



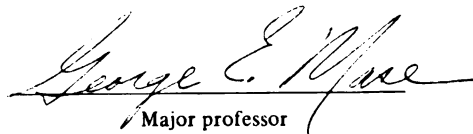
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SIDE IMPACT OCCUPANT PROTECTION:
THE DEVELOPMENT OF A SIMULATION MODEL
TO AID IN THE AUTOMOBILE DESIGN PROCESS

presented by

Patrick Michael Miller II

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**SIDE IMPACT OCCUPANT PROTECTION:
THE DEVELOPMENT OF A SIMULATION MODEL
TO AID IN THE AUTOMOBILE DESIGN PROCESS**

By:

Patrick Michael Miller II

(Advisor: Dr. George Mase)

A THESIS

**Submitted to
Michigan State University
in partial fulfillment of the requirements
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ABSTRACT

SIDE IMPACT OCCUPANT PROTECTION:
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By

Patrick Michael Miller II

The purpose of this thesis was to develop a computer simulation which would model the dynamics of a full scale side impact. In keeping with current practice in automotive research, this thesis is experimental, rather than theoretical, in nature. The approach employed in this thesis was to obtain force-deflection characteristics, through laboratory testing, for the door and the mechanical dummy typically used in side impact research, and implement these characteristics into a multi-purpose computer program which models the dynamics of a system of masses inter-connected by linear or non-linear resistive elements. The output from the computer simulation was then compared to actual full scale side impact crash data. The results of this thesis indicate that the dynamics of a full scale side impact can be effectively modeled. This model can then be used as an aid in automobile design with regard to side impact occupant protection.

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INTRODUCTION

Over the past thirty years, interest in automobile safety has gradually increased. One area of particular concern has been the field of automobile crashworthiness. Whenever an automobile is involved in a collision, a change of velocity by the automobile takes place in a fraction of a second. Any occupant in this vehicle must also experience this rapid velocity change. Crashworthiness is defined as the application of forces to the occupant with mechanical restraint devices (i.e. seat belts, airbags), as well as the efficient dissipation of energy through vehicle deformation, in an effort to decrease the likelihood of injury to the occupant.

Crashworthiness, as it is defined here, can be applied to many different types of automobile accidents. Among them are frontal impacts, rearward impacts, and side impacts. Frontal impacts are the cause of approximately forty-seven percent of all serious injuries from automobile accidents [1]. In a frontal impact, the principal concern is in protecting the occupant's head and chest. Many innovative ideas have been incorporated into today's automobile design which provide

protection in a frontal impact. Seat belts, air bags, child safety seats, and energy absorbing front structures are examples of these protective features.

Rearward impacts lead to approximately one percent of all serious injuries from automobile accidents [1]. Although this is significantly less than the amount of injuries due to frontal impacts, it is the nature of these injuries which is of utmost concern. Rearward impacts are responsible for most automobile accidents involving fire due to the location of the fuel tank. Injuries caused by fire are the most frightening and debilitating in nature. Because of this, much effort has been spent in the design of fuel systems and the containment of fuel in the event of a rear end accident.

Side impacts account for approximately twenty-six percent of all serious injuries from automobile accidents [1]. Side impact research and methodologies related to side impacts are the areas of interest which motivate this thesis.

One standard method of evaluation of crashworthiness for a vehicle is a full scale, dynamic crash test. A crash test is basically the impacting of a test vehicle into a barrier or vice versa. A crash test is an experiment used to evaluate automobile design with regard to occupant injury. The occupant in a crash test is a mechanical dummy. The dummy has been designed in such a way that it will respond in a manner similar to a human occupant. The dummy is instrumented to record data (accelerations, displacements, velocities, and forces) at various locations on the body. A crash test is

usually designed to model a typical real world automobile accident. For example, a 30 mph crash test into a rigid barrier is analogous to two automobiles travelling at 30 mph each and colliding head on. There are many examples of real world accidents which are similar to this type of crash test. This particular crash test is designed to model a statistical majority of accidents which occur in real life.

One issue which must be addressed is the role of crash testing in vehicle development and federal standards. In vehicle development, crash testing provides important data regarding occupant safety, collision repair, and other types of basic information relating to vehicle design. Full scale dynamic testing becomes even more relevant because various crash tests must be performed to demonstrate compliance of certain federal standards. All federal standards must be satisfied before an automobile can legally be brought to market. Currently, full scale frontal and rearward crash tests are necessary to verify compliance of certain federal standards. The frontal crash test is a 30 mph impact of the test vehicle into a rigid, stationary barrier. The criteria for compliance is based on the dummy head and chest accelerations, as well as force loads experienced by the femur of the dummy. Also, the vehicle is checked for fuel leakage after impact. The rearward impact is a 30 mph impact of a 4000 pound rigid barrier into the rear of the test vehicle. The compliance for this standard is based on the amount of fuel leakage immediately after impact. Figure 1 provides a

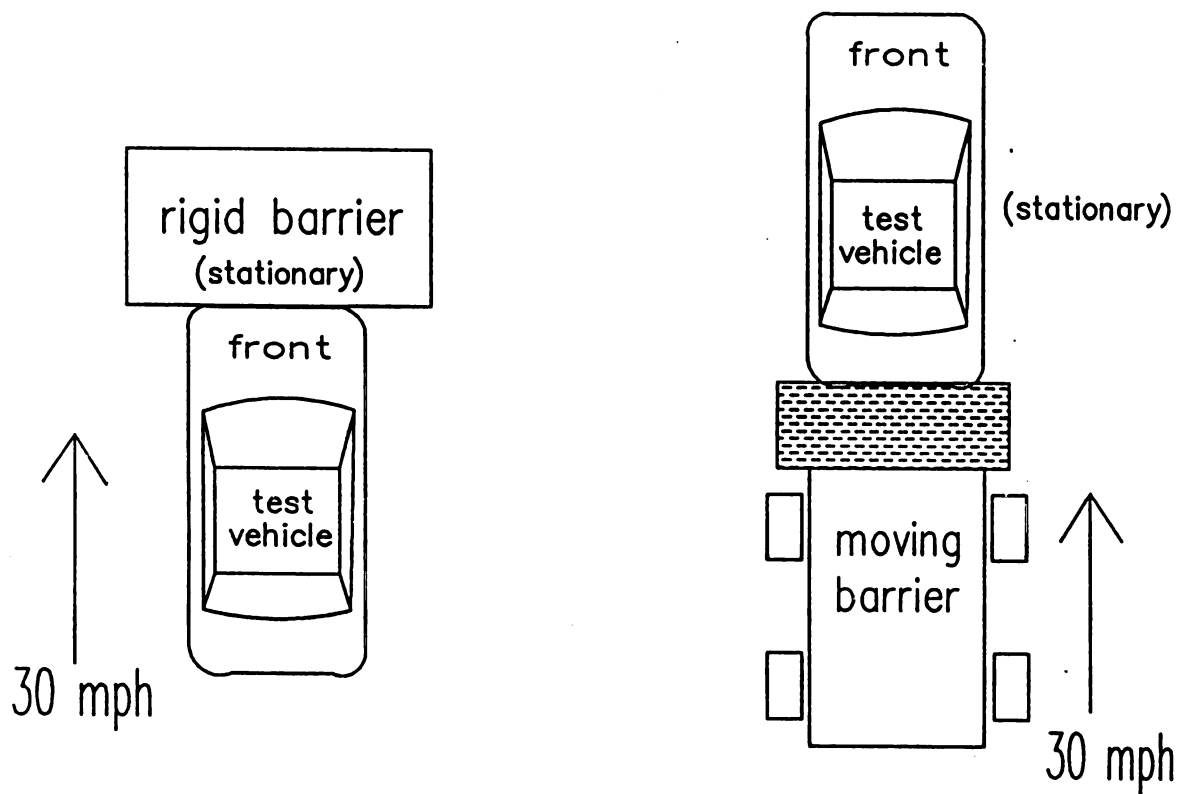


Figure 1 - Diagrams of a) Frontal and b) Rearward Impacts

diagram describing each standard.

