streetcar, fixed route bus, and paratransit.

Characteristics of Rail Transit (Steel Tire)

Rail transit systems are characterized by a vehicle with steel tires operating on rails within a metropolitan area. According to the Transit Capacity and Quality Services Manual, intercity passenger service such as Amtrak is not included as a rail transit mode. The vast majority of systems in North America use two guidance rails and steel tire vehicles. The four main types of steel tire transit are heavy rail, light rail/streetcar, commuter rail, and automated guideway transit. The table below includes the definitions of these service types.

Table 1 *Steel Tire transit types defined by National Transit Datebase (National Transit Data Base, 2015)*

System Type	Mode Definition	Example
Heavy Rail	A transit mode that is an electric railway with the capacity for a heavy volume of traffic. It is characterized by: • High speed and rapid acceleration passenger rail cars operating singly or in multi-car trains on fixed rails • Separate rights-of-way (ROW) from which all other vehicular and foot traffic are excluded • Sophisticated signaling • Raised platform loading	Bay Area Rapid Transit (BART), San Francisco, CA
Commuter Rail	A transit mode that is an electric or diesel propelled railway for urban passenger train service consisting of local short distance travel operating between a central city and adjacent suburbs. Service must be operated on a regular basis by or under contract with a transit operator for the purpose of transporting passengers within urbanized areas (UZAs), or between urbanized areas and outlying areas. Such rail service, using either locomotive hauled or self-propelled railroad passenger cars, is generally characterized by: • Multi-trip tickets • Specific station to station fares • Railroad employment practices • Usually only one or two stations in the central business district	CalTrain, California
Light Rail (LRT)	A transit mode that is typically an electric railway with a light volume traffic capacity compared to heavy rail (HR). It is characterized by: • Passenger rail cars operating singly (or in short, usually two car, trains) on fixed rails in shared or exclusive right-of-way (ROW) • Low or high platform loading • Vehicle power drawn from an overhead electric line	TriMet MAX, Portland, OR
Streetcar	This mode is for rail transit systems operating entire routes predominantly on streets in mixed-traffic. This service typically operates with single-car trains powered by overhead catenaries and with frequent stops.	Portland Streetcar, Portland, OR
Monorail/ Automated Guideway	Monorail and Automated Guideway modes operate on excusive guideway without using steel wheels on rails.	Disneyland Monorail, Anaheim, CA

The number of cars that can operate as a train determines the flexibly in a rail transit system. Many systems operate single cars or married pairs of cars as a train. Rail transit systems have three primary power sources: electrified third rail, electrified overhead catenary, and diesel. Heavy rail most often uses an electrified third rail and is fully separated. The entire system operates on exclusive right-of-way due to the safety risks with the electrified third rail. Light rail and streetcar systems commonly use overhead electrical wires and vehicles catenaries. The overhead wires supply current to the vehicle. The overhead wires are safe for other modes to operate below and do not pose the same safety risks as an electrified third rail.

In the United States, diesel power is most commonly used by commuter rail systems. Commuter rail systems usually share track with freight rail and the trip length is much longer than urban rail transit. A few commuter rail systems are electrified in the United States (TCRP 165).

Characteristics of Buses (Rubber Tire)

Bus service is the most common public transit service in the United States and in 2011 accounted for 52% of all transit trips (TCRP 165, 2013). According to the Transit Capacity and Quality of Service Manual, “The bus mode is highly flexible in that service can be provided by many different types of vehicles, can operate on many different types of rights-of-way, and can implement a variety of stopping patterns (TCRP 165, 2013).” Bus transit includes rubber tire vehicles operating on paved roadways. Bus rapid transit, fixed route, and demand responsive transit are the three main bus service types. Definitions for these modes from the National Transit Database are below in Table 2. Other bus transit modes are electric trolleybus and commuter bus.

Table 2 *Rubber Tire transit types defined by National Transit Datebase (National Transit Data Base, 2015)*

System Type	Mode Definition	Example
Bus Rapid Transit (BRT)	Fixed-route bus mode: • In which the majority of each line operates in a separated right-of-way dedicated for public transportation use during peak periods; and • That includes features that emulate the services provided by rail fixed guideway public transportation systems, including: • Defined stations o Traffic signal priority for public transportation vehicles • Short headway bidirectional services for a substantial part of weekdays and weekend days • Pre-board ticketing, platform level boarding, and separate branding This mode may include portions of service that are fixed-guideway and non-fixed-guideway.	LTD EMX, Eugene, OR
Fixed Route	Services provided on a repetitive, fixed schedule basis along a specific route with vehicles stopping to pick up and deliver passengers to specific locations; each fixed route trip serves the same origins and destinations, such as rail and bus (MB); unlike demand responsive (DR) and vanpool (VP) services	Corvallis Transit Service (CTS), Corvallis, OR
Demand Responsive	A transit mode comprised of automobiles, vans or small buses operating in response to calls from passengers or their agents to the transit operator, who then dispatches a vehicle to pick up the passengers and transport them to their destinations. A demand response (DR) operation is characterized by the following: • The vehicles do not operate over a fixed route or on a fixed schedule except, perhaps, on a temporary basis to satisfy a special need; and • Typically, the vehicle may be dispatched to pick up several passengers at different pick-up points before taking them to their respective destinations and may even be interrupted en route to these destinations to pick up other passengers.	Dial-a-Bus Services, Benton County, OR

Bus transit service types can interact with each other and the vehicles can move seamlessly between different operating regimes. Bus service modes can easily be mixed throughout a system. For example, most cities that have bus rapid transit also have fixed route service. Buses operate on roadways with varies types of rights-of-way. Most bus services, fixed route and demand responsive, operate on mixed right-of-way with other vehicles. There may be transit preference infrastructure such as signal timing and bus lanes. One of the key principles for bus rapid transit systems is the inclusion of exclusive right-of-way.

Bus transit vehicles range in size from small passenger vans and minibuses, to standard buses and on up to large articulated buses that are matched to service type. Paratransit and rural transit services may use minibuses and a large city transit system will operate articulated buses or double decker buses to transport the maximum number of passengers. In addition, many transit systems operation multiple types of vehicles. For example, Lane Transit District operates standard 40-foot buses for most routes and large 60-foot articulated bus for other routes including a bus rapid transit system. These buses interface at transit centers and are maintained at a single location with similar infrastructure. Most transit buses are diesel, gas or alternative fuels powered. A few transit systems still operate trolley buses, rubber tired buses, with overhead power systems.

American's with Disabilities Act (ADA)

The American's with Disabilities Act of 1990 is a federal law in the United States. This civil rights legislation "prohibits discrimination and guarantees that people with disabilities have the same opportunities as everyone else to participate in the mainstream of American life -- to enjoy employment opportunities, to purchase goods and services, and to participate in State and local government programs and services (American's With Disabilities Act Accessibility Specifications for Transportation, 1998)." This law has influenced the design of both steel and rubber tire vehicles.

The National Transit Database defines an ADA accessible vehicle as "Public transportation revenue vehicles which, in compliance with ADA requirements, do not restrict access, are usable, and provide allocated space and/or priority seating for individuals who use wheelchairs, and are accessible using lifts or ramps (National Transit Data Base, 2015)."

Wheeled Mobility Devices (WhMD)

The Federal Transit Admiration defines wheelchairs in Section 37.3 of the United States Department of Transportation regulations for implementing ADA as "a mobility aid belonging to any class of three- or more-wheeled devices, usable indoors, designed or modified for and used by individuals with mobility impairments, whether operated manually or powered (American's With Disabilities Act Accessibility Specifications for Transportation, 1998)." For this research, the expanded definition of a WhMD is used. According to the Transit Cooperative Research Program (TCRP) Report 171 Use of Mobility Devices on Paratransit Vehicles and Buses, WhMDs are "wheeled mobility devices, also referred to as mobility device, and include manual wheelchairs, three and four wheeled scooters, power wheeled mobility devices, walkers, and other wheeled devices such as the Segway®. Of primary concern are manual, power wheelchairs and mobility scooters (TCRP 171, 2014)." Each of these devices have unique characteristics and properties. Below are the definitions for the TCRP 171:

> *Manual Wheelchairs*
> Manual chairs were the most common mobility devices in the past decades. They are light, some are foldable, have large rear wheels, small front casters, and are still mainly used by persons with strong arms to propel themselves. They have push bars at the rear for those occupants who cannot propel themselves and are pushed by another person, typically in hospitals, transportation terminals, and institutional places. The "common manual wheelchair," measuring 25 in. wide and 42 in. long when occupied, was for many years used as a base for regulations and standards with a recommended footprint of 30 in. × 48 in. and a turning radius of 36 in. With the advent of making private and public transportation accessible, systems were developed to secure the wheelchair to vehicles, mainly by tie-downs to prevent forward and rearward movement. These were rated for an acceleration of 20 g which corresponds to a force of 20 times the weight of the chair. Most wheelchair frames are not strong enough to withstand these acceleration forces without proper structural integrity and attachment points for securement systems. (TCRP 171, 2014)

Scooters
Indoor 3- and 4-wheeled scooters typically have small wheels, and their narrow width (usually about 20 in.) makes them more prone to tipping. However, these devices often are used in environments that they are not designed for and as a result tip over. These scooters should never be occupied during transport, and they are not equipped with designated attachment points as specified by WC-19. Oversized 3-wheel scooters have been developed for the outdoor environments. These devices have three large wheels and can be powered by batteries or gas engines. The may measure from 49 to 54 in. or longer and can also weigh over 200 lbs. With their size, weight, and turning radius of 70 in. they cannot generally be accommodated onboard public transportation vehicles. (TCRP 171, 2014)

Power Wheelchairs
Power wheelchairs are powered by batteries and operated by joysticks or other control means. They may have special postural control systems or cushioned seats and back, a headrest, and padded armrests. These devices typically measure about 25 in. wide by 38 to 43 in. long, and can weigh up to 300 or even 400 pounds depending on their power pack and accessories. They are usually very nimble and have a small turning radius of about 28 in., and their footprint can easily be accommodated on public transportation vehicles, provided the user is capable of maneuvering in and out of their position on-board a vehicle. Some manufacturers are complying with WC-19 to equip these chairs with attachment points for securement. In addition there are powered chairs with added features to tilt the chair and also provide extended leg and upper body supports. As a result of the additional features these chairs can vary in length and weight, and can easily exceed the standard foot print of 30 × 48 in., thus making transport on public vehicles difficult. (TCRP 171, 2014)

Other mobility devices such as crutches, oversize versions of WhMDs and guide dogs. These devices are used by passengers on transit vehicle but were not included in this research.

Securement Systems

The Americans with Disabilities Act (ADA) transportation regulations require some transit vehicles to have securement/containment systems on the vehicle. ADA compliant buses over 22 feet in length must have 2 securement areas per ADA regulations (American's With Disabilities Act Accessibility Specifications for Transportation, 1998). On light rail vehicles, ADA requirements are for clear floor space for WhMDs but there are "no requirements for securement systems or tie down devices (Questions and Answers Concerning Wheelchairs and Bus and Rail Services, 2013).” ADA does not require any person to use the provided securement or containment system on vehicles where other passengers do not have use securement systems. For example, if seatbelts are required for all passengers then, the passenger restraint and securement system must be used.

There are two groups of securement/containment systems for large transit bus: active and passive systems. Active systems use belts or straps to secure the WhMD. Additional passenger restraint systems may be used to secure the person (seatbelts). Passive or containment systems are typically rear facing and located longitudinally in reference to the bus centerline. The key terms related to WhMD securement from TCRP 171 are below:

Footprint: the static two-dimensional area occupied by a wheeled mobility device (TCRP 171, 2014).

Forward-facing securement: Securement of wheelchairs facing forward in the driving direction of the vehicle (TCRP 171, 2014).

Rear-facing containment/securement: An area in a vehicle where the passenger in a wheeled mobility device travels facing rearward or backwards from the direction of travel (TCRP 171, 2014).

Tie-down: Belts/straps to be used to attached to a mobility device and the vehicle floor to prevent the mobility device from moving (TCRP 171, 2014).

Examples of active and passive systems on buses are shown the in figure 2 below. The active system includes the four straps that attach to the WhMD. The passive system has an aisle side bar that creates a containment area. Active systems on buses are generally forward facing and passive systems are rear facing.

