IDEA

Innovations Deserving Exploratory Analysis Programs

Transit IDEA Program

Independent Wheelchair Securement

Final Report for
Transit IDEA Project 57

Prepared by:
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2012

TRANSPORTATION RESEARCH BOARD
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ACKNOWLEDGEMENTS

The Oregon State University research team acknowledges the tremendous support from Lane Transit District in Eugene, Oregon on this Transit IDEA project. We also acknowledge and greatly appreciate the efforts of the expert review panel for this project. The project's expert review panel included:

- Terry Parker, Accessible Services Manager, Lane Transit District
- Uwe Rutenberg, President, Rutenberg Design, Inc.
- William Botten, Accessibility Specialist, United States Access Board

Table of Contents

EXECUTIVE SUMMARY

The goal of this project was to develop an aisle-side containment device to enable users of wheelchairs to safely and independently use rear-facing containment on large buses, in lieu of the current standard, a four-point tie-down wheelchair securement system. The device includes a backrest and a movable aisle-side containment structure. The operation would involve the user backing into the securement space until the rear of the chair is in contact with the backrest. Activation of the aisle-side device would provide the second side of containment and the bus wall acts as the third side.

This project was completed in two stages. The first of these stages included research and analysis to determine design requirements for aisle-side containment. The second stage used those requirements to complete detailed development of a backrest and aisle-side containment system.

The methodology used in the first stage to address the research hypothesis consisted of two parts; data collection and data analysis. The data collection consisted of measurements on a variety of wheelchairs to determine acceptable contact surfaces and the location of their mass centers when occupied. The data analysis used that information to determine for each type of wheelchair how it may move in a containment system, what minimum size surface is required to prevent excessive aisle-side movement, where an aisle-side containment surface must be located relative to the rear backrest, and what force that surface must support to prevent movement.

The second stage of this project, design of a solution to the aisle-side containment requirements, took place in three steps. First, based on the research in Stage 1 and information obtained with the assistance of Lane Transit District (LTD) in Eugene, Oregon, the design requirements were identified and posed both as customer requirements and as engineering requirements. Second, a variety of concepts were created and then evaluated to select a best concept. Finally, the concept was developed to the point of having a complete computer-based 3-D model from which a working prototype was built.

The final design is a four-bar linkage that rides on a pair of guide shafts mounted to the backrest. The shafts allow the linkage to move into the aisle space and unfold into position when needed. When not in use, the linkage folds up and retracts next to the backrest. The motion is accomplished with a pair of pneumatic actuators that can be fully automated with push-button operation. By balancing the moments of the top and bottom links, the linkage requires a very small amount of force to fold. This is the first system to provide an effective aisle-side barrier that can be completely retracted out of the aisle space when not in use.

The prototype developed in this project successfully demonstrated a retractable aisle-side barrier system capable of protecting a passenger in a wheelchair from the forces encountered on a transit vehicle while maneuvering. In field tests using a manual wheelchair and a four-wheel scooter, the prototype successfully demonstrated the effectiveness of this retractable aisle-side containment system. Wheelchair rotation and tipping during extreme vehicle maneuvering were both shown to be prevented by the aisle-side containment system.

Introduction

The current method of wheelchair[*] securement is well defined *(1)*, but has proven to be difficult to use correctly in practice. *(7, 8, 9)* This leads to unsafe riding conditions for passengers seated in wheelchairs. The concept of a rear-facing containment system is now gaining in popularity with both transit providers and passengers who use wheelchairs because it is faster and more independent. *(2, 5)*

It has been shown[1] that on large buses, wheelchair users can board quickly and ride safely without any assistance from the operator if an appropriate 3-sided rear-facing wheelchair containment station is available. The as-yet unresolved problem is providing the third side of containment, that on the aisle-side of the wheelchair space. The challenge is to provide aisle-side containment that will not affect other passengers but will allow wheelchair users to ride the bus without any assistance. This will require that the solution not interfere with movement in the aisle, that it provide room to maneuver a wheelchair into the designated space, that it will minimize need for additional wheelchair space, and that it will allow the rider to use the space independently.

This project was done in two distinct stages. The first stage included research to clearly define the problem, and the second stage included design of an effective aisle-side containment system based on those findings.

As presented in the first part of this report, the goal of Stage 1 was to confirm the hypothesis that there are some key design parameters for aisle-side containment given the variety of wheelchairs currently in use, and also to clearly define the minimum requirements for that aisle-side containment. Because a wide variety of wheelchair types are to be served, this required collecting and analyzing data on representative samples of all of the common types of wheelchairs. The information required was the nature of the movement to be prevented (i.e. rotation or translation), the force required to prevent that movement, and locations on wheelchairs where that force could safely be applied.

The second part of this report describes the design and selection of a concept for an automated stowable aisle- side containment system to meet these requirements and the subsequent development of that concept into a working design. The specific customer and engineering requirements are presented, a few of the concepts that were considered are described, and a detailed description of the development of the final choice is presented.

Research Goals

In this section of the report, the methods and results of the research are presented. The measurements that were made and the analysis that was applied to a variety of wheelchair types are described. In all cases, the chairs were occupied by a 50th percentile male anthropomorphic test dummy, a condition that approximates the real situation and that results in a substantial difference in wheelchair response when compared to an empty chair, particularly in force required to prevent tipping. The specific goal of this research was to answer the research hypotheses:

- *A minimum area aisle-side containment surface for use as part of a rear facing wheelchair containment can be found that will be effective for all readily available wheelchairs.*

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[*] "wheelchair" is meant to include manual chairs, powered chairs, and scooters.
[1] Transit IDEA Project 38, January 2005; and Transport Canada Report No. TP 14429E, 2006

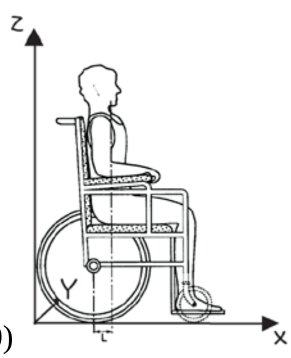
- *The minimum area will be of a size that it can be readily positioned to eliminate interference with the movement of other passengers when it is not in use.*

- *The forces acting on the area as it prevents excess lateral movement of a wheelchair will not be so large as to require structural members that conflict with the previous requirement.*

Research Procedures

Center of Gravity

The first part of the project was to determine the center of gravity (CG) of five different types of loaded wheelchairs. A standard axis was established to ensure that all of the chairs were measured similarly and the final product development would fit the broadest range of different chairs possible. The origin of the coordinate system was established by backing the chairs against a vertical wall and placing the origin at the intersection of the wall and the floor along the right edge of the chair. (Fig. 1)



(0,0,0)

FIGURE 1 Coordinate system used for all wheelchairs in this project.

The chairs were loaded with a 175 pound, 50th percentile dummy and weighed. The weight of the chair was measured on the front, rear, and both sides to determine the horizontal location of the CG. A 2x4 was placed on top of the scale allowing two wheels to be combined into a single force. The opposite two wheels were placed on a 4x4 to keep the chair level during the weighing. (Fig. 2)

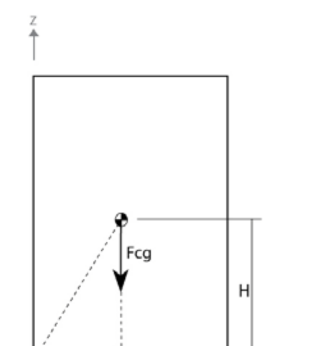


FIGURE 2 Weighing the right side of the Quickie S-262.