For side impacts, a full scale crash test is not required to demonstrate compliance to a federal standard at this point in time. A federal standard related to side impacts is a static loading test on the vehicle door with the criteria for compliance depending on the force-energy characteristics of the door. It is expected that The Department of Transportation (DOT) will pass an additional standard relating to side impacts. The proposed standard would require a full scale, dynamic crash test. Very likely, the standard will require the performance of a 33.5 mph, crabbed angle, impact of a 3000 pound moving barrier into the side structure of a stationary test vehicle [2]. The term crabbed angle refers to the fact that the longitudinal axis of the barrier is perpendicular to the test vehicle but the four wheels of the barrier are turned 27 degrees to the right of this axis. The velocity of the barrier is 33.5 mph in the direction of the wheels. This velocity vector corresponds to a 30 mph component perpendicular to the longitudinal axis of the impacted car as well as a 15 mph component in the direction parallel to the axis of the impacted car. Accordingly, the test is modeled after the typical side impact accident, i.e. one car travelling 30 mph colliding with another vehicle travelling at 15 mph at a 90 degree intersection. The crabbed angle simplifies the test in that only the barrier needs to be in motion to effectively simulate this situation. This test is diagrammed in Figure 2. The stationary vehicle contains a

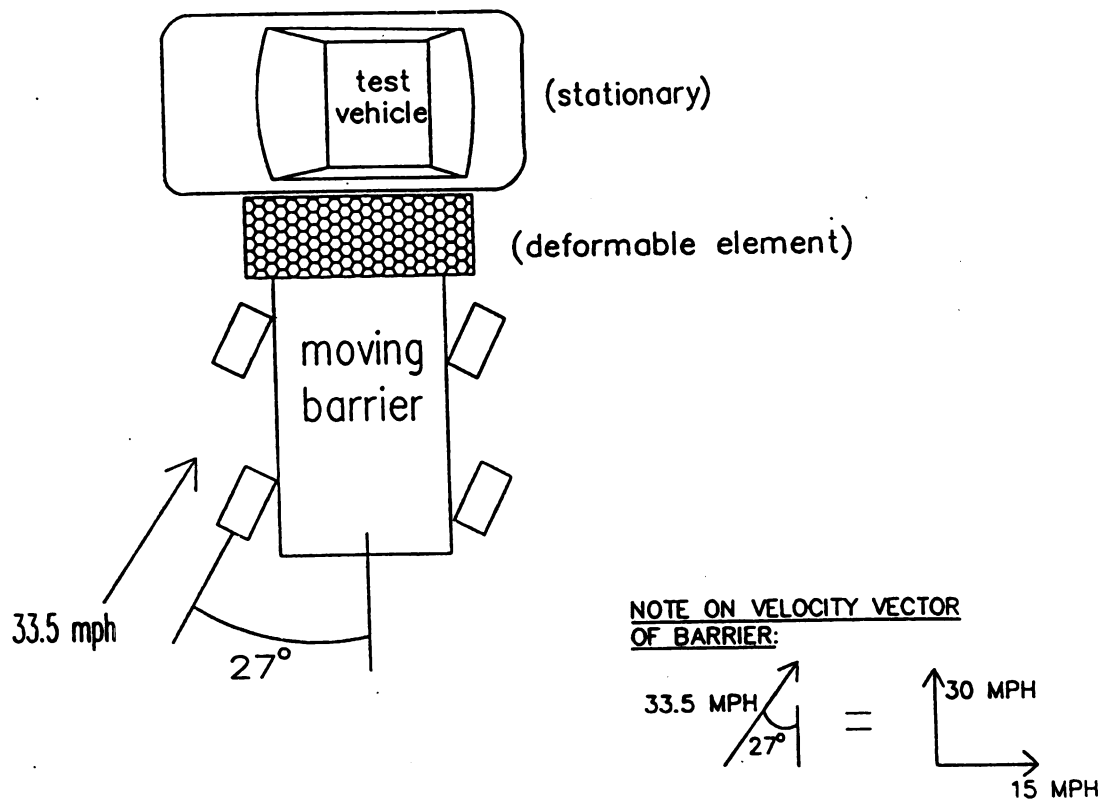


Figure 2 - Diagram of "Crabbed Angle" Side Impact

standard Side Impact Dummy (SID), which is instrumented to record data. The Side Impact Dummy is similar to the mechanical dummy used in the frontal impact case, the only difference being in the design of the chest area (torso). The torso of this dummy has been designed to measure specific accelerations and displacements that are directly related to injuries caused by side impacts. From the data recorded by the SID during the impact, a measure of the injury severity is calculated. This measure of injury severity will be used as the criteria in determining whether or not the test vehicle is in compliance with the proposed federal standard.

The geometry of a side impact provides little protection to the occupant when compared to the frontal impact case. In a frontal impact, the occupant is not only restrained by seat belts (and possibly an airbag), but is also protected by the front structure of the vehicle itself in that there is approximately 40 to 50 inches of available crush area (vehicle mass), which can be used to dissipate much of the energy of the impact. The crush area being referred to is the bumper, engine, body panels, and structural frame members. For a side impact, the distance between the occupant and the impact surface is only 6 to 8 inches. This impact area is basically the door mass and the area around the door (the B-pillar, and rocker panel). In a side impact, the velocity of the door will approach the velocity of the barrier within this 6 to 8 inch space before contact with the occupant is made. Occupant protection in a side impact offers a greater challenge when

compared to frontal impacts.

Besides full scale crash testing, there are a variety of other techniques available today which aid in crashworthiness research. One of these techniques is computer simulation. Computer simulation is the use of a computer to implement a mathematical model of the dynamics involved in a crash test in order to analyze occupant response. The first step in computer simulation is laboratory testing of the mechanical dummy used in the crash test for physical characteristics, e.g. geometry, mass values, and force-deflection properties. The next step is the testing of component level parts involved in the full scale test. Component level parts are the individual pieces that are assembled to form the complete automobile. Examples of component level parts would be instrument panels, seats, and steering columns. Once the characteristics of all the important components have been obtained, they are used in a mathematical simulation of the crash test. The mathematical representation may be a spring, damper, mass system or some other formulation. The primary goal of the simulation is the solution of the equations of motion which are related to the dynamics of an actual crash test. In solving these equations in a step-wise fashion at short time increments, the use of a computer becomes necessary. The most pertinent output of a computer simulation of a crash test is the occupant response data. The results of the simulation allows an engineer to determine whether or not the altering of a component will have a positive or negative

effect on occupant response. Thus simulation avoids having to perform a full scale crash test, and requires only a component level test. Such an approach is extremely cost effective, as well as time saving.

One approach to computer simulation of a full scale side impact is currently being pursued by the Committee of Common Market Automobile Constructors (CCMC), an European trade association. The name of this approach is The Composite Test Procedure (CTP) [3]. CTP is conventional in its approach in that the equations of motion (representing the dynamics of a side impact) are solved at each time step. It is unique in that the method used to obtain force-deflection characteristics of the test vehicle is one that requires two static loading devices used sequentially during one test procedure. One loading device represents the barrier and the other represents the torso of the dummy. This test procedure yields a deformation pattern on the side structure of the vehicle which is similar to the pattern that would be obtained from a full scale side impact test, and is explained in detail in Chapter 1. The results of CTP are comparable to the results obtained from a full scale side impact test.

The objective of this thesis is to enhance and expand the Composite Test Procedure approach to side impact modeling. This objective will be accomplished through a series of progressive steps, the first of which is analyzing the CTP approach in depth.

