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SIDE FACING WHEELCHAIR OCCUPANT SAFETY

A SLED TESTING AND COMPUTER SIMULATION STUDY

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INTRODUCTION

The proper use of well designed restraint systems can significantly decrease the risk of death and serious injury in motor vehicle crashes involving occupants that are in a reasonable state of physiological well being (bone strength, muscle tone, etc.). Most vehicles sold to the motoring public in the United States are equipped with restraint systems for the protection of forward-facing occupants in crashes. These restraint systems have been demonstrated to have the capability of providing a reasonable level of protection by complying with the performance requirements of various Federal Motor Vehicle Safety Standards (FMVSS) such as FMVSS 208, 209, and 210. With few exceptions, and for many valid reasons, these restraint systems are designed for protection of the 50th percentile male size occupant in frontal collisions. However, there exists a large population of van and bus occupants who are transported in a side-facing configuration who are virtually unrestrained in the current transportation environment. Available restraint systems are not sufficient to protect these occupants in the event of frontal or rearward collisions. These occupants include physically and mentally handicapped children and adults and who are confined to wheelchairs.

Extensive research, development, testing and evaluation (RDT&E) efforts by government and industry have led to the promulgation of the federal motor vehicle safety standards for forward-facing occupant protection in automobiles, vans, and light trucks and the compliance with these regulations. The technology developed through those RDT&E efforts that have been expended have not here-to-fore been expanded nor exploited toward the protection of a rapidly growing segment of the transported population in the United States, the ever increasing physically disadvantaged wheelchair passengers. By comparison, the unique problems of the protection of physically disadvantaged occupants seated laterally in vehicle crashes has only recently become the subject of government or industry RDT&E. Most industry research has been limited to forward-facing wheelchair tie-down mechanisms with regard to comfort and convenience leaving little effort being directed toward occupant crash protection and the overall crashworthiness of the systems. In particular, the crashworthiness of wheelchair tiedowns, occupant restraint systems and innovative safety systems for wheelchair occupants transported in the side-facing configuration has not been the subject of government and industry RDT&E efforts.

Crash protection for the above mentioned populations can be significantly enhanced by the use of a compartmentalized crash protection system which will protect wheelchair occupants from contact with the adjacent wheelchair/occupant complex, prevent excessive lateral flexion of the upper torso and cushion the occupant's head and torso during both frontal and rearward collisions. This paper discusses the RDT&E of such a system designed for use by van and bus passengers seated in wheelchairs and riding in the lateral configuration.

Significance of the Problem

There are a wide range of schemes used for restraining wheelchairs and their occupants in vans and buses. All of the wheelchair securement systems ('tiedowns') currently available provide some means of restricting forward movement of the wheelchair (with varying degrees of actual crash protection) in the event of a frontal collision when the wheelchair is front-facing. In general, securement is accomplished either by devices that 'hook' onto the wheels of the wheelchair or by straps and/or webbing that attaches from the floor of the vehicle to the frame of the wheelchair. However, there is very little (if any) lateral constraint built into either of these tiedown configurations. Furthermore, there are no accessory safety devices available to protect the occupants during lateral crashes if they are front facing in the struck vehicle or if they are in side-facing wheelchairs during a frontal or rear-end crash situation.

It is common practice to transport the wheelchair population facing sideways in vans and buses. These wheelchair occupants are extremely vulnerable to injury in even moderate speed crashes because of the open environment in which they are being transported today. Often the wheelchairs are secured only by 'hooks' that extend through the spokes of the rear wheels. These 'hooks' do not attach to the rims of the wheels but only extend from the rear and inboard side toward the outboard side of the wheels. The wheelchair is free to move somewhat during the normal operation of the vehicle. There is no securement for the front wheels of the chair. It is possible to develop a system to provide proper protection for this class of transported persons using the concepts of compartmentalization and inflatable restraints to more effectively secure the wheelchair and its occupant in most crash situations.

Transporting wheelchair occupants in this side-facing orientation is based on two reasons; ease of ingress/egress and economy. Almost without exception, the lifts for loading the wheelchairs and occupants are positioned at the curb side doors of the vans. The wheelchairs can be loaded and positioned easily and rapidly when the orientation is such that the passengers face the right hand side of the vehicle. This positioning scheme requires that the floor between the rearmost position and the lift area is clear of any structures needed for tiedown anchors. The side-facing position provides an economic advantage to the transit companies since most transit systems (modified stretch vans) can carry more side-facing wheelchairs than front facing. This is partially due to requlations that (in some states) specify a minimum distance between wheelchair occupants and structures in front of them. It is, therefore, very unlikely that this method of operation will be changed without the intervention of Federal or State legislation. Such intervention (to preclude the transportation of side-facing wheelchairs) would carry significant cost impact to the transporters. Unfortunately, for the wheelchair occupant, the above noted circumstances constitute a dilemma. On the one hand they compound to expose them to a disproportionate amount of danger in the event of frontal or rear-end collisions. On the other hand, mandating only forward facing wheelchair transportation would expose them to a disproportionate amount of danger in the event of lateral collisions. Intersection collisions may constitute the majority of transporter crashes.

