

**Innovations Deserving
Exploratory Analysis Programs**

Transit IDEA Program

Assessment of Rear Facing Wheelchair Accommodation on Bus Rapid Transit

Final Report for Transit IDEA Project 38

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TABLE OF CONTENTS

EXECUTIVE SUMMARY	1
IDEA PRODUCT	3
CONCEPT AND INNOVATION.....	3
INVESTIGATION	5
Testing Overview	5
Equipment Used	5
Test Vehicles	5
Wheelchairs	6
Anthropometric Dummy.....	7
Securement Arrangement.....	7
Instrumentation	7
Survey Instrument	7
Test Procedures	8
Normal Maneuvering Tests.....	8
Extreme Maneuvering Tests.....	8
Crash Tests	9
Data Reduction	10
RESULTS	11
Bus Dynamics- Normal Driving.....	11
Bus Dynamics- Extreme Driving.....	16
Bus Dynamics- Crash Tests	19
Wheelchair Response	21
Wheelchair Response Rear Facing Backstop Only.....	23
USER AND POTENTIAL USER RESPONSE.....	26
PLANS FOR IMPLEMENTATION	28
CONCLUSIONS	29
INVESTIGATOR PROFILE.....	30
REFERENCES	30

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LIST OF FIGURES

FIGURE 1	Concept BRT Vehicle	3
FIGURE 2	Sketch of Rear Facing Securement	3
FIGURE 3	Rear Facing Securement Station.....	4
FIGURE 4	Test Vehicles and Wheelchairs	6
FIGURE 5	Calibration Apparatus	7
FIGURE 6	Tri-Axial Accelerometers	7
FIGURE 7	35Ft Low Floor Test Vehicle	9
FIGURE 8	Vehicle Interior Showing Instrumentation	10
FIGURE 9	Distribution of Forward Acceleration	12
FIGURE 10	Distribution of Left Turn Acceleration	13
FIGURE 11	Distribution of Right Turn Acceleration	14
FIGURE 12	Distribution of Stops	15
FIGURE 13	Example Accelerations Extreme Maneuvering.....	17
FIGURE 14	Car and Bus after 30 MPH Crash	20
FIGURE 15	Floor Accelerations of Large Urban Bus	21
FIGURE 16	Construction of Backrest in Test Apparatus.....	22
FIGURE 17	Test Dummy in Three Wheeled Scooter	22
FIGURE 18	Power Wheelchair in Side Facing Tests	24
FIGURE 19	Panic Stop and Manual Wheelchair	25
FIGURE 20	Rear Facing Mobility Aid Securement Station	26

LIST OF TABLES

TABLE 1	Key facts on Test Vehicles	6
TABLE 2	Summary of Normal Accelerations	16
TABLE 3	Summary data for 40 ft. Low Floor Bus.....	18
TABLE 4	Summary of data for extreme maneuvering.....	19

EXECUTIVE SUMMARY

Background

Securement of wheelchairs on large urban transit buses has been limited to forward facing belt-type systems since before the advent of the Americans with Disabilities Act (ADA) in 1990. Although this system is time consuming, requires operator assistance, and is sometimes difficult to correctly use, it has served the transit industry adequately.

Bus Rapid Transit (BRT) is in the early stages of implementation in a number of cities around the country. This concept is based on minimizing dwell time at stations to provide much shorter transit travel time than is possible with conventional urban bus transit systems. To accomplish short dwell times, ticketing can be done at the stations prior to entering the bus and vehicles can have multiple doors, all of which can be used for both entry and exit.

Clearly the wheelchair securement system currently in use is incompatible with the concept of short dwell time. An alternative that has been used in Europe and Canada is to allow the wheelchair user to station themselves in a securement station facing the rear of the bus with the rear of their wheelchair against a padded backrest. This system appears to have great promise for use in BRT, but before this passive securement system is used in regular transit operations, the comfort and safety that it provides wheelchair users must be evaluated. This project reports results from an extensive and verified study of vehicle dynamics under normal and extreme driving conditions. In addition, qualitative studies were also conducted using rear and side facing orientations with different types of wheelchairs under extreme driving conditions.

Project Description

The goal of this Transit IDEA project was to evaluate the rear facing wheelchair securement for BRT and investigate wheelchair and wheelchair-user response to this method. This was done in three distinct parts: measurement of vehicle dynamics to provide a clear basis for any conclusions about alternative securement systems; evaluation of wheelchair response to bus motions using rear facing and side facing passive securement; and evaluation of user response to the concept of rear facing securement. A major collaborator on this project was Lane Transit District in Eugene Oregon, where all the normal driving tests were conducted, and many of the extreme driving tests were also conducted.

An effective opportunity presented itself early in this project. A very complementary project was starting at the same time in Canada with Rutenberg Design, Ltd. and BC Transit in British Columbia, Canada. Collaboration with this team resulted in this project having access to more types of buses for testing, an opportunity to survey users of rear facing securement in Victoria, B.C., as well as an opportunity to participate in crash tests between buses and automobiles to evaluate securement forces required in a crash scenario.

Vehicle dynamics for normal in-service operation were measured by recording bus floor accelerations of Lane Transit District buses in Eugene, Oregon, as they went on their various routes. Extreme maneuvering vehicle dynamics were evaluated for six different models of large urban transit vehicles: a 30 ft. low floor bus, a 35 ft. low floor bus, a 40 ft. low floor bus, a 40 ft. high floor bus, a 40 ft. double-decker bus, and a 60 ft. articulated bus.

Wheelchair response to normal and extreme maneuvering was evaluated for three types of wheelchairs and three configurations of passive securement. A manual wheelchair, three-wheel scooter, and a power-base type wheelchair were evaluated for motion when secured on a bus with (a) a backrest only rear-facing arrangement, (b) a side facing with forward wall only arrangement, and (c) a rear facing compartment with a backrest, sidewall, and aisle-side armrest. In all cases the wheelchair was occupied by a 50th percentile male anthropometric dummy with its chest strapped to the backrest of the wheelchair as might be done as an aid for posture.

Users of BC Transit rear facing securement in Victoria were surveyed and potential users of rear facing securement at Lane Transit District in Eugene, Oregon were surveyed to determine how they do (or would) use this type of securement and what their attitudes are about it. The same questions were asked of both groups but the Lane Transit group received a two page description of the concept of rear-facing securement along with their survey.

Results

The first results from this project were vehicle accelerations, the source of motion for a wheelchair in a securement station. Three numbers are presented for forward accelerations, side accelerations (turning), and rearward accelerations. The first two numbers presented come from measurements taken on buses during normal in-service operation. These numbers report the average acceleration and the maximum acceleration in the given direction. The third number comes from measurements taken on a test track and reflect the maximum accelerations the drivers could achieve under any circumstances short of damaging the bus. In the case of forward accelerations the average for normal driving was about 0.10g and the maximum recorded was 0.2g; the maximum forward acceleration during extreme maneuvers was 0.4g. For turns, the average during normal driving was about 0.18g but the maximum recorded was 0.4g; the maximum acceleration during extreme maneuvering was 0.45g. For rearward accelerations (decelerations) the normal driving average was 0.19g with a maximum recorded value of 0.37g; during the panic stops of extreme maneuvering the maximum decelerations were as high as 0.86g.

Wheelchair movement was strongly dependent on wheelchair type. During normal driving, the manual chair would rotate during turns, the three-wheel scooter would tip during the stronger turns, and the power wheelchair was stable under all normal conditions. During extreme maneuvers, all three types of wheelchairs could be made to tip over if provided with a backrest or wall on only one side. The wheelchair would tip over during extreme turns when rear facing and during a panic stop when side facing. The three-wheel scooter would tip during turns when rear facing and during a panic stop when side facing. The power wheelchair would tip over backwards during an extreme turn when side facing.

Results of the survey were remarkably similar for users and potential users. Overall approximately 70% were enthusiastic about rear-facing securement, about 10% had no opinion and about 20% did not want to use rear facing securement.

Conclusions

Passive wheelchair securement such as the rear-facing approach used in some countries is attractive to providers of mass transit because it requires no operator assistance and it is fast. The results of this project, however, demonstrate the importance of proper implementation. During normal driving conditions, users of manual wheelchairs and three-wheel scooters must expect some normal movement of their wheelchairs¹. The securement stations in buses using rear facing securement must be equipped with handrails, stanchions, or armrests in addition to the necessary backrest so that the user can assist in preventing the incidental movement of their wheelchair.

In the event that extreme maneuvering is required, such as swerving to avoid an accident or making an emergency stop, catastrophic motion (tipping over) of an occupied wheelchair may result if the rear facing securement station does not provide support on both sides as well as the front of the securement station. If containment on three sides of the station is provided, it can be reasonably expected that a wheelchair will move but stay upright and not be seriously damaged during extreme maneuvering.

The results of this project make it clear that rear facing securement of wheelchairs, a fast and independent approach that has important advantages for BRT, can be successful. More work needs to be done to identify the best ways to minimize incidental movement and prevent catastrophic movement for all types of wheelchairs, but there are no inherent barriers to successful implementation of this approach.

¹ In this report, wheelchairs refers to the family of wheeled devices used by people with mobility impairments. Manual wheelchairs, power wheelchairs, power bases and scooters are members of this family of devices.

IDEA PRODUCT

The results of this Transit IDEA project will have a major impact on the design and understanding of wheelchair securement, and it will open the door for a review of the existing Americans with Disabilities Act (ADA) requirements. The project results will provide more options for the interior design of Bus Rapid Transit (BRT) vehicles (Figure 1) in particular and of new transit vehicles in general. Finally, in the long run, it is anticipated that securement of wheelchairs on mass transit vehicles may be effectively resolved for both the wheelchair users and the vehicle operators.

The principle benefit of the research has been a determination on the adequacy of rear facing compartment securement systems (Figure 2). Specifically, the project determined whether this type of passive securement provides acceptable levels of comfort and safety for users of wheelchairs. In addition, the project has resulted in an increase in knowledge of bus transit vehicle operating dynamics, the effect of those dynamics on passengers using wheelchairs, and detailed information that would justify less restrictive requirements for mobility aid securement.



FIGURE 1 - Concept BRT vehicle, (courtesy of Lane Transit District, Eugene, OR)

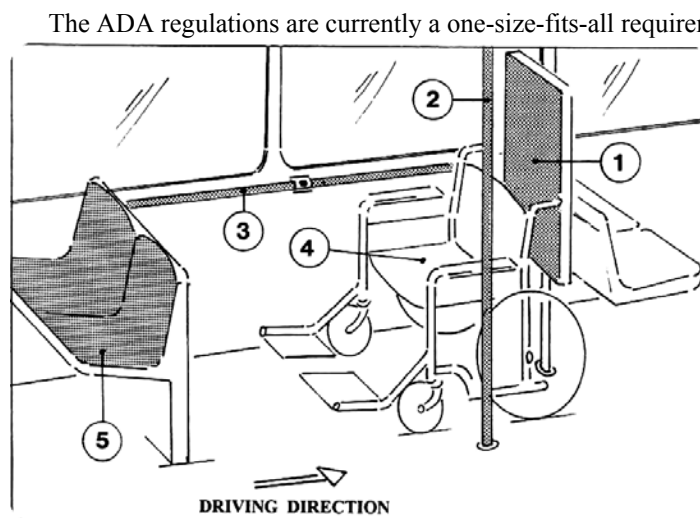


FIGURE 2 - Sketch of rear facing securement (courtesy Uwe Rutenberg) Numbered features are (1) rear-facing load bearing back rest, (2) aisle side vertical stanchion, (3) horizontal handrail, (4) rear facing wheelchair (5) rear facing general seats.

