APPLICATION OF A COMPUTER MODEL AS AN ENGINEERING TOOL FOR EVALUATING SIDE IMPACT DESIGN REQUIREMENTS FOR CHILDREN AND SMALL ADULTS

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ABSTRACT

This paper describes a computer modeling system and its application in evaluating several vehicle designs for side impact protection of children and small adults.

INTRODUCTION

An analytical study was undertaken to investigate the problem of protecting small vehicle occupants in side impacts. Because the vast majority of the side impact research to date has focused on the 50th percentile adult male, design insights for small and very large occupant sizes are sorely lacking. The main objective for the current study was to evaluate the side impact design requirements for the smaller occupant sizes. A secondary objective was to evaluate the performance of candidate designs for the very large occupant population, represented by the 95th percentile adult male.

A computer modeling system, SIFEM, was used to simulate the impact event and to evaluate the vehicle design concepts of interest. The design concepts included: interior padding, a hip restraint device and an airbag system. Data from selected side impact tests were first used to validate the model then extrapolations were made to the crash condition, occupant sizes, and vehicle designs of interest.

THE DESIGN PROBLEM

Padding systems play an important role in protecting vehicle occupants during a collision. This is especially true in side impacts where the occupant is very likely to make contact with the interior surfaces of the vehicle. Even when fully restrained by a conventional seat belt, the upper torso of the occupant is free to rotate about the hip joint and make direct contact with the intruding surfaces. Although energy absorbing materials mounted to these surfaces provide a measure of protection for the occupant, they are not a panacea. Padding systems in general do not offer equal protection for all occupant sizes. What is adequate for a large occupant may be inadequate and even harmful to the very small occupant. The converse is also true. In addition, there are areas in the vehicle interior where the use of padding is not even a practical consideration (e.g., the window areas).

Trajectory control is an important factor in the design of occupant restraints for frontal impacts. Out-of-phase loading of body components during impact can introduce secondary effects such as whiplash, excessive body movement and harsh contacts with the vehicle interior. In side impacts, body phasing and trajectory control are also important design considerations, as will be shown later in this paper.

In side impacts, the reactive surfaces generally exclude the side window areas. Current side window glazing materials do not provide a reliable surface since they are often destroyed during impact. Also, the window can be left in the open position by the occupant. Because of this, the area below the window opening usually becomes the primary supporting surface for padding and airbag systems. For large occupants, this forces the reaction loads below the torso c.g., causing the occupant's upper torso and head to rotate into (and sometimes through) the window opening during impact, as illustrated in Figure 1. This allows the occupant's head to make direct contact with the impacting vehicle or with the stiff lower edge of the window. Several new inflatable concepts such as the airbag curtain and the ITS (Inflator Tubular Structure) are currently being considered by several automobile manufacturers as possible solutions to this problem. These concepts are beyond the scope of this study.

For small children, the reaction forces are generally closer to the torso c.g., however, the occupant's head and torso can still rotate onto the lower edge of the window if the torso and hip reactions are not properly phased (see Figure 2).

Airbag systems have become the norm in modern safety systems. For frontal impacts, history has proven that airbag systems are an effective and reliable means for protecting occupants in real life accidents. History has also proven, however, that airbag systems do not automatically provide equal protection for all occupant sizes. Deaths of small children have occurred even in relatively mild impacts. These fatalities have been attributed directly to the performance of the airbag. The lesson here is that an airbag system designed for one occupant size will not automatically work satisfactorily for another. History clearly shows us that what is needed in the design process is a true systems approach. An approach that will optimize the performance of the airbag over a range of occupant sizes, rather than on a specific

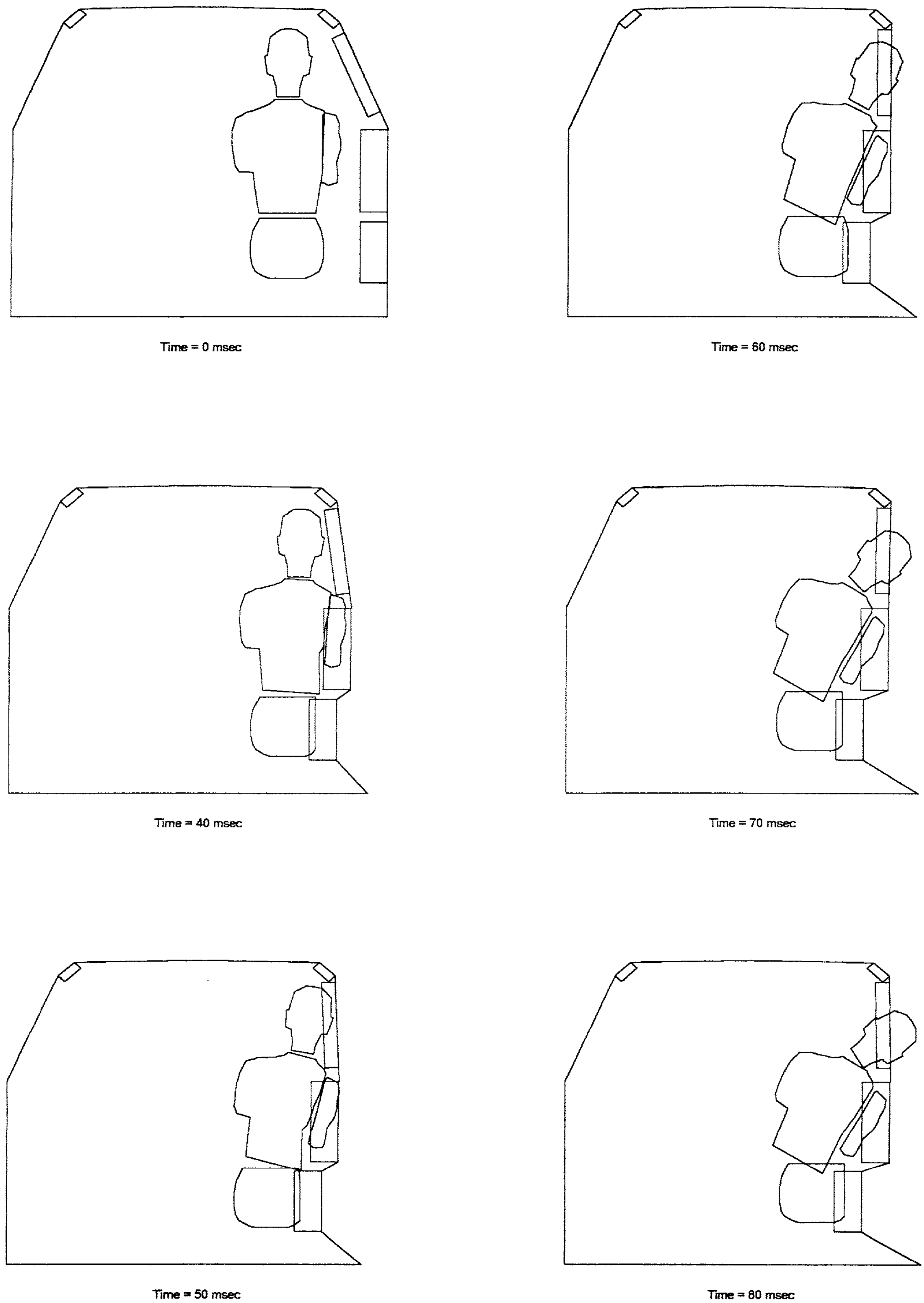

Figure 1. Occupant trajectory, 50th percentile adult male.

