PERFORMANCE VALIDATION OF TWO SIDE IMPACT DUMMIES

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Abstract - The history of public domain finite element models of the side impact anthropometric test dummy are summarized and recent improvements are briefly discussed. The performance of the two most recent finite element models are discussed with respect to the predictions of acceleration time histories as compared to standard bench calibration tests as well as an in-vehicle full-scale vehicle crash test. The thoracic trauma indices and the maximum pelvis accelerations are calculated based on the finite element models and are compared to the results obtained in physical calibration tests. The responses and fidelity of the finite element models are discussed and recommendations for further improvements are provided.

NOTATION

LURY	maximum lateral acceleration observed at the left upper rib
LLRY	maximum lateral acceleration observed at the left lower rib
TTI	thoracic trauma index
T_{12}	maximum lateral acceleration observed at the 12th spine segment
Py	maximum lateral pelvis acceleration

INTRODUCTION

Several finite element models of the Side Impact Dummy (SID) have been developed over the past several years for use in exploring the crashworthiness of vehicles and roadside safety structures. A finite element model of the Part 572 Subpart B Side Impact Dummy (e.g., the SID) will be discussed in detail in the following sections but other side impact dummy models have been developed in recent years.[12] The purpose of this paper is to compare the performance of the two most recent public domain SID finite element models to physical tests. Three types of physical tests will be used as the basis for the comparisons: (1) the thorax calibration test, (2) the pelvis calibration test and (3) an in-vehicle rigid pole test.

History

One of the most useful ways of evaluating the side impact collision environment is by using an anthropometric test device (ATD) to estimate the forces and accelerations that would be experienced by a human in a similar environment. There have been a variety of ATD's developed in recent years but the oldest side impact device is the one that is still required in side impact crash tests in the United States, the instrumented Part 572 Subpart F Side Impact Dummy (SID). The SID ATD was developed in the early 1980's by the Highway Safety Research Institute (HSRI) for the U.S. National Highway Traffic Safety Administration (NHTSA).[3] The SID represents a 50th percentile male and is instrumented to collect accelerations at the T_{12} segment of the spine, the upper rib, the lower rib and the pelvis. These accelerations are used to assess the hypothetical risk to human occupants using the thoracic trauma index (TTI) and the pelvis acceleration (P_y) as defined in Federal Motor Vehicle Safety Standard 214 (FMVSS 214).[4]

While the physical SID device is a very useful experimental tool, there is also a need for a mathematical model of the SID that can be used to assess occupant responses in collisions prior to performing physical tests. While there were several lumped-mass discreet-element models of the SID, the first three-dimensional finite element model with a detailed geometry and material properties closely approximating the physical SID was developed by SRI International in 1992 in a project sponsored by NHTSA.[5] The model, referred to in this paper as the PD-SID-V1 (e.g., public domain Sid Version 1), was developed using the Ingrid preprocessor and the public domain DYNA3D finite element code.[6] The objective of this initial project was to develop a model for the SID with a good description of the thorax structures that would demonstrate the feasibility of the detailed finite element modeling approach. The model was developed without any material testing and without a precise digital model of the physical device so while the response of the model was encouraging, further improvements were needed to obtain good results as compared to physical tests. All subsequent public domain versions of the SID models have a common root with the first version, PD-SID-V1.

NHTSA continued its sponsorship of a public domain model when the PD-SID-V1 model was modified by Quantum Consultants Inc in 1995.[7] The PD-SID-V1 model was translated into the PATRAN preprocessor where it was further modified to take advantage of the LS-DYNA3D analysis code.[8] The head-neck-spine, spine-hip, legs and damper assemblies were improved to achieve more realistic body motion. Some additional parts were modeled such as the abdominal insert. Two new material models, low density urethane foam for arm-pad foam, shoulder foam and rib wrap and Mooney-Rivlin rubber for neck spine, thorax rubber parts and anti bottoming pad were incorporated in LS-DYNA3D after conducting extensive material testing. The calibration tests of the model, referred to hereafter as the PD-SID-V2 model, showed that the dummy response for thorax impact was within the acceptable SID response corridors developed from physical thorax calibration tests. The pelvis response, however, still did not compare well with response corridors developed from physical tests.

NHTSA sponsored a third modeling effort and in 1997 EASi Engineering released another public domain version of the SID finite element model, referred to hereafter as PD-SID-V3.[9] The model is similar to the previous versions with respect to the thorax geometry but has a more detailed description of the pelvic region of the dummy. The model takes advantage of the PATRAN preprocessor and the LS-DYNA3D analysis code. The primary area of improvement in the third version is a more detailed model for the lower extremity structures. In the initial development of the PD-SID-V1 the lower extremities were modeled as rigid bodies with the appropriate geometry and mass. The PD-SID-V2 model had deformable lower extremities, however, without modeling the structural skeleton inside the SID lower extremities; this version produced unrealistically large deformations. The lower extremities in the PD-SID-V3 have both improved geometry as well as the appropriate deformable material descriptions of the foam and rigid pelvis internal structures.

The effort described above summarizes NHTSA's efforts to develop, improve and validate a public-domain Sid model that can be used to assess crash events using LS-DYNA3D.