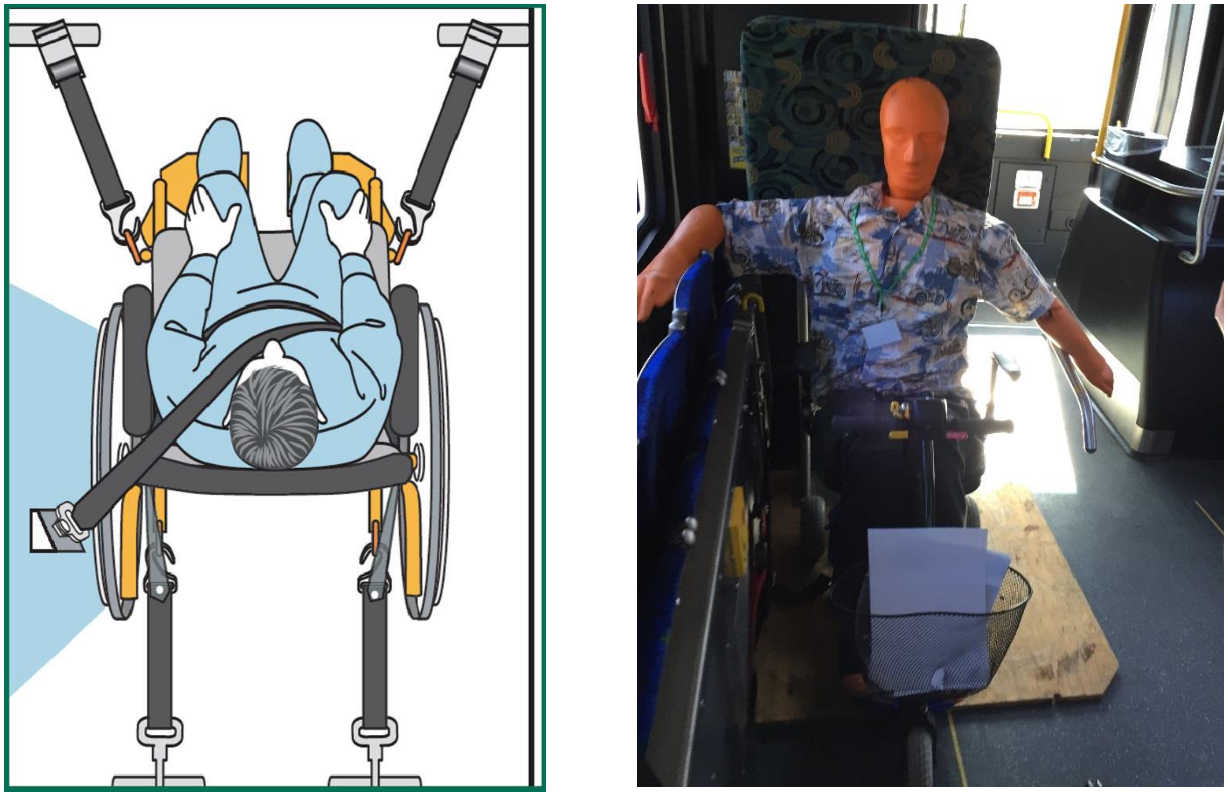

Figure 2 *Right- Forward facing wheelchair tiedown with occupant restraint (Ride Safe University of Michigan, 2015). Left- Passive rear facing WhMD containment (Lane Transit District)*

Over the past twenty years, active tie-down systems have been the most popular on large transit vehicles. Recent research shows that there is a large amount of misuse of the active system by people using WhMDs (Frost et. all, 2008). During a study of over 200 WhMD trips, over 70% of wheelchair users did not use any straps to secure their WhMD (Frost et. all, 2008). This causes safety risks to all passengers on board the vehicle.

Figure 3 illustrates the different orientations on light rail vehicles. The WhMD can with be in line with driver (longitudinal) or perpendicular to the driver (side facing). In addition to the orientation, the pictures show the footprint and the clear space on the vehicle for the WhMD. The pictures were taken during testing at TriMet for the study in Chapter 2.

Figure 3 *WhMD on light rail vehicle showing orientation of WhMD and floor space*

Introduction to Testing

Testing was conducted at four locations within Oregon using three vehicle and systems types. The locations included two in the Portland metropolitan area and two in the Eugene/Springfield metropolitan area. The vehicles included a streetcar, light rail train and articulated bus.

Locations

Locations for testing included the United Streetcar Test Track (Clackamas, OR), TriMet Test Track (Gresham, OR) and Lane Transit District (Eugene, OR). Testing of the streetcar occurred at the United Streetcar test track location in Clackamas, Oregon. The test track included tangent sections and highly curved sections. The streetcar vehicle operated bi-directionally on the test track.

Testing at TriMet occurred at the Ruby Junction Yard test track in Gresham, OR. This track is part of the eastside maintenance facility for the TriMet's MAX system. The facility includes two level 900 ft. tangent sections and two curved sections as well as access to the main MAX line. The test track also includes access to the maintenance and train storage facilities.

Two different locations were used during the testing at Lane Transit District (LTD). The first location was the flat maintenance parking lot at the headquarters of LTD in Springfield, Oregon. The maintenance facility served as the testing location for the isolated horizontal curves. Additionally, roadways in the Eugene/Springfield area were used. These roadways are streets that are used for fixed route revenue service and include different roadway classifications ranging from local streets to freeways.

Vehicles

Three different vehicles were used for the testing; streetcar, light rail vehicle, and articulated bus. A streetcar is a steel tired vehicle that operates in shared right-of-way. Streetcars operate in mixed traffic on two guidance rails that are placed on the street. Streetcars are single unit vehicles often with an articulation point. Electric power from overhead catenary lines are typically used to power the vehicles. The Portland Streetcars have a capacity of 156 passengers and feature a fully accessible low floor center section (City of Portland, 2014). The Portland Streetcar is approximately 8 feet wide and 66 feet long (City of Portland, 2014). This is almost a foot narrower and a third of the length of the standard TriMet MAX configuration.

Electric catenary overhead lines power the MAX light rail vehicles. Configurations of the light rail trains include a married pair of two vehicles. The light rail system operates in mixed traffic in the downtown core area and on exclusive right-of-way in most of the other sections. For the TriMet light rail vehicles, the passenger capacity depends on the age or generation of vehicle but most married pairs can carry over 300 passengers (TriMet Community Affairs). TriMet features one of shortest total train lengths of light rail vehicles due to the small block lengths in the downtown Portland area.

Large articulated transit buses are diesel powered rubber tire vehicles that operate on the streets or on bus rapid transit right-of-way that is more exclusive. The articulated buses are “extra-long (54 ft. to 60 ft.) buses with two connected passenger compartments. The rear body section is connected to the main body by a joint mechanism that allows the vehicle to bend when in operation for sharp turn and curves and yet have a continuous interior (National Transit Data Base, 2015). The buses used in the tests were the new EMX buses that feature low floor boarding (no stairs). The bus has several access points and a figure of the bus can be found in Chapter 3.

Personnel

For all testing Dr. Hunter-Zaworski was present along with a group of graduate researchers. Dr. Hunter-Zaworski and the graduate researchers performed visual observations as well as managed the accelerometers. At each test location, representatives from the company or agency were present for testing. For example, during the testing at Lane Transit District (LTD) representatives from the risk management group were present for all tests. The operator of the vehicle during each and all of the tests was an employee of the agency or company. This ranged from vehicle mechanics to drivers of revenue service routes.

Equipment

Gulf Coast Data Concepts Model X2-2 USB Accelerometers were used to collect acceleration data though out the process. Two accelerometers were calibrated and tested before data collection. Using two accelerometers for each tests insured that the collection of data occurred. The accelerometers collect data in 3-axis direction axial, longitudinal, and vertical. The sample rate varied throughout the tests. For the steel tire (streetcar and light rail) tests, the sample rate was 100 Hz. For the rubber tire tests (large articulated bus) tests the sample rate was 32 Hz. For all the tests, the accelerometers were placed on the floor of the vehicle parallel to the center line of the vehicle and in line with the direction of travel.

In some of the tests, a video camera was used to record videos and take pictures of the devices. Testing on the light rail vehicle at TriMet included the use of video cameras. At LTD, no video recording was conducted however still pictures were taken for reference of movement.

The research team and agency/company personnel conducted visual observations during testing. This included multiple viewpoint and angles of the WhMD. Records were kept during of the testing of the visual observations, vehicle attributes, and driver characteristics.

Chapter 2: Investigation of wheeled mobility device orientation and movement on streetcars and light rail vehicles during normal and emergency braking.

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Journal of Public Transportation

National Center for Transit Research

Center for Urban Transportation Research

College of Engineering

University of South Florida

4202 East Fowler Avenue, CUT100

Tampa, FL 33620-5375

Abstract

Wheeled mobility devices have been accessing public transit vehicles for decades, and most new rail transit systems are accessible. This has increased ridership by people with disabilities. Side facing orientation on rail transit vehicles has been suggested as an option to increase capacity for wheeled mobility devices. This paper reports findings of a study of vehicle dynamics and wheeled mobility device orientation on rail transit vehicles. This study used acceleration data and field observations to evaluate wheeled mobility devices in longitudinal and side facing orientation on streetcar and light rail vehicles. Results from the study include the recommendations for longitudinal orientated areas for wheeled mobility devices as well as additional public outreach on best practices for passengers who use wheeled mobility devices on rail transit vehicles.

Keywords: Wheeled mobility device, orientation, rail transit vehicle dynamics

Introduction

The study examined the movement of occupied wheeled mobility devices (WhMD) in two different orientations during the routine and emergency braking regimes of streetcars and light rail vehicles. The research questions that were addressed:

> (i) Do occupied wheeled mobility devices require securement or containment on streetcars or light rail vehicles that operate in traffic?
>
> (ii) Is side facing orientation an option for occupied wheeled mobility aids on streetcars or light rail vehicles?

Background

The braking regimes of streetcars and light rail transit vehicles are specified by the transit industry and transit agency standards (APTA, 2013 and German Institute for Standardization, 2015). These regimes are tested routinely as part of the acceptance procedures of new transit vehicles. The research reported in this paper evaluated the movement of occupied wheeled mobility devices in longitudinal and side facing orientations during normal, emergency and panic braking regimes on new streetcar and light rail vehicles on rail test tracks.

The term longitudinal seating describes both forward and rear facing seating orientation. The research team used the same procedures that were used for vehicle dynamics tests of small and large transit buses (Hunter-Zaworski and Zaworski, 2009, Hunter-Zaworski, 2009, and Zaworski et al 2007). There have been studies that have related acceleration and braking as a measure of passenger ride comfort on rubber tired vehicles but, to date none have been reported on rail transit vehicles.

Rail transit vehicle acceleration is controlled by the vehicle's electrical system. The acceleration regime parameters are specified by the operating transit agency during vehicle procurement. Rail transit vehicle acceleration for streetcars and street running light rail transit (LRT) vehicles are very low and are not of concern for this study. Rail transit vehicle braking is the focus of this study. Hoberock was the first to study transit vehicle braking behavior. The braking behavior, characterized by deceleration rate and jerk, and are used as a measure of ride comfort (Hoberock, 1976). Jerk is the rate of change of acceleration. There are significant differences in the level of tolerance between side facing and longitudinally seated passengers. Recent studies by the research team on rubber tired vehicles have confirmed the observations: (i) that most accidents occur under normal operations, and (ii) manual wheelchairs and scooters are more unstable than power chairs in rapid deceleration conditions.

In order to mitigate some of the instability wheelchair brakes must always be applied, and the power wheelchairs and scooters must be powered off (Salipur et all 2001).

This paper concentrates on streetcars and street running LRT vehicles. Using the definition of the National Transit Data Base to define the modes and these are shown in Table 3.

Table 3 *Definitions of Rail Transit Vehicles (National Transit Database) (National Transit Database, 2015)*

MODE	Vehicle Type
Light Rail (LR) A transit mode that typically is an electric railway with a light volume traffic capacity compared to heavy rail (HR). It is characterized by: Passenger rail cars operating singly (or in short, usually two car, trains) on fixed rails-in shared or exclusive right-of-way (ROW); Low or high platform loading; and Vehicle power drawn from an overhead electric line via a trolley or a pantograph.	Light Rail Vehicles (LR) Vehicle type: Rail cars with: Motive capability; Usually driven by electric power taken from overhead lines; Configured for passenger traffic; and Usually operating on exclusive rights-of-way (ROW).
Streetcar Rail (SR) This mode is for rail transit systems operating entire routes predominantly on streets in mixed-traffic. This service typically operates with single-car trains powered by overhead catenaries and with frequent stops.	Streetcar Vehicles (SR) Vehicle type: Rail cars with: Motive capability; Usually driven by electric power taken from overhead lines; Configured for passenger traffic; and Often operates in shared use corridors (Shared ROW)Typically operates with one car trains

Three general classifications of wheeled mobility devices are considered, and these are defined as follows.