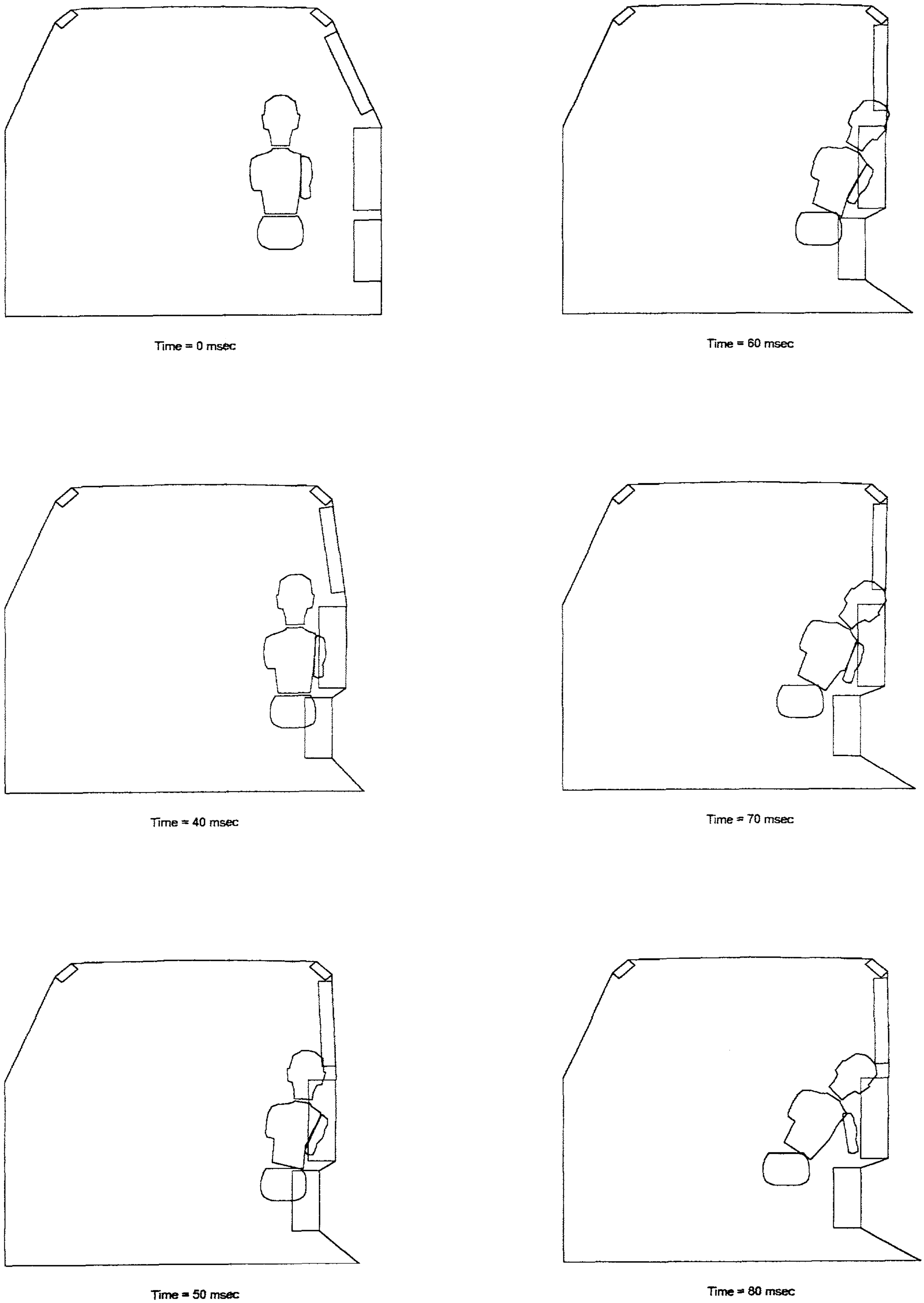

Figure 2. Occupant trajectory, 3 year old child.

size. This observation, no doubt, carries over into the side impact realm as well.

In the current study SIFEM was used as our main systems design tool. SIFEM models real life side impact accidents and simulates the performance of several occupant restraint concepts. These concepts include:

1. Energy Absorbing Padding (upper door, lower door and B-pillar)
2. Window Glazing (as an energy absorbing surface)
3. Hip Restraint Device (horizontal and vertical control)
3. Airbag Systems
4. Pressurized Padding Systems.

ANALYTICAL APPROACH

In this study we limited our scope to one crash condition and three restraint design concepts. The design concepts included door padding, a hip restraint device and a combination head/torso airbag system. This section describes the analytical approach.

Crash Scenario

The side impact event for this study consists of an intersection collision with the striking vehicle traveling at 30 mph and the struck vehicle traveling at 15 mph. The orientation angle of the striking vehicle is 90 degrees with respect to the longitudinal axis of the struck vehicle. This crash scenario was represented by an actual full scale crash test conducted by the Vehicle Research and Test Center of East Liberty Ohio (Reference 1). This test consisted of 1988 Hyundai Excel 4-door sedan impacted on its side by a NHTSA moving deformable barrier.

The referenced test provided the acceleration histories for the passenger compartment and the driver side door. This information was used in SIFEM to represent the baseline vehicle design. Figure 3 shows the acceleration-time history and Figure 4 the velocity-time history for the door assembly. It should be noted that this data represents a production vehicle, not a vehicle that has been structurally optimized for side impact.

Padding System

The padding system consists of energy absorbing materials mounted onto the upper and lower surfaces of the door (below the window opening). The padding material was limited to a single class, one having relatively "flat" pressure-displacement characteristics and little strain-rate effects. Several materials fitting this class are metal and paper honeycombs and some rigid foams. Because of their nearly ideal energy absorbing characteristics, these materials have found wide use in past safety research (e.g., References 2 and 3) . In the current study we assumed two crush strength values for the candidate material, 140 kPa (20 psi) and 280 kPa (40 psi). Reference 3 indicates that paper honeycomb materials having these crush strength levels were used in a sled test evaluation of the SID-IIs dummy, presumably to simulate an actual padded interior of a vehicle. Reference 2 documents the results of dynamic testing with child and adult body forms on paper honeycomb material (KNC1-80(0) EDF, Kraft paper). This material had a static and dynamic crush strength of approximately 30 psi. The test results indicate a relatively flat pressure-displacement curve for approximately 75 percent of the material thickness, when the material begins to "bottom-out". This characteristic was modeled in SIFEM.

Hip Restraint Device

The hip restraint model in SIFEM consists of three non-linear springs acting against the hip mass. Two springs act in the horizontal direction (side-side and fore-aft) and the other in the vertical direction. Each spring can be assigned arbitrary force-displacement characteristics (both tension and compression), with hysteresis effects. With this arrangement, SIFEM can simulate a lap belted occupant and an occupant interacting with various interior surfaces such as the seat-back, seat cushion and a center console made from an energy absorbing material.

Airbag System

The airbag system in this study represents a current state-of-the-art design. The geometry and size of the airbag was based on information from Reference 3. The cited reference indicates that an airbag system "chosen to be representative of an advanced technology" was being used to evaluate the performance of the new SID-IIs, 5th percentile adult female dummy. The airbag is a combination chest-head side impact system having a static volume of approximately 20-30 liters. Photographs indicate that the static depth of the bag is approximately 6 inches. Figure 5 shows the static geometry of this airbag, as modeled in SIFEM. This geometry was selected as the baseline design. Reference 3 does not provide detailed information concerning the performance of the airbag inflator so we made the assumption that the flow rate history of the inflator is trapezoidal (see Figure 6) with the time period, corresponding to the "flat" portion of the curve, a variable to be evaluated. We also assumed that the working pressure for the bag was limited to a value in the neighborhood of 15 psig.

A series of computer runs were conducted to derive the inflator flow and bag venting characteristics for this

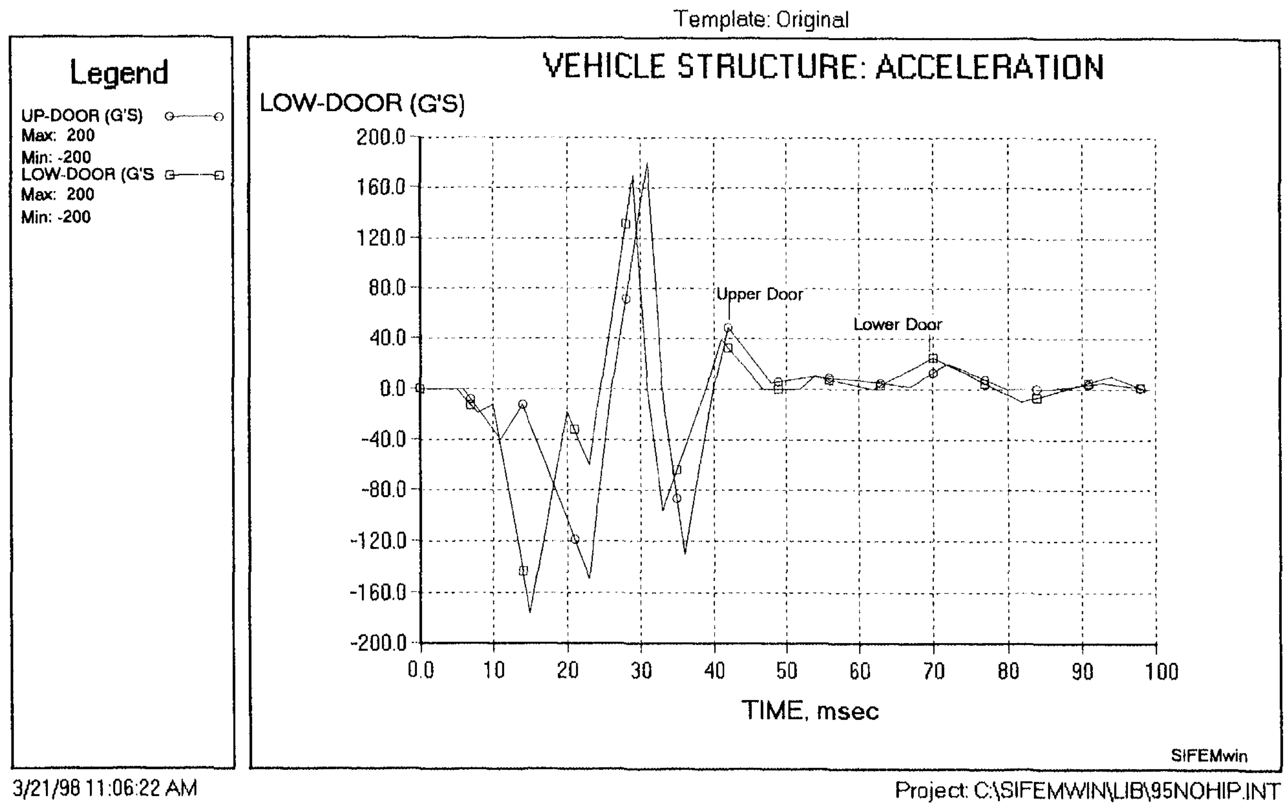

Figure 3. Door acceleration, baseline vehicle.