Improvements

Independently of the NHTSA development effort, SRI continued to refine and improve the original public domain SID model, PD-SD-V1. Additional developments of the SRI SID model were based on an occupant model created at SRI for high-speed rail collision occupant simulations (SRI-SID-V1).[10] Lower extremities were modified in this model to include joint definitions at the hips, knees, and ankles with the appropriate range of motion for crash dummies. Similarly the model for the rubber neck piece and lower spine from the SID were improved and validated by performing simulations on the neck/head pendulum calibration test to determine appropriate viscoelastic neck properties so that the model performs within the appropriate calibration corridor. The inner neck and spine cables which influence the behavior in more severe loadings were also included. Additionally, modifications such as improved material properties were taken from the PD-SID-V2 and PD-SID-V3 models and included in the SRI SID model. Finally, refinements to the thorax were made to eliminate shortcomings in the initial model development. This version of the model, therefore, combined most of the earlier improvements to the public domain SID.

The Federal Highway Administration (FHWA) has also been interested in using finite element models to assess occupant risk in roadside hardware collisions.[11] As a result the FHWA has sponsored research at the University of Iowa to develop test and evaluation procedures for roadside hardware side impacts. Using finite element models was thought to be one good method for better understanding the crash environment. As a result both the PD-SID-V3 and SRI-SID-V1 have been extensively examined to assess their ability to correctly predict TTI and pelvis accelerations.

In collaboration with SRI the research team has continued to improve the SRI SID. First, the SRI-SID-V1, which was developed in Ingrid was translated to a similar preprocessor TrueGrid.[12] Next a variety of changes have been made to improve the performance, especially in more complicated in vehicle simulations of roadside hardware impacts. These modifications include:

- Addition of its lumbar spine cable,
- Addition of an anti-sag thorax damper spring
- Improved penalty factors on many of the contacts
- Improved damper properties on the rib structure
- More robust joint rotation torque load curves

One particularly difficult problem has involved arm pad foam to jacket contact in more realistic in-vehicle simulations. The contact in the SRI-SID-V1 worked well for the calibration test but showed extensive inter-penetration in the more demanding in-vehicle test. This was corrected by changing the contact types and readjusting the penalty factors. The resulting model is referred to hereafter as SRI-SID-V2.

The SRI-SID-V2 and PD-SID-V3 share many features but there are some notable differences. The SRI-SID-V2 has a more refined head neck model which is important in assessing impacts with fixed objects like poles. The PD-SID-V3 has a more refined pelvis and lower extremities with all the internal parts explicitly modeled whereas the SRI-SID-V2 has appropriate joint behaviors but uses rigid bodies for the hips and various leg sections. The SRI-SID-V2 has an improved thorax model. The modeling of the thorax components in the PD-SID-V3 has remained virtually unchanged since the preliminary phase of model development in 1992 with the exception of some material properties. However, several modifications have been made to the thorax of SRI-SID-V2 including:

1. An improved model of the outer jacket was created with a better fit to the internal components and

better mesh resolution.

2. An improved model of the ribcage and ballast weights was created with increased mesh resolution and elimination of the tied interface between the ribs and ballasts. Elimination of contact interfaces help both with model efficiency and stability.

3. Increased mesh resolution was added to the armpad foam and rib wrap. A model of the rib-wrap inner liner was added. The arm-foam to rib wrap sliding interface was eliminated.

4. Increased mesh resolution was added to the shoulder foam and abdominal insert. The edges of shoulder foam were rounded for greater stability in interface contact with the outer jacket.

5. The anti-sag device with the chest plate connection bracket were added to the model.

6. A nonlinear spring was added to the chest damper that limits the stroke to the appropriate range and includes the spring force that restores the piston to it's initial position when unloaded.

7. Modifications were made to the lower extremity hinge blocks to improve the lateral stiffness in more severe side impacts.

Other changes were made to the SRI-SID-V2 model to facilitate data collection so that data collection in the simulation would be as similar to data collections with physical device as is possible. Accelerations obtained from earlier SID models use global rather than local coordinates whereas the physical devices record local accelerations. Local coordinates can be easily obtained in LS-DYNA3D if a local coordinate system is defined and attached to the nodal location of interest. Most of the points in the model that corresponded to accelerometer locations were modeled using rigid materials. Unfortunately, a local coordinate system can not be added to a rigid body so small portions of the mesh around the accelerometer locations were defined as deformable materials so that a local coordinate system could be added. Nodal rigid bodies and corresponding local coordinate systems were attached to the lower spine, upper and lower ribs and the pelvis of the SRI-SID-V2 in order to obtain data in local coordinates.

The PD-SID-V3 model also uses an option in LS-DYNA3D were averaged accelerations are calculated and written to the output rather than the true accelerations. The SRI-SID-V2 uses the actual true accelerations instead since setting the averaged acceleration flag has the effect of smoothing the response. Data from the SRI-SID-V2 was processed by calculating actual accelerations and then sampling and filtering the data using the sample programs and protocols used for the physical test device to filter the data. The remainder of this paper will compare the performance of the SRI-SID-V2 and the PD-SID-V3.