The ADA regulations are currently a one-size-fits-all requirement that wheelchairs on buses be forward facing and secured such that there never be more than two inches of motion under normal operations². At the time these regulations were created there was very little data available to justify taking into account the mass and operating characteristics of transit vehicles. As a result, the ADA requirements have made the adoption of securement systems that are appropriate to the size and type of transport vehicle particularly challenging. This research is fundamental for the transit industry, as well as for persons with disabilities in that it will provide a clear justification for review of the current ADA requirements. A number of federal agencies, such as the U.S. Department of Transportation, the U.S. Department of Justice, and the U.S. Access Board will benefit from the results of this research. The results of this research are key to providing information for re-evaluating the regulations of the ADA concerning mobility aid orientation and securement. These are changes that are needed as a precursor to the design of BRT vehicles and new transit vehicles.

CONCEPT AND INNOVATION

Bus Rapid Transit (BRT) systems need to feature very rapid loading and unloading to minimize the station dwell time, as is done with light rail transit systems. Wheelchair securement is an essential element of rapid loading and

² The wheelchair orientation requirements given in ADA part 38.23 (d) (4) actually do permit rear facing securement in vehicles that are greater than 22 feet in length provided that at least one of the securement positions is forward facing. The rear facing securement position includes a padded barrier. It should be noted that in vehicles less than 22 feet in length only one securement location is required by the ADA and it may be either forward or rearward facing. It should be noted that in the US the overwhelming practice is to provide forward facing securement locations.

unloading, so technologies such as rear facing compartments, docking systems, and two-point oblique systems are being considered to replace the traditional forward facing four-belt securement systems. This project studied the response of wheelchairs as well as users to the use of rear facing compartment securement. The concept is that wheelchairs can be safely transported using passive securement rather than active securement such as the belt securement currently in use by virtually all transit agencies. This passive securement would be accomplished by stationing a mobility aid at a location where its movement is constrained by the walls of a compartment. This project demonstrated this system and determined both the safety and the user comfort level for this type of mobility aid accommodation.

Wheelchair securement is an issue in public transit that has not been clearly resolved, even though it has been more than 14 years since passage of the Americans with Disabilities Act (ADA) in 1990. Fundamentally, the ADA³ requires that wheelchairs be secured forward facing and such that they will not move more than two inches in any direction, vehicle under normal operating conditions. There is no discussion of wheelchair movement under crash conditions. Rear facing securement is an option only if there is a forward facing securement station. Since the ADA was put into law, some advances have been made in securement technology but they have yet to make it into the marketplace. In recent years, there has been a renewed interest in Bus Rapid Transit (BRT). One of the keys to BRT is the design of new transit vehicles that can operate in a fashion analogous to light rail. An important factor in the success of BRT implementation will be minimization of the bus stop dwell time. Two of the major contributors to dwell time are mobility aid securement and fare collection procedures. Off-vehicle fare collection reduces dwell time, and permits the use of multiple access/egress doors. The securement of wheelchairs is still a major problem for the designers of new transit vehicles.



FIGURE 3 - A rear-facing securement station on a BC Transit vehicles showing the padded backrest and aisle side stanchion.

In Europe and Canada, a different concept in wheelchair securement has emerged. This consists of a padded compartment for a wheelchair in a rear facing orientation (Figure 3). The wheelchair is stationed in this compartment but there are no belts or other attachments to the chair. It should be noted, that some rear facing systems have belts available as an extra option. Currently, this concept is not considered in the U.S., due to public perceptions on rear facing and interpretation of the transportation regulations of the ADA. However, this approach appears very attractive for the innovative BRT systems which will use new transit vehicles, new modes of operation and new operating conditions.

An important part of the successful development of new securement concepts is a thorough demonstration of both their effectiveness and user acceptance. This would necessarily include demonstrations based on commonly occurring circumstances in vehicle operation, situations such as accelerating around a corner, crossing railroad tracks, or starting on a steep hill. The assessment of wheelchair securement must include both a measurement of mobility aid dynamics and a measurement of bus vehicle dynamics during these operations. For the vehicle, the principle variable of interest is acceleration because it is the driving force behind motion of passengers and wheelchairs. For the wheelchair the principle variable of interest is displacement because it is motion of the mobility aid that leads to both user discomfort and potential safety hazards. The assessment also included a review of user perceptions as related to specific events encountered during the demonstration.

The demonstration and evaluation of rear facing compartment securement was carried out using a variety of vehicles and a variety of wheelchair types. Throughout this project, Lane Transit District (LTD) of Eugene, Oregon, was a primary collaborator. Their participation continued the partnership that Oregon State University (OSU) has had in the past for the testing of new approaches to securement. LTD currently has a fleet of buses which were made available to the research team to install the necessary systems. This fleet includes traditional style buses, articulated buses, low floor buses, and most recently hybrid power (gas turbine/electric) buses. It should also be noted that they will be one of the first transit systems in the nation to be implementing BRT.

³ ADA part 38.23.(d) (5)

INVESTIGATION

This investigation into rear facing securement as an option for large mass transit buses was designed to answer two basic questions:

1. Is the level of securement acceptable during normal bus operations both from a safety perspective and the user's perceptions?
2. Does rear facing securement provide an adequate level of safety for emergency conditions of evasive maneuvering or a crash?

Both of these questions involve two distinct sets of characteristics, the vehicle dynamics and the wheelchair dynamics inside of that vehicle. To answer these basic questions the investigation was designed to identify the key vehicle dynamic characteristics and the primary response of wheelchairs to that motion. In the sub-sections that follow, an overview of the testing is given, the equipment used for this investigation is described, the procedures are outlined, and the results are presented.

It should be noted that a very similar project involving BC Transit and sponsored by Transport Canada was underway simultaneously with this investigation. Because of the complementary nature of the two projects, arrangements were made to collaborate in a way that provided both teams with substantially more data than was originally written into the project work plans. [Rutenberg, 2004]

TESTING OVERVIEW

The concept of rear facing securement was tested using a variety of vehicles, driving conditions, and wheelchairs. Initial testing and development of test procedures was completed using the 40 ft high floor bus, a rear facing securement system, and three types of wheelchairs - a manual chair, a three wheeled scooter, and a power chair. Following the initial testing, the vehicle dynamics during normal in-service operation were measured by riding the bus and recording accelerations as Lane Transit District buses went on various routes in Eugene, OR.

The next major tests were to determine the response of buses during a 30mph frontal impact with an automobile. These tests were conducted by the Canadian research team with the assistance of the Transit IDEA project team and the sponsorship of BC Transit in Victoria, British Columbia. The acceleration of the buses during the impact was recorded to provide a basis for evaluation of the safety of rear facing securement during a crash.

The final stage of testing characterized the dynamics of buses during extreme maneuvering and evaluated the motion of wheelchairs during those maneuvering and normal driving conditions. For this stage multiple bus types were used with testing being done both at Lane Transit in Eugene, OR and at a test track in Delta, B.C. Also, for the extreme maneuvering tests at both locations, three basic types of wheelchairs were used and for the tests they were occupied by a 50th percentile male test dummy.

The results of this test project provide a summary of what accelerations can be expected in a bus during normal driving, extreme driving, and a crash. It also resulted in some clear conclusions about the response of an occupied wheelchair in a rear facing securement system to normal and extreme driving conditions.

The acceptability of rear-facing securement from the point of view of users and potential users was evaluated through a survey of mobility aid users, some of whom have used this type of securement and some of whom have only read about it.

EQUIPMENT USED

Test Vehicles - In all cases, the test platform for this project was an accessible urban bus of one type or another. A total of 6 different models of bus were used for the various portions of this project. Figure 4 is a photo of two BC Transit test vehicles and wheelchairs. They were as follows:

- 40 ft. high floor bus,

- 30 ft. low floor bus,
- 35 ft low floor bus,
- 40 ft low floor bus,
- 40 ft low floor double-decker bus,
- 60 ft articulated bus.

Additional details on the buses used for these tests is are provided in Table 1



FIGURE 4 - Some of the BC Transit buses and wheelchairs used in the course of determining vehicle dynamics and the corresponding response of wheelchairs when secured in a rear facing compartment.

TABLE 1 – Key facts about buses used in the testing of bus dynamics. All buses were subject to extreme maneuvering tests. The normal in-service driving tests were done using only the 40 ft (12.2m) low floor bus and the 60 ft (18.3m) low floor articulated bus.

Description	Manufacturer	Year Built	GVW	Brakes
30 ft(9.2 m)Low Floor	Dennis (Guilford, England)	1999	11,500 kg (25,330 lbs)	No ABS
35 ft(10.7 m) Low Floor	Dennis (Guilford, England)	2000	12,960 kg (28,546 lbs.)	ABS
40 ft(12.2 m) Low Floor	New Flyer	1998	13,230 kg (29,141 lbs)	No ABS
40 ft(12.2 m) Low Floor Double Decker	Dennis (Guilford, England)	2002	23,100 kg (50,881 lbs)	ABS
60 ft(18.3 m) Low Floor Articulated	New Flyer	2004	65,050 lb (29,533 kg)	ABS
40 ft(12.2 m) High Floor	Gillig	1985	38,240 lb (17, 361 kg)	No ABS

Wheelchairs – Five wheelchairs representing the three basic types (manual, scooter, power) were used at different times during the project. Most work focused on the first three of the list that follows:

- Manual Wheelchair weighing approx 40 lb (18kg)
- Three Wheel Scooter weighing approx 120 lb (55kg)
- A Heavy Powered Chair weighing approx 200lb (91kg)
- A Lighter Powered Chair
- A Four Wheel Scooter

Anthropometric Test Dummy- A 50 percentile male crash test dummy was used for all the normal, extreme and crash tests. The test dummy sat in each of the wheelchairs.