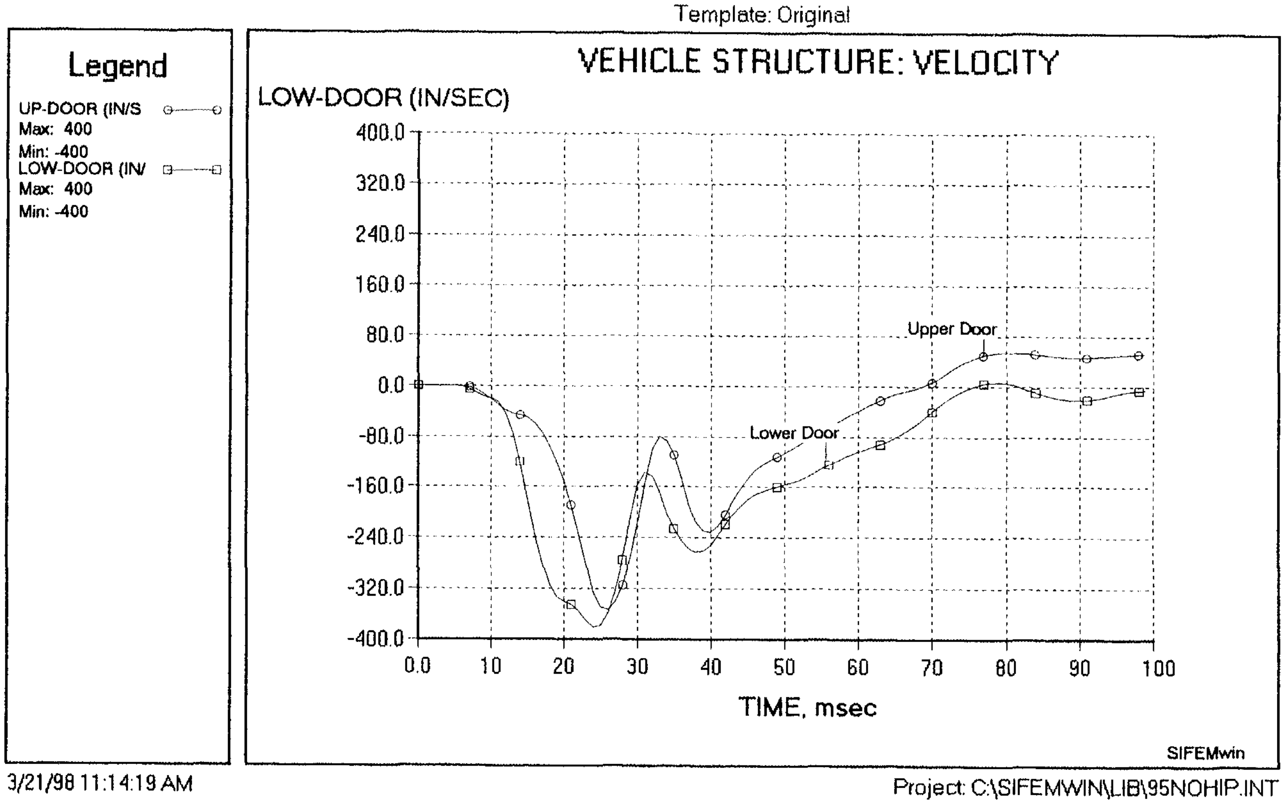

Figure 4. Door velocity, baseline vehicle.

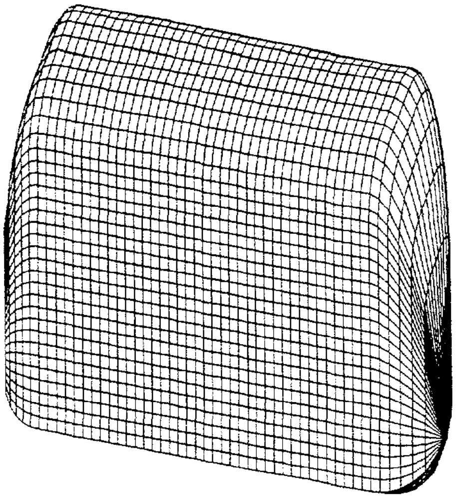

Figure 5. Airbag geometry modeled in SIFEM.

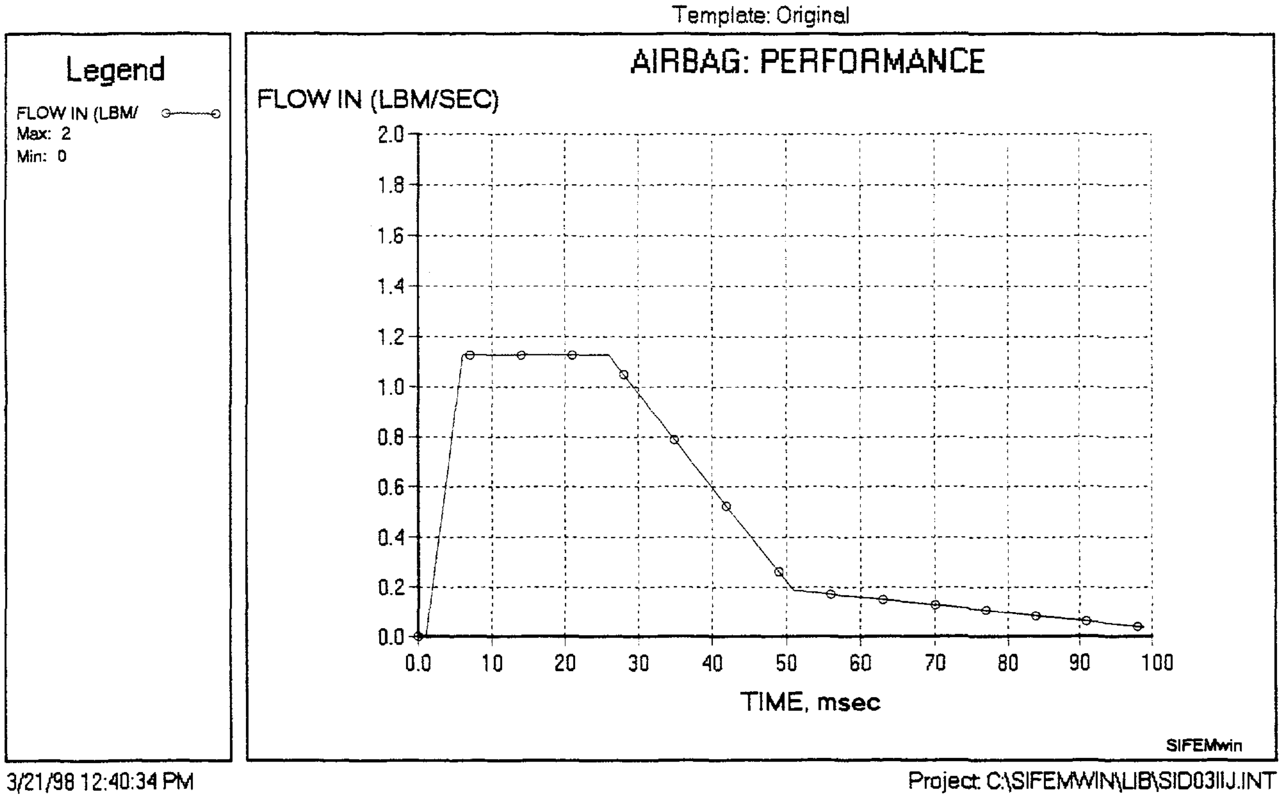

Figure 6. Inflator flow characteristics modeled in SIFEM.

study. Combinations of inflator flow and bag venting were investigated to evaluate the effects of high-flow/high-venting and low-flow/low-venting on system performance. These characteristics were also varied to derive the near optimum combinations for the occupant sizes of interest.

Occupant Simulation

To make this study applicable for the full size range of occupants, it was necessary to make some basic assumptions. Currently there are no standard side impact dummies representing the small 3 year old child and the large 95th percentile adult male. For these occupant sizes we were forced to create our own "theoretical" dummies.