CALIBRATION TESTS

A natural first step in assessing the performance of a finite element model is to simulate the calibration test impact conditions and determine if the finite element model responses fall within the range required of the physical test devices. This was done using the SRI-SID-V2 and the PD-SID-V3. NHTSA’s Laboratory Test Procedures for Federal Motor Vehicle Safety Standard (FMVSS) Number 214 give calibration test procedures and acceptance criteria for the physical SID.[13] The test procedures state that the SID should be struck in the lateral direction at the thorax and the pelvis with a 152-mm diameter 23.35 kg cylindrical ballistic pendulum at 4.3 m/s. The SID ATD is placed without back support on a flat surface whose length and width dimensions are not more than 406 mm so that the midsagittal plane of the SID is vertical and centered on the surface. The legs are stretched and positioned so that their centerlines are in planes parallel to the midsagittal plane.

The NHTSA test procedures also specify how the accelerometer data should be sampled and processed. Analog data is recorded in accordance with the SAE J-211 Class 1000 specification.[14] The data is then processed with the Finite Impulse Response (FIR100) filter program. The FIR100 filters the data with a 300 Hz SAE Class 180 filter, sub-samples the data at 1600 Hz and then removes bias. The NHTSA FMVSS 214 test procedures establish a window for the peak response but do not place any particular requirements on the whole time history of the event.

In order to ensure that the whole dummy model is responding correctly it is more useful to look at the time history in a calibration test. NHTSA has conducted a series of physical calibration tests and defined test corridors (e.g., the mean response plus and minus one standard deviation) for the dummy response. The data obtained from the test series was averaged and the corridor is shown in the following graphs as a shaded region. A finite element SID model that provides responses within these corridors is as good a predictor as a physical SID. Both criteria will be used in assessing the performance of the SIDs the following sections.

Pendulum Thorax Calibration Test

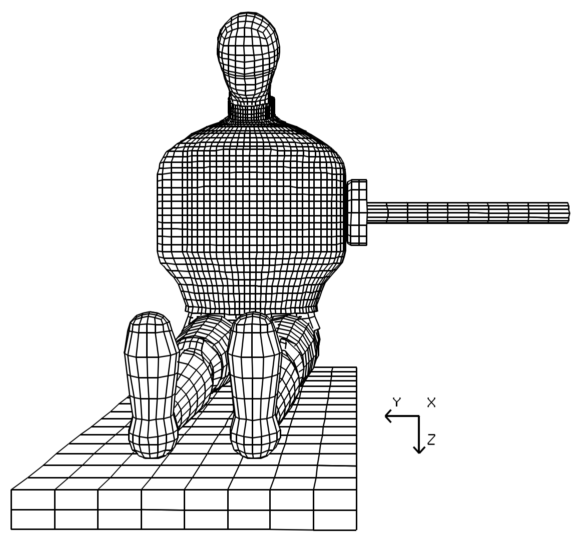

Figure 1. Thorax Calibration Test Setup.

The SID has three accelerometers mounted in the thorax for measurement of lateral accelerations. The primary axis of each accelerometer is aligned perpendicular to the midsagittal plane of the thorax. One accelerometer is mounted on the Thorax to Lumbar Adaptor by means of the T_{12} Accelerometer Mounting Platform and the T_{12} Accelerometer Mount. The other two accelerometers are mounted on the rib bar, one on the top and the other at the bottom of the rib bar, on the struck side. The accelerometer at the top represents the left upper rib lateral (e.g., Y) acceleration or LURY and the accelerometer on the bottom represents the left lower rib lateral (e.g., Y) acceleration or LLRY. The longitudinal centerline of the test probe is placed at the lateral side of the chest at the intersection of the centerlines of the third rib and the rib bar and perpendicular to the midsagittal plane of the thorax. The SID ATD position for the thorax impact is shown in Figure 1. According to the calibration test procedures, the peak T_{12} acceleration must be between 15 and 22 g's, the peak LURY acceleration must be between 37 and 46 g's and the peak LLRY acceleration must also be between 37 and 46 g's.

	Acceptable Range (g’s)	SRI-SID-V2 (g’s)	PD-SID-V3 (g’s)
T_{12} peak acceleration	$15 < T_{12} < 22$	23.1	30.7
LURY peak acceleration	37 < LURY <46	39.3	43.4
LLRY peak acceleration	37 < LLRY < 46	41.7	43.8
TTI	26 < TTI < 34	32.4	37.2

Table 1. Lateral Impact Thorax Performance of Side Impact Dummies.

The pendulum thorax calibration test results are shown in Table 1 and Figures 2 through 4. The acceleration time histories for the finite element simulations of the calibration test were sampled and filtered in exactly the same manner as the physical tests using the same filter programs. The PD-SID-V3 and the SRI-SID-V2 responses are plotted along with the NHTSA test corridors. The shaded areas in all the plots show the acceptable range for the peaks.

Table 1 shows that SRI-SID-V2 peak responses are within the acceptable range specified by the calibration procedures except the lower spine which is just slightly over the upper limit. The PD-SID-V3 predicts a higher lower spine response (T_{12}) although the rib responses of PD-SID-V3 are within acceptable range. The figures showing the finite element model responses against NHTSA’s test corridors indicate that both models are stiffer and they both peak about 10 ms late with respect to the physical tests. The response of the SRI-SID-V2, though stiffer than the corridors, is a better approximation of the corridors than the PD-SID-V3. Both models result in a TTI that is within the acceptable range.