Securement Arrangements – Two orientations for securement and three variations on the rear facing compartment were tested during the course of the project:

- Rear Facing no aisle side support
- Rear Facing with a stanchion
- Rear Facing with an armrest
- Side facing with forward support

INSTRUMENTATION

The basic instrumentation consisted of accelerometers for the measurement of bus accelerations and video recording of the mobility aid response to bus accelerations. The accelerometers were Crossbow 4-g tri-axial accelerometers model CXL02LF3-R) which have a sensitivity of 2V/g and include internal supply voltage regulation. The analog output signal of the accelerometers was connected to an IOTech model 300 Logbook standalone data acquisition system. This system is capable of analog to digital (A/D) conversions at a rate of 100 kHz and it uses a 16 bit A/D converter. Both before and after testing, the accelerometer and data acquisition unit were calibrated as a package using a static calibration procedure based on accelerometer orientation. A digital format video camera was used to record mobility aid response during bus maneuvers. Figure 5 shows the calibration equipment, and Figure 6 shows the mounting of the tri-axial accelerometers.



FIGURE 5 – The calibration apparatus for checking the offset voltage and calibration constant for each axis of the accelerometers.

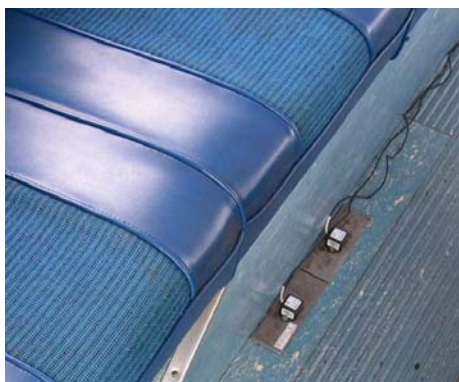


FIGURE 6 – A pair of tri-axial accelerometers mounted on the floor of a LTD bus.

SURVEY INSTRUMENT

The survey of users and potential users was a two page questionnaire that was developed specifically for evaluation of user and potential user response to the concept of passive, rear-facing wheelchair securement. This instrument was approved by the Oregon State University Institutional Review Board (IRB) prior to its use.

TEST PROCEDURES

Two types of tests were completed as a part of this project: normal vehicle dynamics testing and extreme maneuvering vehicle dynamics testing. Both of these tests included installation of acceleration monitoring equipment to obtain a quantitative recording of the bus floor accelerations. In addition, for the extreme maneuvering tests the video cameras were installed to obtain a video recording of the response of wheelchairs to the various bus accelerations. In addition to the driving tests, this project assisted the Canadian team in the measurement of bus dynamics during a 30 mph full frontal crash with an automobile.

All of the testing involved vehicle dynamics. In particular, the acceleration of the vehicle floor during the test event was the quantity of interest. When a bus is moving and a wheelchair in it is well secured, then as the bus experiences a negative acceleration (a deceleration) it exerts a force through the securement system to the mobility aid causing the mobility aid to decelerate as well. The magnitude of the force required is expressed by Newton's second Law, $F = ma$. For the bus to accelerate a mobility aid of mass "m" at an acceleration "a", it must exert a force on the mobility aid of magnitude "F". Thus knowledge of the bus acceleration is necessary to develop an understanding of the securement forces required for the mobility aid. The "jerk rate", which is the rate of change of acceleration, was not measured because the study focused on the response of the wheelchair not that of passengers. Jerk rate is an important consideration when measuring the reaction of passengers to a rapid change in acceleration.

To determine the acceleration of vehicles, a tri-axial accelerometer is used. It is oriented in the vehicle such that the x-axis is parallel to the aisle, the y-axis is perpendicular to the aisle, and the z-axis is up and down. With this sensor, a clear measurement can be made of the bus speeding up (negative x-acceleration), slowing down or braking (positive x-acceleration), turning left (positive y-acceleration), turning right (negative y-acceleration), or moving up and down (positive and less positive z-acceleration respectively⁴).

Normal Maneuvering Tests – The measurement of bus accelerations during normal operation was conducted by installing the accelerometers on buses that were currently in-service and recording the accelerations as they completed their route. Installation of the accelerometers had been streamlined such that the observer could carry on the instrumentation package and have the accelerometers installed at one end of the mobility securement station in a matter of one or two minutes. The observer therefore was able to ride several buses on several routes on any given day.

The routes for which data was collected included stop and go inner-city traffic, high speed sweeping curves, and steep hills. Because the topography of cities can vary greatly, no effort was made to obtain a statistically valid sample of the routes for these tests. Inclusion of routes with extreme conditions, however, was considered important so that the full range of normal driving conditions might be represented.

A result of using sensitive accelerometers is that some level of noise is recorded along with the primary signal. This noise, combined with the low levels of acceleration associated with normal driving and the data collection rate of 100 Hz for each axis, made standalone analysis of the data very challenging. As an aid in identifying features of the recorded accelerations, the observer on the bus maintained a log detailing the times of starts, turns and stops so that these events could be found more readily in the large quantity of recorded data.

The response of wheelchairs in rear facing securement was not included in this part of the testing. That was because of the necessity of keeping the securement areas available for customers.

Extreme Maneuvering Tests- Extreme maneuvering tests were conducted in buses with no passengers. The test areas were a large open area at the Lane Transit District yard in Eugene, Oregon and a test track in Delta, British Columbia, Canada. The tests involved driving the bus on a prescribed path that included maximum accelerations, maximum turns, and maximum stops. Figure 7 shows a 35 ft low floor bus being driven through the extreme maneuvering test track.

⁴ In the x and y-directions the accelerometer has an output of 0g when the bus is at rest. However, in the z-direction the accelerometer shows an output of one "g" when the bus is at rest. Therefore, the z-direction accelerations are centered on 1g rather than 0g.



FIGURE 7 – A 35 ft low floor BC Transit bus being driven through the extreme maneuvering test track.

The tests done at Lane Transit District in Eugene, Oregon, started with a “pedal-to-the-metal” acceleration to approximately 25 mph followed by left turns that were as severe as the driver was willing to do. The bus was then returned to a straight track to perform a panic stop from about 25 mph. The test was then repeated but in the opposite direction to get maximum severity right turns.

At the test facility in British Columbia the design of the course sequence was as follows: a maximum acceleration to 30 mph on a straight section, a swerve to the right and back, a straight section, hard turns to the right, a panic stop while turning right, continuation to the right then a return to the straight section, a swerve to the left and back, a straight section, hard left turns with a panic stop, a final return to the straight, and a panic stop from 30 mph. This track contains exactly the same elements as the Lane Transit District track. Where the Lane Transit District tests were completed in two parts, the British Columbia tests were done in three parts. There was a brief pause after each panic stop to check equipment.

The magnitude of accelerations during these maneuvers was recorded using the same dual tri-axial accelerometer setup and data collection rate (100Hz for each axis) as was used for the normal driving tests. Four to eight runs, each with a full collection of extreme maneuvering events, were completed for each bus.

In addition, for most of the extreme maneuvering tests, wheelchairs occupied by a 50th percentile anthropometric male test dummy were positioned in either a rear or side facing securement test station. In the course of the extreme maneuvering tests, accelerations corresponding both to normal driving conditions and to extreme maneuvering were experienced. The motion of the mobility aid and test dummy to all accelerations was recorded on video for review in parallel with the measured acceleration data. Figure 8 shows the equipment set up on a test vehicle.

Each bus was tested a minimum of three times on the track with a different mobility aid each time. Most buses were tested more than three times either because of observed anomalies during the tests or, in a couple of cases because of mechanical problems that occurred during a test.

Crash Tests – As previously mentioned, the tests being run by BC Transit in parallel with this project included crash tests, which were not included in the work plan for tests at Lane Transit District. Data was collected on bus accelerations for three full frontal crashes between 40 ft. high floor accessible buses and automobiles at a closing speed of 30 mph. The primary goal was to determine the actual accelerations experienced in the bus during a standard 30 mph crash to compare with the current standard of a 20g acceleration. Accelerometers were mounted both on the floor of the wheelchair securement station in the bus as well as on the flip-up passenger seat associated with that securement area. Additional instrumentation included multiple video cameras, closing speed measurement, and impact sensing.



FIGURE 8 – Looking forward in a BC Transit test bus with a video camera in the foreground to record motion of the dummy seated in a rear facing manual wheelchair.

DATA REDUCTION

For each of the normal and extreme maneuvering tests at Delta, British Columbia, acceleration data was collected as a stream of 100 Hz voltages for each of the three axes being monitored. The data reduction included averaging to a rate of 20 Hz, scaling according to the accelerometer calibration, identification of key features, and plotting the results for visual review of the calculated results.

The first step in acceleration data reduction was averaging. The reason for collecting data in a fashion that averaging is a part of the data reduction is as follows:

- With the data collection equipment being used, the period for A to D conversion of the accelerometer output to a digital signal is 10 μ -sec (this corresponds to a maximum rate of 100 kHz)
- Typically there is some noise in the acceleration signal of interest due either to background noise such as engine vibration or due to a once-only event such as an object striking the accelerometer.
- 20 Hz is a common rate for data collection in moving vehicles not involved in a crash.
- Given the system that was used for this project, if data were collected at 20 Hz there is a high likelihood that any given data point would not be representative of the acceleration of interest. This is because the data point represents only a 10 μ -sec period and it is likely that a high frequency noise will result in that data point being either higher or lower than the signal of interest for that very brief instant.
- By collecting at 100 Hz, every 5 points of raw data can be averaged to a single point to yield a 20 Hz data set that better represents the actual signal of interest.

The second step was converting the recorded accelerometer voltage outputs to accelerations in units of “g”. The accelerometers had a linear output so this step required adjusting the output voltage by a calibration offset and then multiplying by the calibration constant. Both the first and the second step of data reduction were done in a custom written program which created an output file suitable for use with a spreadsheet program.

The third step was to graph the 20 Hz x, y, and z acceleration data to confirm that it matched the test pattern from which the data was collected (accelerations, turns, and stops). While in the spreadsheet, maximums and minimums were identified and recorded.

RESULTS

The results of this project are presented in two parts: the bus dynamics are presented first and the mobility aid response to those dynamics follows.