During sled tests of side-facing wheelchairs, the wheelchair user's neck, hips, and knees are subjected to bending in an abnormal direction and the wheels of the wheelchair usually collapse. All of the wheelchairs twist and/or rotate toward the direction of impact with the dummy upper torso rotating over the armrest from 45 to 90 degrees causing dummy head contact with the structures placed beside the wheelchair (forward of the wheelchair in the vehicle). In addition to the violent contacts between wheelchairs and wheelchair occupants which will obviously occur during frontal and rearward crashes when wheelchairs are placed side-by-side in a bus or van, the wheelchair occupant is exposed to the dangers of internal injuries. Lateral flexion of the upper torso over the armrest of the wheelchair can allow concentrated loading of the armrest into the abdominal cavity. This intrusion puts many vital organs such as the spleen, kidneys, liver, and the large and small intestines at risk. Insult to any of these organs can be life threatening and the probability of serious insult is heightened by the often degenerative physical condition of many wheelchair dependent persons.

Research Program - Adults

The transportation needs of the handicapped are becoming increasingly more salient to both the Department of Transportation and the automotive manufacturers. It is the primary purpose of this program to provide these occupants with a restraining device which provides at least an equivalent amount of protection as that available to the rest of the motoring public. There are currently no Federal Regulations governing the crashworthiness of restraint systems designed for handicapped automotive occupants. Accordingly, the Society of Automotive Engineers (SAE) has formed an Adaptive Devices Standards Committee to deal with the safety of the handicapped motoring public (1)[1]. The committee has been invited to participate in the International Standards Organization (ISO) Wheelchair Restraint Systems Working Group (ISO/TC-173/SC-1/WG-6) in the development of an international wheelchair restraint standard (2). This Working Group (3) has suggested that the Australian Standard 2942-1987, Wheelchair Occupant Restraint Assemblies for Motor Vehicles, (4) be used as the basis for the ISO standard. This standard establishes design and performance requirements for wheelchair restraints and includes details of dynamic testing procedures. The standard does not specify a standard design for wheelchair occupant protection systems, but

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1. Numbers in parentheses refer to the references at the end of this paper

rather is intended to ensure effective crash protection for wheelchair occupants with a minimum of restriction on restraint design.

An inflatable compartmentalized crash protection system, as suggested by Clark (5), could protect wheelchair occupants from contact with the adjacent wheelchair/occupant complex, prevent excessive lateral flexion of the upper torso and cushion the occupant's head and torso during a crash. As part of the system, a wheelchair securement mechanism must be incorporated which provides both frontal and lateral stability and restraint.

The research efforts discussed and the information presented in this paper were generated during the performance of U. S. Department of Transportation (DOT) Small Business Innovation Research (SBIR) Phase I Contract No. DTRS-57-89-C-00145 and an extension of the DOT Contract as authorized by the New York State Science and Technology Foundation (NYSS&TF) contract no. SBIR 90027. The results of these research efforts to-date include:

1. The definition of transportation problems encountered by transporters of wheelchair bound occupants and the lack of crash protection that exists in todays environment for these passengers.

2. The development of a computer model of the occupant, wheelchair, and air cushion in the environment of a transporter van for wheelchair passengers for use in the Crash Victim Simulation, Version III (CVS III) computer program.

3. The design and fabrication of a dynamically testable prototype of an inflatable safety compartment for crash protection for side facing wheelchair occupants.

4. The successful sled testing of the inflatable safety compartment concept with the demonstration of significant crashworthiness improvements for the wheelchair occupant with the use of the system when evaluated against the dynamic sled test results of a wheelchair occupant with no safety compartment (as they are currently being transported).

5. Refinement of CVS III input parameters to more closely simulate the electronic and kinematic responses resulting from the sled test program.

The conceptual design of the inflatable airwall is displayed in Figure 1. The figure depicts a housing console with a reaction surface divider separating two rows of horizontal inflated tubes. The lower portion of the console houses the inflation ducting or inflators. All tubes are manifolded together at either or both ends of the console. The reaction surface is reasonably compliant to aid in energy-management and ride-down. The original concept developed was one of building partitions into transporter vans to separate the wheelchairs when they are in a side-facing configuration.