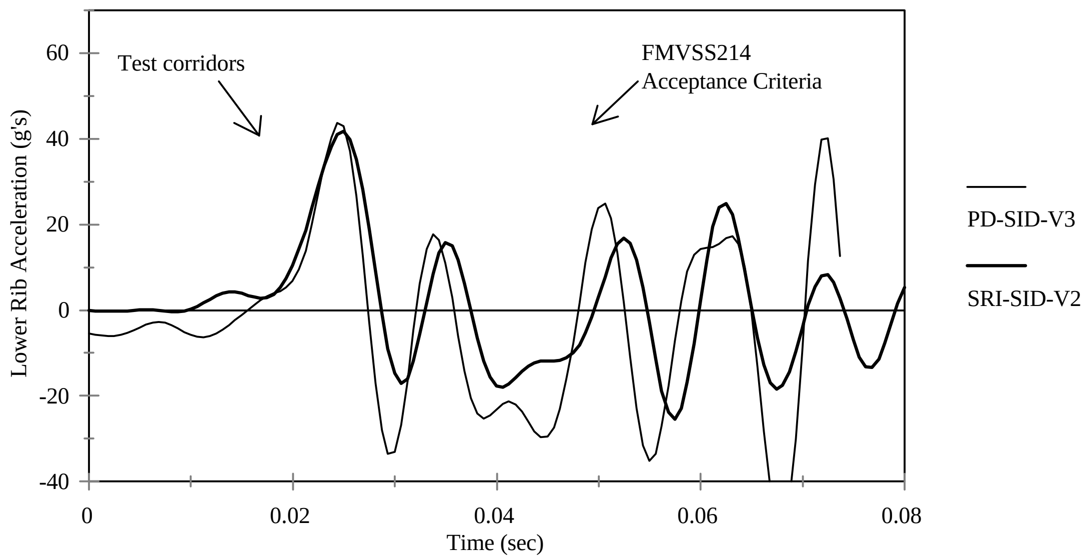

Figure 3. Calibration values for lower rib.

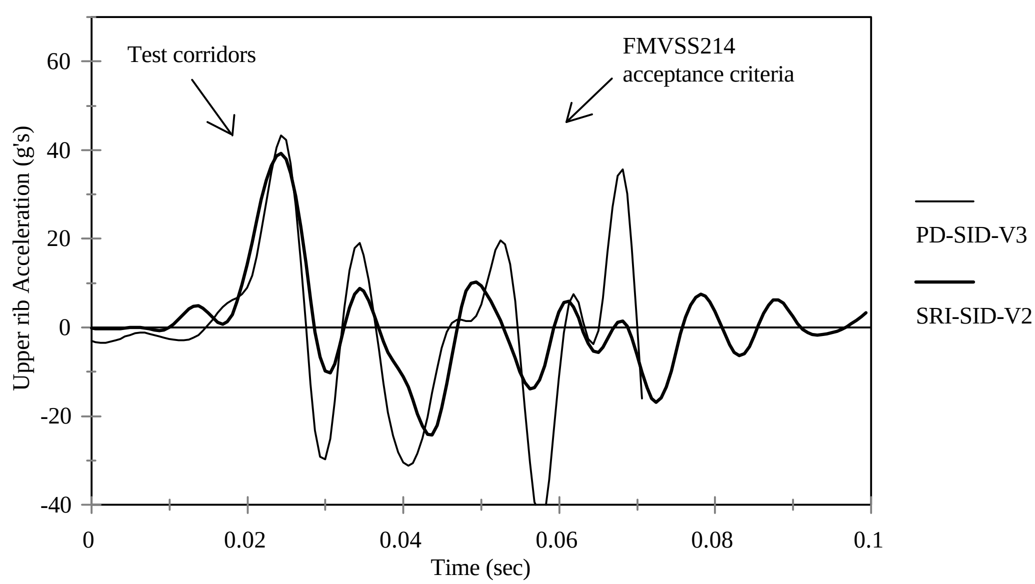

Figure 4. Calibration values for upper rib.

Pendulum Pelvis Calibration Test

The SID ATD has an accelerometer mounted in the rear wall of the pelvis instrument cavity for measurement of lateral acceleration in the pelvis. The primary axis of the accelerometer is aligned perpendicular to the midsagittal plane of the pelvis. The longitudinal centerline of the test probe is placed 99.1 mm above the seating surface and 121.9 mm ventral to a transverse vertical plane tangent to the back of the SID ATD buttocks. The SID ATD position for the pelvis impact is shown in Figure 5. The peak acceleration in this test condition must be between 40 and 60 g's. The acceleration time history for the test should be unimodal (to the extent that oscillations occurring after the main acceleration pulse of the FIR filtered data are less than 10 percent of the main pulse) and should lie at or above the + 20 g level for an interval of not less than 3 ms and not more than 7 ms.[6]

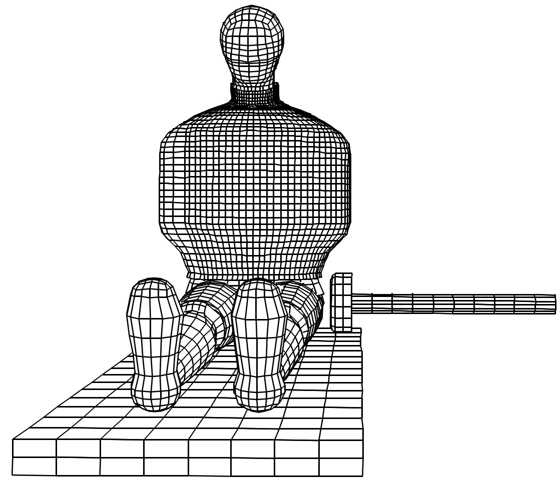

Figure 5. Pelvis Calibration Setup.