BUS DYNAMICS – NORMAL DRIVING

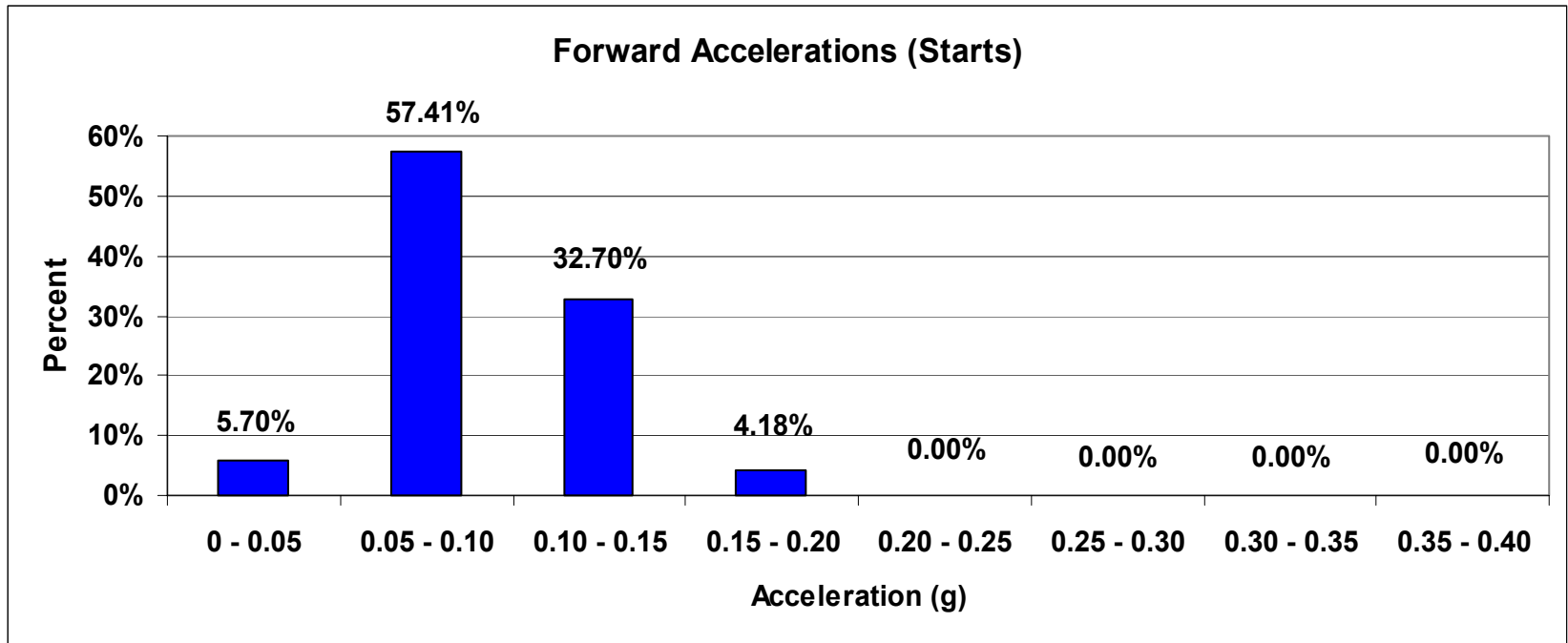
As described in the section on procedures used, the accelerations in the forward, side, and up-and-down directions were measured on buses as they went through their normal routes in Eugene, Oregon, picking up and dropping off passengers. The raw data consisted of many tens of thousands of data points. From this data the accelerations of key identifiable events were put into lists according to the type of event – start, left turn, right turn, or stop. The accelerations from a variety of routes and buses were included as a distribution of acceleration magnitudes was developed for each direction. In the paragraphs that follow, that distribution is presented both as a graph and in table format for accelerations due to starting, accelerations due to turning left and right, and accelerations due to stopping. The accelerations in the up and down direction are summarized. Accompanying each summary is an explanation which includes an interpretation of the data and a summary of its significance.

The first acceleration experienced in any given ride is that due to starting the bus. The distribution of accelerations measured during bus starts is shown in Figure 9. As would be expected, buses do not accelerate particularly strongly in normal service. The highest acceleration experienced in the course of these tests was 0.19g and 90% of the time the acceleration was between 0.05 and 0.15g. This forward acceleration is the one that, for a mobility aid in a rear-facing securement station, would result in the wheelchair rolling towards the rear of the bus if that wheelchairs brakes were not adequate. As a point of reference, for a wheelchair with a combined weight (occupant and wheelchair) of 290lb, the maximum starting acceleration of 0.19g would have the same effect on the mobility aid as applying a pulling force of 55lb. Most wheelchairs have brakes that can resist this force.

The accelerations in turns were separated for left and right turns so that any differences might be identified. The acceleration distributions for turns are shown both graphically and in tabular form in Figures 10 and 11 respectively. As can be seen in Figure 10, during normal operation of a transit bus, almost 90% of left turns result in accelerations in the range 0.1 to 0.25g. The distribution in this range is skewed towards the lower g accelerations.

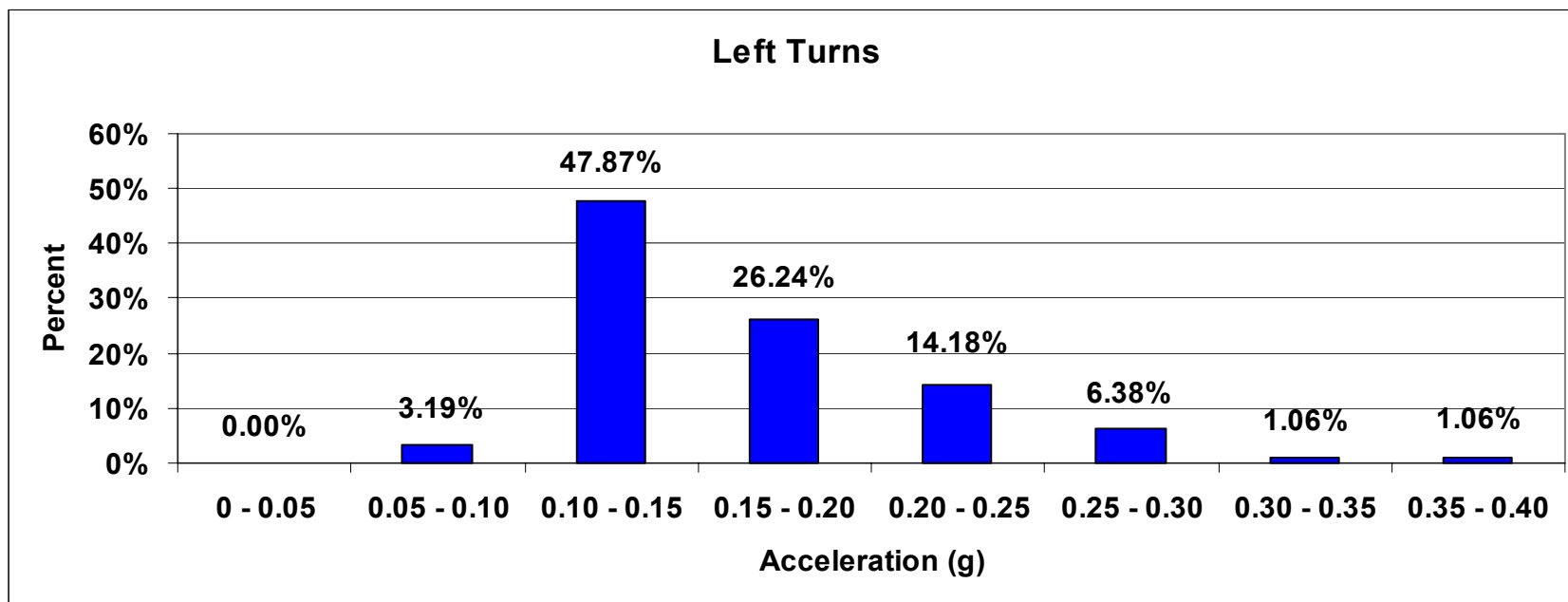
In general, turns can be expected to generate accelerations somewhere between 0.1 and 0.3g. It is interesting to note that the distribution is nearly identical for left turns and right turns. There was speculation by drivers that right turns would be shifted towards the lower end. The rationale was that right turns would be slower than left turns because a typical city block has a curb and a pole at the corner around which the bus must go when turning right. In transportation engineering terms, the radius of curvature for right turn is much smaller, or tighter than the radius of curvature for a left turn.

Stops were expected to result in the strongest accelerations but, as can be seen by comparing Figure 12 with the previous two figures, stopping acceleration is in the same range as accelerations for turns. In fact, except for starting accelerations which are limited by the bus power train, all accelerations which are controlled by the driver are remarkably similar. Based on the data collected for these normal driving accelerations, a summary of maximum and average accelerations for each direction were developed and are shown in Table 2.



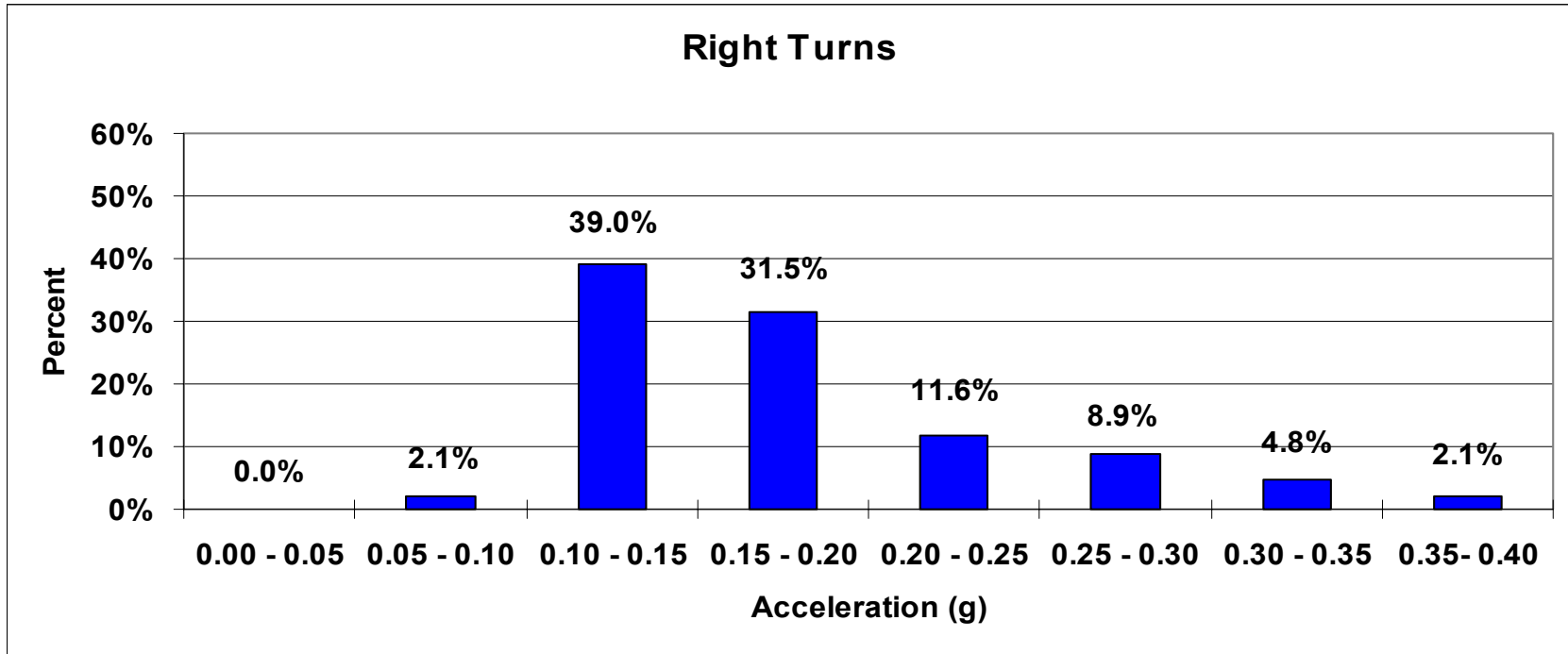
Acceleration(g)	Percent of starts
0.00 - 0.05	5.7%
0.05 - 0.10	57.4%
0.10 - 0.15	32.7%
0.15 - 0.20	4.2%
0.20 - 0.25	0.0%
0.25 - 0.30	0.0%
0.30 - 0.35	0.0%
0.35 - 0.40	0.0%

FIGURE 9 –Distribution of normal driving forward accelerations shown graphically and in a table. The accelerations are shown in units of “g” and the percentages represent the number of starts at a given acceleration out of the total of 270 accelerations that were identified in the data.