In prior validation work, a SIFEM database was developed for the SID dummy (50th percentile adult male) and the SID-IIs dummy (05th percentile adult female). This database has been checked against available design and test data (References 3-8) and has been found to give good and reasonable simulation results. A simplified scaling rule was used to expand this database to include the 95th percentile and the 3 year old occupant sizes. The scaling rule is based on the assumption that the stiffness and damping characteristics of a given body part are proportional to the component mass. Further, we assumed that the overall geometry and mass distribution for our fictitious dummies are identical to the 95th percentile and 3 year old frontal impact dummy counterpart. The rib mass and the spring and damping characteristics for the various body parts were scaled from the SIFEM database, based upon the assumed mass distribution. The 95th percentile dummy was scaled from the SID data set and the 3 year old child dummy was scaled from the SID-IIs data set. Thus, our 95th percentile adult male dummy is armless and contains hydraulic dampers to represent the force-displacement characteristics of the rib-cage (like the SID). The 3 year old child dummy has a pivoting arm and a spring steel rib cage (no hydraulic dampers) like the SID-IIs.

A Cautionary Note

Because of the assumptions made in this study, caution must be taken when interpreting and using the results. Future side impact dummies may be constructed differently and may not have the same characteristics assumed herein. The main objective for this study was to gain additional insight and knowledge concerning side impacts, not to derive specifications or hard and fast rules for design. This work must be updated as new and improved side impact dummies are made available.

MODEL DESCRIPTION

SIFEM is a Windows(R) based modeling system designed for use on micro computers. SIFEM uses the lumped mass and finite element methods for simulating the occupant and vehicle interactions during a side impact event. The model simulates the performance of padding, airbag and a hip restraint systems. Figure 7 illustrates the side-side portion of the model. A similar model is used to simulate the fore-aft movement of the occupant in oblique and crabbed steering side impacts where a significant longitudinal acceleration component is imposed on the vehicle

Padding materials with arbitrary pressure v.s. displacement and hysteresis characteristics are modeled. by SIFEM. Padded surfaces include the upper and lower areas of the door, the B-pillar and a hip restraining surface (i.e., a center console or a lap belt). The side window is modeled as a nonlinear, energy absorbing surface, having arbitrary force v.s. displacement characteristics. The interactions of the occupant with these surfaces are modeled with sufficient detail to account for: occupant size, sitting location and posture, geometry of the major body parts (head, upper and lower torso, hip and upper arm) and the instantaneous orientation and geometry of each energy absorbing surface within the vehicle interior. The model uses the Adams-Moulton predictor-corrector method to solve the equations of motion.

Figure 8 illustrates the SIFEM airbag model. The airbag cushion is modeled using surface elements. The statically deployed shape of the bag is designed using a built-in CAD routine. The shape of the bag can be arbitrary (along with the inflator flow characteristics). The shape of the bag is defined with over 3500 surface elements. Simplified stretch and deployment algorithms are used to model the interaction of the airbag surface with the occupant and other interior surfaces of the vehicle. Bagslap, catapult (membrane) and pressure contact phases are all modeled in the program.

SIFEM allows the user to model the full size range of occupants. The occupant model simulates the stiffness of the following body parts:

- Cranial (head impacts)
- Neck (side-side and fore-aft directions)
- Shoulder/Arm
- Arm Flesh
- Rib (three rib masses, includes arm interaction)
- Abdomen (includes arm interaction)
- Pelvic Girdle
- Hip Joint (side-side and fore-aft directions)

Modeling options include "no-arm" and "with-arm" configurations. The "no-arm" configuration removes the arm mass from the simulation. This allows the rib masses and the abdominal spring to directly contact the vehicle and airbag surfaces. The "with-arm" option includes the

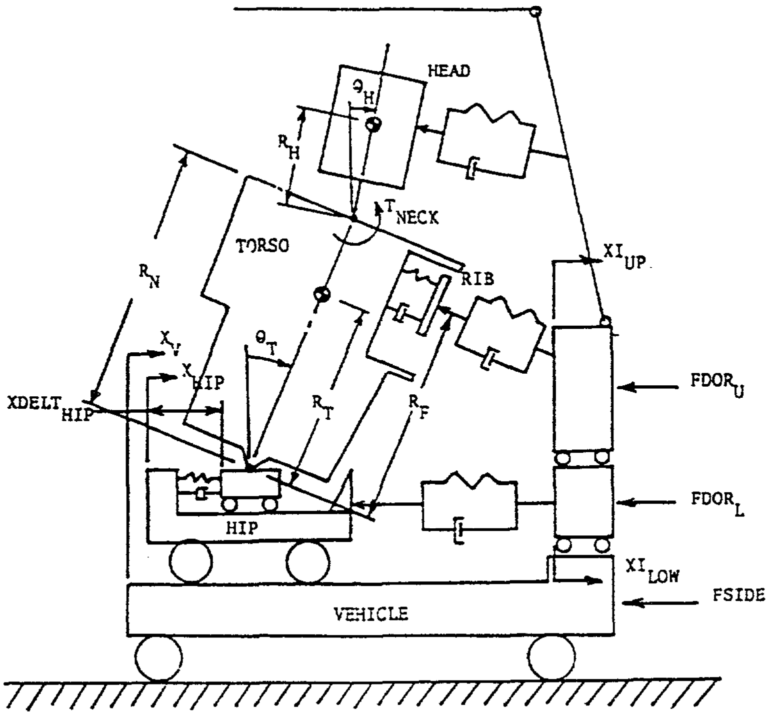

Figure 7. SIFEM model (side-side portion).

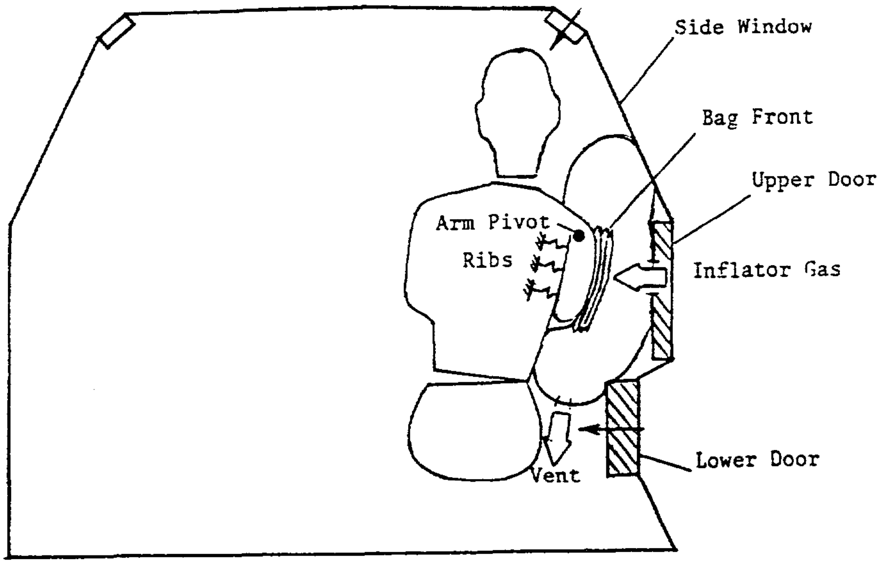

Figure 8. SIFEM airbag model.

arm mass in the simulation to account for its interactions with the vehicle interior and the upper torso mass. The occupant model calculates the following injury measures:

- Head Injury Criteria HIC
- Peak Chest Acceleration (3 msec clip)
- Peak Femur Load PFL
- Peak Pelvic Load PPL
- Hip Acceleration
- Viscous Criteria V*C (each rib plus abdomen)
- Thoracic Trauma Index TTI (each rib)
- Hip Joint Load, Displacement, Velocity and Acceleration (fore-aft and side-side)
- Neck Moment and Head Rotation (fore-aft and side-side)

MODEL VALIDATION

Prior to this study a validation effort was conducted using SIFEM. Although this effort was not exhaustive, good success was achieved in modeling various full scale crash tests and sled tests involving the SID and SID-IIs dummies. Some of these tests are reported in References 3 through 8. It is premature at this point to claim full model validation for SIFEM, however, the results to date do indicate that SIFEM is capable of providing reasonable simulations for both the SID and SID-IIs dummies. This validation work will continue as new and more detailed test data are made available.

SIFEM SIMULATIONS

Three occupant restraint designs were evaluated in this study. The designs were: 1) door padding, 2) a hip restraint device and 3) an airbag system. For the simulations herein, it was assumed that the occupant is normally seated in the seating position adjacent to the door. It was also assumed that the child occupant was seated on a booster seat in a normal, upright position. The window was assumed to be in the open position for all computer runs.

Door Padding (baseline design)

The baseline design for this study was energy absorbing padding material mounted to the interior surface of the door. Two cases were evaluated. Case #1 consisted of 140 kPa (20 psi) material for the torso padding and 280 kPa (40 psi) material for the hip padding. Case #2 was reversed with 280 kPa (40 psi) material for the torso pad and 140 kPa (20 psi) material for the hip pad.

Case #1 - The simulation results for Case #1 are summarized in Figures 1 and 2 and Table 1. As indicated in Figures 1 and 2, this design allows the occupant to rotate into the door and side window area during impact. Figure 1 shows the trajectory for the 50th percentile occupant and Figure 2 shows the trajectory for the child. For the larger occupant sizes, the head actually rotates through the plane of the window (see Figure 1) and eventually strikes the lower window sill. The maximum window penetration occurs for the 50th percentile occupant size (see Table 1, WSPen=2.8 inches). For the small child occupant, the head rotates directly onto the window sill (see Figure 2).