Manual wheelchairs

Manual chairs were the most common mobility devices in the past decades. They are light, some are foldable, have large rear wheels, small front casters, and are mainly used by people with strong arms to propel themselves. They have push bars at the rear for those occupants who cannot propel themselves and are pushed by another person, typically in hospitals, transportation terminals and institutional places. The "common manual wheelchair," measuring 25 inches wide and 42 inches long when occupied, was for many years used as a base for regulations and standards with a recommended footprint of 30 inches x 48 inches and a turning radius of 36 inches. With the advent of making private and public transportation accessible, systems were developed to secure the wheelchair to vehicles, mainly by tie-downs to prevent forward and rearward movement (Hunter- Zaworski and Rutenberg, 2014).

Power Wheelchairs

Power wheelchairs are powered by batteries and operated by joysticks or other control means. They may have special postural control systems or cushioned seats and back, a headrest and padded armrests. These devices typically measure about 25 inches wide by 38 to 43 inches long, and can weigh up to 300 or even 400 pounds depending on their power pack and accessories. They are usually very nimble, have a small turning radius of about 28 inches, and can usually be accommodated on public transportation vehicles, provided the user is capable of maneuvering in and out of their position on-board a vehicle. Powered chairs often have added features to tilt the chair and provide extended leg and upper body supports. Because of the additional features, these chairs can vary in length and weight, and can easily exceed the standard footprint of 30” x 48 inches, thus making transport on regular public transit vehicles more difficult (Hunter-Zaworski and Rutenberg, 2014).

Scooters

Designed primary indoor use scooters generally have 3 or 4 wheels. These devices typically have a pedestal seat with a tiller or joystick control and small wheels. Many of the bases of these devices are narrow with a width of about 20 inches makes them more prone to tipping. In addition, these devices are often procured outside the medical prescription process. Many scooter riders do not received proper training or recommendations for the correct scooter for their size and mobility level (Hunter-Zaworski and Rutenberg, 2014).

This paper reports experiments that were conducted using a standard manual wheelchair and a four-wheel scooter. Prior research conducted by the team has shown that the power base wheeled mobility devices is more stable than either the manual wheelchair or scooter.

Orientation of Wheeled Mobility Devices

Prior to the regulations associated with the American's with Disabilities Act, sled tests showed that manual wheelchairs did not withstand side accelerations (Stewart and Reni, 1981). These results contributed to the ADA regulations specifying that a wheeled mobility device (WhMD) should always be transported oriented in the longitudinal direction on rubber tired vehicles (American's With Disabilities Act Accessibility Specifications for Transportation, 1998). Subsequent sled testing of securement systems and WhMDs has confirmed that in high acceleration or high "g" environments the WhMD must be in the longitudinal direction.

In many cities, the implementation of rail transit is due to increasing demand and population density. Rail transit operators are studying methods to increase vehicle capacity for WhMDs. Side facing seating orientation for WhMDs has been suggested as an option to increase rail vehicle capacity for WhMD. It is also widely observed that in crowded conditions many passengers in WhMDs sit sideways in or near the vehicle vestibule because they cannot access areas designated for wheeled mobility devices. This study examines whether side facing orientation is a viable option for rail transit, based on braking studies conducted on light rail test tracks.

Vehicle dynamics of rail transit vehicles

The vehicle dynamics of rail transit vehicles are significantly different from rubber tired vehicles. Rubber tired vehicles acceleration and deceleration are much more variable because of the operator, tires, pavement conditions, and vehicle propulsion and transmission systems. The basic difference is the coefficient of friction between rubber tire and steel tire vehicles and influences the rate of acceleration and deceleration. In rubber tire operations large transit buses will experience much higher longitudinal and lateral acceleration forces than rail transit vehicles due to operating conditions and roadway geometrics.

In the United States, most streetcars and street running light rail transit systems are electric and the parameters for acceleration and braking are preset and controlled.

Scope of Study

The focus of this study examined the orientation of WhMDs and brake testing regimes on new light rail and streetcar vehicles.

The study used both video recordings of movement and an accelerometer data acquisition system to record vehicle dynamics. To analyze the effect of the extreme braking regimes on an occupied WhMD, a 50 percentile male anthropometric test dummy was used for all the tests. The anthropometric test dummy was also used to simulate a passenger with very low or no upper body strength. Two types of WhMDs were used in this study; a standard manual wheel chair and a four wheel scooter. Both WhMDs were considered to be in used condition, however the manual wheelchair had functional brakes and the scooter could be powered off.

During testing, the WhMDs were oriented in either the longitudinal or the side facing orientation. Most transit systems operate the trains bi-directionally, and during testing the trains operated bi-directionally. The WhMD faced either forward or rearward when they were positioned longitudinally. Similarly, when the WhMD were positioned in the side facing orientation they were exposed to braking forces on tangent, concave and convex curved track.

Description of testing

The questions that the research is attempting to answer are:

(i) Do occupied wheeled mobility devices require securement on street running rail transit?

(ii) Is side facing orientation an option for WhMD on streetcars and light rail transit?

The vehicle electronic system limited the accelerations that occur when a train is leaving the station. Full accelerations were evaluated, but the resulting movement by the test dummy and WhMDs in all orientations were insignificant.

The evaluation of braking regimes for regular, full and emergency braking are included in this study. In order to evaluate the impact of not applying brakes on the manual wheelchair, a member of the research team occupied the manual chair and did not set the brakes. It was necessary for the researcher to restrain the chair manually to prevent excessive motion.

Testing occurred at two locations. The streetcar was evaluated on the United Streetcar test track in Clackamas, Oregon and the light rail vehicle was evaluated on the TriMet test track in Gresham, Oregon.

Streetcar (United Streetcar test track)

United Streetcar located in Clackamas, Oregon, manufactured the streetcars used by the City of Portland. The manufacturing facility had a test track with both tangent and highly curved sections of track. The tracks were wet due to rain during testing. Trains operated bi-directionally on the track. In the tests reported, the 50% male test dummy occupied the manual wheelchair. The wheelchair brakes were applied and during most of the tests and the wheelchair was oriented in the longitudinal position with the arm of the dummy over the fold up seat.

Light Rail (TriMet test track)

Conducted in May of 2015, the primary testing occurred at TriMet’s light rail maintenance facility in Gresham, Oregon. The test track was dry. The test track is primarily a flat tangent section although low speed brake tests were done on a sharply curved section of track. There were negligible elevation changes in the track. The light rail vehicles were coupled as a married pair and operate bi-directionally. The bi-directional operation permitted both forward and rear facing orientation for the wheeled mobility devices, and the side facing permitted the use of a side barrier in one direction only. Regular and emergency brake tests were conducted on the curve section. No panic stops were conducted on curve sections.

Braking Regimes

Three braking regimes included in this study, for both streetcar and light rail vehicles, were; normal braking from 25 MPH to full stop at a station, emergency stops, and panic stops (only on tangent sections). At the TriMet light rail tests, the braking regime specification depended up whether the bogies or trucks have power. There are three bogies per vehicle, two powered with electric motors and one without power located in the articulated or middle section of the vehicle. The powered bogies have both electrodynamic braking systems with a back-up friction brake system. The un-powered bogie just has a friction brake system. The control of the braking is independent of speed except for some modes of friction only braking. The braking regime depends upon requested and actual achieved braking rates and these are dependent on passenger loads and rail adhesion levels. The powered bogies provide most of the braking force and electrodynamic braking primarily provides this. The un-powered bogie assists in braking only if there is a high passenger load or the vehicle is not reaching the commanded brake rate. The normal service braking or deceleration rates are:

(i) Normal service braking ranges from 0.426 ft/s^2 to 4.4 ft/s^2 (0.13 m/s^2 to 1.34 m/$s^{2)}$,
(ii) Emergency and safety braking rates are 7.67 ft/s^2 (2.34 m/s^2) minimum.

The characteristics of the streetcar and LRT test tracks limited the scope of testing. Both of the test tracks are level track. The TriMet test track has a short tangent section of track that limits the maximum speed to 25 MPH. The test track allowed for low speed braking on the highly cured sections. Due to the risk of damage to both the rail and vehicle wheels, panic brake regime tests were completed only once per site.

During the light rail vehicle tests, the manual wheelchair and four wheeled scooter were occupied by the 50% male test dummy during the tests. The wheelchair had brakes applied and was occupied by the test dummy. The scooter had its powered turned off and was occupied by the test dummy.

Streetcar Testing and Observations

The testing at United Streetcar included the 50% male test dummy occupying a manual wheelchair. The standard regular and emergency braking regimes were tested. Testing occurred with the wheelchair brakes engaged and orientated longitudinally. When the wheelchair was oriented in the side facing direction it encroached in travel path of passengers through the vehicle. During the brake tests when the dummy's arm was on the back of the side facing folded up seats, there was no significant movement. There was a little more movement, but this was not of any concern, when the dummy's arm was resting in the lap of the dummy. This did show that a person holding onto a seat back prevents movement even in an emergency braking regime, and this is similar to a passenger holding on to a stanchion.

Observations showed that side facing orientation of the WhMD severely affects interior circulation in the aisle and other spaces. Side facing orientation of the WhMD during braking was not evaluated on the streetcar due to the restricted interior circulation if a WhMD in the side facing orientation.

Light Rail Testing and Observations

Data collection involved the use of accelerometer data, video recording and visual observations. The three dimensional accelerometers used were Gulf Coast Data Concepts Data USB X2-2 data logger that includes a high-sensitivity, low noise, three-axis +/-2g accelerometer sensor. They were calibrated and collected data at 100 hz.

Placed on the floor of the vehicle the accelerometers were orientated longitudinally or in line with the direction of travel. To insure data collection, two accelerometers collected data. The data from the accelerometers was transferred to Microsoft Excel for further analysis. During testing, a handheld video camera recorded the WhMD movement. A researcher recorded all of the videos from the same point in the vehicle. Visual observations were taken from the remaining members of the research team and staff from the agency for other points in the vehicle.

Testing Results

The results showed that during regular braking the deceleration observed was in the 0.15 g range. During panic stops, the maximum observed deceleration was 0.41 g. These were all within the specified range for the vehicles.

The following tables describe the tests, and the observed motion of each test and maximum deceleration. The description of the test includes the restraint of the test dummy and the track geometry. The driving regime section includes the different movements testing. The observed movement section includes the information of the different type of movement the WhMD encouraged during the test. It is important to note that the acceleration was for the vehicle acceleration and not for the WhMD.

One operator drove the train for the testing on the tangent track. The manual chair occupied by the test dummy was tested first then the test dummy was moved to the scooter and the tests were repeated with the scooter. A different vehicle operator drove the train on the curved track tests, and only the scooter was tested with the test dummy.

Table 4 shows the test plan and observed accelerations of the occupied manual wheelchair. The table shows that tests used both tangent and curved track in the TriMet testing facilities. Testing included a control test with regular acceleration and deceleration before each test group. The table illustrates performance of control tests prior to experimental braking tests. For the curved track test, only rapid decelerations were tested. On the tangent track, tests rapid acceleration and panic stops were used. The variables that changed during this testing were the track geometry, upper body restraint, and test deceleration.

Table 4 *Test description, results and observations for the Manual Wheelchair*

Manual Wheelchair Testing						
Test Number	Description		Driving Regime		Max Acceleration Observed	Observed movement
1	Upper body used for restraint	YES	Control Movement	Normal acceleration/deceleration	0.12 g	None.
	Track Type	Straight Track	Test Movement	Rapid Acceleration	0.15 g	None.
			Test Movement	Panic Stop	0.39 g	None.
2	Upper body used for restraint	NO	Control Movement	Normal acceleration/deceleration	0.15 g	None.
	Track Type	Straight Track	Test Movement	Rapid Acceleration	0.147 g	None.
			Test Movement	Panic Stop	0.398 g	Slight movement. Casters moved and device moved within designated area.
3	Upper body used for restraint	YES	Control Movement	Normal acceleration/deceleration	0.09 g	None.
	Track Type	Curve Track	Test Movement	Rapid Acceleration	0.12 g	None.
4	Upper body used for restraint	NO	Control Movement	Normal acceleration/deceleration	0.08 g	None.
	Track Type	Curve Track	Test Movement	Rapid Acceleration	0.15 g	None.

The scooter testing followed a similar testing sequence as the manual chair testing. Control movements and test movements were tested. The scooter testing included testing on tangent and curved track. The scooter was tested after the manual chair for the tangent section with the same securement location used. Table 5 shows the test plan and observations for the scooter.