Acceleration (g)	Percent of Left Turns
0.00 – 0.05	0.0%
0.05 – 0.10	3.2%
0.10 – 0.15	47.9%
0.15 – 0.20	26.2%
0.20 – 0.25	14.2%
0.25 – 0.30	6.4%
0.30 – 0.35	1.1%
0.35 - 0.40	1.1%

FIGURE 10 – Distribution of normal driving left turn accelerations shown graphically and in a table. The percentages shown are out of the total of 282 left turns identified in the data.



Acceleration (g)	Percent of Right Turns
0.00 – 0.05	0.0%
0.05 – 0.10	2.1%
0.10 – 0.15	39.0%
0.15 – 0.20	31.5%
0.20 – 0.25	11.6%
0.25 – 0.30	8.9%
0.30 – 0.35	4.8%
0.35- 0.40	2.1%

FIGURE 11 - Distribution of normal driving right turn accelerations shown graphically and in a table. The percentages shown are out of the total of 146 right turns identified in the data

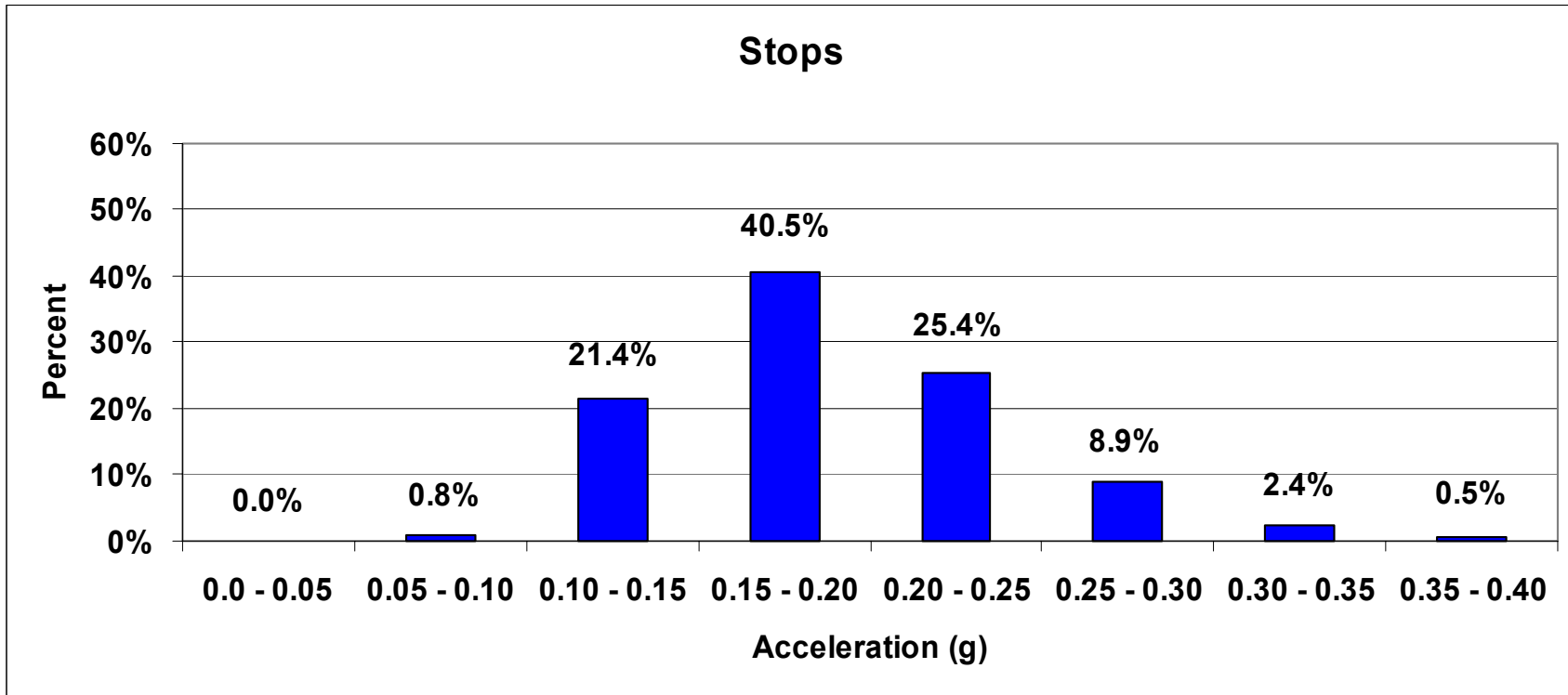


FIGURE 12 - Distribution of normal driving decelerations (stopping or slowing down) shown graphically and in a table. The percentages shown are out of the total of 370 decelerations identified in the data.

Accel.(g)	Percent of Stops
0.0 - 0.05	0.0%
0.05 - 0.10	0.8%
0.10 - 0.15	21.4%
0.15 - 0.20	40.5%
0.20 - 0.25	25.4%
0.25 - 0.30	8.9%
0.30 - 0.35	2.4%
0.35 - 0.40	0.5%

TABLE 2 - A tabular summary of the starting, left turn, right turn, and stopping accelerations recorded during normal bus operations in Eugene, Oregon.

	Max	Avg	Std Dev
Start	0.20g	0.10g	0.03
Left	0.39g	0.17g	0.06
Right	0.40g	0.18g	0.07
Stop	0.37g	0.19g	0.05

In addition to the forward/stopping and left/right turns, acceleration in the up/down direction was also measured. Several factors contribute to making it inappropriate to collect and report up/down data in the fashion used for forward, turning, and stopping accelerations. First, the bus operator has no direct control over the vertical motion of the bus. Thus, there are no readily observable cues that can be used to flag a particular point in the data as being significant (cues such as observing the turning of the steering wheel and recognizing an impending turning acceleration). Second, because of the short duration of typical up and down events, observers were very poor at estimating the magnitude of events and thus being able to log events which were significant. Finally, for an up/down acceleration to have an impact on wheelchair movement it must occur simultaneously with an acceleration in another direction.

BUS DYNAMICS – EXTREME MANEUVERS

As described in the section on procedures used, accelerations in the forward, side, and up-and-down directions were measured on buses as they were driven through a prescribed path of extreme maneuvers. The tests done at Lane Transit in Eugene typically included a “pedal-to-the-metal” acceleration to approximately 25 mph followed by left turns that were as hard as the driver was willing to do and finally a straightening out and a panic stop from about 25 mph. The test was then repeated but in the opposite direction to get maximum right turns.

At the test facility in British Columbia the design of the course sequence was as follows: a maximum acceleration to 30 mph, a swerve to the right, a straight section, hard turns to the right a panic stop while turning right, a return to the straight section, a swerve to the left, a straight section, hard left turns with a panic stop, a final return to the straight and a panic stop from 50 mph. This track contains exactly the same elements as the Lane Transit District track but they are all in sequence where the Lane Transit District tests were completed in two parts. In practice, the British Columbia tests were done in three parts with a brief pause after each panic stop to check equipment and straighten the wheelchair and test dummy as necessary.

In contrast to the normal driving tests, the events of interest were very clearly identified in these extreme maneuvering tests. No manual logging of events was necessary as each event was easily identified from the accelerometer recordings. A sample of the reduced data from one run on the B.C. track is shown in Figure 13. The top plot is of acceleration along the primary axis of the bus. That is to say, it is a track of forward/rearward accelerations. On this plot negative values correspond to the bus accelerating forward and positive values correspond to decelerations (slowing or stopping). The lower plot is of side accelerations. In this plot negative values correspond to right turns and positive values correspond to left turns. These plots are for the same run so there is a direct correspondence between the top and bottom curves.

The performance of each of the six buses tested was measured multiple times by running each bus on a test track multiple times. The results for each run were reduced as previously described. The reduced data was then plotted as the example shown in Figure 13, and from that data the maximum values of forward, rearward, left, and right accelerations that occurred during the run were identified and recorded. The maximum accelerations for each run for a given bus were then assembled into a single table and average maximums computed to take as representative of the maximum accelerations that should be expected when putting that bus through extreme maneuvers.