CHAPTER 1

THE COMPOSITE TEST PROCEDURE

1.1 Laboratory Testing

The Composite Test Procedure for side impact protection is a combination of static testing and computer simulation. The static test procedure begins with mounting an unfinished vehicle known as a body-in-white onto a static loading frame. A body-in-white is the main chassis of the test vehicle, including doors and body panels, without any of the other parts of the car assembled into it. It is called a body-in-white because it has been taken off the assembly line immediately after being dipped in paint primer, thereby resulting in a grayish-white color. Once the body-in-white is secured to the frame, two static loading devices are set up and activated. One loading device, representing the barrier, has a deformable element mounted on the front of it. This deformable element is identical to the one used on the front face of the moving barrier in a full scale side impact test, and is used to deform the exterior side structure of the body-in-white. The other static loading device is placed inside the body-in-white, with a space of 6 to 8 inches

between it and the inner door padding. The location of this loading device correlates with the orientation of the dummy's torso when seated in an upright position. The body-in-white is then loaded sequentially (by both devices) in such a way that force-deflection characteristics for the side structure and the inner door can be obtained.

The method used for testing this body-in-white is based on three events which occur during a typical real world side impact accident. First, there is contact of the front of the striking vehicle with the side structure of a struck vehicle. Penetration of the struck vehicle occurs until the occupant contacts the interior surface of the door (Step I). The occupant then deforms the inner surface of the door, at which time lateral acceleration of the occupant starts (Step II). Finally, the striking vehicle continues to penetrate the struck vehicle, which is followed by a separation of vehicles [3]. These three steps of the CTP (I,II, and III), are shown in a diagram in Figure 3 [3].

1.2 Computer Simulation

CTP treats these three events as different stages of energy dissipation performed in sequence. Accordingly, each event is described in terms of a force-deflection curve. These two force-deflection curves, one representing the side structure (and deformable element) characteristics, and the

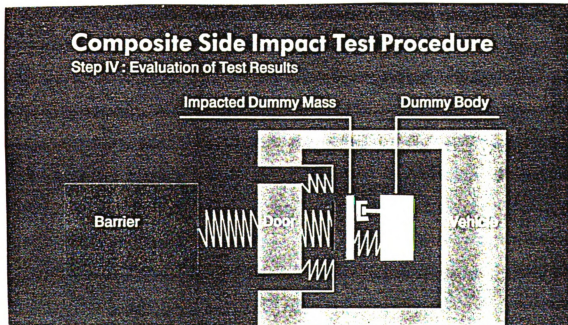
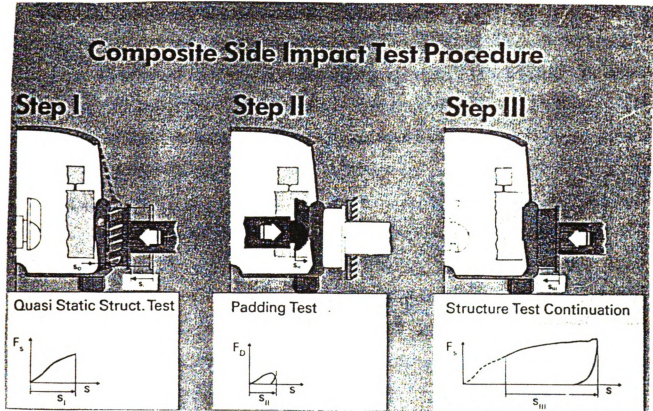


Figure 3 - The Four Steps of the Composite Test Procedure

other representing the inner door padding, are then used as input for the computer simulation. This is Step IV of CTP. The computer simulation solves the equations of motion for the model representing the interaction of the moving barrier, test vehicle, door, and dummy as shown in Figure 3 [3]. From this model, the responses of the torso and rib masses are calculated. Using these results, appropriate injury values can be determined.

1.3 Advantages of CTP

CTP has many advantages when compared to other methods of improving occupant protection in side impacts. First of all, this procedure requires no mechanical dummy, only a computer dummy. Dummy maintenance, calibration, and repair are no longer necessary. It is also believed that this test method will provide better repeatability when compared to the full scale side impact. In addition, it is much more cost effective in that only a body-in-white and a door are needed to perform the test procedure. This allows side impact testing and research on a vehicle to take place at an earlier stage in vehicle development. Perhaps the greatest advantage of CTP is its flexibility. Dummy characteristics, impact speeds, door characteristics, changes in mass, and so on can all be evaluated using the computer simulation (Step IV).

1.4 Enhancements to CTP

Now that the Composite Test Procedure has been presented, it is appropriate to focus on possible improvements to this model. One improvement is a modified representation of the dummy. Currently, CTP uses a two mass dummy representation, one mass being an impacted rib mass and the other being the dummy body. The mechanical dummy used (simulated) in this thesis was the standard Side Impact Dummy (SID). A SID was disassembled and analyzed in terms of mechanical properties of the ribs, spine, and pelvis. A schematic drawing and photograph of the dummy are shown in Figure 4 [1]. The different parts of the dummy were weighed individually in order to obtain correct mass values for the model. After careful consideration, a four mass representation was settled upon, those masses being the upper rib, lower rib, spine and pelvis. In addition to these masses, characteristics for the upper arm, lower arm, and abdomen were implemented into the model (although the SID does not have actual arms, there is foam padding on the outside of the rib cage that can be considered "arm" mass). This representation, as shown in Figure 5, portrays the springs representing the force-deflection characteristics between the appropriate masses as having circles superposed on the usual linear spring symbol. The reason for this is that the characteristics that are to be obtained cannot be represented with a linear spring