Table 5 *Scooter test plan and observations*

Scooter Testing						
Test Number	Description		Driving Regime		**Max Acceleration Observed**	**Observed movement**
1	Upper body used for restraint	YES	Control Movement	Normal acceleration/deceleration	0.14 g	None.
	Track Type	Straight Track	Test Movement	Rapid Acceleration	0.15 g	None.
			Test Movement	Panic Stop	0.41 g	None.
2	Upper body used for restraint	NO	Control Movement	Normal acceleration/deceleration	0.13 g	None.
	Track Type	Straight Track	Test Movement	Rapid Acceleration	0.15 g	None.
			Test Movement	Panic Stop	0.27 g	Slight Movement of the upper body.
3	Upper body used for restraint	YES	Control Movement	Normal acceleration/deceleration	0.06 g	None.
	Track Type	Curve Track	Test Movement	Rapid Acceleration	0.11 g	None.
4	Upper body used for restraint	NO	Control Movement	Normal acceleration/deceleration	0.02 g	None.
	Track Type	Curve Track	Test Movement	Rapid Acceleration	0.08 g	None.

The only tests that showed movement of the WhMD were the panic stops. If the upper body of the test dummy was propped on the seat back, there was no observed movement. This confirms observations that when passengers hold on to stanchions or the back of a seat, their movement is limited.

The third part of the testing included a member of the research team sitting in the manual chair without any brakes or upper body restraint while the train traveled on the tangent and curved track sections and was included to illustrate the effectiveness of the WhMD brakes. The performance of this test illustrates the effectives of the WhMD on board braking system. The preformation of these tests did not occur during any rapid acceleration or deceleration tests because of safety concerns.

The largest change in acceleration was in the longitudinal direction for all tests. The largest accelerations occurred during panic stops or rapid decelerations. The graphs shown in Figures 4 and 5 show the segment of the tests when the rail vehicle went into a panic stop. Note that the vertical scale in the two diagrams are not the same. The graphs show the constant velocity phase (zero acceleration) that proceeded the application of the brakes followed by the rapid decelerations. This is followed by the application of the track brake that produces a significant “jerk” reaction. The last segment shows the “damping” effect of the vehicle suspension system. Jerk is the rate of change of acceleration and often the jerk causes standing passengers to lose their balance and seated passengers to reach for a stanchion or armrest. The observable “Jerk” occurred in all the braking tests. The panic braking tests were the only tests where the research team all reached for stanchions and arm rests for stability. In figure 5 the “jerk” on the street car is larger than the “jerk” on the light rail vehicle and this is attributable to the difference in mass and suspension systems of the two vehicles.

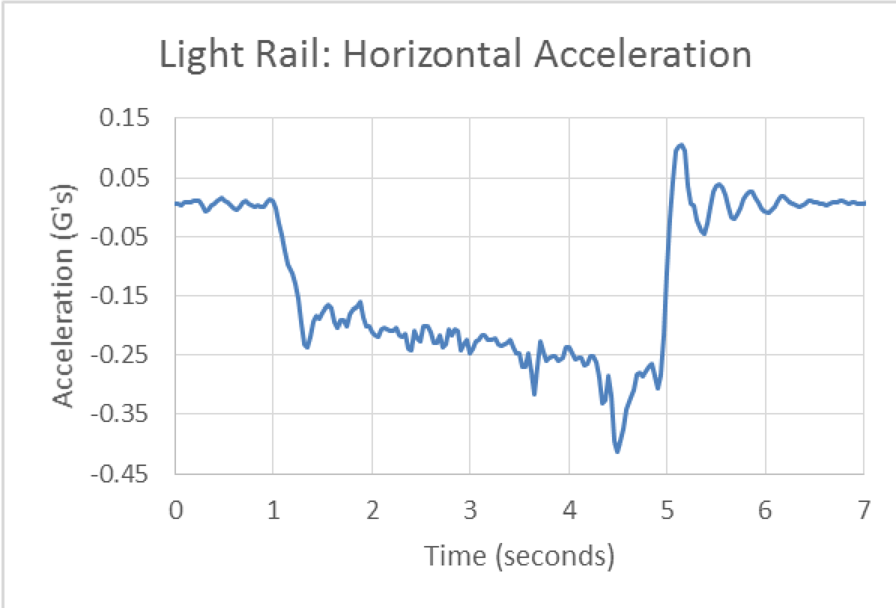

Figure 4 *Panic Brake Longitudinal Acceleration (Light Rail Vehicle*)

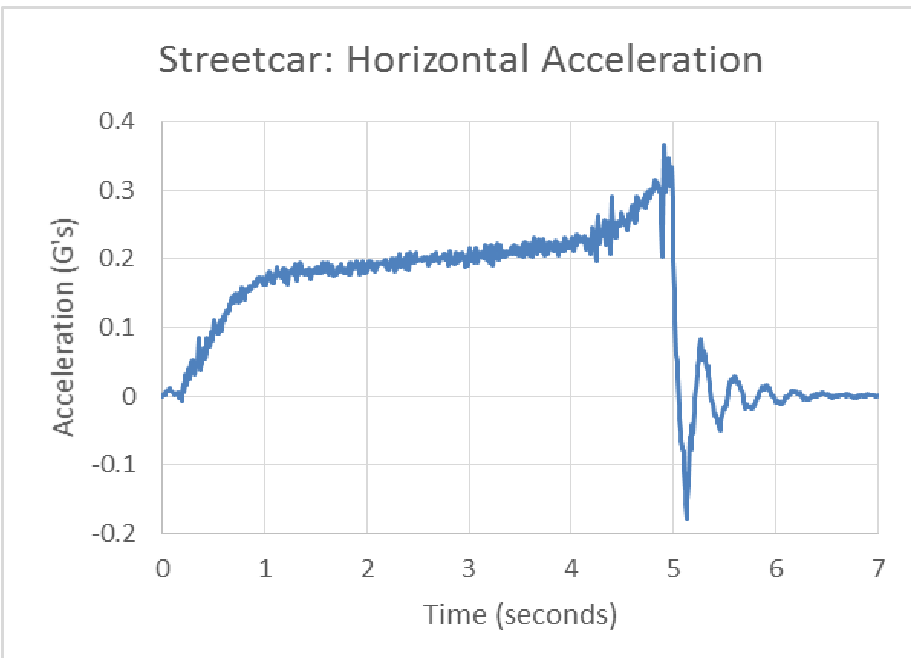

Figure 5 *Longitudinal Acceleration Panic Stop (Streetcar)*

The data collected by the accelerometers is independent of the securement type, WhMD, and direction of securement. The placement of the accelerometers is on the vehicle and not on the WhMD. The sign of the acceleration is also dependent on the vehicle direction. The accelerometer directions where not changed when the train reversed direction. The change in magnitude of acceleration response is of interest when reporting acceleration.

All of the testing was within the parameters for TriMet with the overall maximum acceleration of 0.41 g in the longitudinal direction for the light rail. For the streetcar data, the maximum acceleration was recorded at 0.36 g., Table 6 summarizes these results. Note the large difference in maximum acceleration for different movements. The panic stop resulted in much larger accelerations than rapid acceleration.

Table 6 *Summary of Maximum Accelerations*

Vehicle	Movement	Max Acceleration
Light Rail	Rapid Acceleration	0.15 g
Light Rail	Panic Stop	0.41 g
Streetcar	Panic Stop	0.36 g

Discussion of Results

Side facing Orientation

During the light rail testing at TriMet, the side facing orientation of both the scooter and manual wheelchair did not show significant movement during the regular or emergency braking regimes when the brakes were applied on the manual wheelchair or when the scooter was powered off. Active control by the occupant was needed during occupied side facing testing with the brakes were not set. It was observed that the toes and footplates of the manual wheelchair and the front of the scooter both encroached into the aisle of the rail vehicle and would impact the interior circulation of passengers standing or moving through the aisle. This resulted in reduced flow of

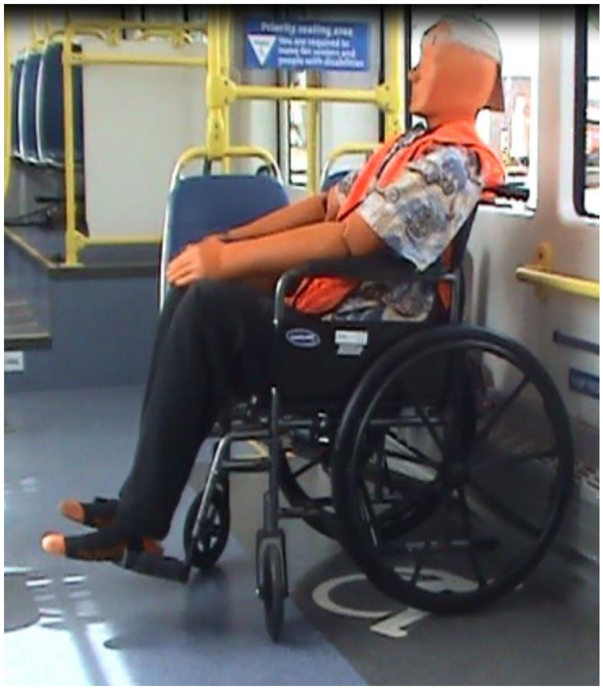

Figure 6 *Side facing occupied manual wheelchair on a light rail*

passengers passing the securement areas. Figure 6 shows the side facing test dummy. It is important to note that the right arm of the test dummy is resting on the top of the flipped up seat and the front casters are rotated which can increase instability. The wheelchair brakes were engaged in this figure.

Containment Type

In both streetcar and light rail vehicle testing, it was observed that in the tests of occupied WhMD, that when the dummy’s arm was put on the flipped seat back for forward and rearward orientation or on a modesty panel for side facing that there was almost no motion of the WhMD during all the braking regimes. This is analogous to passengers holding on to stanchions or bracing against a seat. Figure 7 shows a manual wheelchair in longitudinal orientation with the dummy’s arm resting on a horizontal bar. Slight movement of the WhMD occurred when the dummy’s arm was not restrained. The movement did not result in movement outside the securement area or any tipping.

Figure 7 *Occupied Manual Wheelchair-longitudinal orientation*

The brakes on the WhMD were applied during all brake tests that when the dummy was used. To evaluate the effectives of the brakes on the wheelchair, a member of the research team occupied the manual wheelchair without applying the brakes. During normal braking conditions on tangent and curved sections of the track, the wheelchair moved around the vehicle and the researcher had to control the motion of the wheelchair actively. The wheelchair moved outside the designated area but, it did not tip and all four wheels stayed in contact to the floor of the vehicle during the test.

Conclusions and Recommendations

The results showed that most people would not experience large movements during emergency braking in any of the orientations of the WhMDs, when the WhMDs either are powered off or have functioning brakes. The tests on the light rail vehicles showed that side facing and longitudinal orientation are options. Even though both orientations are viable, the longitudinal orientation of the WhMD also avoided incursions into the aisle space and reduce the impact on other passenger moving through the vehicle. This is especially important for crowed vehicles. The movement in either orientation was very small even in the lightweight mobility aids. During the side facing testing on the light rail vehicle it was very difficult for standing passengers to move around the WhMD and access other parts of the vehicle. Train operators expressed concern about the need for a clear aisle during regular and emergency operations. All the testing procedures showed the importance of WhMDs applying brakes or powering off and the impact on movement of the WhMD during regular and emergency braking regimes. Active control of the wheelchair was necessary to prevent it from moving around the vehicle when the brakes were not used on the manual wheelchair.

The tests also showed that all passengers should hold on to a stanchion or seatback to minimize movement during braking. Suggestions included the placement of placards onboard the vehicle to indicate to the WhMD passengers the location of safe areas to hold on for those who are able. In addition, placards should reminder WhMD passengers to use their brakes or powered off.

In summary, longitudinal orientation is recommended for all transit vehicles. Side facing orientation does not pose a significant safety risk on rail transit vehicles as it does on bus transit during braking. Side facing orientation may be convenient during short trip segments when it is difficult for WhMD passengers to access the space assigned to passengers with disabilities. It should be noted that large WhMD might influence internal circulation for other passengers.

Recommendations for Future Testing

The tests performed did not measure the impact of vertical curvature. The research team recommends the need for further testing on tracks with vertical curves. While track vertical curvatures is much lower than on roadways, there are elevations changes. A positive or negative vertical grade change could impact the stability of the wheeled mobility devices. This is likely to be especially important during side facing orientation.

Acknowledgements

The research team acknowledges the cooperation provided by United Streetcar and TriMet. Both agencies supplied vehicles, operators and access to the test track facilities for the testing.

References

American's With Disabilities Act Accessibility Specifications for Transportation Vehicles, (1998) 49 CFR Part 38, September 1998.

American Public Transportation Association (APTA),(2013) "*Modern Streetcar Vehicle Guideline."*. APTA Standards Development Program. Washington, D.C., 2013.