The trajectories displayed in Figures 1 and 2 are undesirable since they expose the occupant to possible head injuries. The clockwise rotation of the occupant is a result of the reaction loads acting too low on the occupant. This action is further enhanced by the current padding design with its relatively "soft" torso pad and "hard" hip pad.

Additional details of the simulation can be obtained by examining the data in Table 1. To help us in this examination, we will divide the data into the following groups:

1. Head
2. Rib/Spinal-Mass
3. Abdomen
4. Hip/Hip Joint

For the head data group two measures apply, HIC and window penetration WSPen. The data in Table 1 shows that for this data group the trend of lower HIC with increasing occupant size is broken by the 50th percentile occupant. Closer examination shows that this occupant impacts the window sill more solidly than either the 5th percentile or the 95th percentile, causing the increase in HIC. The 50th percentile occupant size also has more window penetration, as indicated by the WSPen measure.

For the Rib/Spinal-Mass group the key measures are: Thoracic Trauma Index TTI, Viscous Criteria V*C, rib displacement DispRib and peak chest acceleration (3msec clip) PCG. The three rib masses in the model are identified in the table as upper, middle and lower. The data in Table 1 shows TTI decreasing with increasing occupant size, except for the 5th percentile female occupant size. This occupant size seems to have unusually low values compared to the two larger occupants. More detailed examination of the data indicates that the larger occupants are "bottoming-out" the torso padding and are "working" the padding material at significantly higher contact stresses.

For the V*C measures, the trend is not clear. The small child appears to respond most favorably for this data group. There are several explanations for this. First, the larger occupants are "bottoming out" the padding and the loading rates for their rib springs are higher due to the increase in the stiffness of the padding. Second, the child occupant may be benefiting from favorable effects

Table 1.
Simulation Results for Baseline Design, Case #1,
Torso Pad = 140 kPa (20 psi), Hip Pad = 280 kPa (40 psi)

Measure	03 Year Old	05th Percentile	50th Percentile	95th percentile
HIC	333.5	182.5	248.3	70.2
PCG-3ms (g's)	66.9	60.44	61.38	63.6
TTIup (g's)	130.0	73.9	90.74	85.7
TTImid (g's)	139.0	67.8	99.3	95.4
TTIlow (g's)	136.0	85.7	111.0	101.9
V*Cup (M/s)	.2537	.5447	.4648	.4019
V*Cmid (M/s)	.5148	1.0662	.8682	.9044
V*Clow (M/s)	.8608	1.4353	1.2731	1.3643
HipF (lbf)	1035	2478	3361	3851
HipA (g's)	-85	-68	-70	-68
AbdF(lbf)	-25.2	-16.7	-119.1	-166.5
V*Cabd (M/s)	1.0254	2.0614	.4518	.3965
DispRibu (in)	-.5330	-1.110	-1.7610	-1.7434
DispRibm (in)	-.8100	-1.5190	-1.9296	-2.0712
DispRibl (in)	-1.105	-1.9580	-2.0849	-2.2867
DispAbd (in)	-1.200	-2.500	-.6600	-.6200
HipJntA (in/s^2)	+56/-64	+24/-28	+33/-36	+24/-34
HipJntV (in/s)	+80/-36	+48/-9	+79/-16	+40/-10
HipJntD (in)	+2.4	+.93	+1.0	+.40
BagP (lb/in^2)	-----	-----	-----	-----
HipRestrY (lbf)	0	0	0	0
HipRestrZ (lbf)	0	0	0	0
WSPen (in)	0	-.376	-1.397	.-6997

resulting from the dynamic response of the arm mass. The larger male occupants (represented by a SID type dummy) do not have articulating arms. For these occupants the mass of the arm is added to the rib mass and the ribs are allowed to make direct contact with the padded surface during impact. Also, the rib springs for these larger occupants are represented by hydraulic dampers and the resulting spring-mass system is highly damped. For the smaller occupants (represented by the SID-IIs dummy type) the arm mass translates and rotates at its connection point with the shoulder spring and interacts with both the padded surface of the vehicle and the rib and abdomen springs comprising the occupant's torso. For these occupants the rib springs represent a steel-spring structure (i.e., the SID-IIs design) and are not as highly damped as the ribs in the SID design. Although both the child and the 05th percentile occupants have similar rib and arm designs, the small child appears to perform better in this category. This may be a result of the child's lighter and more responsive spinal mass, which helps to reduce the rib displacements.

The abdomen data group is represented by the abdomen force AbdF, abdomen viscous criteria V*Cabd and the abdomen displacement DispAbd (see Table 1). The data in Table 1 shows that the smaller occupant sizes are clearly at a disadvantage here. The abdomen V*C and displacement values are significantly higher than those for the larger occupants. This is the result of the arm mass interacting with the abdomen spring. This interaction is modeled In SIFEM by proportioning the area associated with the arm/abdomen contact to the total area of the abdomen spring. This explains the lower abdomen forces and large deformations for these smaller occupants. For the larger occupants (no arm mass) the entire abdomen spring is allowed to make contact with the padding.

The results for this case indicate a potential for serious abdominal injuries from the oscillating arm mass. Relatively large penetrations of the abdomen can be induced due to the small contact areas involved. The high loading rate imposed on the abdominal spring, by the arm mass, drives the V*Cabd parameter to its high value. It is not known how accurately these results reflect real life. Further research and study is needed in this area.

The hip and hip-joint data group is represented by the hip force HipF, hip acceleration HipA and hip joint parameters. The hip-joint parameters are associated with the acceleration HipJntA, velocity HipJntV and displacement HipJntD of the hip joint spring. For the current padding design the small child occupant does not perform as well in this data group as the others.

Simulation Results, Case #2 - For this design the padding materials were reversed so that the 280 kPa (40 psi) material was positioned for the torso and the 140 kPa (20 psi) material positioned for the hip. The results of the simulations are summarized in Table 2.

A general observation for this case is that the trajectories for all occupant sizes were significantly improved. The occupant remains in a more upright posture during impact, compared to Case #1. This improved trajectory is reflected in the lower HIC and window penetration WSPen values (see Table 2). The improved posture helps to reduce the risk of head injuries by reducing the window penetration and the hard contact with the window sill (larger occupants). Note, the HIC value for the child occupant remains relatively high at 325. The reason for this is that the initial height of the child's head is nearly the same height as the window sill (see Figure 2) and solid contact with it is unavoidable.

We can gain more insight to the effects of the design change by comparing the data in Table 2 with the data in Table 1. To help us with this comparison, a three point rating method is introduced in Table 2. The rating values are: B=Better, S=Same or W=Worse. With this method we can quickly evaluate the effects of the design change and identify the effected parameters. For our comparison we will again divide the data into groups.

For the head data group (HIC and WSPen), all occupant sizes appear to benefit from the design change (although the benefit for the child occupant is not that significant).

For the rib/spinal mass data group (TTI, V*C, DispRib and PCG), the TTI values seem to improve across the board while the V*C, DispRib and PCG parameters have mixed results. In general, the larger occupants seem to perform better in this data group.

The abdomen data group (AbdF, V*Cabd and DispAbd), received W ratings for the two small occupants and a mixed rating for the larger occupants. The only gain was the V*Cabd parameter for the two larger occupant sizes. The stiffer torso padding appears to have increased the risk for the abdomen.

The hip and hip-joint data group(HipF, HipA, HipJntA, HipJntV and HipJntD) received a W rating for the child and a mixed rating for the other sizes. All of the occupant sizes (except for the child) received a B rating for the hip joint parameters. The larger occupants (except for the 95th percentile) received B ratings for the HipF and HipA parameters. Note that the 95th percentile occupant size begins to "bottom-out" the hip padding.

An overall view of the data in Table 2 indicates that this design change provides significant benefits for the larger occupants but makes matters worse for the small child (except for some minor improvements in the HIC, TTI, and HipJntD parameters).