NHTSA "SID" DUMMY

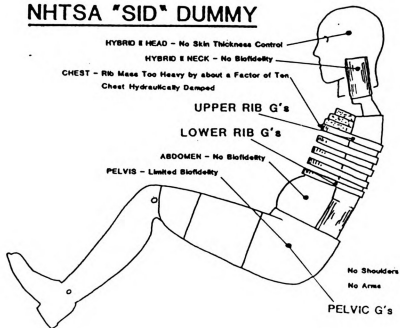


Figure 4 - The Side Impact Dummy: a) Photograph b) Schematic Drawing

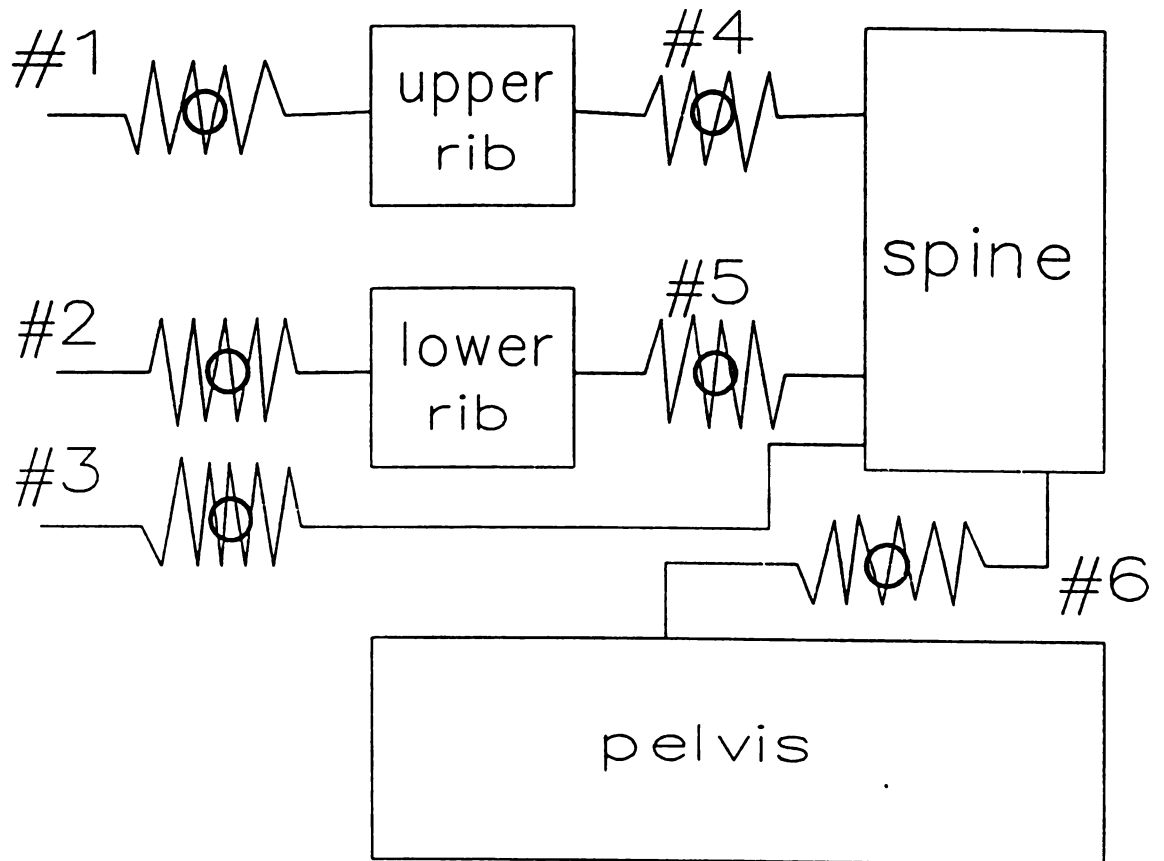


Figure 5 - Four Mass Representation of Side Impact Dummy

alone, due to the presence of damping in most types of mechanical dummies. In particular, for the Side Impact Dummy, this is certainly the case as the torso contains a linear dash-pot which greatly influences dummy response [4]. The spring-circle symbol will be referred to as a mass-connector. Referring to Figure 5, mass-connectors #1, #2, and #3 represent the upper arm, lower arm, and abdomen characteristics respectively. The interactions between the upper rib and spine, lower rib and spine, as well as the spine and pelvis, are represented by mass-connectors #4, #5, and #6. With this representation, it is now necessary to obtain padding characteristics at four different contact areas of the inner door, these being the areas contacted by the upper rib, lower rib, abdomen, and pelvis during a typical side impact. This representation of the inner door padding is also an improvement to CTP in that there was previously only one characteristic curve used to describe the padding of the door, whereas now there are four.

Now that the improvements to CTP in terms of dummy enhancement and door padding characteristics have been outlined, it is appropriate to discuss other possible improvements to the CTP approach. One improvement would be to slightly alter the CTP methodology so that the door padding characteristics could be determined without a body-in-white. This would save both time and money in the vehicle development process. Once reasonable side structure characteristics have

been obtained using the standard CTP method, it would be beneficial to be able to concentrate on the inner door padding alone, without having to repeat Steps I,II, and III of the CTP in order to obtain new inner door padding characteristics. If a simple and dependable method for testing these inner door characteristics could be devised, the CTP approach will have been streamlined in terms of the amount of laboratory testing necessary, as well as the nature of the tests (testing an individual door is much easier than testing the combined door and body-in-white). Also, this approach allows one to focus on the most important occupant response factors in a side impact accident. These factors are side structure stiffness and inner door padding. These two variables can be efficiently optimized with regard to occupant injury by using both the CTP method in general and by implementing the streamlined approach outlined above.

CHAPTER 2

DUMMY TESTING

2.1 Test Set-Up

To quantify the proposed mechanical components of the dummy, tests were performed at MGA Research Corporation in Burlington, Wisconsin. The purpose of these tests was to obtain response characteristics for a standard Side Impact Dummy. The tests were dynamic impact tests into the side of the dummy. The weight of the impacting mass was 50.6 lbs, the velocity of the mass was 15 mph, and the contact points (on the dummy) for each impact are shown in Figure 6. The front face of the impacting mass was a rigid, 6" diameter steel plate. There were a total of eight impacts performed, two at each of the points shown in Figure 6. These contact points correspond to the locations of the upper rib, lower rib, abdomen and pelvis on a Side Impact Dummy.

Acceleration data was measured in the Y and Z directions (see Figure 6 for coordinate system) at the following locations: upper spine, lower spine, and pelvis. Acceleration data in the Y direction only was measured on the upper and lower ribs, as well as on the rear of the impacting mass. A

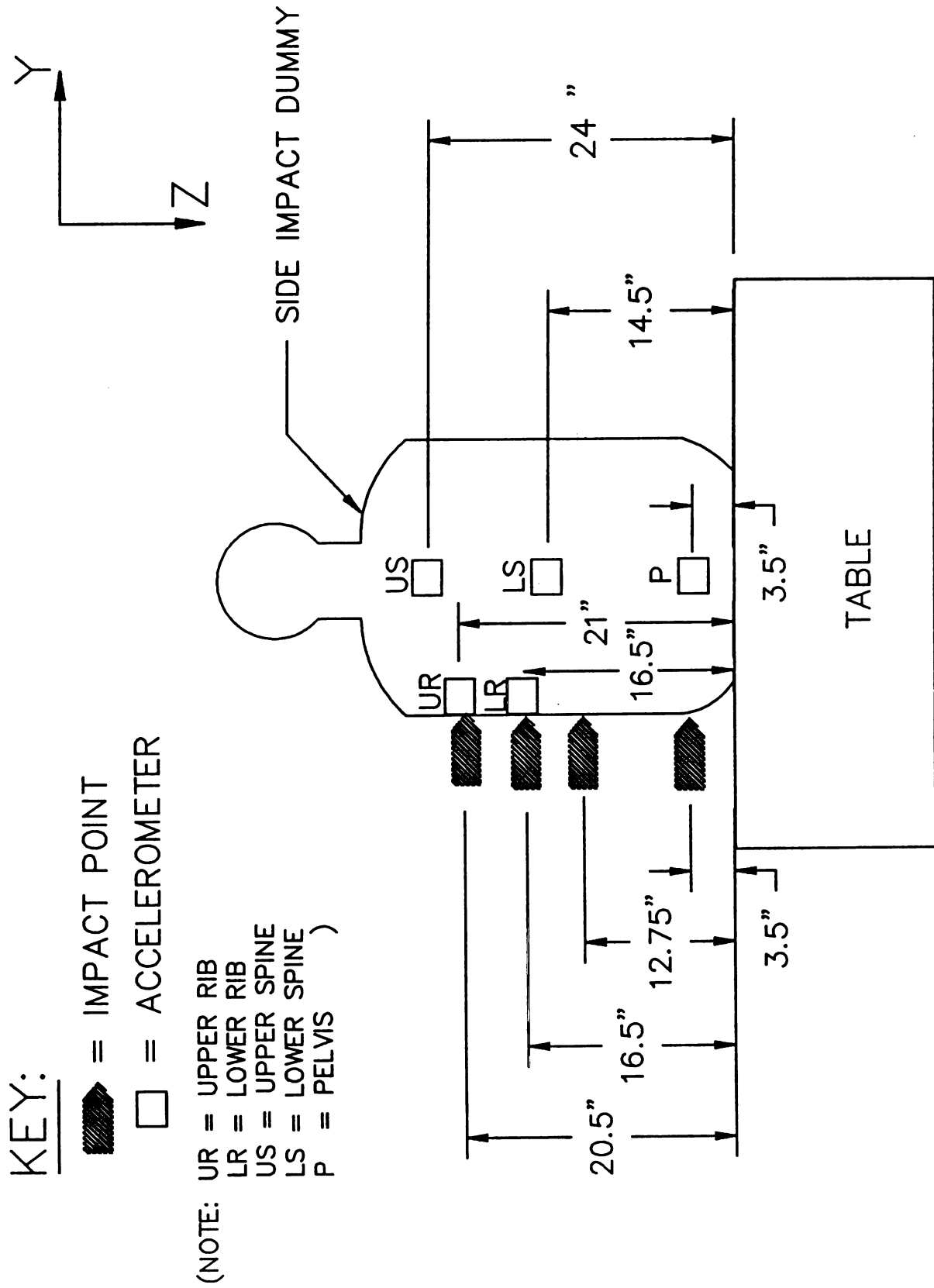


Figure 6 - Impact Points and Accelerometer Locations for Dummy Testing

load cell was placed on the front of the impacting mass (behind the 6" diameter front face) to measure forces during the impact (see Figure 6 for specific locations of the accelerometer mountings). Photographs of the dummy set-up and recording instrumentation are shown in Figure 7. It should be noted that this method of testing is similar to the calibration procedures used for a Side Impact Dummy [4]. The dummy was in an upright seated position, without any external support.