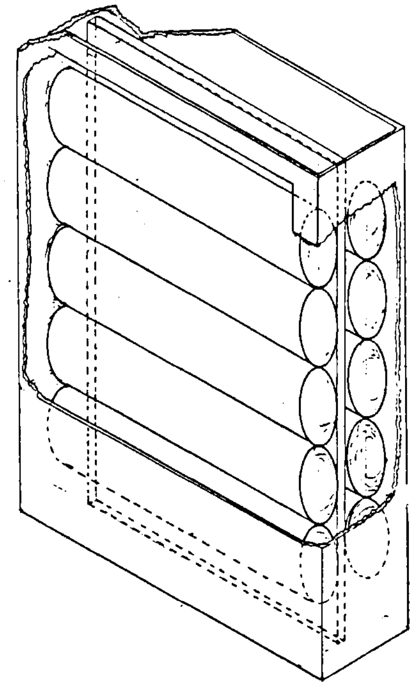


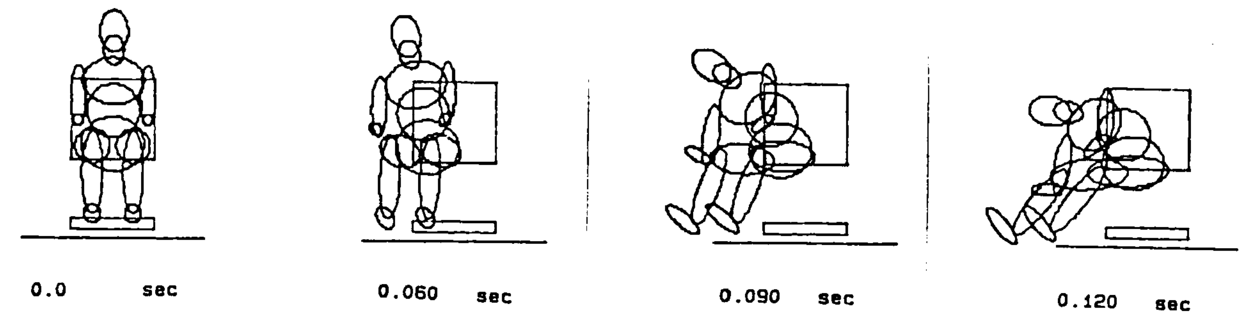
FIGURE 1 CONCEPT RENDERING

During the program we were successful in developing the first three dimensional computer model of a 50th percentile Anthropometric Test Device (ATD) seated in a wheelchair facing sideways in a vehicle. This model was further refined during the research reported herein and used to successfully simulate the kinematic and electronic results generated during the sled tests. The results obtained through the extensive use of this model during the exercise of the NHTSA sponsored, Calspan developed, three-dimensional computer simulation program (CVS III) has provided valuable information on the results that can be expected during sled testing of various crucial components of the wheelchair and air wall system (i.e. changes in the wheelchair force-deflection properties, changes in the air wall housing force-deflection properties, effects of venting of the air cushion, etc.). This type of information provides the necessary inputs for making critical decisions regarding test sample fabrication prior to expensive sled testing, thereby substantially reducing the costs of a sled test program.

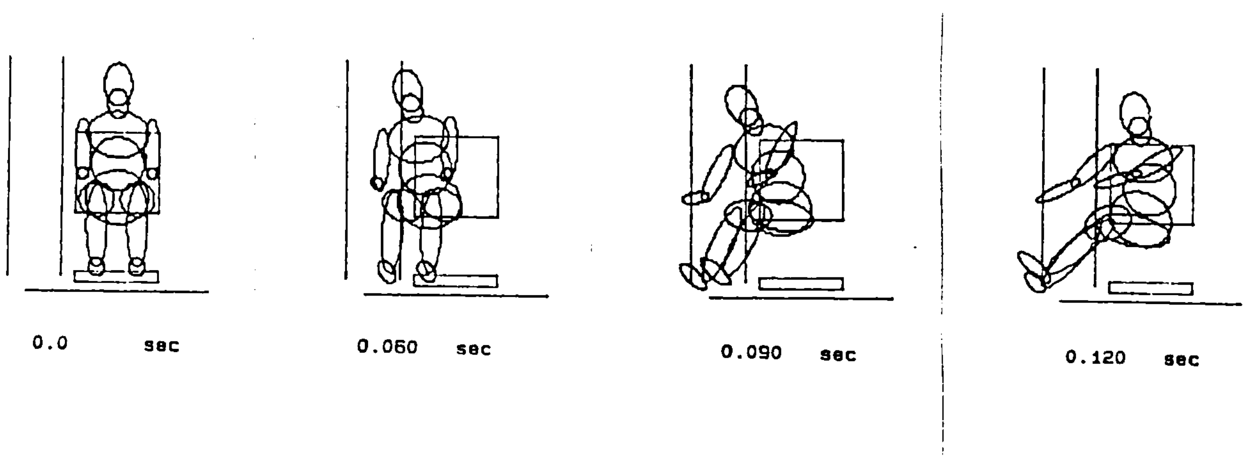
Historically, the CVS III program has been used to simulate the responses of full-size adult occupants, utilizing various types of restraining devices, while being exposed to the forces generated during vehicle crashes. The program itself is very general in nature and has the capability to simulate the three-dimensional rigid body dynamics of any articulated collection of rigid bodies. The application used during this program is quite removed from typical applications in that the program simulates the responses of a side-facing adult occupant/wheelchair complex during frontal crashes both with and without the inflated partition restraint system. In order to accomplish this, four separate sub-systems are required: the van, the wheelchair, the surrogate, and the inflatable protection system.