FIGURE 3 Center of gravity location

both

in an

Once the weights were recorded for the front, rear, and sides, the horizontal (x,y) location of the center of gravity was calculated using a simple moment balance (Eq. 1 & 2, Fig. 3). In figure 3, the variable dx1 was calculated all of the others were measured. The side-to-side (y) location of the CG was calculated identical manner.

$$Fcg = F1 + F2 \qquad (1)$$

$$= 0 \quad \rightarrow \quad (D1)(F2) - (Fcg)(dx1) = 0 \qquad (2)$$

The vertical (z) location of the center of gravity was determined by taking the rear weight measured above, adding a known amount of height under the front wheels in order to tilt the chair rearward, and measuring the new weight (Fig. 4). From these three values the height of the center of gravity could be calculated as shown below.

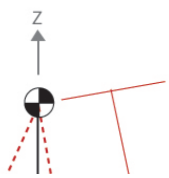


FIGURE 4 CG Height diagram showing the effects of tilting the chair.

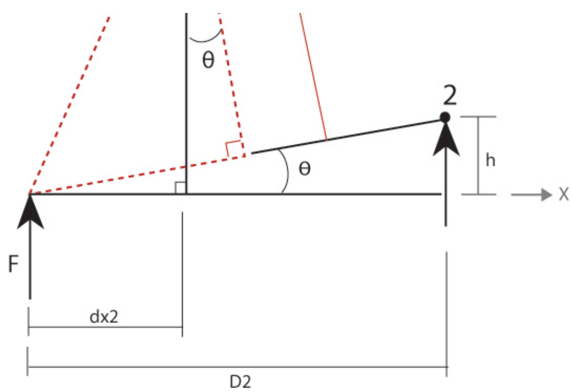
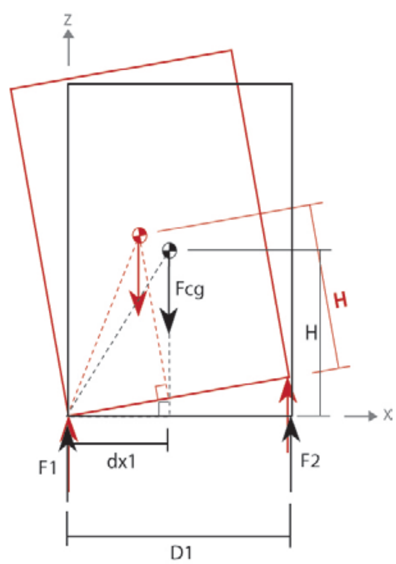


FIGURE 5 Geometry of the CG height calculation figure 4).

(zoomed from

For the variables in the following equations 4 and 5 above. A measured height (h) was added wheels to tilt the chair rearward. The distance D1 for the calculation in equation 2. The distance, D2, by equation 3.



refer to figures under the front was measured was calculated

$$D2 = \sqrt{D1^2 - h^2}$$

The new horizontal distance to the CG, dx2, was calculated by balancing the moments at point 2. (eq. 4) The force at the CG (Fcg) in equation 4 is equal to that determined in the horizontal CG calculation (eq. 1).

$$dx2 = D2 - \frac{(D2)(F)}{Fcg} \tag{4}$$

The angle (θ) was calculated as shown in equation 5.

$$\theta = \sin^{-1}\left(\frac{h}{D1}\right) \tag{5}$$

Finally, the height of the center of gravity (H) was calculated by equation 6. The original horizontal distance (dx1) was calculated in equation 2.

$$H = \frac{\left(dx1 - \dfrac{dx2}{\cos(\theta)}\right)}{\tan(\theta)} \tag{6}$$

Lateral Force Response

The next step in this experiment was to determine all of the different chairs' reaction to a 0.4 G lateral force (equivalent to what would be experienced when a bus navigates a corner). A tilt table was built from ¾ inch plywood that was capable of tilting the chairs through 30 degrees (equivalent to 0.5 G). The loaded chairs were then tilted on this table until they began to move. The type of motion was recorded. The angle at which the motion started was recorded and the corresponding lateral force was calculated. Finally, a fish scale was used to measure the force required to prevent the chair from moving at 0.4 G of lateral load (~23.6°). In cases where multiple types of motion were observed and could not be arrested by a single force, the wheels were chocked to prevent rotation and the amount of force required to keep the chair from tipping over was measured first. Then a vertical board was used to prevent the chair from tipping over, and the amount of force needed to prevent rotation was measured. (fig. 6)

FIGURE 6 EZ Lite wheelchair on the tilt table with a vertical board to prevent tipping.

Force Application Locations

Lastly, all of the chairs were measured to determine the areas where a force could be applied to stop the chair from moving laterally in the bus. This information will be used to accurately place the aisle-side containment in order to have maximum effectiveness on many different types of chairs. The main areas measured were the armrests and wheel locations. All of the areas from the different chairs were then graphed on the same plot in order to assess commonalities.

Research Results

Center of Gravity

During this experiment five chairs were measured that were representative of the broad range of wheel chairs available. Measurements were performed on an Everest & Jennings EZ Lite (manual chair), a Pride Mobility GoChair, a Pride Mobility Quantum610, a Quickie S262 (all three power chairs), and a Fortress Scientific 2200FS (three-wheeled Scooter). The CG measurements are lists in table 1. All measurements are in inches and refer to the coordinate system shown in figure 1. The measurements for the S262 were not yet completed, but will be finished before the project proceeds further.

TABLE 1 - CG locations given in inches relative to the standard coordinate system.

Chair	X	Y	Z
EZ Lite	17.77	9.99	19.49
GoChair	11.48	9.04	26.76
Quantum610	17.72	9.95	9.16
S262*	21.21	10.93	6.08
2200FS	11.42	10.27	21.7

* Due to weight limitations of our scale, the S262 was measured unloaded. The loaded chair would have a slightly higher CG.

Lateral Force Response

Almost all of these chairs have casters in the front that are free to rotate. The lighter chairs, which have higher CG locations, will begin to rotate in the direction of the lateral force. The two heaviest chairs began to tip over first, due to the fact that the heavy power systems on these chairs lowers the CG. Also the heavier chairs tend to have larger tires which aids in arresting lateral motion. Table 2 lists the first motion response of the different chairs.

TABLE 2 - First motion response of each chair to lateral force.

Chair	Motion Type	Angle started (degrees)	Corresponding Force (G)
EZ Lite	Rotation	9	0.16
GoChair	Rotation	9	0.16
Quantum610	Tipping	13	0.22
S262	Tipping	20	0.34
2200FS	Tipping	15	0.26

The force required to prevent motion of the chair was typically measured in two steps as explained in the procedure section. This allowed the different types of motion to be arrested and measured independently. Table 3 lists the different forces required to arrest motion of the chairs.

TABLE 3 -The amount of force required to prevent motion at 0.4 G's.

Chair	Motion Type Arrested	Force (lbs)	Motion Type Arrested	Force (lbs)
EZ Lite	Rotation	27	Tipping	37
GoChair	Rotation	48	Tipping	57
Quantum610	Rotation	< 10	Tipping	40
S262	All	27		
2200FS	All	42		

Force application Locations

Each chair was measured to determine three locations where a containment force could be applied to arrest lateral motion. This information will be used to determine the optimal location(s) for the final containment system design. The three areas on each chair were measured as rectangles that could easily be graphed. The rectangles each correspond to a specific area on the chair such as that shown in figure 7.