Endevco accelerometers (strain gage type), which are the industry standard for measuring dummy accelerations, were used to record data. A standard Wheatstone Bridge set up was used with each accelerometer. This set-up is shown in Figure 8a. A laser beam trap was used to trigger the data recording system. Data was recorded for 250 milliseconds with a sample rate of 8000 samples per second. Figure 8b diagrams the flow of data for a typical channel in this recording system.

2.2 Data Processing

Once the eight impacts were completed, processing of the raw data was performed. Figure 9 contains raw data from the impact on the upper rib. The main goal of this processing was to determine mass-connector characteristics from the acceleration-time and force-time data collected during the impacts. Initially, all the data for a given impact was

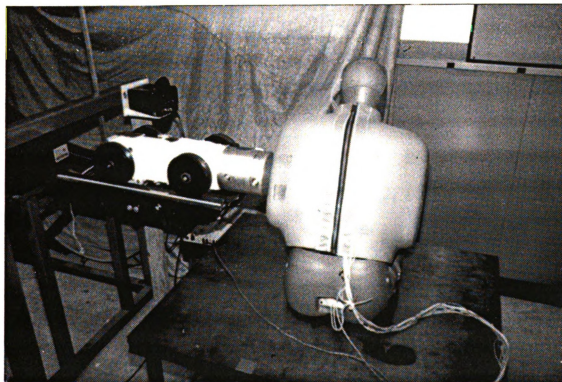
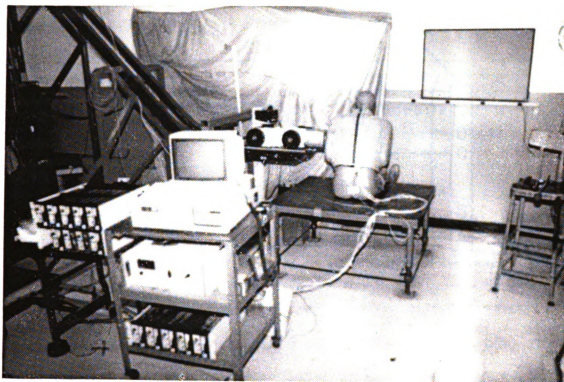
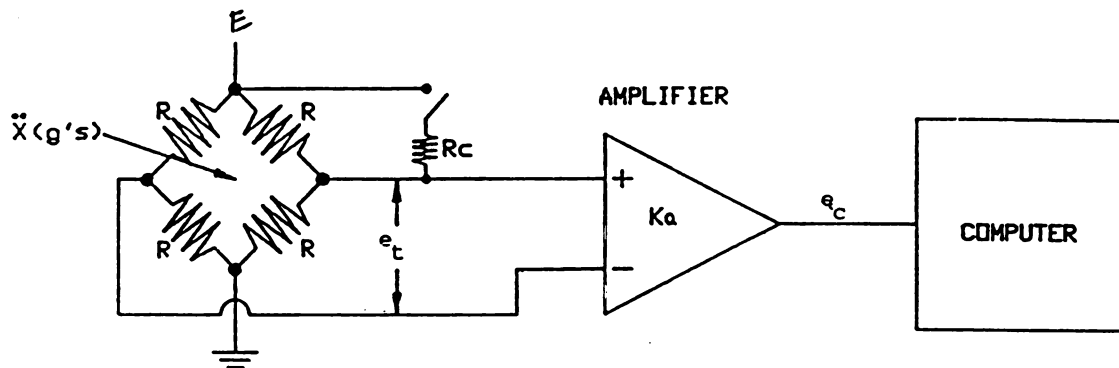
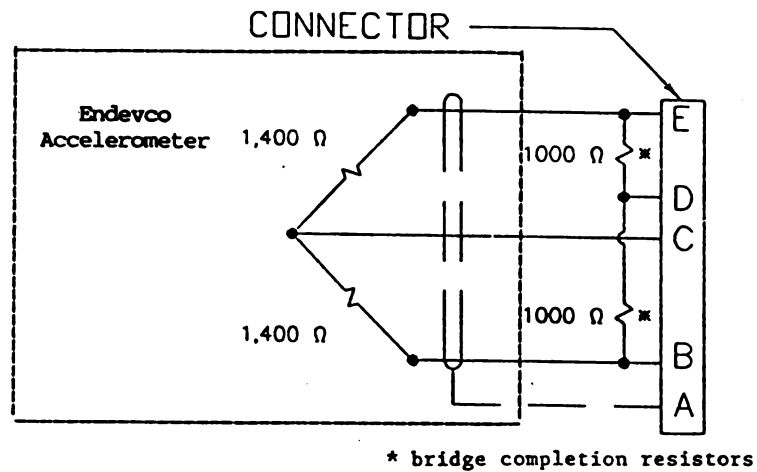


Figure 7 - Photographs of Dummy Testing Set-up



$$e_t = K_t E \ddot{X}$$

WHERE:

- e_t = Transducer Output Voltage
- K_t = Constant for a Given Transducer
- E = Bridge Excitation voltage
- $\ddot{X}$ = Input Acceleration

$$e_c = K_a E t = K_a K_t E \ddot{X}$$

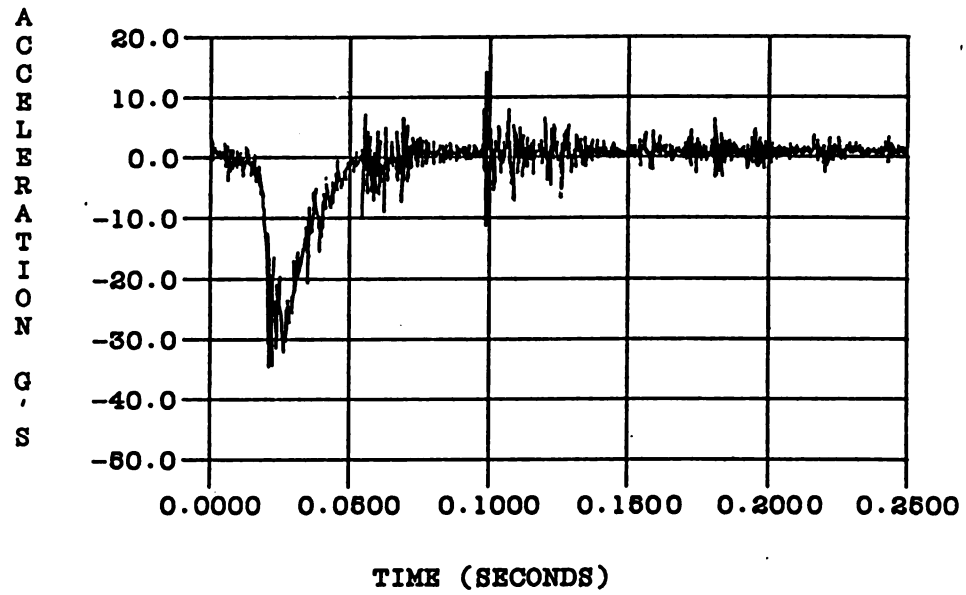
WHERE:

- e_c = AMPLIFIER OUTPUT VOLTAGE
- K_a = AMPLIFIER GAIN

$$\ddot{X} = \frac{e_c}{K_a K_t E}$$

Figure 8 - Data Recording Instrumentation - a) Wheatstone Bridge Set-up of Endevco Accelerometer Circuit
b) Schematic Drawing of Data Flow For a Typical Channel