Once the 50th percentile model, seated in a side-facing wheelchair with the inflatable protection system was successfully developed, a brief analytical study of the compartmentalized safety system was undertaken using the CVS III program. The objectives of the study were to explore the effects of safety system geometry with various initial inflation pressures on the kinematics of the occupant. For comparative purposes, CVS III simulations of side-facing wheelchair occupants without the safety system in place were also studied. Figure 2 presents the 50th percentile male ATD kinematics generated by the CVS III program both with and without the safety system.

Based on the positive results of the CVS III study, a prototype compartmentalized safety system was designed, fabricated and subjected to drop tests. Two dynamic crash simulations were performed at the sled testing facility of MGA Research Corporation in Burlington, Wisconsin. Sled test No. H90141 was a 21.7 mph crash simulation using a 50th percentile male size Anthropometric Test Device (ATD) seated in a side-facing wheelchair, and the air wall system. Sled test No. H90142 was a 22.6 mph crash simulation with test conditions set to replicate No. H90141 with the exception that the air wall system was not used. Detailed analyses of the electronic data and the high speed film were performed. Of primary concern in the analyses were the head excursions, the head accelerations, and the chest accelerations. Of secondary interest was the air wall pressure measurement. In addition to these data, evaluation of the efficacy of the safety system was based on structural integrity of the system, and acceptable kinematics of the ATD regarding the subjective evaluation of potential for internal injury.



ADULT ATD KINEMATICS - WITHOUT SAFETY SYSTEM



ADULT ATD KINEMATICS - WITH SAFETY SYSTEM

FIGURE 2 - CVS III ADULT ATD KINEMATICS

Table 1 presents the performance criteria generated during the two tests.

TABLE 1

SLED TEST PERFORMANCE CRITERIA

TEST NUMBER		H90141	H90142
SLED VELOCITY	(mph)	21.7	22.6
SLED ACCELERATION	(G's)	15.2	15.9
HEAD RESULTANT ACCELERATION	(G's)	42.1	207.0
HEAD INJURY CRITERIA	(HIC)	170.2	979.3
CHEST RESULTANT ACCELERATION	(G's)	17.5	40.4
AIR CUSHION PEAK PRESSURE	(psi)	5.5	N/A

The differences between the inflated safety system and the non-safety system results are dramatic. The demonstration of the protection capability of the inflated system is even more remarkable considering that the sled test velocity was nominally 20 mph and the ATD head contacting a structural component through a 5 inch thickness of foam still experienced this extremely high level of deceleration.

Subsequent analysis of the high-speed film indicate that the concept of an inflatable safety system provided control of the occupant/wheelchair kinematics, cushioning the occupant's head and torso during the crash while allowing the lower section of the air wall to crush in a predetermined manner while being loaded by the wheelchair. The kinematics observed during the sled test without the safety system in place showed complete structural failure of the right side wheelchair wheel. The occupant's head struck the outside frame of the sled buck which had been covered with 5 inch thick foam padding to protect the ATD. It is obvious that the wheelchair and occupant would continue to move laterally until stopped by contacting another wheelchair/occupant complex or a structural member of the vehicle.

When using a mathematical model to simulate real world, or laboratory, events one must proceed through the often laborious task of validating the model within the constraints of the particular experimental protocol that is to eventually be simulated. Once a certain degree of confidence in the model's performance is reached, predictive simulations can be made based upon perturbations in the system configuration and/or physical properties. At the point in the research program the data from the sled tests were analyzed. The results of this analysis were then compared with the data from the simulations. Excursion measurements were obtained of the occupant and the wheelchair and deformation measurements of the wheelchair and the safety system from the high-speed film of the sled tests. These data were utilized to incorporate more realistic force-deflection characteristics into the CVS input. The CVS III input parameters were then modified from those used during the initial computer runs based upon these comparisons. The most significant changes were realized from the input of the following parameters which replaced the idealized wheelchair configuration used in the Phase I simulations.

1. Venting the air wall during the loading phase.

2. Moving the air wall reaction surface further away from the test surrogate.

3. Contact surface interactions between the wheelchair wheels and the air wall housing.

4. Varying the wheelchair arm rest force-deflection characteristics.

5. Varying the amount of slack in the restraint harness.

The end result of the research program, to date, was the design, fabrication and testing of a prototype inflatable air wall restraint system for passengers in wheelchairs being transported in a side facing configuration in a van. Further dynamic sled testing of prototypes, finalization of the air wall restraint system design, incorporation of the hardware required for inflation, fabrication of the final design and further sled testing of the system to demonstrate a significant increase in the level of protection potential with the use of the air wall based on the injury criteria of Federal Motor Vehicle Safety Standard No. 208 (FMVSS 208) - Occupant Crash Protection is needed.