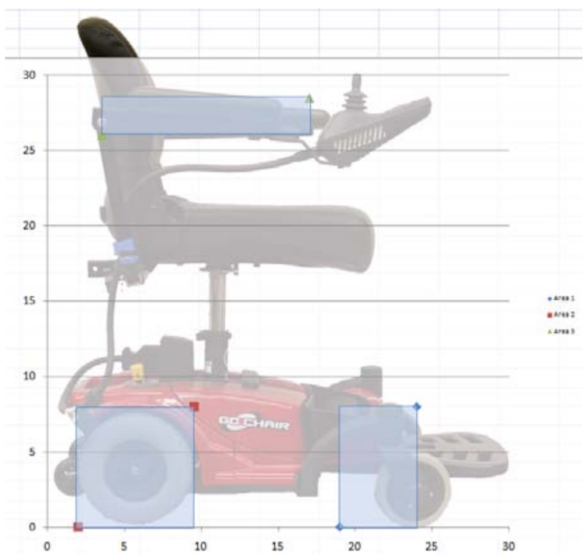


FIGURE 7 Location analysis graph for the GoChair. All dimensions in inches.

The analyses from all of the different chairs were composited onto one graph (fig 8). This graph allows common areas to be easily assessed and the final prototype design will be located to intersect as many of the common areas as possible. Notice the common areas around the armrest location and the front wheel.

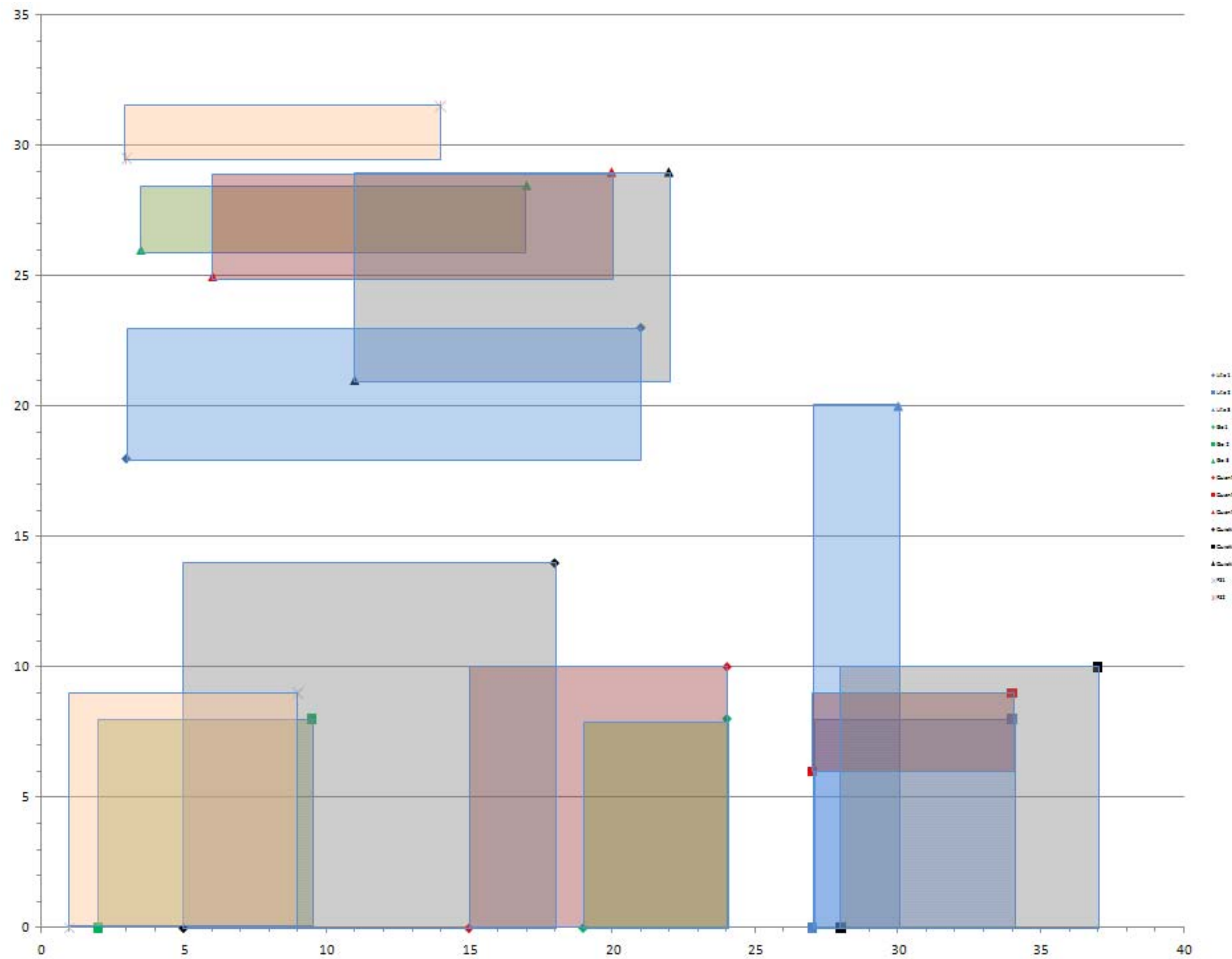


FIGURE 8 - Locations measured off all of the chairs. All dimensions are in inches. Blue represents the EZ Lite, green represents the GoChair, red represents the Quantum610, gray represents the S262, and orange the 2200FS.

In order to make the restraint system as universally applicable as possible, an additional ten chairs representing a variety of power chairs and three wheeled scooters were measured and added to the graph in figure 8. The additional chairs included several Pride Mobility models (Big Jazzy 1420, Jazzy 113, Celebrity XL, GoGo Elite Traveler, Victory), two Golden models (Liteway, Buzz Around Lite), a Quickie Prelude, a Nova Transport Chair, and an Invacare Storm TDX3. Figure 9 shows the complete location analysis.