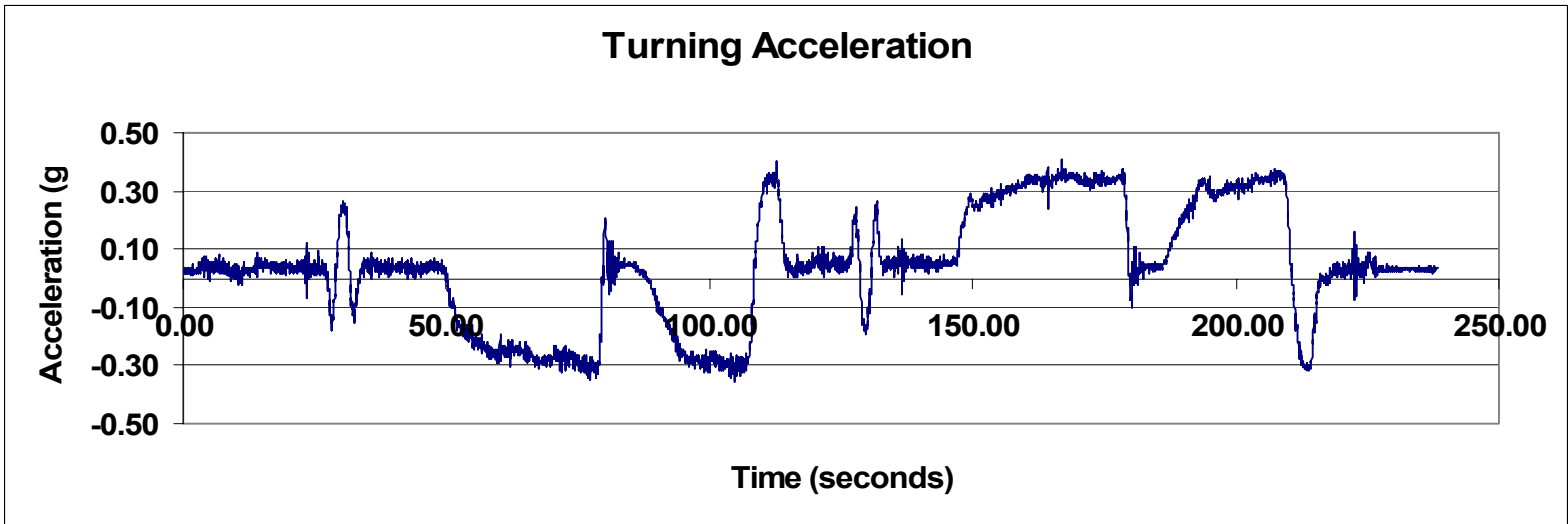
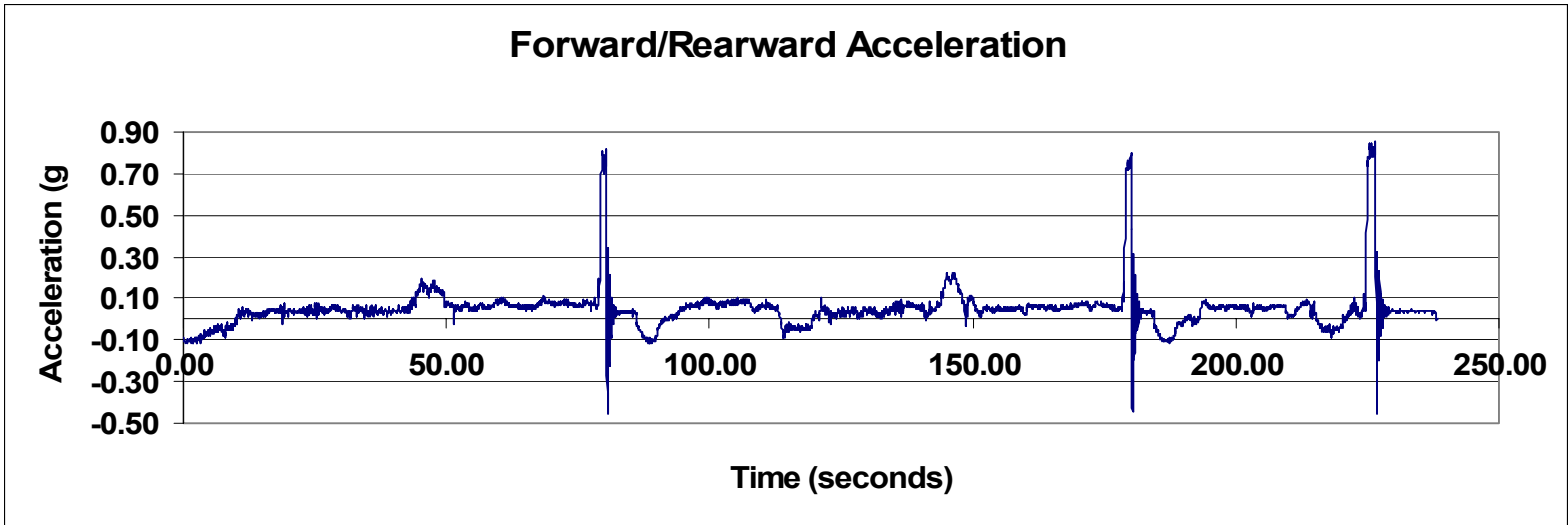


FIGURE 13 – An example record of accelerations from an extreme maneuvering test. In the top plot positive values of “g” correspond to bus decelerations and vice versa. In the bottom plot positive values of “g” correspond to left turns and negative values of “g” correspond to right turns.

An example summary for results from an extreme maneuver test sequence is shown in Table 3. It provides the maximum accelerations recorded for the 40 ft low floor bus as it was run through the test course 8 times. Out of all of those runs, the absolute maximum accelerations recorded were 0.98g rearward (stopping), 0.41g forward, 0.41g during a left turn and 0.43g during a right turn. More representative of what should be expected during extreme maneuvering of this bus are the averages of all of the maximum values for the runs. For this bus they were as follows: 0.85g rearward (stopping), 0.37g forward, 0.39g left and 0.39g right⁵. As discussed in the section on normal driving results, the z-axis (vertical) accelerations were recorded but not used in this project.

TABLE 3 – Summary data for a 40 ft (12.2m) Low Floor Bus. A sample of the summarized data that was developed for each bus. Each run includes a complete set of events as shown in Figure 13. When a run was complete, the peak accelerations in each direction were identified and recorded. All runs for a given bus were recorded in this table, and then the summary and average statistics for that bus were calculated.

		X1	Y1	Z1	X2	Y2	Z2
Run 1	MAX(g)	0.8	0.4	1.48	0.81	0.43	1.42
	MIN(g)	-0.4	-0.35	0.66	-0.39	-0.32	0.63
Run 2	MAX(g)	0.97	0.41	1.58	1	0.44	1.53
	MIN(g)	-0.36	-0.37	0.64	-0.35	-0.35	0.61
Run 3	MAX(g)	0.98	0.4	1.47	1.02	0.44	1.48
	MIN(g)	-0.39	-0.39	0.64	-0.38	-0.36	0.42
Run 4	MAX(g)	0.83	0.41	1.59	0.84	0.45	1.57
	MIN(g)	-0.34	-0.39	0.54	-0.32	-0.36	0.54
Run 5	MAX(g)	0.8	0.36	1.36	0.79	0.39	1.34
	MIN(g)	-0.28	-0.37	0.71	-0.26	-0.32	0.71
Run 6	MAX(g)	0.81	0.41	1.61	0.82	0.47	1.7
	MIN(g)	-0.41	-0.41	0.44	-0.38	-0.36	0.41
Run 7	MAX(g)	0.8	0.38	1.47	0.83	0.44	1.46
	MIN(g)	-0.37	-0.43	0.64	-0.34	-0.37	0.62
Run 8	MAX(g)	0.8	0.38	1.47	0.83	0.44	1.46
	MIN(g)	-0.37	-0.43	0.64	-0.34	-0.37	0.62
AVG	MAX(g)	0.85	0.39	1.50	0.87	0.44	1.50
AVG	MIN(g)	-0.37	-0.39	0.61	-0.35	-0.35	0.57

Overall maximums: X1 0.98g (stop) 0.41g (rebound)
 Y1 0.41g (left) 0.43g (right)
 Z1 1.61g (down) 0.44 (less down)

Once similar tables had been prepared for all six of the buses, the average maximum accelerations were assembled for comparison and to establish an overall average set of maximum accelerations for large urban transit buses. These results are presented in Table 4. Based on these numbers, a reasonable set of extreme maneuvering accelerations to describe large urban transit buses would be:

- Rearward accelerations of 0.8g occur during a panic stop and have a short duration.
- Left and right turns may result in peak accelerations of 0.4g but these accelerations may continue for an extended time as in the case of a sweeping large radius 270 degree turn taken at high speed.

⁵ Note that there are differences between accelerometer 1 and accelerometer 2. The differences are less than 2% of full scale (4g). To avoid confusion, only numbers from accelerometer 1 are used in the discussions.

- Forward acceleration may be expected to reach 0.4g but not for the reasons usually given. A review of the plot of accelerations (Figure 13) reveals that acceleration resulting in speed increases is in the range of 0.2g. The actual peak forward acceleration occurs immediately following a panic stop and is the result of rebound of the bus suspension.

TABLE 4—A summary of the accelerations in buses during extreme maneuvering and overall statistics for all buses. All values are in units of “g”.

Individual Bus Summaries				
	Stop	Start	Left Turn	Rt. Turn
<u>Bus</u>	X1 Max	X1 Min	Y1 Max	Y1 Min
30 Ft L.F.	0.72	-0.34	0.34	-0.45
35 Ft L.F.	0.84	-0.51	0.37	-0.40
40 Ft L.F.	0.85	-0.37	0.39	-0.39
DD L.F.	0.86	-0.46	0.38	-0.36
60 Ft. L.F.	0.74	-0.26	0.48	-0.45
40 Ft. H.F.	0.72	-0.34	0.34	-0.45
Fleet Summary				
Avg	0.79	-0.38	0.38	-0.42
St Dev	0.07	0.09	0.05	0.04
Max	0.86	-0.26	0.48	-0.36
Min	0.72	-0.51	0.34	-0.45

BUS DYNAMICS – CRASH TESTS

As a result of the collaboration with BC Transit and the Transport Canada study, the Transit IDEA project team was able to participate in crash tests involving large buses and automobiles. Although existing U.S. Securement standards require testing with a simulated 30mph 20g crash, no actual crash data was used in establishing that standard. In these tests, conducted at the test track in Delta, B.C., a passenger cruiser was crashed into a 40 ft high floor bus at a closing speed of 30mph. The goal was to obtain actual accelerations on the bus floor during the crash to compare to the 20g acceleration that is used in the ANSI/RESNA wheelchair securement standard WC-19. The test was conducted by Innovative Vehicle Testing, Ltd. of Delta, British Columbia (Canada).

The significant details of the crash tests are as follows:

- Three types of cars were used, 3 sedans and 1 station wagon. All were ballasted to weigh the same, approximately 3830lb.
- The buses were an accessible 40 ft high floor buses made by General Motors and weighing approximately 22,000lb.
- The car was towed straight (full frontal) into the bus at a closing speed of 30mph
- Primary instrumentation included:
 - Closing speed measurement immediately prior to impact
 - Crush switch to provide an electronic marker of impact
 - Accelerometers mounted on the bus floor

Four separate crash tests were performed, each crash using a new pair of vehicles. For each test, the bus was empty (as light as possible) and left in a free rolling condition (no brakes set) to maximize the acceleration resulting from impact. The car was used as delivered except for the installation of a guide system to ensure a full frontal crash and installation of a radio controlled emergency braking system to allow a test abort if necessary.

As can be seen in Figure 14, the bus was damaged as a result of the collision, but the majority of the crash energy was dissipated in crushing the front end of the car. In fact, the bus was drivable after the crash test although the steering system had been damaged. Following the impact, the unbraked bus rolled backwards at a speed of several feet per second until its progress was stopped by an attached safety cable. The car did not move following the impact.

The acceleration of the bus floor was recorded at a rate of 2kHz (one reading every 0.0005sec). After reducing the raw data a plot of acceleration as a function of time was prepared. This plot is shown in Figure 15. The features of this plot that should command the attention of anyone involved in securement are that (a) the accelerations are substantially lower than the standard of 20g currently in use, (b) the actual acceleration resulting from a crash is not a simple rectangle as is usually used in sled test simulations of crashes, and (c) on impact the bus frame appears to ring at a frequency of about 45 Hz

The details of this test and the results are being prepared as part of a report to Transport Canada on bus accelerations that affect wheelchair securement. The reference for this report to be published in early 2005 is: "Rutenberg U., Baerg R., Macnabb M., Little A.,2004. "Assessment of Low Floor Transit Bus G Forces on Rear-Facing Wheelchair Securement Systems", for Transportation Development Center, Transport Canada.