Research Program - Children

Based on the positive results of the research program utilizing the adult size male ATD, the US Department of Education (DOED) awarded a Contract, Number R590086015, to develop child size models for use as side-facing wheelchair occupants in the CVS III computer simulation program and to design safety systems for use in school buses.

During this program, Hartley Associates, Inc. proposed to adapt the concept of the safety system to accommodate school-age children in wheelchairs, fabricate a down-sized safety system using materials similar to those used during the DOT Phase I Contract, and perform drop tests on the re-designed systems using six-year-old and twelve-year-old size surrogates.

The performance of this research program includes the following four tasks:

TASK 1 Define the specific transportation problems encountered by the subject category of occupants (school bus passengers) and perform a detailed examination of wheelchairs and the types of vehicles that are used for transporting wheelchair bound school children.

TASK 2 Exercise the Crash Victim Simulation, Version III (CVS III) program to evaluate the effects (on the occupant and the wheelchair) of various concepts of wheelchair containment and lateral protection.

TASK 3 Design and fabricate a restraint system with inflatable capability to function in the modified environment and within the available space in the transport vehicle.

TASK 4 Perform dynamic sled tests of the prototype restraint system to demonstrate the increased protective capabilities and safety benefits of the system.

To date, efforts have been expended on tasks 1 and 2. These tasks will be discussed below.

One of the primary problems encountered in the transportation of wheelchair occupants is the myriad of wheelchair manufacturers, designs and sizes. Of importance in this research program were the dimensions of wheelchairs. In order to determine the space required for compartmentalization of wheelchairs in a transporter, an envelope of typical wheelchair sizes which must be accommodated by school buses was developed. In addition, all wheelchair schoolbus transporters in the Western New York area were contacted and requested to allow us to inspect their vehicles. The vehicles inspected were the van-type transporters used almost exclusively by the largest transporter of handicapped children in this area. At the transporters request, we have agreed to not use their name in any publication. The vans inspected accommodate both normal seating and wheelchair seating in forward and side facing configurations. Wheelchair dimensions and van measurements are provided in Tables 2 and 3, respectively.

TABLE 2

MANUAL WHEELCHAIR - MINIMUM TO MAXIMUM DIMENSIONS

	Range in inches		
	CHILD	MID-SIZE	ADULT
Overall width	19	- 22	- 26
Overall height	30 3/4	- 35	- 35
Seat height	16	- 20	- 18
Seat depth	11	- 15 3/4	- 17
Seat width	11 1/4	- 16	- 18 1/4
Seat back height	16	- 17 1/2	- 17
Arm rest height	22	- 30 1/2	- 28
Rear wheel diameter	24	- 24	- 24
Front wheel diameter	5	- 8	- 8

TABLE 3

VAN MEASUREMENTS - WHEELCHAIR SPACE

Ceiling height at centerline	74 " **
Ceiling height at start of curve	63 "
Sidewall height at top of window	53 "
Total width of van	90 "
Width of van at wheel wells	53 "
Total length of van cargo space	138 "
Length from lift to rear of van	86 "
Aeroquip track length - 1 wheelchair	28 "
Aeroquip track length - 2 wheelchairs	56 "

** In some of the older vans, the ceilings were not curved and the entire ceiling height was 63 inches.

The results of Task 1 showed that the interior dimensions of vehicles used as school buses are quite different than those used for adult transport. In addition, although many of the child-sized wheelchair wheels were the same diameter as those used by adults, the kinematics experienced by children are expected to be very dissimilar to those of an adult. This indicates that, although the safety system housing may be similar in size for children and adults, the crush characteristics will require extensive experimentation. In order to fabricate and test the proper configurations for the safety system and the safety system housing for children on school buses, a large amount of data must be gathered and analyzed which was beyond the scope of this program.

During Task 2 the GOOD program was installed and a mathematical representation of a 12-year-old size occupant seated in the appropriate size wheelchair was developed. In working toward establishing a twelve-year-old size ATD model we encountered problems with both the anthropometry and the joint properties transfers for this ATD. The anthropometry of the 12-year-old size ATD appeared to be reasonable except in the neck region. The problem with the joint properties transference was discovered during analysis of the "injury criteria" of the program output when the model was exercised. The head injury criteria (HIC) was higher than expected. It was reasoned that a smaller surrogate would have lower reactive joint torque capability than that of an average size adult male. When the joint torques were lowered in the model the HIC value increased rather than decreasing as was expected. The indication from these preliminary computer runs was that as joint torques decrease in level the model reacts as though they were increasing. Subsequent graphic output of the 12-year-old size mathematical models demonstrated that there was a problem with the head and neck ellipsoids, as can be seen in Figure 3.