The results of the pelvis calibration test of the SRI-SID-V2 and the PD-SID-V3 are shown in Table 2 and Figure 6. In both cases the data was sampled, processed and filtered using the same programs and procedures as used in the physical calibration tests. Figure 6 shows the pelvis acceleration corridor based on physical tests. The SRI-SID-V2 over predicts the pelvis accelerations and results in an early peak compared to the test corridors. This is expected since the SRI-SID-V2 is less detailed in the pelvic region and used rigid parts. The PD-SID-V3 predicts much lower pelvic accelerations than the test corridors and the peak occurs later than the test corridors would indicate. Neither finite element model falls within the pelvis test corridors or satisfies the NHTSA calibration requirement.

	Required Range (g's)	SRI-SID-V2 (g's)	PD-SID-V3 (g's)
Pelvis Acceleration	$40 < P_y < 60$	130.9	25.2

Table 2. Pelvis response in the standard pelvis calibration test.

In-vehicle rigid pole test

The next step in assessing the performance of the two SID models is to use them in a more complex in-vehicle simulation. The vehicle used for simulation is the side impact finite element model of Ford Taurus developed by EASi Engineering.[7] The vehicle model was developed using the PATRAN pre-processor and LS-DYNA3D. The model was modified to some extent to improve its performance: Local coordinate systems and nodal rigid bodies were added; The glass windows in the doors were removed; Hour glass

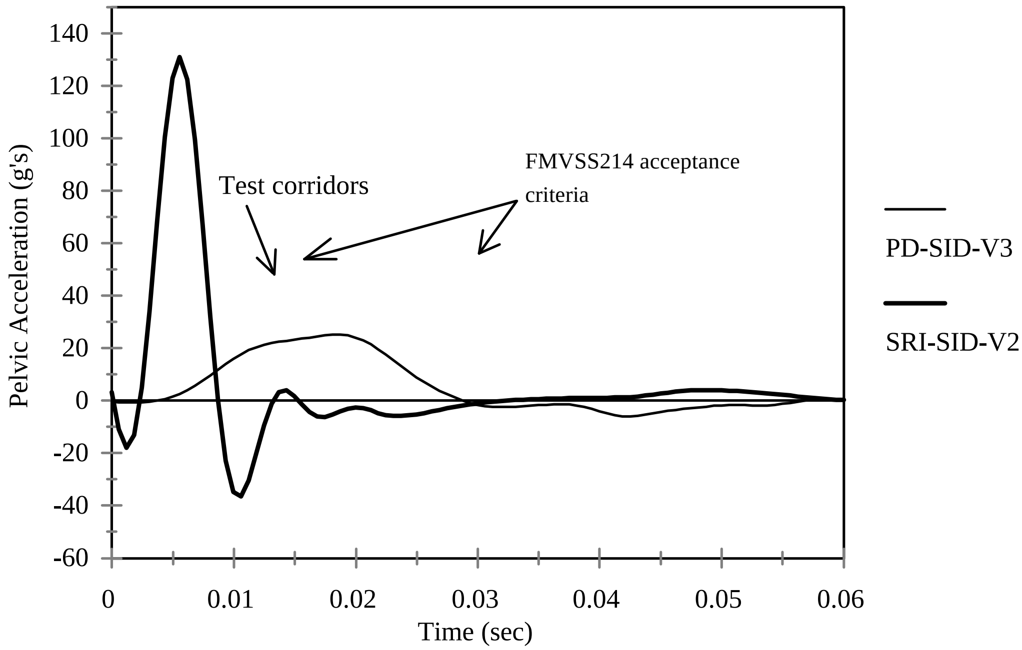

Figure 6. Calibration values for pelvic test.

control parameters for most of the vehicle parts in the impacted region were increased; Several vehicle parts that were not included in the contact definition were included; Rate effects for all materials in the vehicle model were removed and failure criteria for all the materials were removed since it was found to cause problems while using auto-contact in the model. The overall performance of the Ford Taurus seems satisfactory.