German Institute for Standardization, (2005) European Railway applications - Braking - Mass transit brake systems - Part 1: Performance requirements DIN-EN 13452-1:2005

Hoberock, L.L., (1976) “A survey of Longitudinal Acceleration Comfort Studies in Ground Transportation Vehicles,” Research Report 40, Department of Research, Office on University Research, USDOT, Washington, DC

Hunter-Zaworski, K.M., U Rutenberg, (2014) “Use of Mobility Devices on Paratransit vehicles and Buses” , TCRP Report 171, Transportation Research Board, Washington DC

Hunter-Zaworski, K.M. and Zaworski, J.R., (2009) “Dynamics of Small Transit Vehicles,” Final Report, Public Transit Division, Oregon Department of Transportation, June 2009.

Hunter-Zaworski, K.M. and Zaworski, J.R.,(2009) “Independent Wheelchair Securement,” IDEA Project T-57 Final Report, National Academies, Washington DC, May 2009.

National Transit Data Base, Federal Transit Administration, Office of Budget and Policy, February (2015), http://www.ntdprogram.gov/ntdprogram/Glossaries/pdf/Glossary2014.pdf, Last accessed June 25, 2015.

Salipur Z, Frost K, Bertocci G.(2011) “Investigation of wheelchair instability during transport in large accessible transit vehicles”. J Rehabil Res Dev. 2012; 49(6):935–48. http://doi.dx.org/10.1682/JRRD.2011.06.0098

Stewart, CF and HG Reni, (1981) “Wheelchair Securement on Bus and Paratransit Vehicles” California Department of Transportation, UMTA, NTIS, Report UMTA-CA-06-0098-81-1

Zaworski. J.R., K.M. Hunter-Zaworski, and M. Baldwin.,(2007) “Bus Dynamics for Mobility Aid Securement Design,” *Assistive Technology,* RESNA Press, Volume 19, Winter 2007, Pgs. 200-209

Chapter 3: Effects of Speed, Curves, and Driver Behavior on Passive Securement Systems on Large Transit Buses

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Journal of Public Transportation

National Center for Transit Research

Center for Urban Transportation Research

College of Engineering

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Abstract

Wheeled mobility devices that are not secured properly on large transit vehicles pose risks to all passengers. The purpose of this study is to increase the understanding of the effects of horizontal and vertical curves, speed, and driver behavior on the safety and security of people using wheeled mobility device rear facing passive containment systems on large transit buses. Testing included the use of manual wheelchairs and light weight scooters on an articulated low floor transit bus. The project conclusions were derived from data produced by accelerometers placed on the bus as well as visual observations of wheeled mobility device movement. The data showed a clear difference in the amount of movement of the wheeled mobility devices and the comfort of the seated passenger when the bus travel on a combination of horizontal and vertical curves at different driving speeds.

Introduction

The securement of wheeled mobility devices (WhMDs) on transit buses is required under the transportation regulations associated with the Americans with Disabilities Act (ADA) (American's With Disabilities Act Accessibility Specifications for Transportation, 1998). Since the enactment of the ADA, securement systems have been studied, designed and deployed to increase passenger safety, security, and comfort. Large transit buses are equipped with two types of securement systems: active and passive. Common active securement systems include auto docking systems or belt type tie down. Active systems that have belts or straps usually require a second person to attach them to the wheeled mobility device. This often increases dwell time at bus stops and encroachment on the passenger's personal space.

WhMDs on large transit buses that have a Gross Vehicle Weight that is greater than 26,000 pounds are required to be equipped with one forward facing belt type securement in addition to any rear facing containment systems. The belt type securement systems usually require another person, often the driver, to secure appropriately the WhMD. This increases the vehicle dwell time at stops and can influence the transit schedule. Rear facing passive systems are designed to allow the passenger to secure himself or herself without the assistance of another person. These containment systems have widespread use in Europe, and Canada (Hunter-Zaworski and Rutenberg, 2014).

This study focuses on rear facing passive containment systems that are deployed on transit buses that travel on mixed right of way streets with both horizontal and vertical curvature.

Background

In 2001, a survey conducted by the University of South Florida found that all 94 transit agencies included in the study use the belt securement system (Foreman and Hardin, 2002). In 2013, Frost et al. found that for the past 20 years, forward facing belt type securement systems were the most common securement system in the United States on large transit vehicles. The researchers also found that only 7.5% of the trips made by people in manual chairs used the securement systems (Frost et all 2013).

Intersections that are designed for large transit vehicles have recommended geometric design dimensions set forth by the American Association of State Highway and Transportation Officials (AASHTO). The AASHTO Guide for Geometric Design of Transit Facilities on Highway and Streets states that the maximum grade for roadways that transit vehicles operate on is 10% but it recommends a lower grade (Guide for Geometric Design of Transit Facilities on Highways and Streets, 2014). The tables 7 and 8 below show the AASHTO standard bus characteristics used for design and the bus performance characteristics.

Table 7 *AASHTO Standard Bus Design Characteristics (*Guide for Geometric Design of Transit Facilities on Highways and Streets, 2014*)*

AASHTO Standard Bus Design Characteristics (AASHTO Guide for Geometric Design of Transit Facilities on Highway and Streets)			
Item	Regular Bus		Articulated Bus
	40 ft.	45 ft.	60 ft.
Gross Weight	36,900-40,000 lbs.	55,200 lbs.	66,600 lbs.
Turning Radius Inside	24.5-30 ft.	24.5-30 ft.	27.3 ft.
Turning Radius Outside	42.0 ft-47 ft.	42.0-47 ft.	39.8-42 ft.

Table 8 *AASHTO Bus Performance Characteristics (*Guide for Geometric Design of Transit Facilities on Highways and Streets, 2014*)*

Acceleration	**MPH/Sec.**	**Ft/Sec^2**	**g's**
0-10 seconds	3.33	4.9	0.15
10-30 seconds	2.22	3.3	0.10
30-50 seconds	0.95	1.4	0.04
Deceleration	**MPH/Sec.**	**Ft/Sec^2**	**g's**
Normal	2-3	2.9-4.4	0.09-0.14
Maximum	6-12	8.8-17.6	0.27-0.54
Maximum Grade (Sustained-Roadway)	6%		
Maximum Grade (Short Upgrade)	10-12%		

Researchers developed guidelines for transit operations at standard operating speeds around corners. This includes guidelines from transit districts and department of educations (school buses) (Kentucky Department of Education Pupil Transportation Branch, 2008). These recommendations are 10 MPH for turns and 15 MPH for evasive maneuvers (Missoula Urban Transportation District, 2011).

Objectives and Motivation

Lane Transit District in Eugene, Oregon approached the research team with questions concerning several major intersections in there operating systems and the performance of rear facing passive containment systems. The primary objective of the research was to determine the relationship between horizontal and vertical curves and speed and the effect on passive containment for WhMDs on large transit vehicles. This relationship is very complex with multiple factors interacting with each other. The study is designed to isolate several key factors in the field tests.

Description of Testing

Testing was conducted in partnership with Lane Transit District (LTD) located in Eugene/Springfield, Oregon area with LTD staff and buses. LTD operates vehicles in demand responsive paratransit, fixed route and bus rapid transit (BRT). Testing occurred over 2 days, the first in February 2015 and the second in October 2015. Testing included driving trials at the maintenance facility and roadway tests on regular transit routes that included steep hills and sharp turns. The purpose of testing in the yard was to study controlled horizontal turning maneuvers. Testing in the maintenance yard was conducted to calibrate the data acquisition equipment and validate testing assumptions related to horizontal curves. The roadway testing included sharp horizontal and steep vertical curves.

Horizontal Curve Testing

To study the acceleration and WhMD behavior in horizontal curves, testing was conducted in the Lane Transit District's parking lot in Springfield, OR. This provided the research team with the opportunity to conduct sharp horizontal turning maneuvers on a level grade. The bus made sharp left, right and slalom turns through the parking lot. The parking lot was mostly empty while the testing occurred and was similar to the configuration shown in Figure 8. This allowed the driver to make sharp turns to demonstrate the worst-case scenario.

Figure 8 *Aerial view of the flat maintenance parking lot used to test horizontal curves only. (Source: Google Maps)*

Testing on Horizontal and Vertical Curve

The vertical and horizontal curve testing was conducted at an interchange in Eugene, Oregon that has a mix of steep vertical and sharp horizontal curvature and a signalized intersection. The section of roadway is at the end of a highway overpass that includes a signalized intersection that is followed by a left turn on to a downgrade ramp. This intersection in particular was of interest because of the combination of vertical and horizontal curvature, and signal controlled intersection. This intersection has been the location of incidents involving LTD passengers seated in wheeled mobility devices that were secured in an active forward facing securement systems. The bus traveled on the overpass westbound on Goodpasture Island Road, followed by a downgrade to the signal. The intersection has one though/left lane (no right turn). The photos in Figures 9, 10, 11 and 12 show the intersection and the path of travel of the bus.

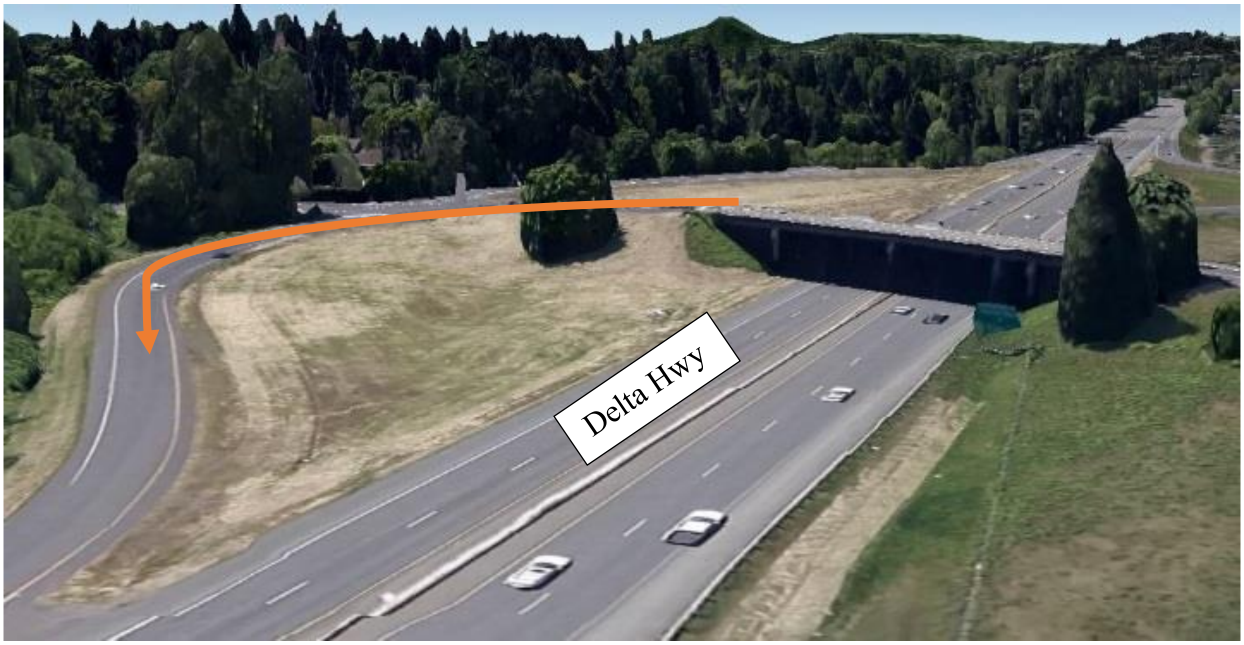

Figure 9 *Three Dimensional view of intersection in testing. (Source: Google Maps)*