Hip Restraint Design

Table 2.
Simulation Results for Baseline Design, Case #2,
Torso Pad = 280 kPa (40 psi), Hip Pad = 140 kPa (20 psi)

Measure	03 Year Old		05th Percentile		50th Percentile		95th percentile	
HIC	325.1	(B)	75.2	(B)	47.5	(B)	55.6	(B)
PCG-3ms (g's)	73.28	(W)	39.89	(B)	45.41	(B)	45.74	(B)
TTIup (g's)	128.3	(B)	66.98	(B)	67.14	(B)	73.16	(B)
TTImid (g's)	127.3	(B)	65.14	(B)	81.22	(B)	75.78	(B)
TTIlow (g's)	146.8	(W)	77.06	(B)	81.69	(B)	75.68	(B)
V*Cup (M/s)	.4961	(W)	.4448	(B)	.5266	(W)	.4678	(W)
V*Cmid (M/s)	1.9042	(W)	1.0191	(B)	.8626	(B)	.7044	(B)
V*Clow (M/s)	3.0772	(W)	2.0465	(W)	.9164	(B)	.7877	(B)
HipF (lbf)	1196	(W)	1878	(B)	1978	(B)	4619	(W)
HipA (g's)	-130	(W)	-60	(B)	-53	(B)	-82	(W)
AbdF(lbf)	-57.7	(W)	-22.4	(W)	-143.6	(W)	-234.4	(W)
V*Cabd (M/s)	5.00	(W)	4.218	(W)	.3548	(B)	.3493	(B)
DispRibu (in)	-.8836	(W)	-1.0530	(B)	-1.8563	(W)	-1.8424	(W)
DispRibm (in)	-1.5970	(W)	-1.9068	(W)	-1.9651	(W)	-1.9779	(B)
DispRibl (in)	-1.9529	(W)	-2.7326	(W)	-1.9784	(B)	-2.1149	(B)
DispAbd (in)	-2.80	(W)	-3.30	(W)	-.730	(W)	-.690	(W)
HipJntA (in/s^2)	+100/-82	(W)	+20/-22	(B)	+8/-14	(B)	+21/-16	(B)
HipJntV (in/s)	+115/-30	(W)	+22/-18	(B)	+9.7/-5.5	(B)	+28/-18	(B)
HipJntD (in)	+1.790	(B)	+.430	(B)	+.200	(B)	+.200/-.200 (B)	
BagP (lb/in^2)	-----		-----		-----		-----	
HipRestrY (lbf)	0		0		0		0	
HipRestrZ (lbf)	0		0		0		0	
WSPen (in)	0	(S)	0	(B)	-.4740	(B)	-.060	(B)

NOTE: Scores are for comparison with baseline padding design in Table 1
B=Better
S=Same
W=Worse

For the hip restraint simulations we assumed the padding configuration for Case #2 above (i.e., 280 kPa torso padding and 140 kPa hip padding).

Two hip restraint designs were evaluated. The first design is a linear device where the hip reaction force is proportional to the hip displacement (i.e., an elastic energy absorber). The second design is a nonlinear device where the hip reaction force is relatively constant (independent of hip displacement) and hysteresis effects during rebound are included (i.e., a near perfect energy absorber). Both designs were "tuned" to give a maximum hip displacement of approximately 3.5 inches for the worst case scenario (95th percentile occupant).

Linear Device - The simulation results for the linear hip restraint design are summarized in Table 3. We can compare these results with our baseline padding design in Table 2, to evaluate the design change. Lets make our comparison by data groups.

For the head data group (HIC and WSPEN), a W rating was received for all occupant sizes, except for the child (WSPEN rating of S). Details of the simulations show that the main cause for this poor rating is the multiple loading of the hip mass. The hip mass is first loaded by the door then by the hip restraint. This creates a slight whipping action of the head mass with corresponding increases in the head acceleration and HIC. The slight increase in window penetration also reflects this action.

For the Rib/Spinal Mass group (TTI, V*C, DispRib and PCG), the ratings are mixed. The TTI values improved for the 95th percentile occupant size but received W ratings for the other sizes (except for the child's TTIup value, which received a B rating).

The V*C parameters, in general, improved for all sizes, except for the upper rib which received a W rating (05th percentile female an exception). Apparently the addition of the hip restraint causes the occupant to lean slightly more toward the door during impact (note the slight increase in the WSPEN parameter). This tends to load up the upper rib (occupants without an articulating arm) and the shoulder spring (occupants with an articulating arm). For occupants with an articulating arm, the phasing of the shoulder displacement and the rotation of the arm will determine the rib loading. For the child case, it appears that the maximum displacement of the shoulder spring is more in phase with the maximum rotation of the arm, causing the higher loading of the upper rib spring. The 05th percentile occupant appears to be benefiting from a more "out of phase" response of the arm mass

The PCG parameter received a W rating for all sizes except the small child. The small child appears to be benefiting here from its more responsive torso mass, perhaps receiving a greater benefit from the 3 msec clip.

The abdomen data group (AbdF, V*Cabd and DispAbd) received B ratings for all occupant sizes. The hip restraint appears to provide a real benefit for this data group.

The hip and hip-joint data group (HipF, HipA, HipJntA, HipJntV and HipJntD) received a mixed rating. The hip force HipF parameter received W rating for all occupant sizes while the hip acceleration parameter HipA received a S or B rating across the board. The hip-joint parameters (HipJntA, HipJntV and HipJntD) received a W rating for all occupant sizes except for the child occupant, which received an S or B rating. It is expected that this group would show some performance reduction due to the added energy being transferred to the hip-joint by the hip restraint. The child occupant seems to benefit slightly here.

Nonlinear Device- The simulation results for the nonlinear hip restraint design are summarized in Table 4. Comparing this data with the data for the linear hip restraint design in Table 3, we see that the 95th percentile occupant size appears to have received little benefit from this design change. The other occupant sizes received some benefit, primarily in the reduction of the TTI parameters.

An Overview of the Padding and Hip Restraint Designs - In our evaluation of the padding and hip restraint designs we observed some modest gains for the larger occupant sizes (50th and 95th percentile). Most of the improvement came from switching the padding so that the stiffer (280kPa) padding material is positioned for the torso and the softer (140kPa) padding for the hip. This helped to prevent the large occupants from "bottoming out" the torso padding. It also helped to improve the trajectory for all occupant sizes.

Although we have seen some small areas of improvement for the smaller occupant sizes, these occupants are not adequately protected by any of the designs evaluated so far. The critical areas for the smaller occupants are the TTI and V*C parameters. The high TTI and V*C values appear to be associated with the articulating arm mass.

Airbag System

The airbag system in this study represents a "state of the art" design. Some details of the design are presented above. Two cases were evaluated. For Case #1, the airbag system was optimized for the 50th percentile occupant size. The optimization was carried out by trial and error. The flow characteristics of the inflator and the vent characteristics of the bag were varied until the injury

Table 3.
Simulation Results for Elastic Hip Restraint,
Torso Pad = 280 kPa (40 psi), Hip Pad = 140 kPa (20 psi)

Measure	03 Year Old		05th Percentile		50th Percentile		95th percentile	
HIC	479.6	(W)	112.8	(W)	54.5	(W)	62.0	(W)
PCG-3ms (g's)	67.34	(B)	47.56	(W)	46.41	(W)	46.68	(W)
TTIup (g's)	126.67	(B)	81.48	(W)	70.97	(W)	68.01	(B)
TTImid (g's)	143.7	(W)	89.02	(W)	83.6	(W)	69.98	(B)
TTIlow (g's)	189.58	(W)	91.67	(W)	84.21	(W)	70.03	(B)
V*Cup (M/s)	.9979	(W)	.3169	(B)	.6880	(W)	.5696	(W)
V*Cmid (M/s)	1.2849	(B)	.8325	(B)	.7834	(B)	.6434	(B)
V*Clow (M/s)	1.7875	(B)	1.4943	(B)	.8171	(B)	.7028	(B)
HipF (lbf)	1401	(W)	2038.8	(W)	3262	(W)	[1]4583.3+	(W)
HipA (g's)	+90/-100	(B)	+41/-55	(B)	+32/-54	(S)	+31/-46	(B)
AbdF(lbf)	-46.17	(B)	-17.94	(B)	0	(B)	-42.20	(B)
V*Cabd (M/s)	2.7582	(B)	2.5911	(B)	0	(B)	.1201	(B)
DispRibu (in)	-1.0911	(W)	-.9415	(B)	-1.9141	(W)	-1.9255	(W)
DispRibm (in)	-1.3094	(B)	-1.6723	(B)	-1.9438	(B)	-1.9574	(B)
DispRibl (in)	-1.5946	(B)	-2.2476	(B)	-1.9339	(B)	-1.9956	(B)
DispAbd (in)	-2.2	(B)	-2.7	(B)	0	(B)	-.39	(B)
HipJntA (in/s^2)	+85/-100	(S)	+24.5/-12	(W)	+29/-21	(W)	+28/-9	(W)
HipJntV (in/s)	+57/-80	(B)	+36/-55	(W)	+83/-86	(W)	+10/-65	(W)
HipJntD (in)	+1.0	(B)	+.52/-.52	(W)	+.5/-1.65	(W)	+.2/-1.65	(W)
BagP (lb/in^2)	-----		-----		-----		-----	
HipRestrY (lbf)	+350/-1200		+900/-2400		+850/-3250		+950/-3500	
HipRestrZ (lbf)	+290/-20		+190/-10		+180/-10		+36/-8	
WSPen (in)	0	(S)	-.0438	(W)	-1.310	(W)	-.3140	(W)

NOTE: Scores are for comparison with baseline padding design in Table 2
B=Better
S=Same
W=Worse

[1] Data still rising at end of computer run.