FIGURE 14 – The car and bus (rolled back into pre-crash position) showing the damage resulting from a 30mph full frontal crash. (BC Transit)

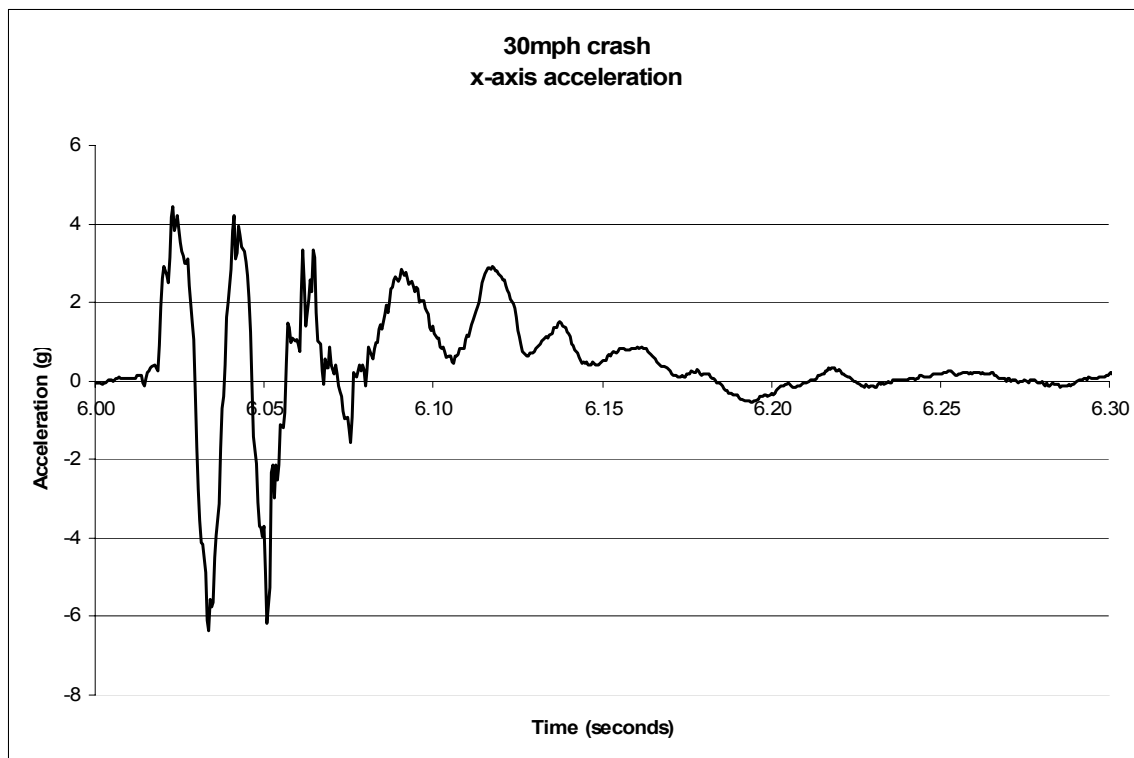


FIGURE 15 - A time history of the floor acceleration of a large urban transit bus. The plot starts immediately prior to impact in a 30mph full frontal crash with an automobile. This curve differs greatly from a typical sled test simulation. (Courtesy Innovative Vehicle Testing, Ltd., Delta, B.C., Canada)

WHEELCHAIR RESPONSE

The second element of this project was evaluation of wheelchair response to normal and extreme maneuvers when in a passive (unbelted) securement station. The primary tests for this project were completed in Eugene, Oregon, with Lane Transit District buses. Similar testing for rear facing was done as part of the collaborative project and used for confirmation of previous results.

The bus used for these tests was equipped with two side facing seats immediately across the aisle from each other. This provided a wide area which was available for testing of securement with no additional constraints such as side walls or adjacent seat and with a good camera angle for recording the wheelchair response on video. The first tests conducted were therefore done using a custom built cantilever rear facing securement backstop mounted on a gridded base in the center of the bus.

The backstop was a steel frame to which rigid foam was attached. Because some wheelchairs have batteries or other objects that extend behind the plane of the seat back, the foam was used to move the position at which the seat back contacted the backrest approximately 8 inches away from the backrest frame. The construction and shape of the backrest is shown in Figure 16.

For testing purposes, the backrest was mounted on a plywood base which had been marked with a grid to aid in monitoring wheelchair movement both during the tests and when reviewing video of the tests. This base also had an area of very high friction boat decking material located in the area of the the rear wheels of the wheelchair. The entire assembly was then mounted in in an open area near the front of the bus (Figure 17). This allowed testing of the backrest



for both forward and side facing securement without having any other surfaces potentially impinging on or otherwise restricting movement of the wheelchairs.

In addition to tests of rear facing using this backstop arrangement, the same setup was used to test side facing securement with only a forward wall. The second set of tests was for rear facing securement only, but in an existing securement station outfitted with a backstop and movable aisle-side armrest (Figure 18). Finally, tests were observed in the BC Transit buses where wheelchair were stationed in existing rear facing securement stations and their motion observed as the buses were run through the extreme maneuvering tests.

FIGURE 16 – Construction of the backrest used in rear facing Securement tests. A steel frame was built and welded to a base plate. The wheelchair contact plane is moved away from the frame using foam to allow lower portions of the wheelchair to fit.



FIGURE 17 – Test dummy in Three-Wheel Scooter backed against rear-facing securement backstop mounted in center aisle of LTD bus.

Wheelchair Response Rear Facing Backstop Only – The tests using the three types of wheelchairs demonstrated clearly the importance of recognizing that different wheelchairs will respond differently. In order, tests were done on a manual wheelchair, a heavy power wheelchair, and a three wheel scooter.

For the very first tests, the manual wheelchair was positioned against the backrest with its brakes set. The test dummy was seated in the wheelchair with its torso belted to the backrest of the wheelchair. The bus was driven through the standard course of acceleration, left turns, braking, acceleration, right turns and braking and then, because of observations made during the planned tests, some additional tests of straight braking were executed. The results of these tests were as follows:

- During maximum normal acceleration there was no noticeable movement of the manual wheelchair.
- During turns in both directions, rotation of the wheelchair started almost immediately on initiation of a turn. During left turns the wheelchair would rotate to the left from the wheelchair occupant's point of view and during right turns the rotation was to the right. The rotation involved the front wheels castering and the locked rear wheels of the wheelchair sliding over the high friction material. On continuation of the turn the wheelchair would reach the end of its tethers at an angle of about 30 degrees from the bus axis. If the turn resulted in an acceleration of about 0.2g or more, the occupied wheelchair would then start to tip over.
- Stops with the wheelchair at an angle to the backrest but in contact with it resulted in the wheelchair stopping at that angle. There was no straightening out of the wheelchair during the stop. In that case and when the wheelchair was squared up with the backrest, the only movement of the wheelchair during the stop was a slight rotation backwards that resulted in the front wheels lifting off the bus floor approximately 1 inch. At the instant of stop, however, the wheelchair would rebound violently and move (slide) away from the backrest approximately one foot. This result was a surprise and so the stop tests were repeated several times.

The second tests with the rear facing backrest were done with the power chair. This power wheelchair had a weight of about 250 lb (unoccupied). As with the manual wheelchair, the test dummy was seated in this power wheelchair with its torso belted to the wheelchair back. The results of the driving test for this wheelchair were as follows;

- During maximum normal acceleration there was no noticeable movement of the power wheelchair.
- There also was no movement during turns when both rear wheels were engaged to their motors, even at 0.4g accelerations. However, when the left side wheel was disengaged from its hub, the wheelchair would rotate to the right during a right turn and would remain stationary during left turns.
- Stops consistently resulted in the wheelchair rearing up until it was caught by its anti-tip rollers. This resulted in the front wheels leaving the bus floor to a distance of about 3 inches. As with the manual wheelchair, the rebound immediately following the stop resulted in the wheelchair moving away from the backstop, in this case the distance moved was about 5 inches.

The third set of rear facing tests were completed with the three-wheel scooter. As shown in Figure 17, the three wheel scooter was stationed with its brakes on and with the dummy torso strapped to the scooter seat back. The response of this wheelchair type was as follows:

- During normal acceleration there was no noticeable movement.
- During turns in both directions, at an acceleration of about 0.15g, the first motion of the scooter would be to start tipping. The tipping was slow in developing and a continuous turn of several seconds was required to cause the scooter to tip over.
- On stopping, the front wheel would lift approximately 1 inch and rotate so it was no longer pointed towards the rear of the bus. There was very little overall movement during and after the stop.
- At the end of the stop when there was a maximum forward acceleration due to rebound, the scooter would come down on its front wheel but did not move a measurable amount in any direction.

On completion of the initial rear facing tests, a set of side facing tests was conducted. The backrest used for rear facing was moved to a position where it would simulate a wall at the front of a side facing securement station. The wheelchairs were then placed facing the right side of the bus with the torso of the tests dummy lined up with the simulated wall as shown in Figure 18.



FIGURE 18 – The power wheelchair in position for side facing tests. No rear, forward, or right side constraints were used for this test of a simplest possible side facing securement station. (LTD Vehicle)

The first tests were conducted on the power wheelchair. The observed response of this wheelchair to the bus accelerations were as follows:

- During a maximum bus acceleration there was no noticeable movement of the wheelchair.
- In left turns the wheelchair was stable but would slide across the floor starting at accelerations of approximately 0.3g.
- In right turns the wheelchair was stable until a level of approximately 0.3g was reached. At that point the occupied mobility aid would start to slide but then stopped sliding and started to rotate on its back. Continuation of the turn resulted in rotation until it was stopped by the wall (an angle of approximately 45 degrees in this test setup).
- No movement was observed during a panic stop with the wheelchair in the side facing position.

Next, the three-wheel scooter was tested. Its response to bus movement was observed to be as follows:

- During a maximum bus acceleration, there was no movement.
- During turns, both left and right, there was no movement at the normal turn rate. However, when the right turns reached a level of approximately 0.4g the scooter (and occupant) tipped over backwards. During the panic stop the occupied wheelchair was stable during the first portion of the stop because of the wall. However, during the rebound the three-wheel scooter and occupant completely tipped over on its side.

Finally the manual wheelchair with the test dummy was evaluated for movement when positioned in a side facing configuration. Movement resulting from bus accelerations were observed as follows:

- During a maximum bus acceleration there was no observed movement of the wheelchair.
- During left turns the wheelchair slid forward across the floor (wheels were not turning). Right turns were not tested because a simple pull test showed that this wheelchair would tip over backwards even sooner than the scooter.
- Stops, as with the scooter, occurred in two parts. During the stopping phase, the wheelchair would tip forward against the wall but enough for the wheels towards the rear of the bus to lift up. It also tended to rotate towards a forward facing position during the stop phase. The second part of the stop was forward acceleration due to the rebound of the bus suspension system. As a result of the rebound, the manual wheelchair tipped over on its side (Figure 19).