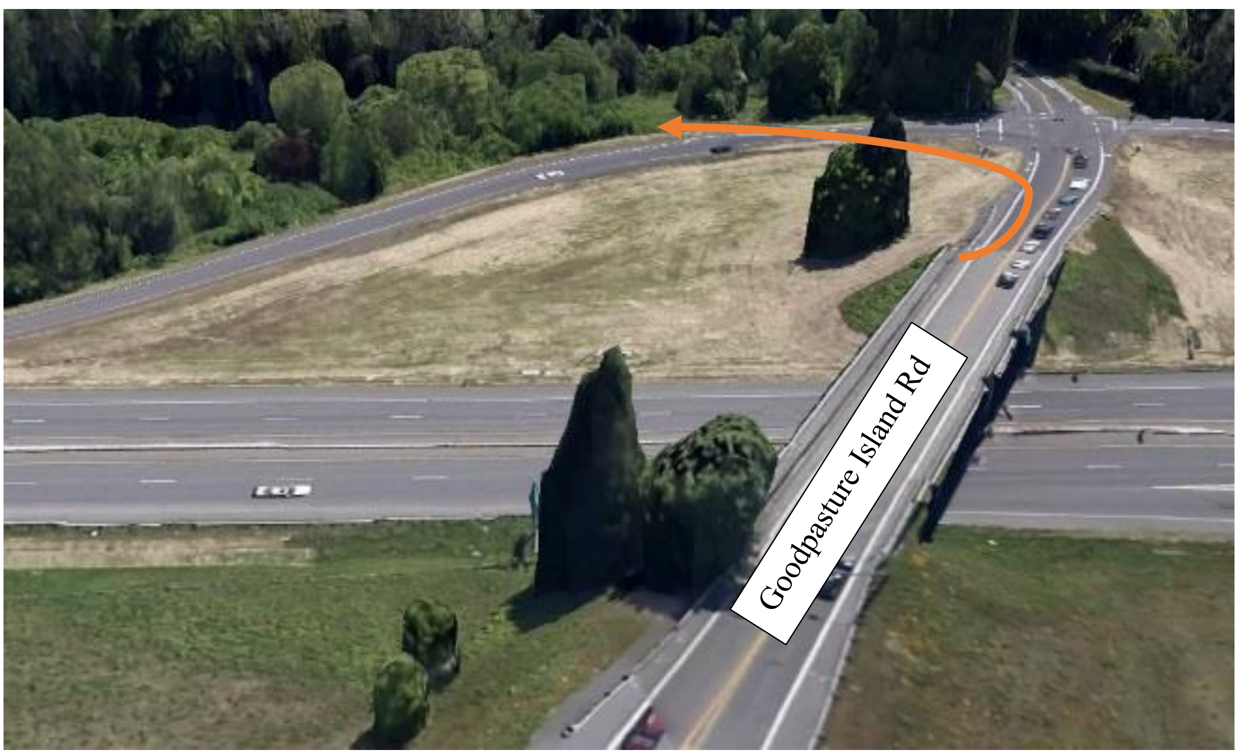

Figure 10 *Overview of Goodpasture Island Road (Source: Google Maps)*

Figure 11 *Intersection of Goodpasture Island and Delta Highway (from Goodpasture Island Rd) (Source: Google Maps)*

Figure 12 *Interchange of Goodpasture Island RD and Delta Highway (from on ramp). (Source: Google Maps)*

Test Methodology

The accelerometers were placed in a longitudinal orientation on the floor of the bus to collect three dimensional acceleration data. The acceleration data collection was independent of the type of WhMDs. During the bus testing, two different WhMDs were occupied by a 50 percentile male anthropometric test dummy (TED) sitting in the seat. The test dummy is used in these data collection activities to minimize human subject risk. The WhMDs types included a standard manual chair and a three-wheeled scooter. The scooter, which was used in the testing, was similar to models that can be bought without a prescription at a non-medical supply store. The scooter is representative of WhMDs that many passengers use when riding LTD vehicles. The center of gravity of the scooter is higher off the ground than the manual chair and is more prone to tipping over. The majority of the tests used the scooter for this reason. Some of the initial tests in the maintenance yard used the manual chair with the test dummy sitting in the wheelchair. Both WhMDs were in good working condition. In all tests, the WhMDs had the brakes set on the device or powered down. Research has shown that during revenue service passengers do not consistently set the brake on their devices. The research team has performed research on other transit vehicles that show that setting the brake has a significant impact on the movement of WhMDs. For the safety of the research team the brakes were set.

The mobility of TED was also limited and he could not use his arms to prevent movement. This was included to test the least mobile passenger type. The picture below, Figure 13, illustrates the placement of his arms during testing. A person has the potential to stabilization themselves if they have mobility and strength in their upper body.

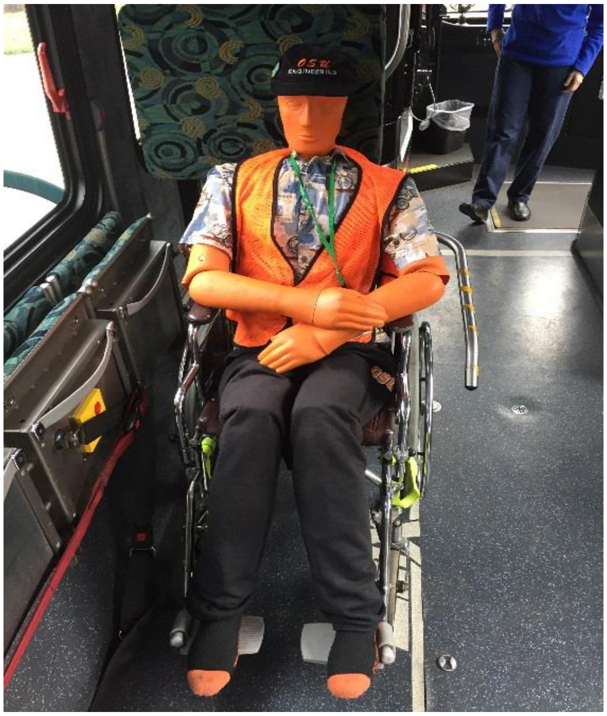

Figure 13 *TED in the experimental condition*

All the testing used the rear facing passive containment system. The rear facing containment system is located directly behind the driver. The passenger is rear facing with the back of their WhMD touching the backboard of the system. The system also features containment on three sides with a bar that extends from the back on the aisle side and a folded seat on the window side. The passenger to increase stability may use the back of the folded seat. Figure 14 shows TED in the rear facing containment location.

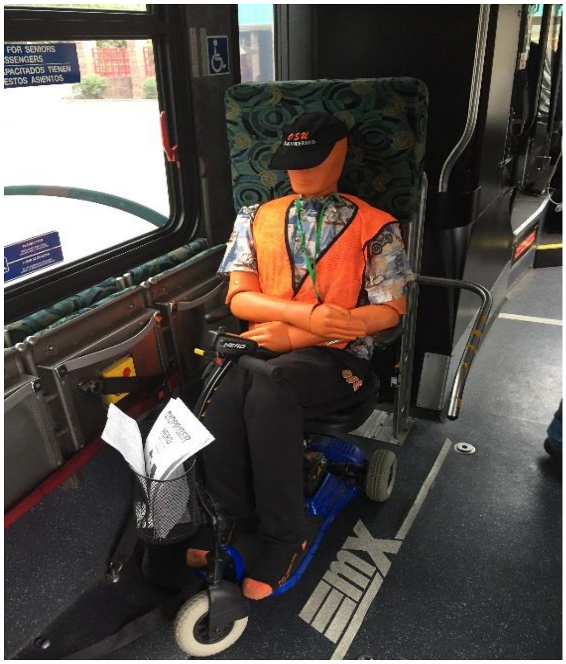

Figure 14 *TED in scoter in passive containment system*

The study included two forms of data collection: observations and accelerometers. Each of the researchers and officials from the transit district conducted observations. One of the researchers was located next to the securement system and one in the middle of the bus. This allowed for multiple viewing angles during testing. Taking pictures only occurred before and after testing for reference of orientation and experimental design.

Data was collected for this study using the Gulf Coast Data Concepts Model X2-2 USB Accelerometers these are shown in Figure 15. The placement of the accelerometers included locations before the vehicle articulation point and over the wheel well. The accelerometers recorded acceleration in 3-axis direction (axial, longitudinal, and vertical) with a 32 Hz sample rate. For redundancy in data, data was collected from two accelerometers. Also used during data collection were time stamps on the accelerometers and GPS tracking. Figure 15 shows the location of the accelerometers.

Figure 15 *Accelerometer placement on bus*

Consistent weather condition prevailed during both days of testing. The days were clear with no rain or moister on the roadway.

During each day of testing, the same operator drove for all the tests but there were different operators in February and October. The operator during the February testing was from the maintenance department and he was very familiar with the performance of the vehicle. The operator in the October was a veteran driver who was also an instructor and operator trainer.

The study used an articulated low floor bus designed for the Bus Rapid Transit system. The only people on the bus during the time of testing were researchers and the LTD Risk Management Staff. The crash dummy occupied the WhMD during the entirety of the testing. Severe cornering test runs were only conducted at the LTD maintenance facility. Figure 16 is a picture of an EMX bus similar to the one used in the study.

Figure 16 *Model of bus used for testing (not actual bus) (9)*

Below Table 9 summarizes the experimental conditions. The table indicates information for both days of testing and data collection location.

Table 9 *Variables in Testing*

Summary of Testing Variables		
Equipment	**Variable**	**Description**
Bus	Constant	Low floor articulated BRT Bus
Wheeled Mobility Device	Variable	Lightweight three wheeled scooter (powered off) and standard wheelchair with brakes applied.
Data collection System	Constant	Accelerometers placed in the same location and collection rate.
Test Location	Variable	Flat maintenance yard to isolate horizontal curves and Goodpasture Island Road intersection to study both vertical and horizontal curves
Driver	Constant/Variable	The driver stayed constant for the day but, different drivers were used in the February and October tests
Speed of Curves	Variable	Curves speed changed to show difference between recommended speed and extreme speed

Study Limitations

Lane Transit District only has rear facing passive containment on the large articulate buses that are used in the BRT service. Rear facing containment is very popular with passengers who use wheeled mobility devices and LTD is considering installing rear facing containment systems on the new non-articulated buses. Limitations to the study included the study included only using one type of bus, and only conducting regular and moderately severe driving conditions. Future testing should consider using non-articulated transit buses, to expand the applicability of the results.

The nature of the data collection process in the field limits the isolation of all contributing factors and conditions. Different tests were used to isolate some factors but not all factors could be limited in the field.

Results

The results of this study are broken into three segments: isolated horizontal curves, combination of horizontal and vertical curves, and driver behavior. Calibration tests for the accelerometers were conducted before the start of the testing. The results of the study are derived from the accelerometer data from the bus and observations made by research team.

Horizontal Curves

The graph in Figure 17 is from the tests conducted at the bus parking lot at the Lane Transit District maintenance facility. The data from the 3 axis accelerometer show the very low acceleration rates during slow speed and increasing to the maximum safe speed on horizontal curves. The lower speeds were at 5 mph and increased to approximately 15 mph. The researchers observed no movement during the test of the manual wheelchair. The testing was completed in one a single session.

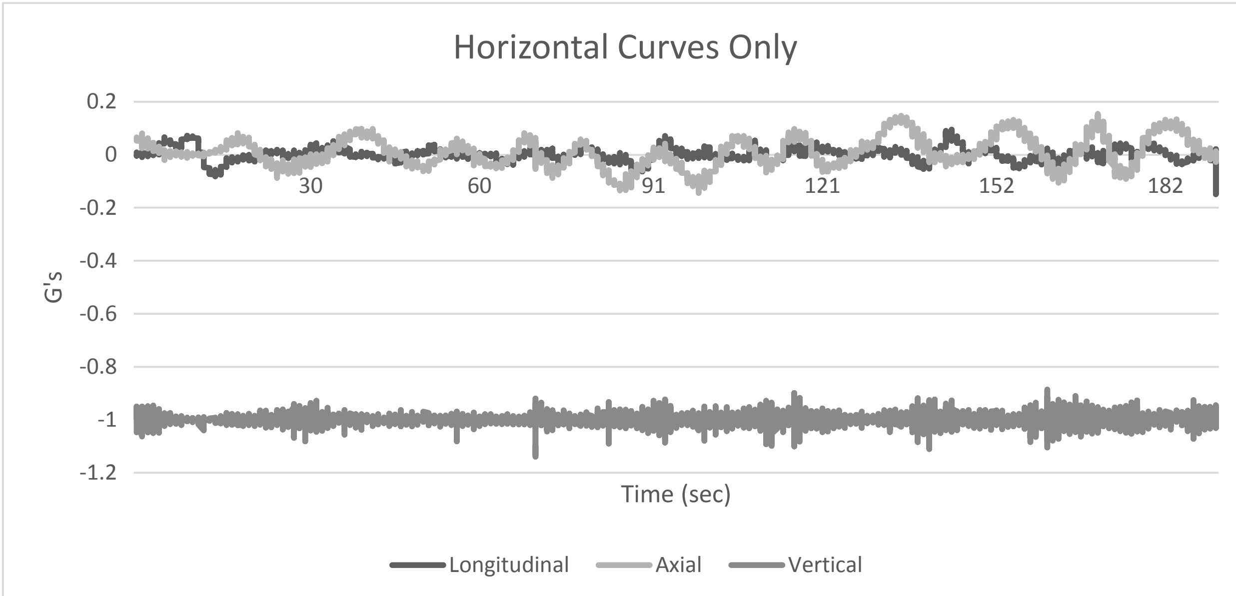

Figure 17 *Data from Horizontal Curves*

Since acceleration is the rate of change of velocity, as the speeds changed during, cornering this was reflected in the accelerations. Figure 17 shows the lateral acceleration resulting from the "S" cornering. The vertical acceleration is measuring the "bumps in the road," and the forward or longitudinal acceleration is the changes in speed until the bus comes to a complete stop (183 seconds)

The observations of the crash test dummy TED showed very little to no movement throughout the testing of the isolated horizontal curvature. The test dummy's movement was very limited to within the containment system and did not cause any alarm for safety.