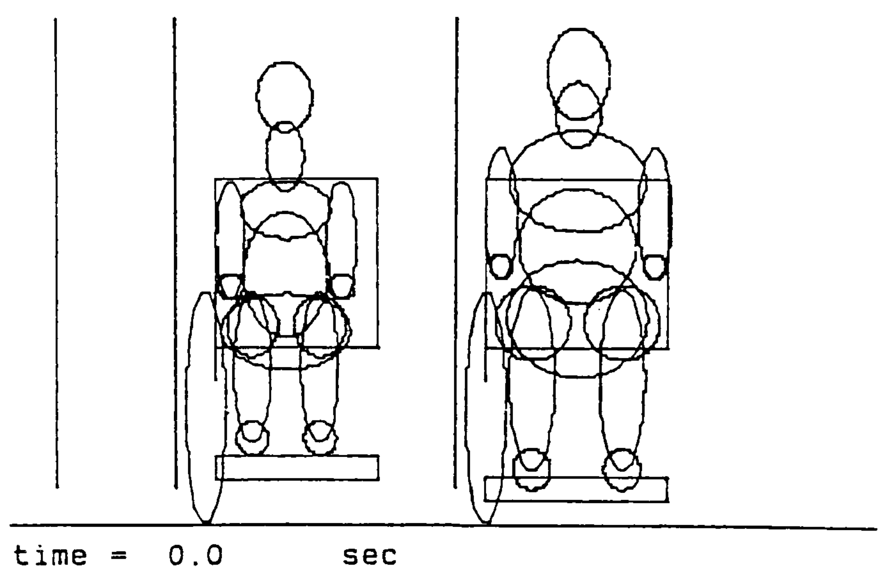


FIGURE 3 - ATD ANTHROPOMETRY COMPARISONS - 12-YR VS 50TH

We were successful in enlisting the aid of personnel from the U.S. Department of Transportation, National Highway Traffic Safety Administration (NHTSA), in developing a more biofidelic model of the 12-year-old and 6-year-old size surrogates. These new models were installed and the CVS III program has been exercised with both of these new surrogates in an inflated compartment configuration with the air cushion model vented at a 2 psi level. The results appear to be very reasonable. Comparisons of kinematics of the 50th percentile male size, 12-year-old size and 6-year-old size ATDs are presented in Figure 4 for the non-airwall (unrestrained) simulations and in Figure 5 for the inflated airwall simulations.

CONCLUSIONS

Based on the results of this limited study, the air wall concept appears to offer the potential for managing the injury severity of side-facing wheelchair occupants over a significant size range in collision situations. Furthermore, at this early stage of the research efforts, the concept of protecting side facing wheelchair occupants in frontal or rear crash situations appears to be quite reasonable. It is the opinion of the authors that the movement to preclude side facing wheelchair transportation by fiat within the transportation community is premature.

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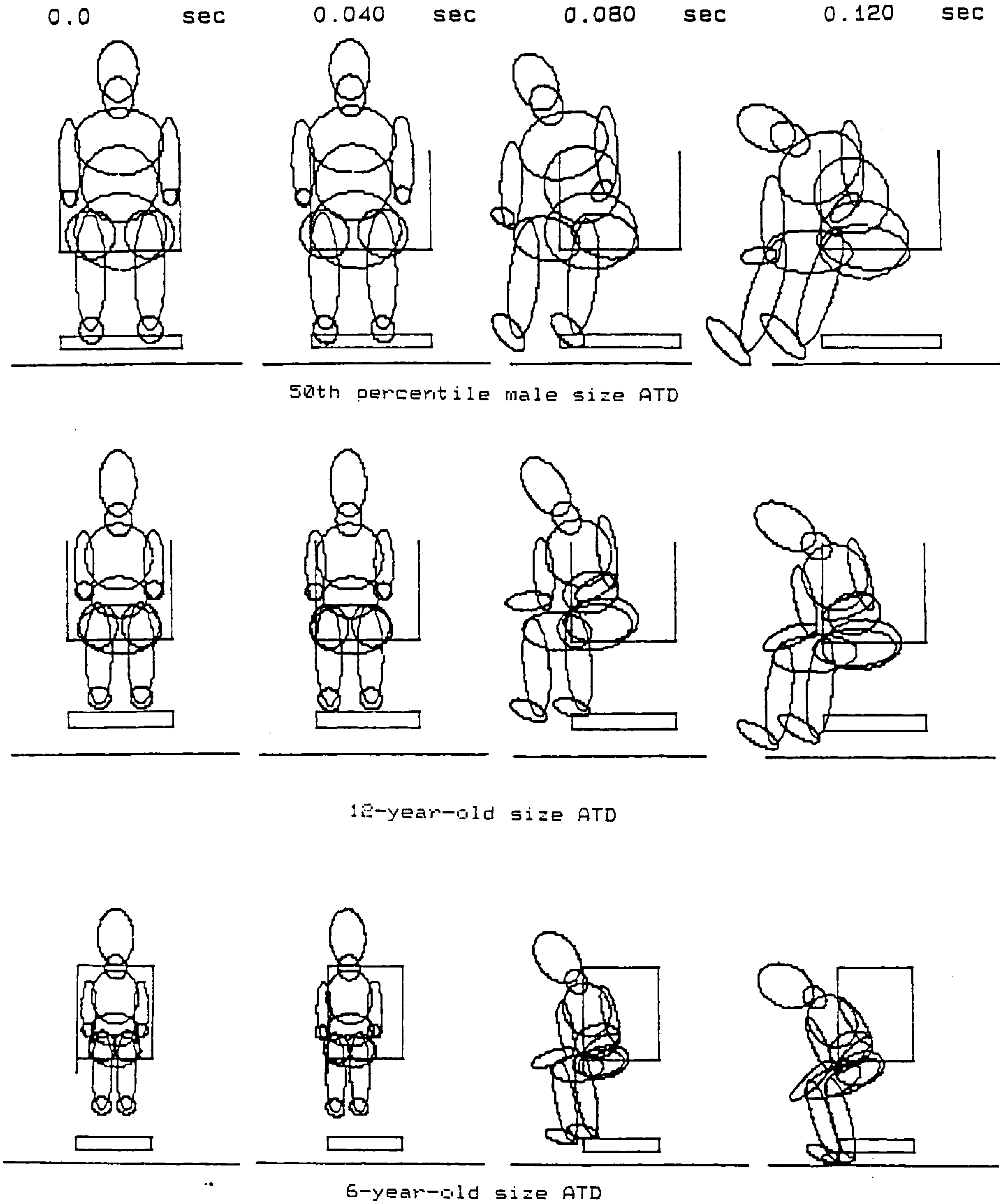