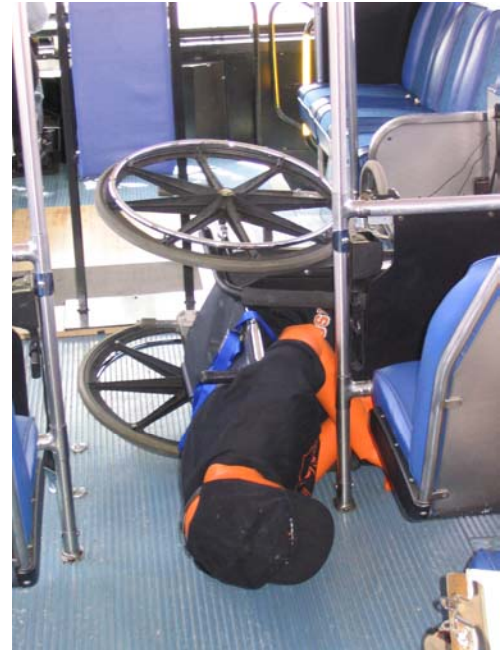


FIGURE 19 – The results of a panic stop when a manual wheelchair occupied by a test dummy is side facing and has only a forward wall for “Securement.” The manual chair did not move appreciably during the actual stop (left) but it tipped over on its side during the forward acceleration due to the bus suspension system rebound (right).(LTD vehicle)

Following the side facing tests, the rear facing system was modified to include an 18 inch long aisle-side movable armrest at a height of 30 inches above the floor. The armrest could be moved from its normal horizontal position to a vertical position to maximize the wheelchair maneuvering room available for entering the securement station. In a second modification, the depth of the foam backing was decreased from 8 inches to 3 inches to maximize the available space (length) in the securement station. This modified system was mounted on a temporary plywood base in an existing securement station on the test bus (Figure 20).

Tests using this Securement arrangement were conducted in the same fashion as previous tests with video recordings used to document the motion of the wheelchairs as the buses were driven through various maneuvers.

The first tests were done using the manual wheelchair with the test dummy as an occupant. The results were the same as the previous tests with the exception that extreme motion was prevented by the existence of a folded up seat on one side and an armrest on the other. Specifically, the observed response of the manual wheelchair was as follows:

- Starts were a non-event. No motion was observed.
- Turns resulting from a swerve maneuver would result in rotation of the wheelchair due to sliding. A long turn would result in rotation until it was stopped either by the seat or by the armrest depending on turn direction.
- Stops were identical to those noted in the prior rear facing tests. There was a sliding of about one foot towards the rear of the bus on rebound from the stop.



Figure 20 -A rear facing wheelchair securement station with a movable armrest. It is mounted immediately behind a wheel well in the LTD test bus.

The second tests were for the three wheeled scooter. This wheelchair was also occupied by the test dummy. The response of this type of wheelchair to the bus maneuvers was as follows:

- Starts resulted in no noticeable motion.
- Turns of magnitude greater than approximately 0.2g resulted in tipping of the scooter until it was stopped by either the wall or the armrest. In both case the wheel that was lifted off the floor was up nor more than approximately 2 inches.
- Stops resulted in an unloading of the front wheel resulting in having it turn but no other motion of the scooter.

The power wheelchair was not tested using this securement setup because it was not possible to maneuver it into the securement space. The space on the bus was 48 inches long; installation of the backrest reduced that distance to 43inches. This overall maneuvering space was not adequate for getting the power wheelchair into the available space. Because of the very clear stability of the power wheelchair as demonstrated in the earlier tests, this was not considered to be of great consequence.

USER AND POTENTIAL USER RESPONSE

The final part of this project was a survey of users and potential user of rear facing securement to determine what perceptions exist about it. There were eighteen current users from Victoria, British Columbia where rear facing securement is available on all BC Transit buses. A summary of the survey results for the current users of rear facing securement is as follows:

User Demographics:

- Age of respondents
 - 6% 0-20 years old
 - 33% 21-50 years old
 - 28% 51-75 years old
 - 33% >76 years old
- Frequency of Bus Use
 - 6% Daily

- 65% Weekly
- 18% Monthly
- 12% Rarely
- Ability to use a Handhold
 - Left Arm/Hand
 - 29% No Strength
 - 18% Limited Strength
 - 53% Full Strength
 - Right Arm/Hand
 - 18% No Strength
 - 23% Limited Strength
 - 59% Full Strength
- Type of Wheelchair
 - Manual Wheelchair 28%
 - Powered Wheelchair 24%
 - Powerbase 12%
 - 3-Wheel Scooter 24%
 - 4-Wheel Scooter 12%

Use of Rear Facing Securement:

- Is it easy to use?
 - 54% Yes
 - 28% Middle
 - 18% No
- Was the Comfort Level Adequate?
 - 62% Yes
 - 15% Middle
 - 23% No
- Did you feel safe?
 - 64% Yes
 - 7% Middle
 - 29% No
- Did you use your brakes?
 - 87% Yes
 - 13% No
- Did you use the handrail or stanchion?
 - 80% Yes
 - 20% No
- Did you require assistance?
 - 38% Yes
 - 6% A Little Bit
 - 56% No
- Should rear facing be an option on all buses?
 - 67% Yes
 - 8% No Opinion
 - 25% No

. The five potential users were from Eugene, Oregon where rear facing securement is being closely studied for implementation. The respondents are all mobility aid users who are regular fixed route transit riders. These respondents were given a two page description of rear facing securement including figures and pictures showing how it is used. Their responses to the same survey were as follows:

User Demographics:

- Age of respondents
 - 0% 0-20 years old
 - 80% 21-50 years old

- 20% 51-75 years old
- 0% >76 years old
- Frequency of Bus Use
 - 33% Weekly
 - 33% Monthly
 - 33% Rarely
- Ability to use a Handhold
 - Left Arm/Hand
 - 40% No Strength
 - 0% Limited Strength
 - 60% Full Strength
 - Right Arm/Hand
 - 80% No Strength
 - 0% Limited Strength
 - 20% Full Strength
- Type of Wheelchair
 - Manual Wheelchair 20%
 - Powered Wheelchair 80%
 - Powerbase 0%
 - 3-Wheel Scooter 0%
 - 4-Wheel Scooter 0%

Use of Rear Facing Securement:

- Will it be easy to use?
 - 60% Yes
 - 20% Middle
 - 20% No
- Will the Comfort Level be Adequate?
 - 80% Yes
 - 20% Middle
 - % No
- Will you feel safe?
 - 60% Yes
 - 20% Middle
 - 20% No
- Will you use your brakes?
 - 100% Yes
 - 0% No
- Will you use the handrail or stanchion?
 - 80% Yes
 - 20% No
- Will you require assistance?
 - 40% Yes
 - 0% A Little Bit
 - 60% No
- Should rear facing be an option on all buses?
 - 100% Yes
 - 0% No Opinion
 - 0% No

PLANS FOR IMPLEMENTATION

The results of this Transit IDEA project will be used directly by Lane Transit District (LTD) and the Greater Cleveland Regional Transit Authority (RTA). Both of these agencies are working with New Flyer, a bus manufacturer, on the design of new BRT vehicles. The new articulated vehicles will incorporate rear facing securement systems. The results of this project will have a direct impact on the interior design of these new vehicles.

The project implementation plan also includes dissemination of results in technical and industrial journals. A Transportation Research Board paper was submitted at the end of July 2004. A technical brief was prepared and is available at the website of the National Center for Accessible Transportation. Other articles will be prepared for the public transit industry trade publications.

CONCLUSIONS

Testing performed using a wide variety of large urban transit buses, three basic securement arrangements, and three different wheelchair types revealed some important facts about the use of rear facing and side facing securement.

First, it was clear from the various driving tests that:

- Accelerations during normal in-service operation of large buses can be expected to be much smaller than extreme maneuvering accelerations for starts and stops.
- In the case of turns, however, accelerations at the level of extreme maneuvering can be expected to occur on occasion during normal in-service driving.
- The maximum possible accelerations for large buses occur during extreme maneuvering and result from (a) maximum turns which result in side accelerations of about 0.4g and (b) panic stops which result in a rearward acceleration of about 0.8g and a suspension rebound forward acceleration of about 0.4g.
- A collision between a 22,000lb bus and a 3,800lb car with a closing speed of 30mph will result in an acceleration substantially less than the 20g currently used in securement standards.

Second, careful review of video records of wheelchairs stationed in buses resulted in the following conclusions about the securement options considered:

- Without the occupant using a handhold, manual wheelchairs and three-wheel scooters can be expected to move in normal operation.
- Rear facing securement with only a backrest and no aisle-side support will likely result in catastrophic movement (tipping over) for scooters and may have the same effect on manual chairs.
- Side facing securement with only a wall on the side of the wheelchair towards the front of the bus will likely result in catastrophic movement during extreme maneuvers for all types of wheelchairs.
- Rear facing securement with a backrest and aisle-side armrest will prevent catastrophic motion for all types of wheelchairs under all driving conditions in which no collision is involved.
- Side facing securement will require a containment device (wall, stanchion, or armrest) on three sides to prevent catastrophic movement during extreme driving maneuvers.

Third, users and potential users of rear facing securement have very similar attitudes about using this approach to wheelchair securement on a bus. It is clear that it is acceptable to many users of wheelchairs but it is also clear that a traditional forward facing active securement system should always be available as an option for wheelchair users.

Overall, the results of this project make it clear that rear facing securement of wheelchairs, a fast and independent approach that has important advantages for BRT, can be successful. More work needs to be done to identify the best ways to minimize incidental movement and prevent catastrophic movement for all types of wheelchairs, but there are no inherent barriers to successful implementation of this approach.

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REFERENCES

Hunter- Zaworski, K.M. and J.R. Zaworski, "Progress in Wheelchair Securement: 10 Years since the Americans With Disabilities Act, *Transportation Research Record 1779* Transportation Research Board, Washington DC, January 2002.

Hunter- Zaworski, K.M. and J.R. Zaworski, "Progress in Wheelchair Securement: the last decade ", The 9th International Conference on Mobility and Transport for Elderly and Disabled People, *Conference Proceedings*, Warsaw Poland, July 2001.

Hunter-Zaworski, K.M., D. G. Ullman, J.R. Zaworski, D.E. Herling, and G. Clarke, *Application of the Quality Functional Deployment Method in Mobility Aid Securement System Design – Volume 1*, Final Report, U.S. Department of Transportation, Federal Transit Administration, Washington, DC, Report No. FTA-OR-11-0006-92-1, December 1992, 134 p.

Hunter-Zaworski, K.M., J.R. Zaworski, and G. Clarke, *The Development of an Independent Locking Securement System for Wheelchairs on Public Transportation Vehicles: Volume 2*, Final Report, U.S. Department of Transportation, Federal Transit Administration, Washington, DC, Report No. FTA-OR-11-0006-92-2, December 1992, 92 p.

Rutenberg, U, and Hemily, B., *Use of Rear-Facing Position for Common Wheelchairs on Transit Buses: A Synthesis of Transit Practice*, TRB TCRP Synthesis Report No. 50, National Academies, Washington, D.C., 2003

Rutenberg U., Baerg R., Macnabb M., Little A., 2004, "Assessment of Low-Floor Transit Bus G Forces on Rear-Facing Wheelchair Securement Systems", for Transportation Development Center, Transport Canada.