Vertical and Horizontal Curves

The second group of tests conducted included a vertical curve and a horizontal curve at the interchange of Goodpasture Island Road and Delta Highway. Three data collection test were done: low speed, high speed, and excess speed on cornering that caused the WhMD to tip within the containment system. Each of the speeds were conducted only once due to time limitations. Accelerometer data, shown in the first graph in figure 18, illustrates the accelerations of the bus at a low speed, 5 MPH, while navigating the horizontal and vertical curvature. The change in acceleration is smallest of any of three tests. The slower speed has the smallest amount of

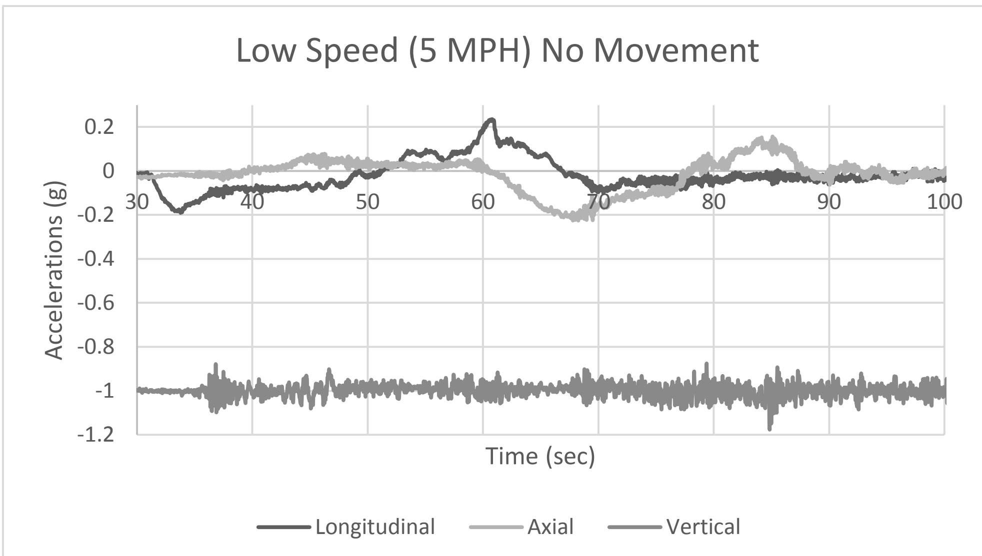

Figure 18 *Low speed acceleration data*

acceleration. This test also has the lowest difference in maximum longitudinal and axial acceleration. Observations of the TED and the WhMD within the containment system were limited too little to no movement.

The higher-speed (14 MPH) test, the top speed the professional driver would drive, saw a minimal movement of the WhMD. This movement would typically occur in regular revenue service performance and would likely not injury to the passenger. When compared to the low speed test, the higher-speed test had much higher changes in the maximum longitudinal and minimum axial acceleration. The changes in acceleration also produced a larger jerk during the turning maneuver. The accelerations of the vehicle are shown in Figure 19.

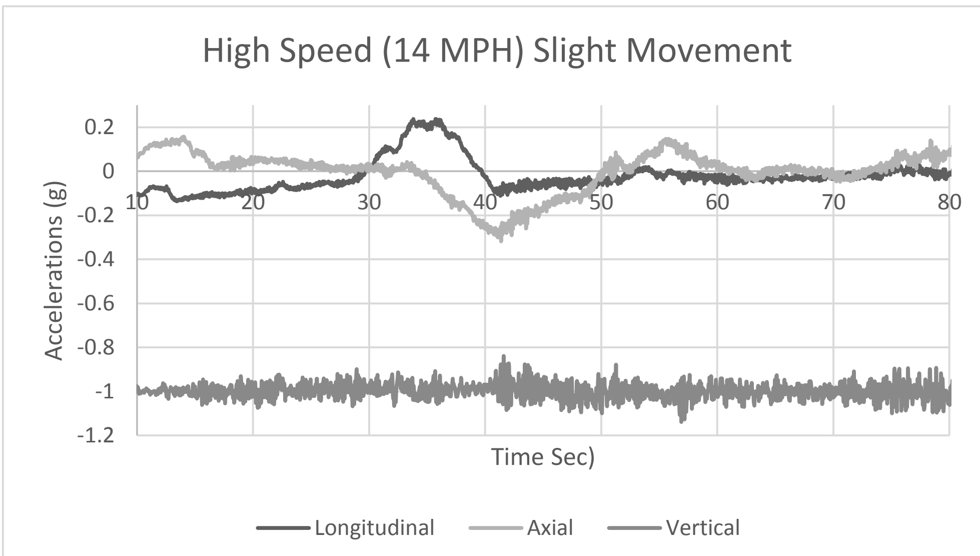

Figure 19 *High Speed acceleration data*

The tipping graph, Figure 20, illustrates the higher levels of acceleration. The jagged lines show the changes in accelerations were sudden. At the approximately the 70 second mark a spike in the acceleration occurred. This was when the bus started from the stop line at the intersection. This is also when the wheels at the front of the WhMDs moved in the direction of the tipping. The maximum acceleration occurred in the middle of the turn. The side-to-side motion of the test dummy inducted some of the motion of the WhMD. This caused the test dummy to shift weight off center and start to tip over. The tipping is also due to the high center of gravity of the scooter with a 50% test dummy.

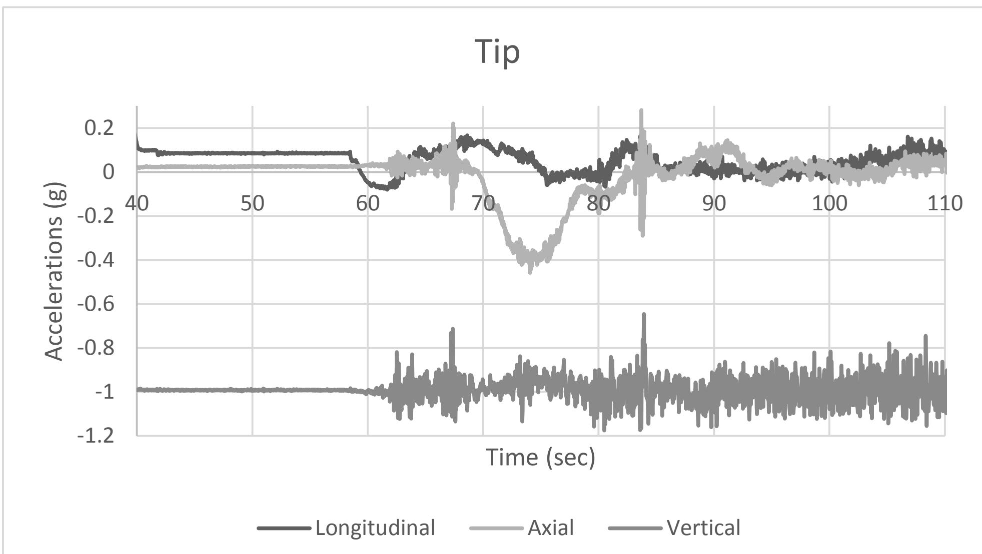

Figure 20 *Acclerations from test that tipped the WhMD*

Driver Performance

Different drivers drove the bus on each day that tested occurred. On the first day, the driver was from the maintenance department and was very experienced with performance of the bus that was used in testing. On the second test day, the driver was very experienced with the bus but was a professional operator with over 20 years' experience as a commercial vehicle operator and was also a bus operator trainer. The differences in how each driver completed turns were shown in the accelerometer data. The first day of testing was designed to look at the maximum or severest driving conditions. The operator drove close to the top level of vehicle performance to simulate severe driving operations. At the intersection of interest, the driver drove through the corner at a high speed. Both the high speed and sudden changes in direction caused the WhMD to become unstable and to tip. On the second day of testing, the professional driver completed all the driving trials within the standard driving parameters. In addition, he called out the speed that he took the corners. The testing began at the low speed and no movement of the WhMD or TED was observed. During the higher-speed tests, there was still very little movement of WhMD or TED. The data also showed that the driver still drove through the curves very smoothly. The research team observed a higher level of passenger comfort (less motion sickness) when the professional driver drove the corners at the suggested speeds that are used in operator training

Conclusions and Recommendations

This study showed that passive rear facing containment systems for WhMD are adequate for preventing users from tipping when the bus is operated within in the normal driving parameters. This also assumes that the passenger and the WhMD have the brakes applied or are powered off and that the WhMD fits in the containment space. The WhMD also must be constrained with the back of the WhMD near or touching the backboard of the passive containment area. Information about proper use of the rear facing containment area should be placed on placards on board so users understand the correct use and the ricks for using the system improperly.

Transit operators need to understand the implications of driver’s behavior on the safety and comfort of all passengers. The acceleration data showed the influence of the driving style of the operator. Driver style during the turns was found to be contributing factor to tipping. This was an unexpected factor. On the first day of testing, a driver from the maintenance department operated the bus that was used for testing and on the second day of testing a professional driver and operator trainer drove the bus. The intent of day 1 was to simulate severe driving and day 2 was normal operations. The difference in the smoothness of the curves was obvious. This is shown in the accelerator data and visual observations.

In the 5 MPH and 14 MPH tests, the lines are smooth while in the tipping the lines are jagged and show greater changes in acceleration in all of the directions. The severe driving was more erratic. Even though speed data was not collected in the tipping, a post testing interview with the driver lead the researchers to believe that the speed was about 20 MPH during the tipping test. In summary, passive rear facing containment, systems are adequate for most roadway geometries with the assumption that drivers operate the vehicle at the prescribed speeds for the roadway geometrics.

Future research

The results of this study were shared with LTD but additional research needs to be conducted in this topic. Three aspects of this study need more research and this includes; securement systems types, data collected, and grade and type of curve. The impact of driving style was a surprising and an unintended outcome from this study. Targeted research to isolate the characteristics of an "expert" driver and the impact on the accelerations would produce better training and best practices for operators. In this study, using only one intersection limited the conclusions. Additional roadway geometry types and intersection are needed to find the extent of the effects of the combination of vertical and horizontal curves.

Acknowledgements

The research team acknowledges the corporations provided by Lane Transit District. They supplied vehicles, operators, and testing locations. The research team would also like to thank the support of Oregon State University.

References

American's With Disabilities Act Accessibility Specifications for Transportation Vehicles, (1998) 49 CFR Part 38, September 1998.

Frost, K. L., Bertocci, G., & Zdravko, S. (2013). Wheelchair Securement and Occupant Restraint System (WTORS) Practices in Public Transit Buses. Assistive Technology (RESNA), 25(1), 16-23. doi:10.1080/10400435.2012.680660

Foreman, C., & Hardin, J. (2002, May). The Challenges of Wheelchair Securement: Searching for Solutions. Bus and Paratransit Conference Proceedings, 3-17. Retrieved from http://www.nctr.usf.edu/pdf/Wheelchair%20Securement.pdf

"Guide for Geometric Design of Transit Facilities on Highways and Streets." Washington D.C.: American Association of State Highway and Transportation Officials (AASHTO), 2014. Print.

Hunter-Zaworski, K.M., & Rutenberg, U. (2014). TCRP Report 171: Use of Mobility Devices on Paratransit Vehicles and Buses. Transit Cooperative Research Program-Transportation Research Board.

Kentucky Department of Education Pupil Transportation Branch. (2008). Driver Instructor Training Manual. 77.

Missoula Urban Transportation District (MUTD). (2011, July 10). Transit Guidelines in Project Development. 23-24.

Questions and Answers Concerning Wheelchairs and Bus and Rail Service. (2013, February 4). Retrieved January 10, 2016, from U.S. Department of Transportation Federal Transit Administration website: http://www.fta.dot.gov/12325_15055.html

WEST EUGENE EMX [Photograph]. Retrieved from https://www.ltd.org/west-eugene-emx/

Chapter 4: General Conclusion

Wheeled mobility devices are widely used on transit vehicles in the United States and there are safety concerns of the WhMD users, other passengers and transit operators. These devices pose specific research demands and risks. Conclusions from this research aim to improve the user experience, safety of all passengers and update securement/containment needs for transit agencies.

Research outlined in the two pervious chapters address the use of WhMDs on rail and bus transit vehicles. In the first paper, Chapter 2, accelerations of the vehicles and visual observations showed that side facing and longitudinal orientation of WhMDs performed the same way in emergency braking.