ACCELERATION OF IMPACTING MASS



FORCE ON IMPACTING MASS

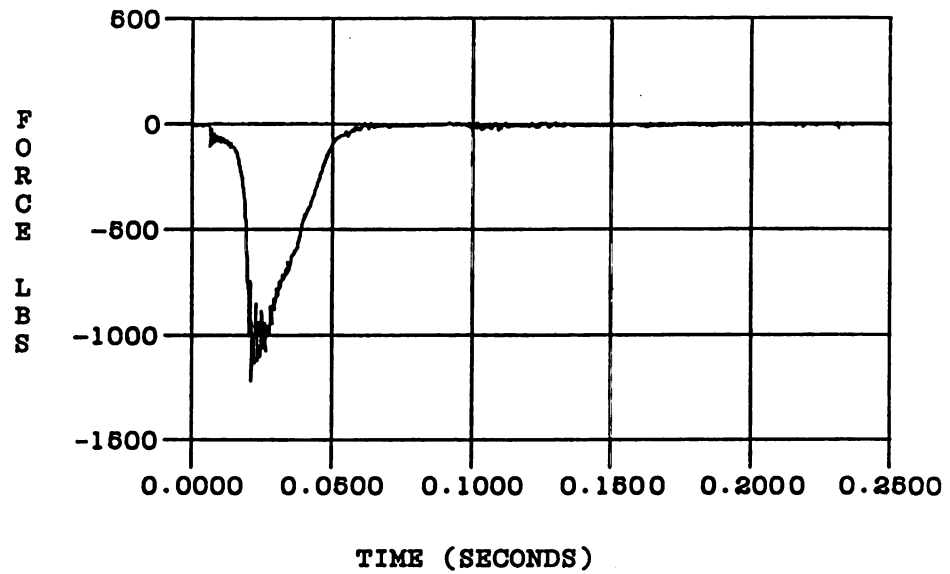
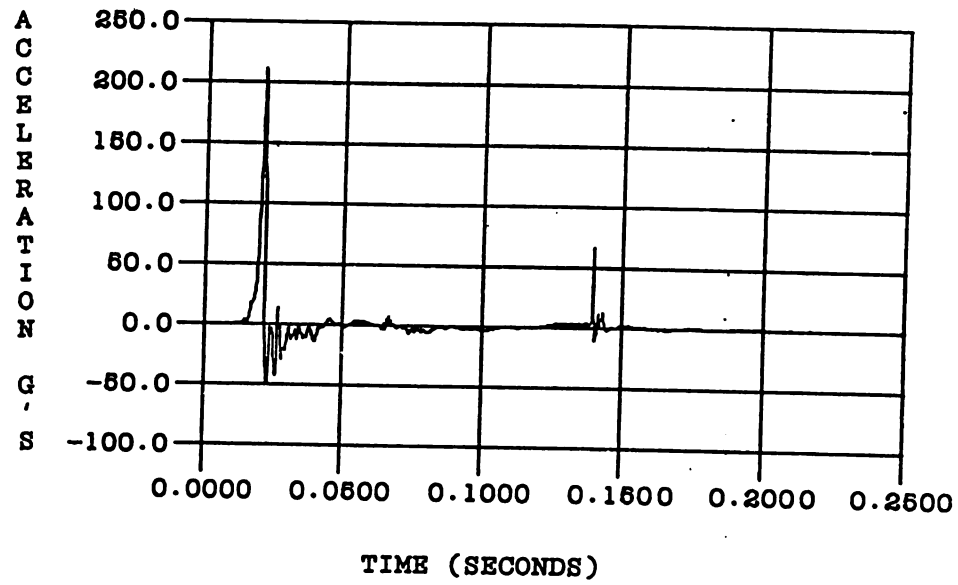


Figure 9 - Raw Acceleration-Time Data From Impact on Upper Rib

UPPER RIB



LOWER RIB

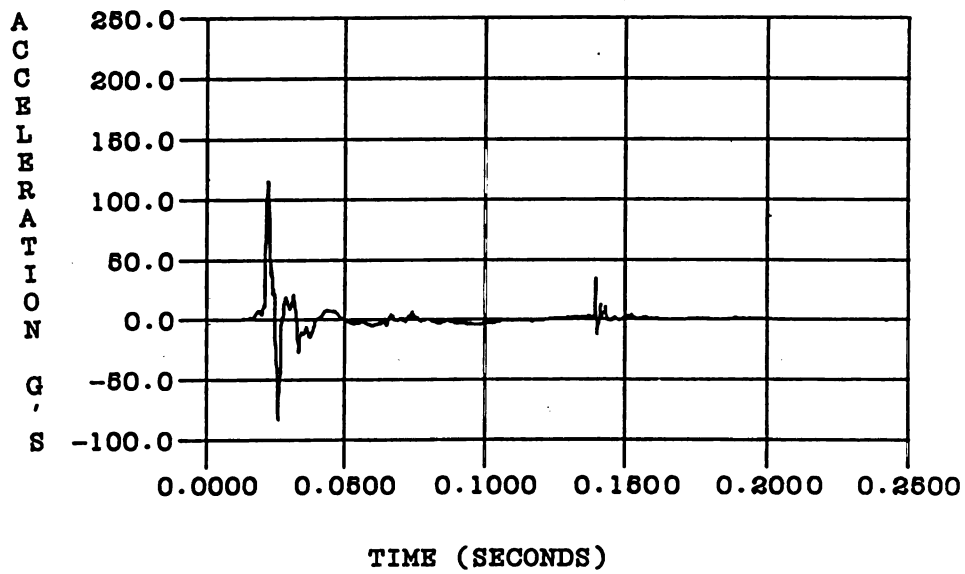
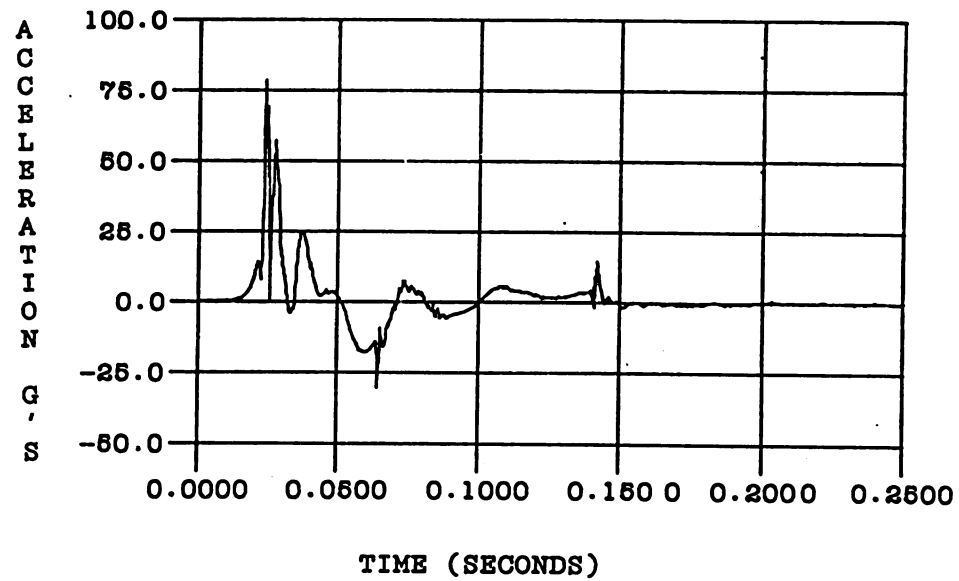


Figure 9 (Cont.)