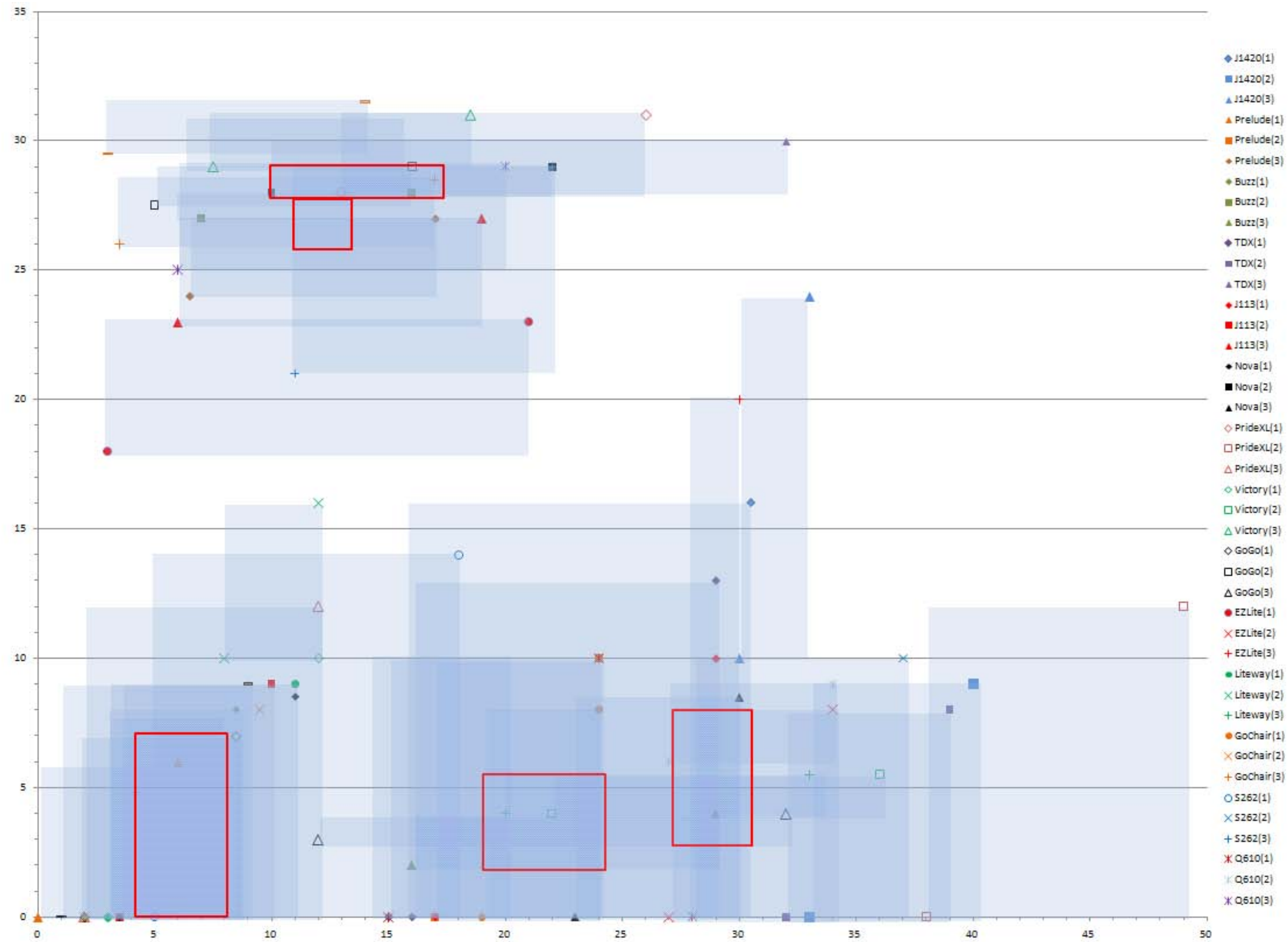


FIGURE 9 Complete location analysis. The most opaque areas are the more commonly shared between chair types.

From the areas outlined in red we will be able to deduce locations that will have the most universal impact for chairs of all varieties. This will aide in the placement and design of the final containment system.

Design Scenario

It is important to understand the environment in which the aisle-side barrier must function. All transit buses are required to have a 30-inch by 48-inch (minimum) wheelchair space clear of obstructions available for a passenger in a wheelchair. *(1, 4)* They must also have a clear center aisle for all passengers to board and exit the bus. Based on measurements taken on the EmX buses at Lane Transit District (LTD), it is 30 inches from the wall of the bus to the aisle. The aisle is 35 inches wide. The far wall is another 30 inches away. Many transit agencies maximize the amount of seating available for able-bodied passengers by mounting folding seats to the wall in the wheelchair space. These seats fold against the wall when a passenger in a wheelchair is occupying the space. The folded seats are 7 to 9 inches wide (fig. 10). Thus, the required 30 inches of clear area for the wheelchair space must include a portion of the aisle. This means that any aisle-side barrier has to be installed in the aisle when in use by a passenger in a wheelchair. Ideally, an aisle-side barrier would deploy 30 inches from the folded seats (in the aisle), and be able to move out of the aisle when not in use.

FIGURE 10 Interior dimensions of the EmX bus at LTD. Notice the folded seats mounted to the right wall. The current rear-facing station is the space on the left.

Design Requirements

Primary Customers

There are three primary customers who will be involved in the application and use of the aisle-side barrier. In the public transit industry, transit agencies may purchase vehicles from the manufacturers with minimal wheelchair safety equipment installed. Upon receiving the vehicle, the transit agency will install safety equipment from a third party manufacturer who specializes in wheelchair securement devices. The three primary customers who must be considered when designing a wheelchair securement system are:

1. *Transit passengers riding in wheelchairs*

Passengers who ride in wheelchairs are the primary end users of the containment system. They will be relying on the aisle side barrier to keep them safe on board transit vehicles. They are concerned with the strength, ease of operation, and aesthetics of the design. The design must preserve the dignity and independence of the passengers.

2. *Transit agencies*

Transit agencies will be responsible for installing, operating, and maintaining the equipment over the course of its useful life. These agencies are particularly concerned about the ease of installation and maintenance, cost, and fit and function of the device on board their particular vehicles. The device must be easy for the mechanics to install and maintain. It should be competitively priced. Most importantly, it must not require the vehicle driver's input to operate regularly, but should include capability for the driver to remotely operate the device.

3. *Wheelchair securement equipment manufacturers*

The wheelchair securement equipment manufacturers specialize in building securement systems and other safety equipment that will be installed on board transit vehicles. They will be building the device and selling it to vehicle manufacturers and transit agencies. This group will be primarily concerned with the ease and cost of manufacturing of the design.

Customer Requirements

The customer requirements for the retractable aisle-side barrier system were determined through conversations with Lane Transit District (LTD) of Eugene, OR, previous work done by a senior design team at Oregon State University (OSU), and general knowledge of the transit situation. The following are the customer requirements for the aisle-side barrier system:

- Must prevent a passenger's wheelchair from tipping or rotating into the aisle during typical bus maneuvers.
- Should give the passenger confidence in their safety.
- Must be easy for passenger to maneuver into and out of the rear-facing station.
- Must be pushbutton operated within easy reach of a passenger riding in a wheelchair.
- Must not obstruct the movement of any passengers (including wheelchairs) when retracted.
- Must leave a clear aisle space when retracted.
- Must be easily installed in the bus aftermarket.
- Should fit in the current aesthetic style of the bus.
- Must withstand normal operating conditions and abuse by passengers for the life of the bus.
- Must be reliable and easy to maintain.
- Must work for all types of wheelchairs that would use the bus, including: manual and power chairs, three and four wheeled scooters.
- Must not require action from the bus driver to operate.
- Controls for operating should be available to the bus driver.

- Must be easy to manually retract in the event of an emergency (collision, power failure, etc).
- Must deploy and retract reasonably quickly.
- Should minimize the possibility of passenger injury during operation.
- Manufacturing costs should be kept as low as reasonable.

Engineering Requirements

From the customer requirements, a set of engineering requirements were developed that were used to guide the concept selection and design process.

- The barrier must not allow an occupied wheelchair to tip or rotate into the aisle under 0.4 *g* turning forces.
- Must cover the armrest and front wheel locations discussed in part 1 (see Fig. 10).
- Will contain a space 30 inches wide from the folded seats when deployed.
- Be built of solid metal parts.
- Passenger in a wheelchair can load and unload in less than 10 seconds.
- Be retracted and deployed automatically.
- Operate with a single pushbutton in the wheelchair station.
- When retracted, the devise will extend less than 0 inches into the aisle, and less than 3 inches from the front of the backrest.
- Mount to existing bus features using 1 tool (wrench or socket).
- Installation takes less than 15 minutes.
- All actuation must be powered by 24 volt DC electricity or 70-psi air (available on most bus models).
- All edges will be rounded.
- Exposed metal parts will be polished to match handrails.
- Must withstand repeated pulls and pushes in all directions of 300 lbs without failure or deformation of greater than 1/4 inch.
- Provide easy access to actuators.
- Require no lubrication.
- No major repairs or component replacements necessary for 15 year of service life.
- No interaction between driver and passenger to operate.
- No out-of-seat time for the driver to secure the passenger.
- Must retract with less than 20 lbs of manual force.
- Motion should take ~ 6 seconds.
- All pinch points and motion must be guarded.
- Passengers will not be contacted with a force greater than 5 lbs.
- Manufacturing target price is $5000.

Concept Selection

Previous OSU Prototypes

The aisle side barrier designed in the current project builds on knowledge gained from two other prototypes designed and constructed at Oregon State University (OSU). These two designs influenced the background understanding and goals for the current design project.