Table 4.
Simulation Results for Inelastic Hip Restraint,
Torso Pad = 280 kPa (40 psi), Hip Pad = 140 kPa (20 psi)

Measure	03 Year Old		05th Percentile		50th Percentile		95th percentile	
HIC	333.5	(B)	110.7	(B)	55.9	(W)	63.0	(W)
PCG-3ms (g's)	73.10	(W)	39.89	(B)	45.38	(B)	45.70	(B)
TTIup (g's)	128.48	(W)	69.40	(B)	67.10	(B)	73.14	(W)
TTImid (g's)	127.48	(B)	65.14	(B)	81.21	(B)	75.77	(W)
TTIlow (g's)	147.0	(B)	77.05	(B)	81.68	(B)	75.67	(W)
V*Cup (M/s)	.4998	(B)	.4344	(W)	.5232	(B)	.4664	(B)
V*Cmid (M/s)	1.9053	(W)	1.0192	(W)	.8627	(W)	.7044	(W)
V*Clow (M/s)	3.0784	(W)	2.0477	(W)	.9165	(W)	.7877	(W)
HipF (lbf)	1198.2	(B)	1878.2	(B)	3112.2	(B)	4619.8	(W)
HipA (g's)	+110/-140	(W)	+58/-58	(W)	+57/-55	(W)	+42/-82	(W)
AbdF(lbf)	-57.64	(W)	-22.38	(W)	-143.2	(W)	-233.9	(W)
V*Cabd (M/s)	4.9894	(W)	4.2163	(W)	.3540	(W)	.3489	(W)
DispRibu (in)	-.8842	(B)	-1.0521	(W)	-1.8564	(B)	-1.8411	(B)
DispRibm (in)	-1.5964	(W)	-1.9066	(W)	-1.9653	(W)	-1.9780	(W)
DispRibl (in)	-1.9522	(W)	-2.7316	(W)	-1.9785	(W)	-2.1149	(W)
DispAbd (in)	-2.800	(W)	-3.400	(W)	-.7200	(W)	-.700	(W)
HipJntA (in/s^2)	+80/-86	(B)	+38/-30	(W)	+39/-54	(W)	+26/-58	(W)
HipJntV (in/s)	+83/-93	(W)	+23/-63	(W)	+30/-116	(W)	+49/-79	(W)
HipJntD (in)	+1.0	(S)	+.4/-.65	(W)	-1.5	(B)	-1.79	(W)
BagP (lb/in^2)	-----		-----		-----		-----	
HipRestrY (lbf)	-950		-2175.2		-3780		-4068	
HipRestrZ (lbf)	+220/-10		-16		+95/-100		-19	
WSPen (in)	0	(S)	0	(B)	-.8580	(B)	-.0966	(B)

NOTE: Scores are for comparison with the elastic hip restraint design in Table 3
B=Better
S=Same
W=Worse

measures for the occupant were minimized. The airbag configuration was then fixed and the remaining occupant sizes simulated. For Case #2, the process was repeated now optimizing for the 3 year old child.

Case #1, Airbag Optimized for the 50th Percentile Occupant Size - Table 5 summarizes the results for this case. To evaluate this design we will compare the data in Table 5 with the data for the elastic hip restraint design in Table 3. Again we will make our comparison by data groups.

A general overview of the data in Table 5 shows us that all occupant sizes benefit from this airbag design since all sizes receive some reductions in their injury measures. Closer examination, however, shows us that some problem areas have been created as well. We will discuss these problem areas as we make our comparison.

The head data group (HIC and WSPen) shows improved performance across the board. All occupant sizes receive a benefit here. Note that the improvement on HIC is greater for the small occupant sizes. The larger occupants already had relatively low HIC values (Table 3). The larger occupants benefit more from a reduced window penetration (i.e., lower WSPen).

The rib/spinal-mass data group (TTI, V*C, DispRib and PCG) also show improved performance across the board, for all sizes. Note, the only W rating in this group are the V*Clow and DispRibL parameters for the child, 05th percentile and 95th percentile occupant sizes. The 50th percentile occupant size performed the best in this group (this is not surprising since the airbag was optimized for this size). Note also that although the small child and 05th percentile occupants benefit here from the design, the TTI and V*C parameters are still high.

The abdomen data group (AbdF, V*Cabd and DispAbd) received a relatively poor rating for all occupant sizes. Although the child occupant receives a B rating for V*Cabd and DispAbd, the reduction is not very much and their values still remain high (same for the 05th percentile). The larger occupants receive a W rating for all parameters in this data group, indicating that this airbag loads the abdominal spring more than the referenced padding design (Table 3).

The hip/hip-joint data group (HipF, HipA, HipJntA, HipJntV and HipJntD) show a relatively good rating. The two larger occupant sizes received all B ratings. The small child occupant received only one W rating (hip joint velocity). The 05th percentile female size rated the lowest in this data group.

Case #2, Airbag Optimized for 3 Year Old Child The results for this case are summarized in Table 6. Figure 9 shows the response sequence for the small child occupant (only the center slice of the bag is shown in the figure).

The results in Table 6 show that for the first time in this study the child TTI and V*C measures have been reduced to reasonable levels (based on current design standards). One exception is V*Cabd which is still relatively high (.855 m/sec). Note, to achieve this improved performance for the child occupant, the pressure in the airbag had to be reduced to 4.5 psig. Note also that the larger occupants now do not perform very well since the airbag is too "soft". Their responses approach that of the reference design (no airbag), summarized in Table 3.

CONCLUSIONS

In this study we evaluated several occupant restraint concepts for side impact protection. The concepts included interior padding, a hip restraint device and an airbag system. The performance of the candidate designs were evaluated for the full size range of occupants (3 year old child, 5th percentile adult female, 50th percentile adult male and 95th percentile adult male).

The results of this study seem to confirm our initial suspicion that occupant size is an extremely important factor in the design of crashworthy interiors for automobiles A design that works for one occupant size may be counter-productive for another. Extreme caution is needed in the design process and a systems analysis approach is truly warranted.

In this study we evaluated two padding designs. Both designs made use of a class of materials having near perfect energy absorbing characteristics ("flat" force-displacement characteristics, with hysteresis effects). These materials include crushable foams and paper honeycombs. This study indicates that although these near perfect padding materials can provide a good measure of protection for large occupants (see Table 2), they are generally too stiff for the smaller occupants and do not provide adequate protection for the small size group.

This study also evaluated the effects of a hip restraint device. The results show that a hip restraint device improves the posture of the occupant during impact, reducing the penetration of the head into the side window opening. It also prevents serious secondary impacts with other parts of the vehicle interior, following the primary impact. Some of the injury measures also showed some improvement (compare Table 3 with Table 2). Others, however, became worse. In general, the hip restraint designs evaluated herein were not able to significantly improve upon the padding performance summarized in Table 2. The larger occupants continued to perform fairly well while the small occupants did not.

The airbag system evaluated herein represents the size and shape of a current state-of-the-art design. Two design conditions were evaluated: 1) system optimized

Table 5.
Simulation Results for Airbag System Optimized for 50th Percentile Adult Male.
Torso Pad = 280 kPa (40 psi), Hip Pad = 140 kPa (20 psi),
Elastic Hip Restraint

Measure	03 Year Old		05th Percentile		50th Percentile		95th percentile	
HIC	120.6	(B)	50.7	(B)	37.4	(B)	59.9	(B)
PCG-3ms (g's)	34.59	(B)	32.68	(B)	37.27	(B)	37.17	(B)
TTIup (g's)	118.4	(B)	78.38	(B)	56.88	(B)	50.3	(B)
TTImid (g's)	105.2	(B)	77.39	(B)	48.57	(B)	59.15	(B)
TTIlow (g's)	121.8	(B)	117.8	(W)	48.91	(B)	61.15	(B)
V*Cup (M/s)	.1282	(B)	.2999	(B)	.4775	(B)	.4239	(B)
V*Cmid (M/s)	.6198	(B)	.8417	(W)	.4679	(B)	.6140	(B)
V*Clow (M/s)	1.3691	(B)	1.7826	(W)	.5746	(B)	.8145	(W)
HipF (lbf)	1186.9	(B)	2525	(W)	1678.6	(B)	1948.8	(B)
HipA (g's)	+46/-100	(B)	+36/-72	(W)	+21/-46	(B)	+18/-40	(B)
AbdF(lbf)	-139.9	(W)	-295.7	(W)	-908.2	(W)	-1015.3	(W)
V*Cabd (M/s)	2.344	(B)	2.642	(W)	.5660	(W)	.6400	(W)
DispRibu (in)	-.4858	(B)	-.9388	(B)	-1.8884	(B)	-1.895	(B)
DispRibm (in)	-1.1011	(B)	-1.6304	(B)	-1.9134	(B)	-1.9591	(S)
DispRibl (in)	-1.6829	(W)	-2.1482	(B)	-1.9330	(S)	-2.0276	(W)
DispAbd (in)	-2.00	(B)	-2.9	(W)	-.85	(W)	-.85	(W)
HipJntA (in/s^2)	+32/-46	(B)	+12/-24	(S)	+18.5/-10	(B)	+9.0/-10.0	(B)
HipJntV (in/s)	+85/-72	(W)	+30/-40	(B)	+19/-46	(B)	+12./-29.	(B)
HipJntD (in)	+.9/-.4	(B)	+.65	(W)	-1.00	(B)	-.88	(B)
BagP (lb/in^2)	8.0		11.0		14.0		16.0	
HipRestrY (lbf)	-680		-1700		-1400		-1400	
HipRestrZ (lbf)	-26		-39		+360		+85	
WSPen (in)	0	(S)	0	(B)	0	(B)	0	(B)