Conclusions from Chapter 3 included vertical curvature and driver attributes having an impact on the movement of WhMD on large transit buses. These conclusions were made with the assumption that wheelchair brakes were set and the scooter was powered off. This also includes the assumption that the WhMD was placed in the containment system correctly with the back of the WhMD touching or near the back of the containment system.

Recommendations

The testing outlined in Chapter 2 led to numerous recommendations for the orientation of WhMDs on light rail and streetcar vehicles. These recommendations included longitudinal orientation of WhMDs, brake setting of the WhMD, future research on vertical curvature tracks and education. The movement of WhMD during extreme rail transit vehicle braking, the worst-case scenario for tangent tracks, was the same for longitudinal and side facing orientation. The main safety concern was the maneuverability of other passengers around the WhMD. In the side facing orientation on the light rail vehicle, other passengers struggled to navigate passed the

WhMD without hitting the feat of the test dummy. This was shown predominately when two passengers would try to pass next to the WhMD. The area for WhMDs on light rail vehicles is located next to the doorway and are a high traffic point within the vehicle. This is the primary reason for recommendation of longitudinal orientation for WhMDs. From observations conducted by the research team, setting the brake on WhMD significantly reduced the movement of the WhMD. This was shown during revenue service speeds as well as emergency braking. The recommendation of setting the brake leads to the recommendation of public information placards on board the vehicle. The signs would recommend setting the brake or powering off the WhMDs. Under ADA regulations, transit agencies cannot force people to set brakes or use securement systems. Research on the best way to illustrate to passengers the safety benefits of setting the brakes on the WhMD is needed. In addition, an agency cannot deny service to a person if their WhMD does not have brakes (Questions and Answers Concerning Wheelchairs and Bus and Rail Services, 2013). The future research outlined in Chapter 2 focuses on both the positive and negative vertical curvature and the effects on the side facing orientation of WhMDs. More testing in extreme conditions is needed before final recommendations can be made for side facing orientation of WhMD. These extreme conditions include braking on vertical and horizontal curvatures.

In Chapter 3, testing on passive containment systems on large transit buses leads to recommendations for continued use of rear facing passive containment systems on large transit buses. These recommendations were based on the assumption that the containment system are used as intended with the back of the WhMD touching the back of the containment area. Field observations by transit agencies have noted that not all users use the containment systems as designed. ADA only requires users of WhMDs to use the securement system if every passenger is required to use a securement system (seatbelts). Recommendations also included that operators drive the large buses at trained and recommended speeds when driving through curved sections. This was shown when tests at increasing speeds through vertical and horizontal curved sections resulted in increased accelerations of the bus and increased movement of the WhMD.

Future Work

While this research was able to suggest conclusions and recommendation on the orientation of WhMDs on transit vehicles, further research is needed in several areas. In the research reported in Chapter 2 further research is needed for passenger education and complex rail geometries. Further research is needed on vehicle operator behavior and characteristics, additional roadway geometries, and additional securement systems.

Public Outreach

During the testing on the steel tire vehicles (light rail and streetcar), it was found that setting brakes on wheelchairs and turning off the power of the power scooters significantly impacted the movement of the device while the vehicle was moving. One of the recommendations from the project includes public outreach programs and placards on the side of the vehicle adjacent to the WhMD area. There has been research on signage and the impact of signs, additional research is needed to determine the most effective way to illustrate the safety risks. Two key stakeholder groups that need to be included in future research on signage: transit agencies and WhMD users. Transit agencies have risks associated with signage. Users of the system have be accessible and practical.

Complex Road and Rail Geometry

Testing of the orientation of WhMD onboard the streetcar and light rail vehicle was limited to maintenance and testing facilities. Facilities included either vertical grade change, grade crossings or complex geometry. The amount of tolerable vertical grade change is smaller on rail than on roadways. In Portland, Oregon, many sections of track have a vertical grade associated with rails. One of the extreme locations in Portland, Oregon is the new Tillikum Bridge that services streetcar, and light rail vehicles. On both ends of the bridge, there are a combination of vertical and horizontal curves. Complex geometry or extreme grade changes may influence the WhMD. Research in Chapter 3 shows that there is a different in the movement of the WhMD when a large transit vehicle travel through vertical and horizontal curvature. Additional intersections with different geometry and grades are needed to create holistic recommendations.

Operator Behavior

During testing, empirical evidence showed that driver's skill and training effect the movement of the WhMD. Additional research to isolate the characteristics of the operator that lead to movement. Once the characteristics are identified, training for drivers needs to be developed and implemented. Driving standards are not uniform across the industry and will take a large amount of time to be implemented.

Additional Securement and Containment Systems

To expand the recommendations additional securement/containment systems need to be tested in a similar fashion. The rear facing passive containment system has a limited use in the United States and a boarder study using multiple systems and types of securement systems would allow more transit agencies to utilize the results. Additional securement systems include the four point belt and auto docking systems. By including these systems industry, wide standards can be made in regards to the effects of the combination of vertical and horizontal curves on WhMDs.

References

American Public Transportation Association (APTA), (2013) “Modern Streetcar Vehicle Guideline.” APTA Standards Development Program. Washington, D.C., 2013.

American’s With Disabilities Act Accessibility Specifications for Transportation Vehicles, (1998) 49 CFR Part 38, September 1998.

APTA. (2013, October). Millennials & Mobility: Understanding the Millennial Mindset [Report]. Retrieved from American Public Transportation Association website: http://www.apta.com/resources/reportsandpublications/Documents/APTA-Millennials-and-Mobility.pdf

Brault, M. W. (2008, December). American with Disabilities: 2005 [Household Economic Studies Current Population Reports]. Retrieved from U.S. Department of Commerce Economics and Statistics Administration U.S. Census Bureau website

Brault, M. W. (2012, July). American with Disabilities: 2010 [Household Economic Studies Current Population Reports]. Retrieved from U.S. Department of Commerce Economics and Statistics Administration U.S. Census Bureau website

D'Souza, C., Steinfeld, E., Paquet, V., & Feathers, D. (2010). Space Requirements for Wheeled Mobility Devices in Public Transportation Analysis of Clear Floor Space Requirements. Transportation Research Board, 66-71. doi:10.3141/2145-08

Fact Book Glossary. (n.d.). Retrieved January 15, 2016, from American Public Transportation Association website: http://www.apta.com/resources/statistics/Pages/glossary.aspx

Frost, K. L., Bertocci, G., & Zdravko, S. (2013). Wheelchair Securement and Occupant Restraint System (WTORS) Practices in Public Transit Buses. Assistive Technology (RESNA), 25(1), 16-23. doi:10.1080/10400435.2012.680660

Foreman, C., & Hardin, J. (2002, May). The Challenges of Wheelchair Securement: Searching for Solutions. Bus and Paratransit Conference Proceedings, 3-17. Retrieved from http://www.nctr.usf.edu/pdf/Wheelchair%20Securement.pdf

German Institute for Standardization, (2005) European Railway applications - Braking - Mass transit brake systems - Part 1: Performance requirements DIN-EN 13452-1:2005

"Guide for Geometric Design of Transit Facilities on Highways and Streets." Washington D.C.: American Association of State Highway and Transportation Officials (AASHTO), 2014. Print.

Harvey, Blake A. "The Transit Experience." 15 Feb. 2016. Corvallis, OR

Hoberock, L.L., (1976) “A survey of Longitudinal Acceleration Comfort Studies in Ground Transportation Vehicles,” Research Report 40, Department of Research, Office on University Research, USDOT, Washington, DC

Hunter-Zaworski, K.M., & Rutenberg, U. (2014). TCRP Report 171: Use of Mobility Devices on Paratransit Vehicles and Buses. Transit Cooperative Research Program- Transportation Research Board.

Hunter-Zaworski, K.M. and Zaworski, J.R., (2009) “Dynamics of Small Transit Vehicles,” Final Report, Public Transit Division, Oregon Department of Transportation, June 2009.

Hunter-Zaworski, K.M. and Zaworski, J.R., (2009) “Independent Wheelchair Securement,” IDEA Project T-57 Final Report, National Academies, Washington DC, May 2009.

LaPlante, M. P., & Kaya, H. S. (2010). Demographics and Trends in Wheeled Mobility Equipment Use and Accessibility in the Community. Assistive Technology (RESNA), 22(1), 3-17. doi:10.1080/10400430903501413

Kentucky Department of Education Pupil Transportation Branch. (2008). Driver Instructor Training Manual. Pages 77.

TCRP 165: Kittelson & Associates, Parsons Brinckerhoff, KFH Group, Texas A&M Transportation In, & ARUP. (2013). Transit Capacity and Quality of Service Manual [Report]. Retrieved from Transit Cooperative Research Program- Transportation Research Board website: http://www.trb.org/Main/Blurbs/169437.aspx

Miller, V. (2015, March 9). Record 10.8 Billion Trips Taken On U.S. Public Transportation In 2014 The Highest Transit Ridership in 58 Years. Retrieved January 15, 2016, from American Public Transportation Association website: http://www.apta.com/mediacenter/pressreleases/2015/pages/150309_ridership.aspx

Missoula Urban Transportation District (MUTD). (2011, July 10). Transit Guidelines in Project Development. 23-24.

National Transit Data Base, Federal Transit Administration, Office of Budget and Policy, February (2015), http://www.ntdprogram.gov/ntdprogram/Glossaries/pdf/Glossary2014.pdf, Last accessed February 1, 2016.

Neff, J., & Dickens, M. (2013, October). 2013 PUBLIC TRANSPORTATION FACT BOOK [Report]. Retrieved from American Public Transportation Association website: http://www.apta.com/resources/statistics/Documents/FactBook/2013-APTA-Fact-Book.pdf

Questions and Answers Concerning Wheelchairs and Bus and Rail Service. (2013, February 4). Retrieved January 10, 2016, from U.S. Department of Transportation Federal Transit Administration website: http://www.fta.dot.gov/12325_15055.html

Public Transportation Use is Growing -- Here Are the Facts. (2014, March 14). Retrieved January 15, 2016, from American Public Transportation Association website: http://www.apta.com/mediacenter/ptbenefits/Pages/Public-Transportation-Use-is-Growing-.aspx

Ride Safe Information to help you travel more safely in motor vehicles while seated in your wheelchair. (2015). Retrieved January 10, 2016, from Transportation Research Institute University of Michigan (UMTRI) website: https://docs.google.com/viewer?a=v&pid=sites&srcid=dW1pY2guZWR1fHdjLXRyYW5zcG9ydGF0aW9uLXNhZmV0eXxneDo2ODhiNmM0MGZlYjg1OWNh

"Ridership Report Archives." American Public Transportation Association. American Public Transportation Association, nd. Web. 9 May 2015. <http://www.apta.com/resources/statistics/Pages/RidershipArchives.aspx>.

Rutenberg, U., & Hemily, B. (2003). Use of Rear-Facing Position for Common Wheelchairs on Transit Buses A Synthesis of Transit Practice [Report]. Retrieved from Transit Cooperative Research Program- Transportation Research Board website:

Salipur, Z., Frost, K., & Bertocci, G. (2012, November 6). Investigation of wheelchair instability during transport in large accessible transit vehicles. Journal of Rehabilitation Research & Development, 49, 935-948. Retrieved from http://www.rehab.research.va.gov/jour/2012/496/pdf/salipur496.pdf

Stewart, CF and HG Reni, (1981) “Wheelchair Securement on Bus and Paratransit Vehicles” California Department of Transportation, UMTA , NTIS, Report UMTA-CA-06-0098-81-1

Streetcar History . (2014). Retrieved February 10, 2016, from City of Portland- Portland Streetcar website: http://www.portlandstreetcar.org/node/33

Transit Authority of River City (TARC). (2013, September). Transit Design Standards Manual. 15.

TriMet Community Affairs. "Improved MAX vehicles added to fleet." Portland-Milwaukie Light Rail Transit Project. TriMet, n.d. Web. 17 Jan. 2016. <trimet.org/newmax/>.

van Roosmalen, L., Karg, P., Turkovich, M., & Porach, E. (2011, November 7). User evaluation of three wheelchair securement systems in large accessible transit vehicles. Journal of Rehabilitation Research & Development, 48, 823-838. doi:10.1682/JRRD.2010.07.0126

WEST EUGENE EMX [Photograph]. Retrieved from https://www.ltd.org/west-eugene-emx/

Wretstrand, A., Petzall, J., & Stahl, A. (2004). Safety as perceived by wheelchair-seated passengers in special transportation services. Accident Analysis and Prevention, 36, 3-11.

Zaworski. J.R., K.M. Hunter-Zaworski, and M. Baldwin.,(2007) “Bus Dynamics for Mobility Aid Securement Design,” Assistive Technology, RESNA Press, Volume 19, Winter 2007, Pages. 200-209