The first generation of the retractable aisle side barrier developed at OSU was a proof-of-concept for a retractable armrest. The backrest was mounted on a rectangular frame which would be attached to the floor of the bus. In the bottom half of the backrest frame, a second, smaller frame housed the armrest. The small frame rolled on a pair of casters. It was pushed into the aisle space by a pneumatic actuator attached to the backrest frame. The armrest then rotated into position alongside the wheelchair with a second pneumatic cylinder mounted within the rolling frame. See figure 11. This prototype successfully demonstrated the functionality of an aisle side barrier that could be fully retracted into the backrest, but it was not strong enough to test under actual operating conditions. The two-step motion developed by this prototype was used in the final design.

An OSU senior design team built a second-generation aisle side barrier. This team designed a barrier that would be strong enough to demonstrate in an operational environment. The aisle-side barrier was dimensioned to fit the standard wheelchair space (30” x 48”). *(4)* The barrier rail was constructed from 1-1/2 inch diameter steel tube. It provided a horizontal armrest alongside the wheelchair. Next to the backrest, one end of the rail attached to a vertical air slide housed in a fixed vertical frame. At the far end of the space, the rail was bent downward to attach to a floor track. To retract the rail, the air slide pulled the near end of the rail vertically, which drew the point attached to the floor track toward the backrest (fig. 12).

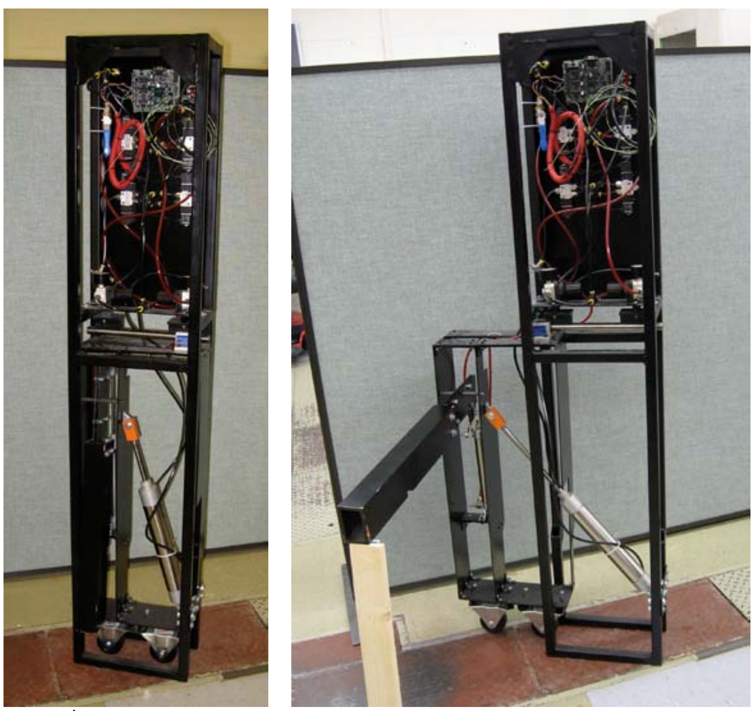


FIGURE 11 1st OSU prototype in the retracted (left) and deployed (right) positions.

FIGURE 12 2nd OSU prototype in the retracted (left) and deployed (right) positions.

This project was again a proof of concept. A number of inadequacies remained that must be addressed by the current design. The barrier rail was sized to fit the full length of the handicap space rather than the size of wheelchairs. It was longer than necessary. The rail was unable to fully retract. The bend in the rail extended a full 18 inches even in the retracted position, making it difficult for the passenger to maneuver into and out of the space. The air slide and floor track had to be permanently installed in a straight line, and it had no ability to retract out of the aisle. These features prevented the design from being practical for in-service use.

Concepts

Design concepts proposed during brainstorming were categorized based on the location where the retracted device would be stored. The main storage areas that were explored were: the floor of the bus, the overhead space, and behind the backrest (fig 13).

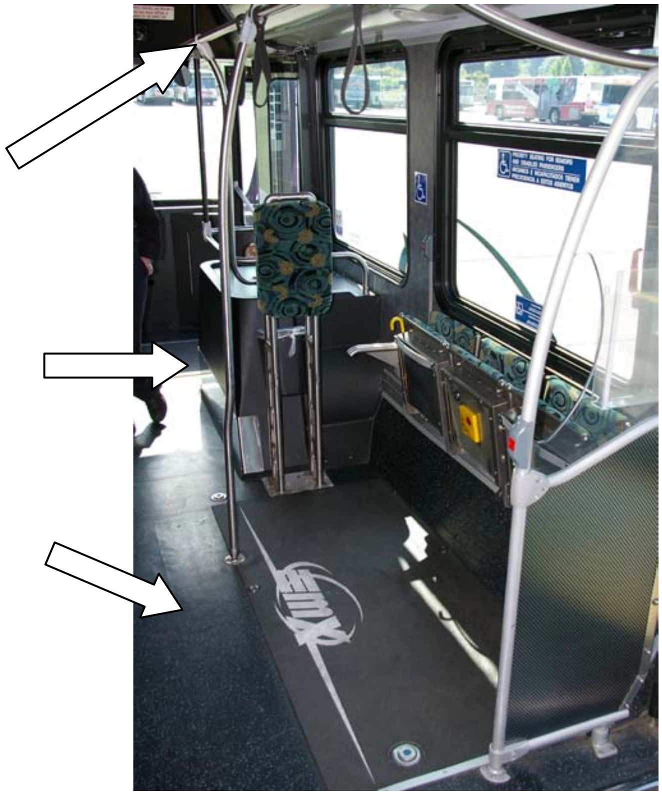


FIGURE 13 Rear-facing wheelchair containment station in EmX bus. Arrows indicate the possible storage locations for the aisle side barrier.

One concept was proposed that comprised a simple four-bar linkage that would rise out of the floor. While the device would have prevented the wheels of a wheelchair from rolling into the aisle, it was not going to be tall enough to properly protect a power wheelchair from tipping over (fig. 14).

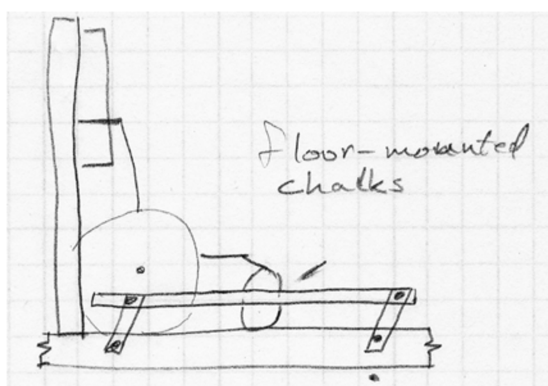


FIGURE 14 A sketch of the floor mounted four-bar concept.

Several ideas were proposed using the overhead space as a possible storage location. One concept looked like a collapsible ladder that would telescope down from the ceiling next to the wheelchair space to protect the passenger in the wheelchair (fig. 15). That concept was rejected because it could not be made sturdy enough to resist deflection during repeated use. Actuating this design would also have been challenging.

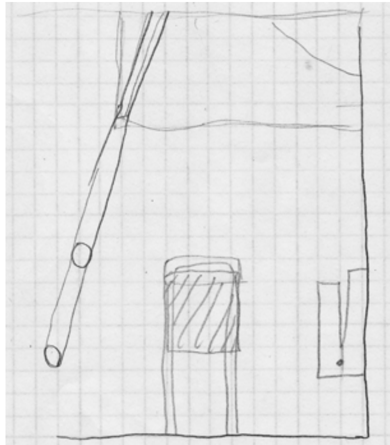


FIGURE 15 Sketch of the overhead ladder concept. View is facing toward the front of the bus.