The performance of the SID models in the simulation were compared to the response of the SID ATD in the physical tests. Two full-scale crash tests of Ford Taurus four-door sedans striking a rigid pole were performed at the Federal Outdoor Impact Laboratory in May 1995 and December 1995.[15][16] The tests were essentially identical in so much as both struck the rigid pole with the centerline of the 220-mm diameter pole aligned with a point 1150-mm rearward of the front axle, just behind the vehicle A pillar. SID devices were used in both tests although a Hybrid-III head and neck were used in test 95S014. The vehicle was accelerated into the rigid pole using a gravity-tow monorail device that breaks free of the vehicle 2 m in front of the test device. The vehicle slides laterally across a concrete runway for the last 2 m in front of the test device. Because the vehicle is sliding, it tends to roll into the rigid pole with the roof rail striking first. The rolling also tends to cause the SID to rotate in the seat prior to impact. It is essential, therefore, to prescribe initial rotations in the finite element simulation to account for the roll angle of both the vehicle and the SID in the physical test. The impact conditions for the two tests are summarized in Table 3.

	95S008	95S014	Simulations
Velocity	36.5 Km/h	32.8 Km/h	32.8 Km/h
Roll	4°	3°	3°

Table 3. Impact Conditions of the Taurus Rigid Pole Tests and Simulation.

The physical test data from test 95S008 could not be used due to lack of lower spine and pelvic acceleration data (i.e., the test accelerometers failed), therefore, the data from test 95S014 was used for comparison with finite element models. Unfortunately, the camera behind the SID ATD in test 95S014 malfunctioned so the position of the SID at the time of impact could not be precisely determined. The SID ATD had started leaning towards the window at the time of impact. Also, a vehicle roll of 3 degrees was observed in the test films. In the finite element simulations the SIDs were given a rotation of 6 degrees towards the impact side door (same position of SID in test 95S008) and the vehicle was given a roll angle of 3 degrees. The vehicle impacted the rigid pole laterally with a velocity of 32.8 km/h. The results of the simulation are shown in Table 4 and Figures 7, 8, 9 and 10. Figures 11 and 12 show the sequential plots of both the finite element simulations.

	95S014	SRI-SID-V2	PD-SID-V3
T_{12} Peak Acceleration	53.00	59.80	62.40
LURY Peak Acceleration	40.70	100.08	-
LLRY Peak Acceleration	45.60	90.84	-
Peal Lateral Pelvic Acceleration	98.90	105.20	141.80
Thoracic Trauma Index (TTI)	49.30	74.94	-

Table 4. Peak Accelerations for a 32 km/hr Side Impact of a Ford Taurus and a Rigid Pole.

The test simulation with the SRI-SID-V2 terminated at 114 ms due to excess mass scaling in the door trim material in the rear right door. The coarse mesh in the rear door trim opposite to the impact side began hourglassing after 100 ms causing the mass scaling. The head of the SID was pinched between the B pillar and the pole causing the SID to rotate about the neck as the seat was crushed by the pole. This behavior is very similar to that observed in the physical test. The results indicate that the SRI-SID-V2 predicts approximately the same lower spine and pelvic accelerations as the physical test. The rib accelerations are however higher and occur later than in the physical tests. The high rib accelerations could be due to the uncertain SID position at the time of impact.

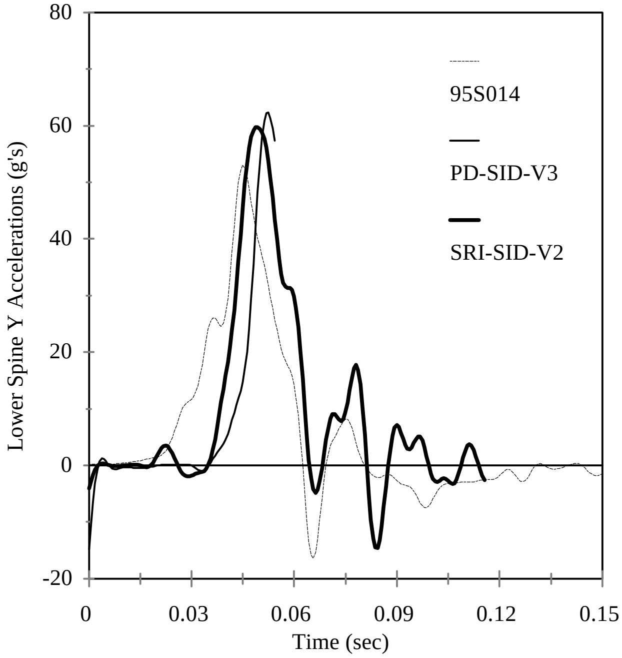

Figure 7. Lower spine accelerations for in-vehicle test.

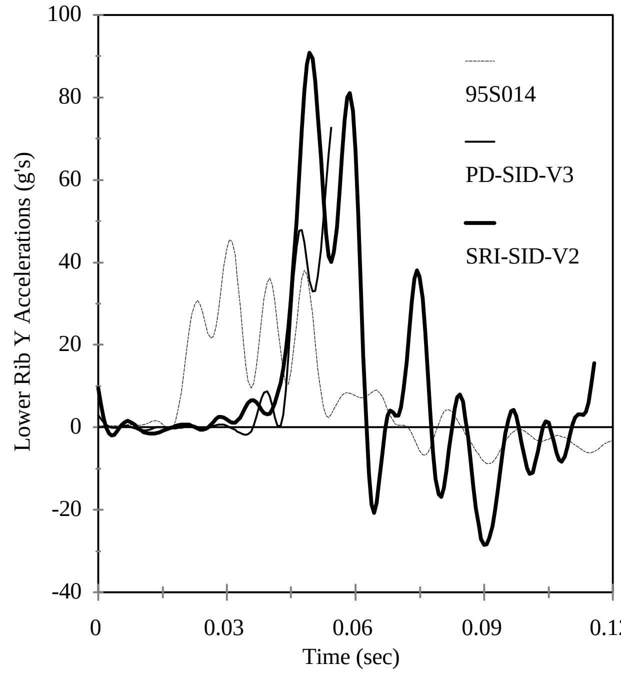

Figure 8. Lower rib accelerations for in-vehicle test.