FIGURE 4 - COMPARISON OF ATD KINEMATICS - UNRESTRAINED

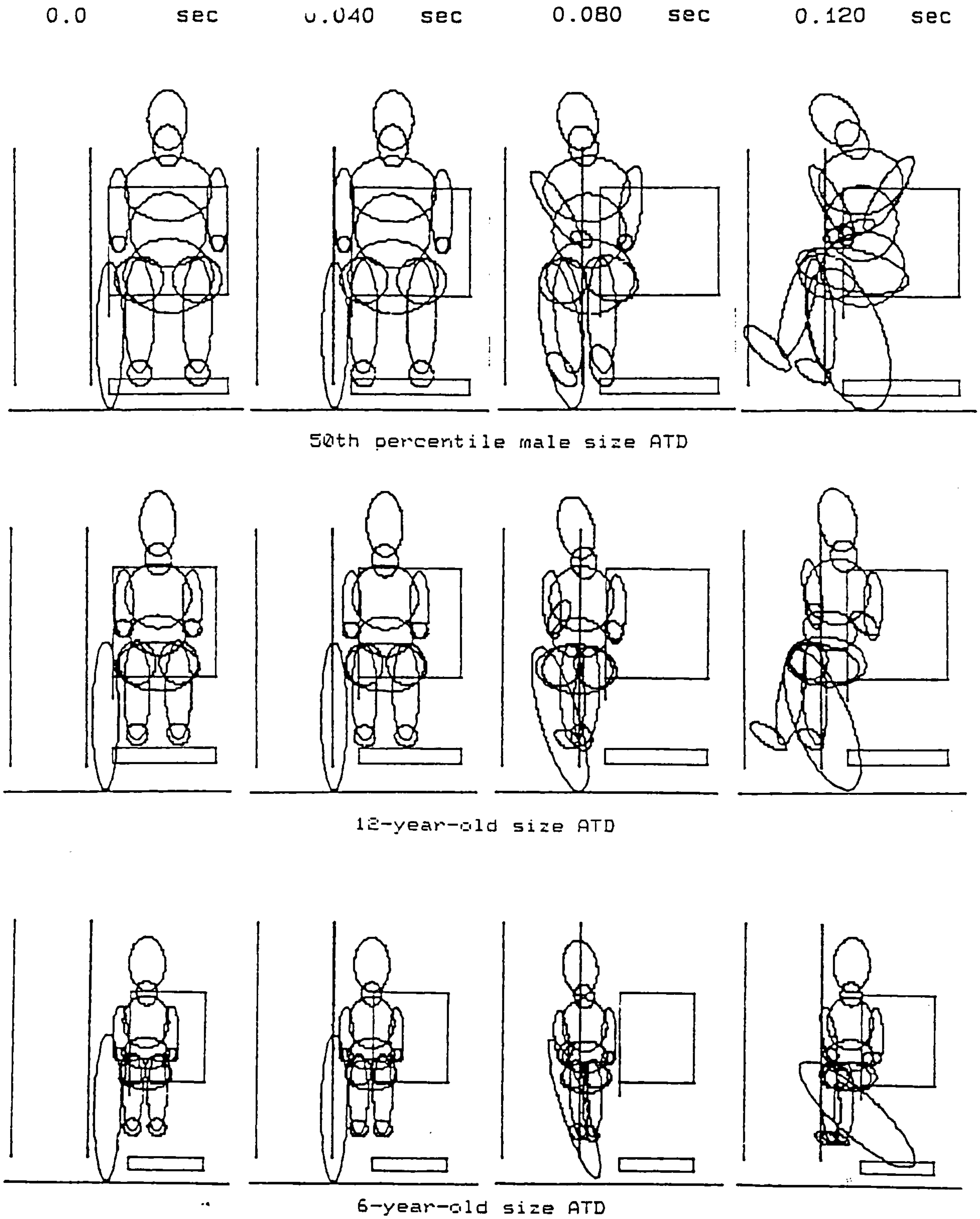

FIGURE 5 - COMPARISON OF ATD KINEMATICS - INFLATED AIR WALL

PAPER: SIDE FACING WHEELCHAIR OCCUPANT SAFETY-A COMPUTER SIMULATION

SPEAKER: Michael Walsh, Hartley Associates

Question:. Larry Schneider, UMTRI

Mike, as you know we've done a lot of work in this area at Michigan and it's a growing problem, I think there are more and more people who are in wheelchairs trying to use transportation. You mentioned that there are two camps. I'm in the other camp saying people should be forward facing and I think, as you point out, there are difficulties dealing with the side facing situations for the frontal impact and there aren't good data on the statistics of people in wheelchairs and what kind of accidents they are involved in. However, I would suspect that the statistics would have to be similar to what the statistics are for the rest of the population. In the absence of other data, I think we have to go with those frontal impacts being the primary concern. Again, that's what we're recommending. You can make a big step forward in getting these people to face forward. You can get the tie down systems to work much better for the frontal impact condition, restraint systems to work much better and I think that's a big step in the right direction. I'd also like to point out that the ISO committees are currently working on this problem and they're recommending forward facing. the SAE committees are recommending forward facing. the Australians have a standard that requires forward facing. Canadian Standards Association is recommending forward facing. So, there's a lot of other people in the other camp that are pushing for the forward facing as I think of as the right step to make a lot of progress to the safety of these people as quickly as possible. There may be ways of doing the side impact protection as you're trying to work on here. I think that's worth exploring but at the same time you have to worry about the practicality of the solutions that you come up with. That is, will transportation companies be willing to accept padded barriers and air cushions and structures that you may need to implement in order to make the side facing on the frontal crash an acceptable situation.