The most obvious storage possibility was the space behind the backrest itself. Several ideas were explored to use this space. One was based on a rollercoaster harness. This system included a large harness mechanism that would rotate overhead to ride against the armrests of the wheelchair thereby securing both the passenger and their wheelchair (fig. 16). The idea was dismissed as being too bulky and intimidating for the passenger. Another one was based on a rotating arm similar to one proposed by the 2007 senior design team. A large side pad would rotate from behind the backrest and push against the side of the wheelchair (fig. 17). The forces required to push the pad against the wheelchair and resist the motion of the wheelchair would have presented a significant risk of passenger injury.

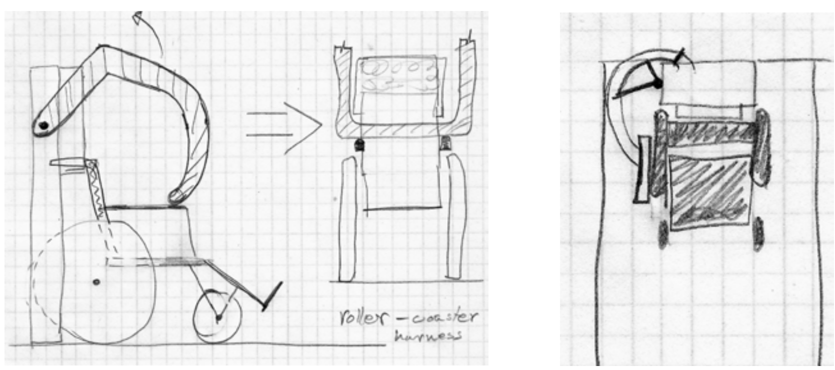


FIGURE 16 The rollercoaster harness concept (left) and the side pad concept (right).

After significant discussion about the benefits and problems with each design concept, two emerged as the best possibilities for successfully meeting the customer requirements for the system. These two concepts were modeled in 3D at a basic level of detail using SolidWorks. They were then submitted to employees of Lane Transit District (LTD) for their review.

The first design concept utilized the overhead space for storage. The design used a horizontal restraint bar that rode on guide rails. The guide rails, similar to the stanchions on the bus, would be installed at the front and rear of the wheelchair station. The restraint bar would retract above the wheelchair space, behind the overhead handrail. When in use, the restraint bar would roll down the guide rails to an appropriate height alongside the wheelchair (fig. 17). Because this system wrapped around the entire space, it could protect either forward-facing or rear-facing passengers using the station. It would be created from the same 1-1/4 inch diameter stanchion material that is already on the bus, thus fitting with the current visual style.

FIGURE 17 The side rail concept in the retracted position (left) and the deployed position (right).

This concept was considered by the designers to be the best concept, as it would be reasonably easy to actuate and would be capable of protecting passengers in either the rear or forward-facing positions. However, the employees of LTD who reviewed the concept, decided that it posed too high of a tripping hazard for able-bodied passengers who may be standing in the aisle next to the restraint bar. It would have reduced the dignity of travel for the passenger as they may feel caged or separated from the rest of the passengers by the horizontal bar. For this reason, that6 concept was deemed unsuitable.

The concept that proved to be most acceptable to LTD was a simple four-bar linkage that would fold out alongside the wheelchair space to provide an aisle-side barrier (fig. 18).. When not in use, it would be able to fold into a compact form and retract next to the backrest for storage. The four-bar concept was simple. An upper and lower horizontal link mounted on a pair of shafts would attach to a vertical post. The two horizontals would rotate upwards to fold the system. The shafts would connect the linkage to backrest frame and allow both linear and rotational motion.

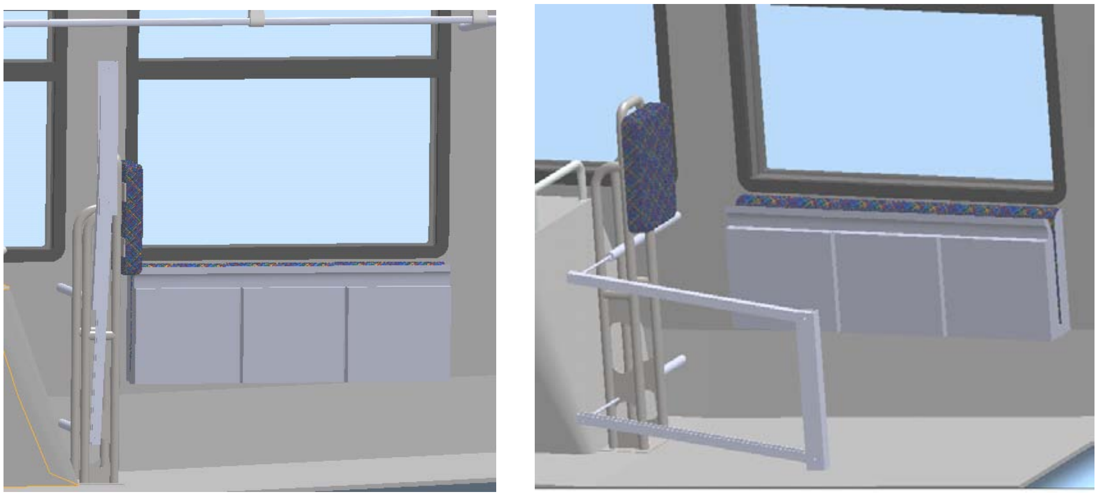


FIGURE 18 The four-bar concept in the retracted position (left) and the deployed position (right).

The downside to this concept was the height of the folded linkage. When the horizontal links rotated upwards, the system would stand over five feet tall. This was taller than the backrest (4.25 ft.). The barrier system would be a significant visual obstruction even when retracted. The concept was modified to achieve a more acceptable form.

Final Design

Description of Final Design

The final design developed from the four-bar concept described above by rearranging the linkage layout to create a system that would fold more compactly. The final linkage layout emulates a large triangle with a divided hypotenuse. The bottom link folds upward. The top link folds downward. These two links are connected by a mid link (fig. 19). The advantage to this system was that it could fold up in a shorter space, only 40 inches tall.

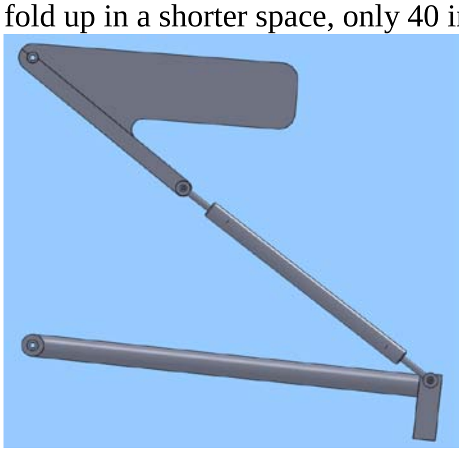


FIGURE 19 An early SolidWorks model of the final design.

In order to test the validity of the concept, a set of wooden links was created as a full-scale physical model. This model was used to understand the relationship of different link lengths and folding dynamics of the system (fig. 20). The bottom link was mounted five inches off the ground. The bottom link was made 36 inches long based on the data collected in part 1. A length of 36 inches allowed the bottom link to be mounted behind the backrest and have the far end of the link reach over 30 inches. The top link was mounted 32 inches above the ground. The top and mid link lengths were determined experimentally by adjusting the connection points until the system folded into its most compact form. It was determined that the lengths for the top and mid links were dependent on the lengths chosen for the mounting heights and bottom link, respectively (table 4).

FIGURE 20 Wood model linkage used to collect data about the link lengths. Shown in the retracted position (left) and the deployed position (right).

TABLE 4 The lengths of the four links determined with the wood model. The mount height and bottom link lengths were chosen and the top and mid links determined experimentally.

Mount height (in)	Top link (in)	Bottom Link (in)	Mid Link (in)
26	18	36	28
27	19	36	28
28	20	36	28
29	21	36	28
26	18	38	30
27	19	38	30
28	20	38	30
26	18	40	32
27	19	40	32
28	20	40	32

These experimentally determined lengths were then used as a starting point for building a SolidWorks model of the design. By using SolidWorks to design all of the parts, the design went through several virtual iterations from a concept to the final form.