NOTE: Scores are for comparison with the elastic hip restraint design in Table 3
B=Better
S=Same
W=Worse

Table 6.
Simulation Results for Airbag System Optimized for 03 year old Child.
Torso Pad = 280 kPa (40 psi), Hip Pad = 140 kPa (20 psi),
Elastic Hip Restraint

Measure	03 Year Old		05th Percentile		50th Percentile		95th percentile	
HIC	52.3	(B)	108.5	(W)	57.3	(W)	67.9	(W)
PCG 3ms (g's)	32.57	(B)	45.2	(W)	45.8	(W)	46.3	(W)
TTIup (g's)	74.07	(B)	71.57	(B)	66.67	(W)	72.48	(W)
TTImid (g's)	50.68	(B)	77.85	(W)	79.8	(W)	72.0	(W)
TTIlow (g's)	55.7	(B)	79.09	(B)	85.04	(W)	71.73	(W)
V*Cup (M/s)	.3229	(W)	.3271	(W)	.67	(W)	.5506	(W)
V*Cmid (M/s)	.3820	(B)	.8681	(W)	.75	(W)	.6248	(W)
V*Clow (M/s)	.4368	(B)	1.7202	(B)	.84	(W)	.7355	(B)
HipF (lbf)	1020.2	(B)	1818.5	(B)	3350.7	(W)	4506.7	(W)
HipA (g's)	+46/-57	(B)	+47/-56	(B)	+36/-55	(W)	+30/-47	(W)
AbdF(lbf)	-60.19	(B)	-107.63	(B)	-223.0	(B)	-345.8	(B)
V*Cabd (M/s)	.8553	(B)	2.5805	(B)	.140	(B)	.1871	(B)
DispRibu (in)	-.7414	(W)	-.9989	(W)	-1.92	(W)	-1.9333	(W)
DispRibm (in)	-.9428	(B)	-1.642	(W)	-1.95	(W)	-1.9834	(W)
DispRibl (in)	-1.1439	(B)	-2.2196	(W)	-1.96	(W)	-2.0219	(B)
DispAbd (in)	-1.25	(B)	-2.8	(B)	-.50	(B)	-.52	(B)
HipJntA (in/s^2)	+32/-24	(B)	+16/-13	(B)	+31/-18	(W)	+25/-9	(W)
HipJntV (in/s)	+30/-57	(B)	+34/-55	(W)	+100/-200	(W)	+5/-64	(W)
HipJntD (in)	+.48/-.55	(B)	+.52/-.4	(B)	+.3/-1.8	(W)	+.1/-1.8	(W)
BagP (lb/in^2)	4.5		4.5		5.8		6.8	
HipRestrY (lbf)	+300/-920	(W)	+900/-2400	(W)	+800/-3300	(W)	+900/-3500	(W)
HipRestrZ (lbf)	+39/-8	(W)	+110/-10	(W)	+180	(B)	+48/-8	(B)
WSPen (in)	0	(S)	0	(S)	-.45	(W)	-.0147	(W)

NOTE: Scores are for comparison with the elastic hip restraint design and airbag optimized for 50th percentile inTable 5
B=Better
S=Same
W=Worse

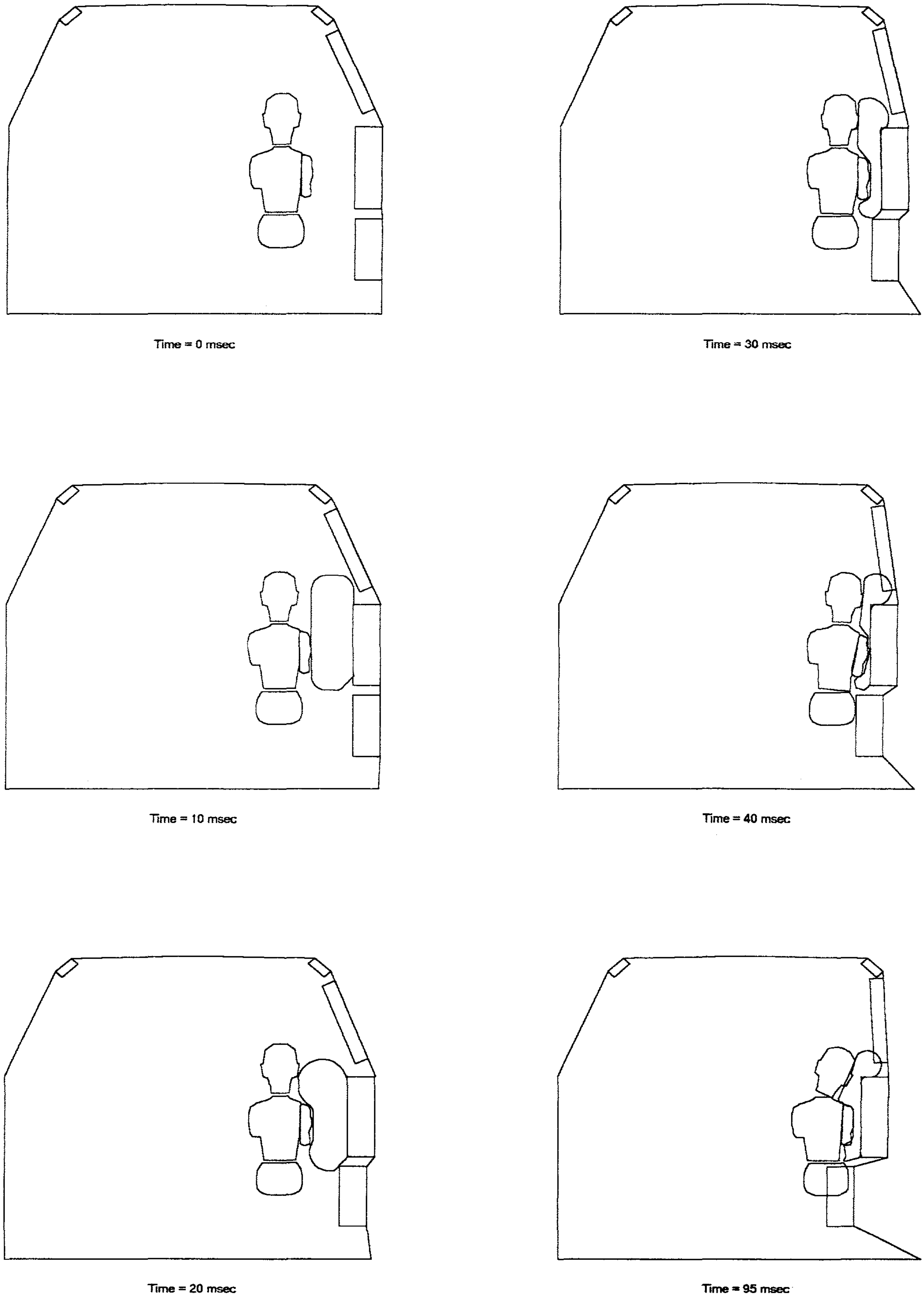

Figure 9. Occupant trajectory with airbag, 3 year old child.

for the 50th percentile adult male occupant and 2) system optimized for the 3 year old child. The results show that each occupant size has its own optimum operating condition. The 50th percentile occupant size requires a bag pressure of approximately 14 psi (see Table 5) while the 3 year old child requires a pressure of only 4.5 psi (see Table 6). Obviously, to protect the full size range of occupants, a "smart" system is needed to adjust to the size of the seated occupant..

Several safety design issues surfaced during the course of this study and are worthy of mention here. First, the study shows that a hip restraint device serves several very positive functions in side impacts. It helps to control the posture of the occupant during impact and thereby reduces the head penetration into the side window area. It also helps to prevent serious secondary impacts with the vehicle interior. However, computer simulations show that a hip restraint adds energy to the hip joint of the occupant during impact. Further research is needed to evaluate the hip joint tolerance of humans in side impacts.

Second, computer simulations in this study show that the pivoting arm mass can be a source of injury to the rib cage and abdomen of the occupant. During impact the arm mass oscillates and transfers energy between the door padding and the rib cage and abdomen areas of the occupant's torso. Large torso penetrations can result because of the relatively small contact areas involved. Further research is needed to determined how important these interactions are in real impacts.

Finally, in our evaluation of the airbag system it has become even more apparent that a "smart" design is needed to protect the full size range of occupants. This will require an inflator that can sense and adjust its flow characteristics to accommodate the size of the seated occupant. The design of such an inflator will require that each stage of the inflator be targeted and optimized for a specific size group. Further research is needed to determine the size groups required to effectively cover the full range of occupants.

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