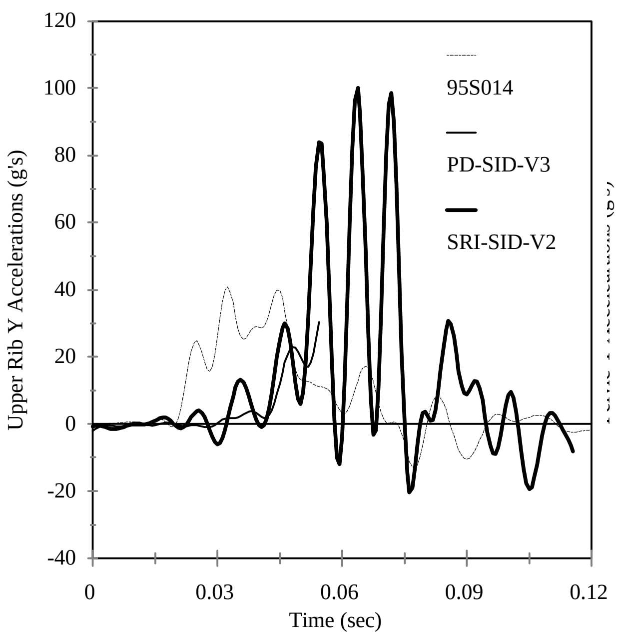

Figure 9. Upper rib accelerations for in-vehicle test.

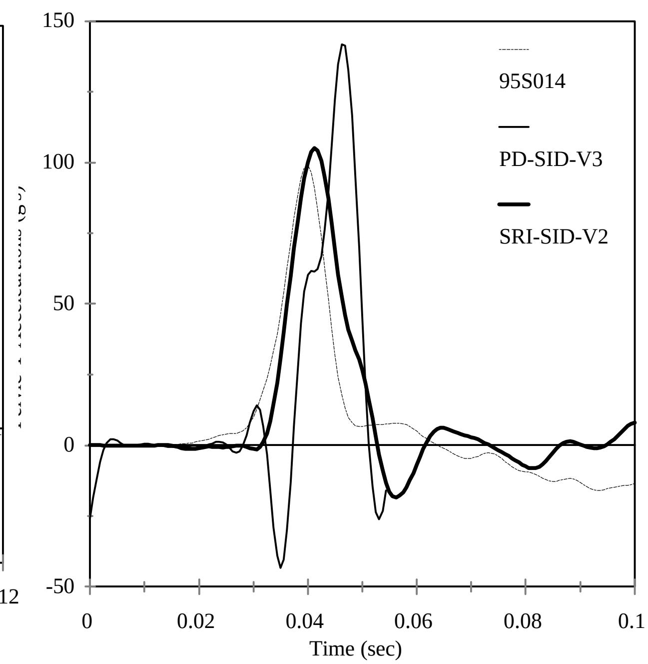

Figure 10. Pelvic acceleration for in-vehicle test.

The finite element simulation with the PD-SID-V3 terminated at about 54 ms due to negative volume error in the rib wrap foam material. The arm foam penetrated the rib foam resulting in numerical problems. Due to early termination the peak responses for upper and lower rib could not be determined and the TTI could not be calculated. The lower spine peak response was found to be close to that of the physical test, whereas the peak pelvic acceleration was much higher than the physical test.

DISCUSSION

The preceding sections have shown a comparison of the dynamic performance of two SID models both with respect to each other and to physical tests. The thoracic pendulum calibration test, the pelvic pendulum calibration test and an in-vehicle rigid pole test were used for this assessment. Neither SID model is, as yet, a good predictor of all the physical injury indices measured by a SID. The SRI-SID-V2, however, is much closer to the corridors for all the calibrations tests and with the exception of the pelvis acceleration, the peak values correspond to the FMVSS214 calibration criteria. The in-vehicle simulations show that the SRI-SID-V2 is, at this point, much more robust and produces reasonable predictions of both the TTI and pelvis accelerations even though improvement is still needed in the time history corridor comparisons . The PD-SID-V3 experiences both constitutive and contact problems that severely limit its utility in the more complicated in-vehicle simulations.

There are still improvements that should be made to both of the models. One area of development is to improve the overall robustness of the models. The primary load application for thoracic impacts is from an external barrier or impactor through a rubber jacket, a low density urethane armpad foam, an ensolite foam rib wrap, and into the ribcage assembly. Modeling these interactions requires sliding interface definitions across surfaces with vastly different material stiffnesses and densities as well as different element types (i.e., shells and solids). The material behavior of the foams are highly nonlinear and they compact to a very small fraction of their initial volume with relatively small applied stress levels. The above combinations of physical characteristics often lead to numerical instabilities in finite element analysis. This has been a problem in all the SID models to date and needs to be resolved.