In order for the system to be most effective for the many wheelchairs in use, it was sized based on the data gathered in the first part of this project (fig. 10). The bottom link must contain the wheels of the chair. This link must extend at least 30 inches from the front of the backrest in order to prevent the front wheel of a light wheelchair from rotating. The bottom link is 36 inches long to allow it to be mounted behind the backrest. An armrest barrier is attached to the top link in order to cover the common armrest areas and stop wheelchairs from tipping. This had to cover an area 26-30 inches above the bus floor and up to 25 inches from the front of the backrest.

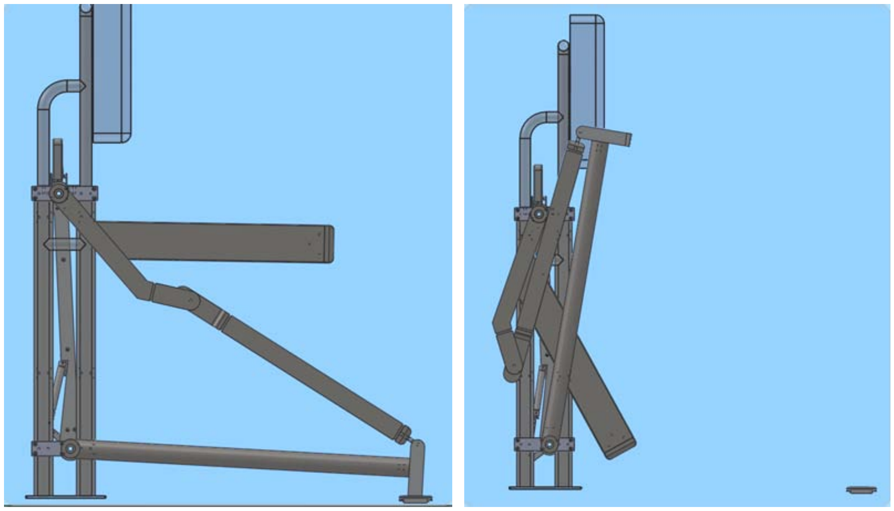


FIGURE 21 Final design of aisle side containment system in the deployed (left) and retracted (Right) positions.

The overall arrangement of the final design is shown both the working and retracted positions in Figure 21. To move the linkage from the stored position to the deployed position, it has to be moved into the aisle space, then rotated to unfold. This movement requires linear and rotational motion. To accomplish this compound motion, the linkage is mounted on a pair of shafts. The ends of the top and bottom links are mounted to separate one-inch diameter shafts. These shafts hold the two links at the designed mounting heights.

The next design consideration was how to power the system to make it automatic. Due to the folding dynamics, the top and bottom links could be balanced to minimize the input torque required to fold the system. The bottom and mid-link needed to be as light as possible. The top link needed to be heavy enough to help drive the upward motion of the bottom link.

Each link was tested for stress and deflection under load using COSMOS, a finite element analysis (FEA) software built into SolidWorks. As noted in the tilt table experiment each chair could be prevented from moving with a force of 60-pounds or less. In practical application however, the system must be able to withstand long-term use and abuse from all passengers on the bus. Therefore, the links were tested with a 300-pound applied force (fig. 22).

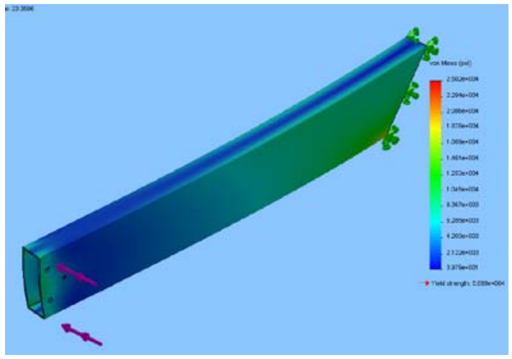


FIGURE 22 COSMOS generated stress diagram of the armrest barrier.

Analysis of Final Design

This is the first aisle side barrier for rear-facing wheelchair containment systems designed specifically to the dimensions of the most common wheelchairs. By studying a variety of wheelchair types, the system could be dimensioned to maximize effectiveness on a broad range of chairs. This system is the only one known that can deploy in the aisle space and completely retract out of the aisle when not in use. The retracted system is less than 4 inches wide and only extends 3 inches in front of the backrest. This leaves the aisle completely clear when the system is retracted. It also makes maneuvering into and out of the space very easy.

The barrier is the only one known to provide both an armrest height barrier and a barrier at wheel height. The armrest barrier is designed to cover the most common armrest locations. This part of the design is capable of protecting a power chair from tipping into the aisle. The bottom link is capable of preventing the wheels of most wheelchairs from rolling or sliding. This feature will protect lighter chairs from rotating. The combination of the two forms of protection should keep most wheelchairs from moving into the aisle.

The system's balanced folding dynamics is one of the biggest achievements of this design. To minimize the risk of passenger injury, the forces required to deploy and retract the system needed to be held to a minimum. By carefully selecting the size and weights of different parts in the linkage, the moments induced by the top and bottom linkage are nearly equalized. Data taken directly from the SolidWorks model was used to calculate the moments for the top and bottom links. For the calculations, half of the mid link weight was applied to the top link hinge and half to the bottom link hinge. The top link produces a moment of 377 in-lbs. The bottom link produces a moment of 390 in-lbs. Because of the folding dynamics, the difference between the moments is the total input force required to fold the linkage. The difference is only 13 in-lbs (fig. 23). This small difference minimizes the amount of input force that is necessary to fold the linkage, thereby decreasing the risk of passenger injury.

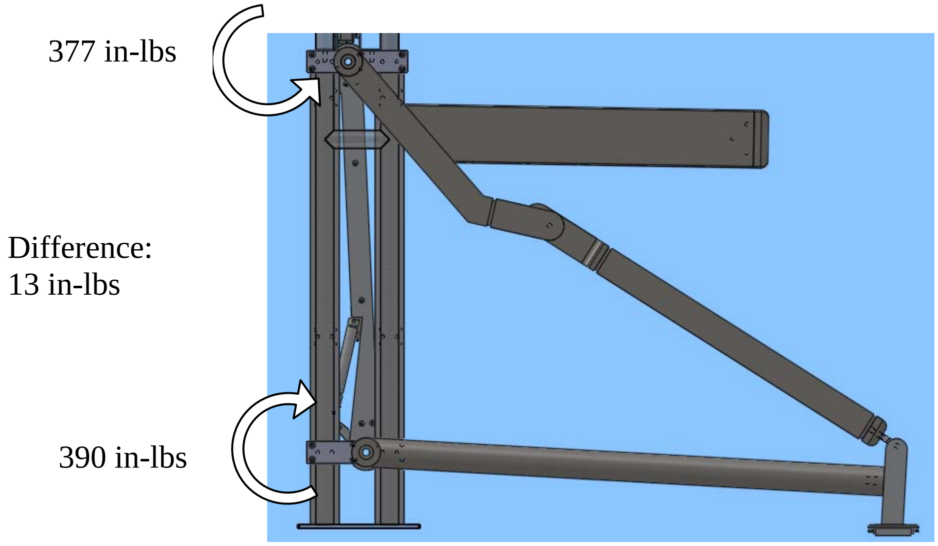


FIGURE 23 The moments (torques) required to rotate the upper and lower links. The mid link was divided and assumed to contribute half its weight to each hinge point. All of the data for this calculation was taken from SolidWorks.