Answer: Larry, I understand what you're saying. let me say that I'm not in either one of those camps. We believe that it is impractical to expect people, carriers, businesse, etc., to tear out all of their equipment and go from carrying five wheelchairs in a bus to carrying three wheelchairs in a bus. I know that you have told me that you talk to people who are more than willing to do that. However, the people that I've talked to, granted from around New York State and Canada, say that they are not going to do it. As I said earlier, one of my concerns is . . . and I don't care about forward facing or side facing . . . I'm just looking at the reality of it, that they are transporting people side facing and it is reasonable to try to protect those people, side facing, if that's the way they are going to be transported. Let's not take the attitude, well, let's not transport them side facing because you're not going to get these people to quit doing this. I don't believe ISO's going to pass that regulation for the next ten years, anyway. Even if they do, there's going to have to be some sort of grandfather clause, as there was in that schoolbus thing, because people just aren't going to go bankrupt themselves doing doing this. So, I think that there's a reasonable retrofit that can be made rather than telling people that you're going to destroy their fleet and start over. I don't want people to get any idea that we are advocates of side facing wheelchair transportation and not forward facing. What we are trying to do is protect the people that are being transported side facing because that's how they are being transported, side facing.

Question: Guy Nusholtz, Chrysler

Just a few questions on what you were doing. First, what type of material were you using for your aircushion, what type of pressures did you have inside of the cushion, are you sort proposing that it be in deployed state or a fully pressurized state all of the time or do you have some sort of mechanism for deploying it?

A: With regard to your first question, the material that we were using was a polyethylene material. It's not a material that would ever take the gaff of day-to-day use. We started out using it for a couple of reasons, the technology for making these things was easily accessible. If you're going to start experimenting with these things and you have to make new air bags and you drop things on them and they break, then you have to try something else. it's nice to be able to do it conveniently, on site. The pressures we decided, based on the CVS III Program, was to start out at . . . the sled test was at 2 1/2 psi static pressure and the dynamic pressure unloading went up to about 5- 1/2 - 6 psi, something like that. To answer your second question, we were essentialy thinking of preinflated when someone was occupying that position.