Optimizing the sliding interface penalties for the various master and slave sides of each contact interface and increasing the mesh resolution in regions where strong deformation gradients occur would improve the model robustness. Other secondary modifications include finding the best hourglass stabilization schemes and investigating how modifications to the armpad and rib wrap stress-strain behaviors influence both the model performance and numerical stability.

Another area of research for application of the SID to determine injury potential in side impacts is the biofidelity of the SID neck. There is interest in using the Hybrid III neck on the SID to help investigate this issue. The SRI-SID-V2 has options for substitution of different components throughout the SID such as replacing the SID neck with a model for the Hybrid III neck. SRI has previously generated an INGRID model for the Hybrid III Dummy neck that can be used with the SRI-SID model. A simulation of the neck calibration test to validate the Hybrid III neck model would also be desirable. The result will allow the effect of neck behavior on injury measures such as HIC to be calculated in the upcoming reporting periods.

Comparisons to the time history corridors for both SID models shows that there is an approximately 10 ms lag in the response. This appears to be due to the geometrical modeling of the thorax, a part of both SID models that was inherited from the very first PD-SID-V1. When the PD-SID-V1 was developed the geometry was approximated using elliptic surfaces. This delay could probably be considerably reduced by digitizing a physical SID and using a more accurate geometry to eliminate incorrect geometry and gaps between materials.

Each sucessive model of the SID has proven to be an improvement on the last. The SRI-SID-V2 is perhaps the best available and most robust finite element model of the SID although it lacks the detailed lower extremities of the PD-SID-V3. Further refinement of the SID models is, no doubt, inveitable as researchers attempt to develop higher resolution, higher fideilty tools for crashworthiness research. The SRI-SID-V2 is relatively effective at predicting the TTI although additional work is needed to improve the comparison with physical response corridoros.

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REFERENCES

1. Chinmoy Pal, Hideaki Ichikawa and Koichi Sagawa, `Development and Improvement of Finite Element Side Impact Dummy (EUROSID) Model Based on Experimental Verifications,' SAE Paper 971041, Anthropomorphic Dummies and Crash Instrumentation Sensors, SAE SP - 1261, Society of Automotive Engineers, Inc., February 1997.

2. Adnan Khan, Thiag Subbian and Chris O'Connor, `Finite Element Development of the BIOSID,' SAE Paper 971140, Anthropomorphic Dummies and Crash Instrumentation Sensors, SAE SP - 1261, Society of Automotive Engineers, Inc., February 1997.

3. R H Eppinger, J H Marcus, R M Morgan, `Development of Dummy and Injury Index for NHTSA's Thoracic Side Impact Protection Program,' SAE Paper 840885, Society of Automobile Engineers, May 1984.

4. NHTSA, "Federal Motor Vehicle Safety Standards: Side Impact Protection," Code of Federal Regulations, 49 CFR 571.214, Washington, D.C., Current through October 14, 1997.

5. B S Holmes, S W Kirkpatrick, `Finite element Model for Side Impact Dummy,' SRI Project No. 3223, SRI International, Menlo Park, CA, October 1992.

6. R. G. Whirley, `DYNA3D (A Nonlinear, Explicit, Three-Dimensional Finite Element Code for Solid and Structural Mechanics) User Manual,' Lawrence Livermore National Laboratory, Report

UCRL-MA-107254, 1991.

7. `Validation and Refinement of a Finite Element Model of the Side Impact Dummy for Crashworthiness Studies,’ Quantum Consultants, Inc., Bettelle Draft Final Report to NHTSA, November, 1995.

8. J O Hallquist, D W Stillman, T L Lin. `Nonlinear Dynamic Analysis of Structures in Three Dimensions.’ LS-DYNA3D User’s Manual, Livermore Software Technology Corporation, 1993.

9. `Development of Taurus/SID Model’, Final Report, EASi Engineering.

10. J W Simons and S W Kirkpatrick, `High-Speed Rail Collision Safety: Crashworthiness and Accident Survivability,’ Technical Report 001-96, Poulter Laboratory, SRI International, Menlo Park, CA, June, 1996.

11. M. H. Ray. `The use of finite element analysis on roadside hardware design,’ International Journal of Crashworthiness, Vol. 2 No. 4, Woodhead Publishing, London, 1997.

12. TrueGrid Manual, Version 0.99, XYZ Scientific Applications Inc, Livermore, California, October 1995.

13. NHTSA, `Laboratory Test Procedures for FMVSS No. 214 — Side Impact Protection; Passenger Cars,’ National Highway Traffic and Safety Administration, Washington, D.C., 1992.

14. SAE, `Instrumentation for Impact Tests’, Specification J211, Society of Automobile Engineers, Warrendale, PA, 1988.

15. C M Brown, `Ford Taurus Broadside Collision with a Narrow Fixed Object -- Test Number 95S008,’ Report Number FHWA-RD-96-106, Federal Highway Administration, Washington, DC, May 1995.

16. C M Brown, `Ford Taurus Broadside Collision with a Narrow Fixed Object, Test Number: 95S014,’ Report Number FHWA-RD-96-127, Federal Highway Administration, Washington, DC, December 1995.