It should be noted that because the retracted linkage is pulled against the backrest, a very few types of wheelchairs cannot back all of the way into the space without running into the linkage. This issue can be mitigated with a well designed user interface and control system. The passenger could initiate the deployment of the device before fully backing against the backrest.

FIELD TESTING

Testing of the design involved tests of its deployment and stowage in the laboratory and tests of its effectiveness as an aisle side barrier in a moving bus. In both cases the testing was qualitative in nature.

FIGURE 24 The prototype aisle-side containment system

A simplified prototype system was built for field testing with the primary goal of confirming that it would provide acceptable side containment during extreme maneuvering (Figure 24). This prototype system consisted of two basic parts, the backrest and the aisle side containment. The backrest was a duplicate of the backrest arrangement currently in use on Lane Transit District's EMX bus rapid transit system vehicles. The aisle side containment was built according the design described in the preceding sections with the exception that the sub-frame that houses the pneumatic system for stowing and deploying the movable arm was not included. All of the arm movement rotation and translation capabilities were included but they were not powered, rather they were done manually. The system was mounted on a piece of plywood that was 30 inches wide and 72 inches long so that it could be tested in the laboratory and then later placed on the floor of the bus without requiring any modifications to the bus floor.

The field testing took place at Lane transit District (LTD) in Eugene, Oregon. LTD made available one of their EMX buses (Figure 25), an articulated bus with doors on both sides. The system was placed in the wheelchair station located immediately behind the front wheel wells on the right side of the bus. A manual wheelchair and a scooter, the two wheelchair types identified in this project as being most in need of aisle side containment, were used in this testing. During the test of each chair, a 50th percentile anthropomorphic test dummy was used as the passenger. Test results were recorded during the driving tests using a single video camera located to the rear of the wheelchair station (but facing forward).

FIGURE 25 The bus on which testing of the prototype aisle side containment device took place was an articulated low floor vehicle used by Lane Transit District as part of their EMX bus rapid transit service. The location of tests on the bus was the wheelchair station located just in front of the center door and on the right side of the bus.

The tests proceeded in the following sequence:

- Install prototype device on bus.
- Position manual wheelchair occupied by test dummy in the wheelchair station. Wheelchair brakes were not engaged to test a worst case scenario.
- Take photographs of initial position.
- Start video camera.
- Begin test drives – driver instructions were to emphasize right turns to try and cause motion into the aisle and to make turns as violent and fast as possible.
- After finishing test drives, take photographs showing where the chair and passenger ended up.
- Repeat test using the scooter in place of the manual wheelchair.
- Remove prototype device from bus.

The results showed no surprises. There was virtually no motion towards the aisle for either type of chair. With the manual wheelchair there was motion towards the wall of the bus during left turns. This is a result of the space between the bus wall and the aisle side containment being considerable wider (approx. 33 inches) than the chair itself (approx 24 inches). After the planned test using a manual chair, the containment device was stowed and driving tests intitated to demonstrate the importance of preventing motion towards the aisle. The results, as can be seen in Figure 26, were dramatic. The very first (and rather modest in terms of acceleration) turn resulted in the rotation and movement of the wheelchair across the bus.

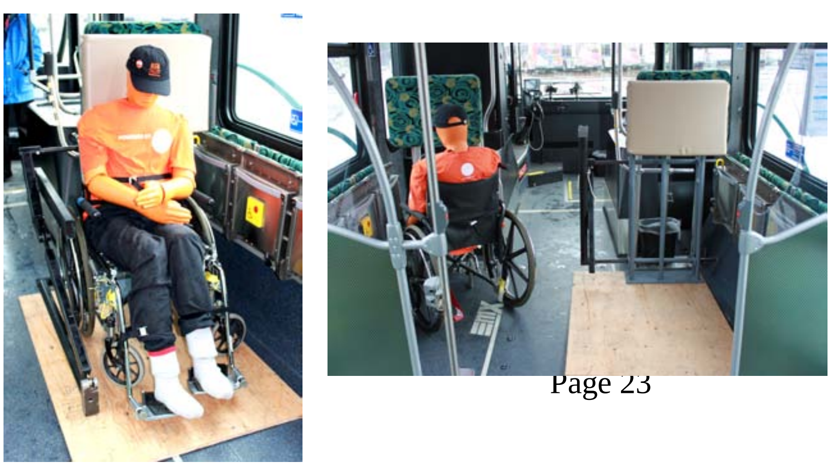


FIGURE 26 Looking towards the front of the bus, the manual wheelchair is positioned in the rear facing wheelchair station with the aisle side containment in place (left). Also shown is the result of a right turn by the bus when the aisle side containment is not used. (right)

When the scooter was tested (Figure 27) there was little movement at all. There was a strong tendency to tip towards the aisle due to the high center of gravity caused by the passenger weighing more than the scooter. There is no question that this occupied scooter would have tipped almost immediately on initiation of right turns had it not been for the aisle side containment. As it was, the scooter stayed snugly against the upper bar of the containment and the only tipping that occurred came during one particularly violent maneuver that caused the plywood base to lift up.

FIGURE 27 – This photograph was taken after extreme maneuvering of the bus in an attempt to cause movement of the contained (but unsecured) scooter. Although there was a very strong tendency for the scooter and passenger to tip over into the aisle, the containment system prevented it from doing so.

CONCLUSIONS

The most difficult aspect of the rear-facing containment system is providing an aisle-side barrier that can resist the motion of the wheelchair, yet not interfere with maneuvering of the wheelchair or the movement of other passengers on board the bus. The research conducted in Stage 1 of this project determined the engineering requirements, both force loading requirements and shape requirements, of an aisle-side barrier by characterizing many of the different wheelchairs currently in use.

The CG locations were measured for five different occupied wheelchairs. The motion response to lateral acceleration was observed and categorized. The force required to arrest the motion was measured. These measurements and observations were used to understand the force requirements for the design of an aisle side barrier. Fifteen different wheelchairs were measured to determine areas on the chairs that could be used to effectively prevent them from moving. These different areas were composited onto a single graph to determine the most effective placement of an aisle side barrier to cover the many different wheelchairs used by transit passengers.

This data then guided the design of a new retractable aisle side barrier for rear-facing wheelchair containment systems. The key customer requirements for the design were determined through an understanding of the transit situation and conversations with employees of Lane Transit District in Eugene, OR. Many different concepts were proposed and eliminated before the final design was selected.

The final design is a four-bar linkage that rides on a pair of guide shafts mounted to the backrest. The shafts allow the linkage to move into the aisle space and unfold into position when needed. When not in use, the linkage folds up and retracts next to the backrest. The motion is accomplished with a pair of pneumatic actuators that can be fully automated with push-button operation. By balancing the moments of the top and bottom links, the linkage requires a very small amount of force to fold. This is the first system to provide an effective aisle-side barrier that can be completely retracted out of the aisle space when not in use.

In field tests of a manual wheelchair and a four-wheel scooter, the prototype developed by this project successfully demonstrated the effectiveness of this retractable aisle-side containment system. Wheelchair rotation and tipping during extreme vehicle maneuvering were both shown to be prevented by the aisle-side containment system.

Principal Investigator Profile

Dr. Joseph Zaworski's background in wheelchair transportation includes work in the area of mass transportation in general and in buses and aircraft in particular. Since 1990, he has been involved in the design, construction, testing and demonstration of securement systems suitable for all types of wheelchairs including manual chairs, powered chairs, scooters, powerbases, and other variations on wheeled mobility aids. In the course of this research, he has developed a good working knowledge of the manufacturers of chairs, the construction of chairs, their power mechanisms, and the mechanics associated with their motion. His experience in working with wheelchairs includes component testing in the laboratory, field testing of chairs for loading and unloading as well as securement, stability testing of chairs using a tilt table, and sled testing of chairs for crash simulation.
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