UPPER SPINE



LOWER SPINE

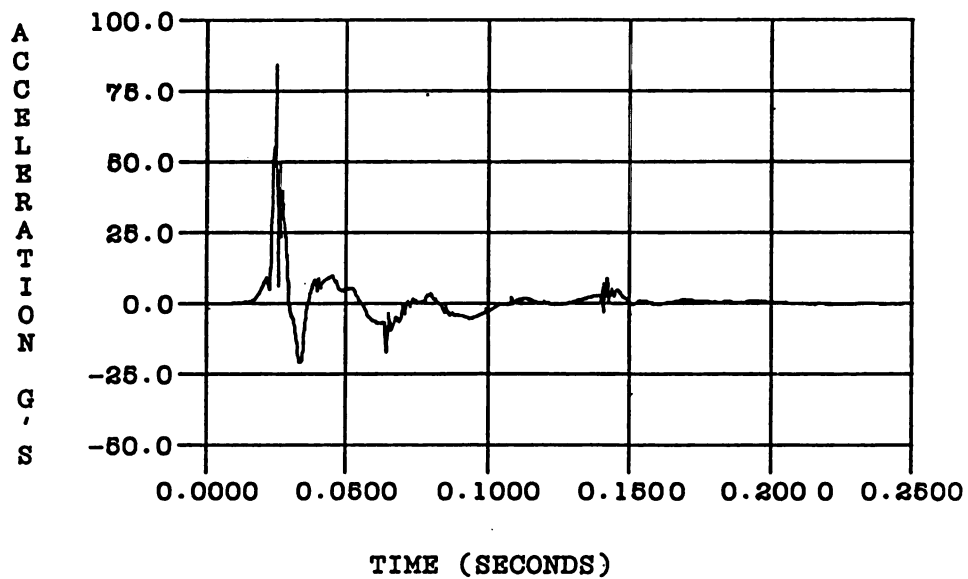


Figure 9 (Cont.)

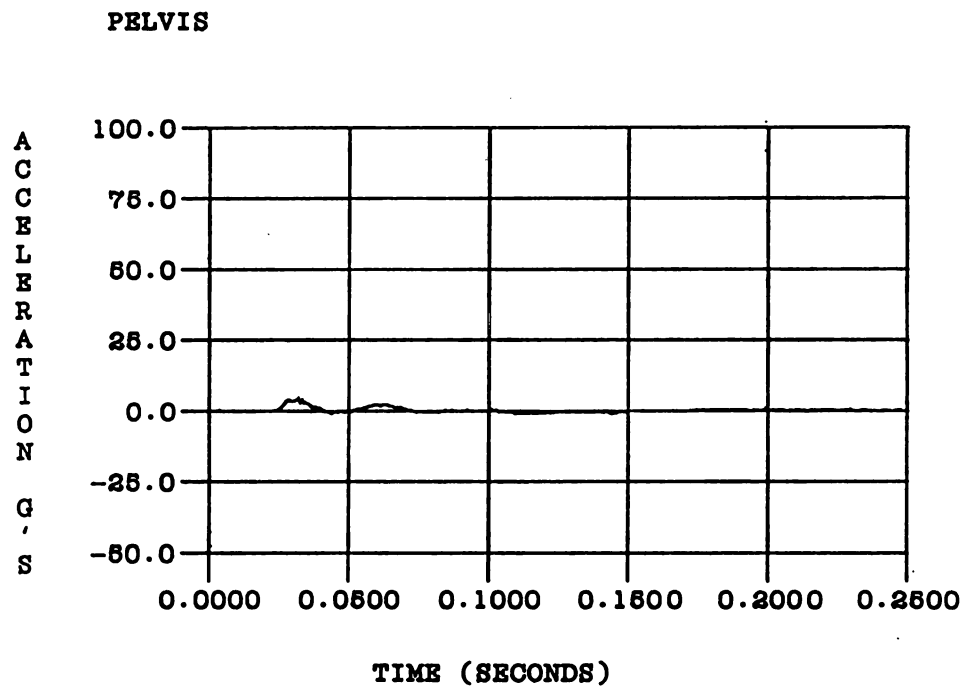
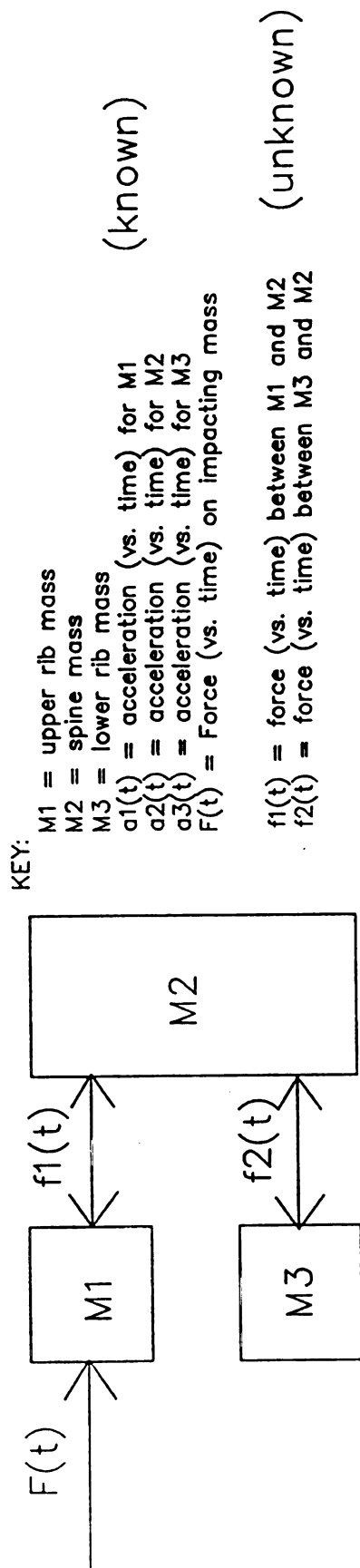


Figure 9 (Cont.)

truncated to the time of contact of the impacting mass with the dummy (time = 0 msec.) The time of contact was determined by analyzing the load cell data on the front of the impacting mass. Then, all the data for a given test was filtered through an SAE Class 180 filter [5]. This is the industry standard for dummy acceleration data.

The rest of the processing consisted of calculating force-time and displacement-time curves for each mass-connector of the simulation model. These two curves would then be cross-plotted to obtain force-deflection curves for each mass-connector. Cross-plotting is achieved by eliminating the time variable between two curves to provide a single curve containing the Y-axis data from the two original curves. In this case, the new X-axis data is the Y-axis data from the displacement-time curve and the new Y-axis data is the Y-axis data from the force-time curve.

Force-time curves for each mass-connector were found by applying Newton's Second Law of Motion to the system of masses representing the dummy. This procedure is outlined in Figure 10. For the mass-connectors representing the upper arm, lower arm, and abdomen (#1, #2 and #3 on Figure 5), the force-time curves were measured directly by the load cell on the front of the impacting mass. Displacement-time curves for each mass-connector were obtained by first integrating the acceleration-time curve for each mass twice with respect to time. This results in displacement-time relationships for



APPLY NEWTON'S 2ND LAW OF MOTION:

UPPER RIB IMPACT:

$$F(t) \rightarrow \boxed{M1} \xleftarrow{f1(t)} \boxed{M2} \xrightarrow{M1a1(t)}$$

$$\rightarrow \sum F_y(t) = M1a1(t)$$

$$f1(t) = F(t) - M1a1(t)$$

LOWER RIB IMPACT:

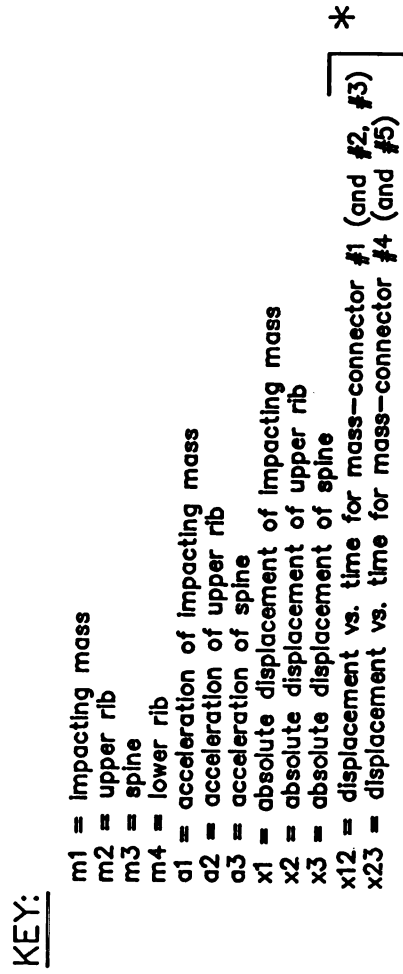
$$F(t) \rightarrow \boxed{M3} \xleftarrow{f2(t)} \boxed{M2} \xrightarrow{M3a3(t)}$$

$$\rightarrow \sum F_y(t) = M3a3(t)$$

$$f2(t) = F(t) - M3a3(t)$$

Figure 10 - Calculation of Force-Time Curves For Mass-Connectors #4 and #5 on Figure 5

each mass in terms of a local coordinate system, i.e. each mass was assumed to have no initial displacement. From there, relative deflections for each mass-connector were calculated by taking the difference of the appropriate mass displacements. This yields relative displacement-time curves for each mass-connector. The procedure is outlined in Figure 11. At this point, cross-plotting was performed to obtain the force-deflection characteristics shown in Figure 12. It should be noted that the characteristic curve used for mass-connector #6 (shown in Figure 5) is similar to pelvis-spine interactions found in other side impact literature [6]. The test procedure used here was not appropriate for determining this characteristic because the spine is rigidly attached to the top of the pelvis in a Side Impact Dummy. One other area which should be addressed is the unloading characteristics of the force-deflection data. The unloading characteristics shown in Figure 12 do not appear to be very realistic. One possible reason for this could be the rotation of the dummy about the pelvis axis immediately after impact. This would distort the data collected in that dummy displacements would no longer be in the Y-direction only. It was decided that reasonable unloading characteristics would be determined and implemented into the simulation model. Actually, for a side impact computer model, unloading slopes are secondary in nature due to their minimal effect on occupant injury.



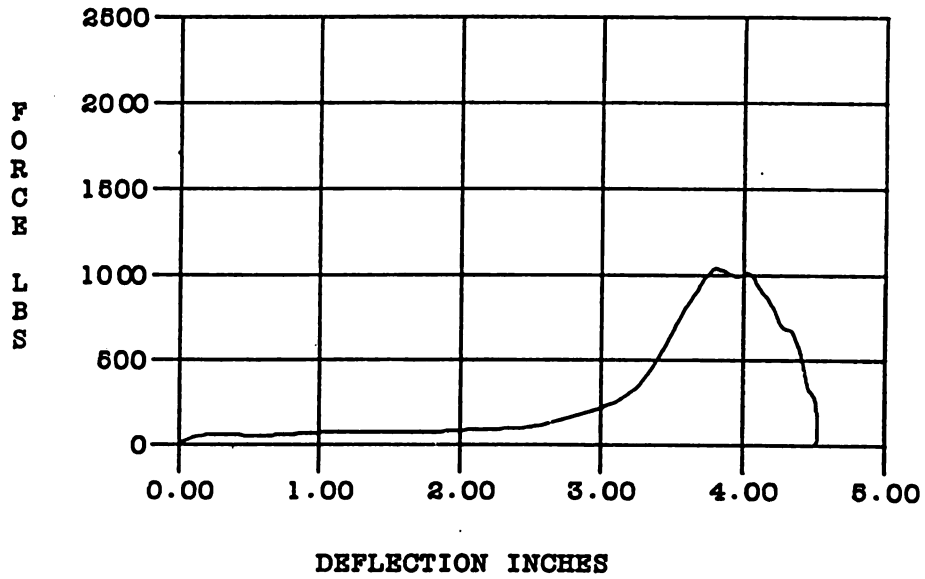
$$x1 = \int v1 dt = \iint a1 dt \quad x2 = \int v2 dt = \iint a2 dt \quad x3 = \int v3 dt = \iint a3 dt$$

$$x12 = x1 - x2 \quad x23 = x2 - x3$$

* displacement vs. time for mass-connectors #2, #3, and #5 are calculated in a similar manner

Figure 11 - Calculation of Displacement-Time Curves for Mass-Connectors #1 through #5 on Figure 5

CHARACTERISTIC CURVE #1



CHARACTERISTIC CURVE #2

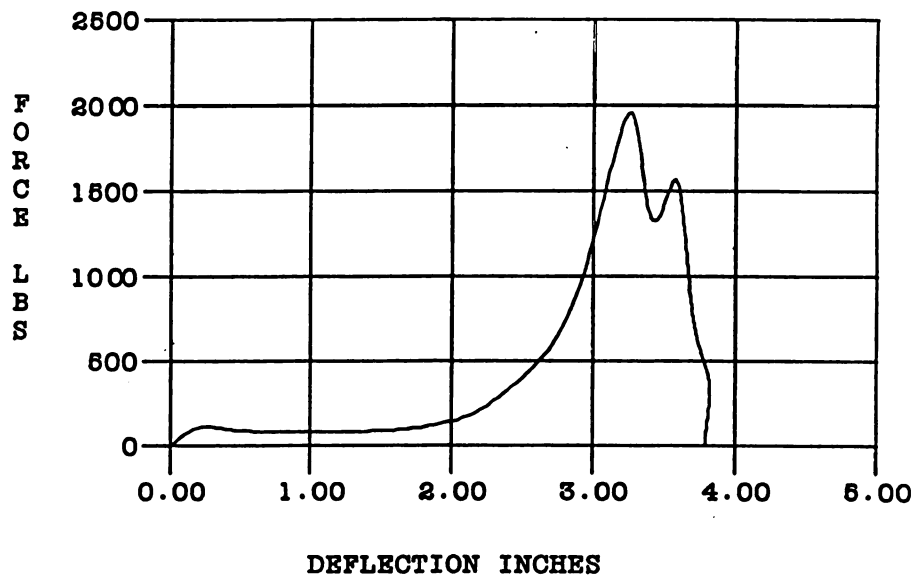
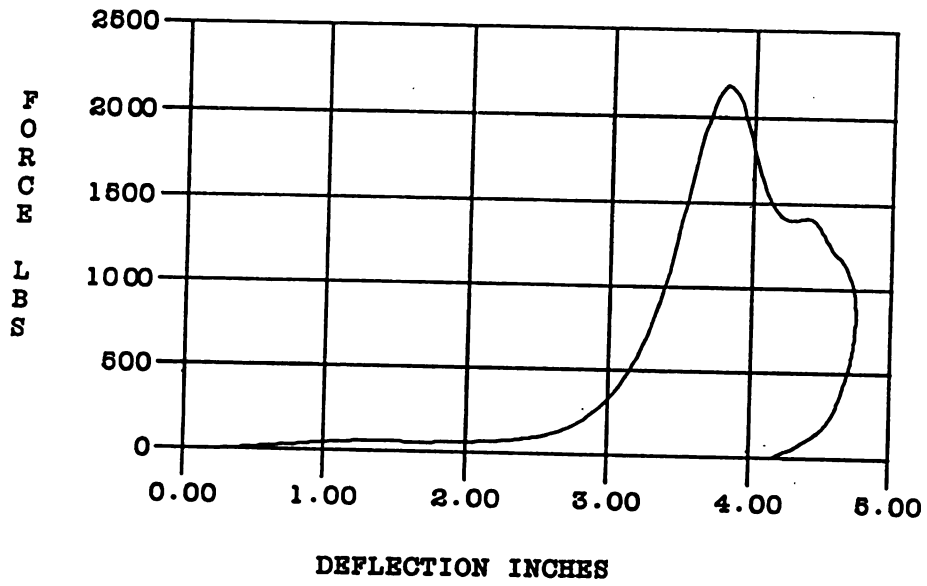


Figure 12 - Force-Deflection Characteristics For Mass-Connectors #1 Through #5 on Figure 5

CHARACTERISTIC CURVE #3



CHARACTERISTIC CURVE #4

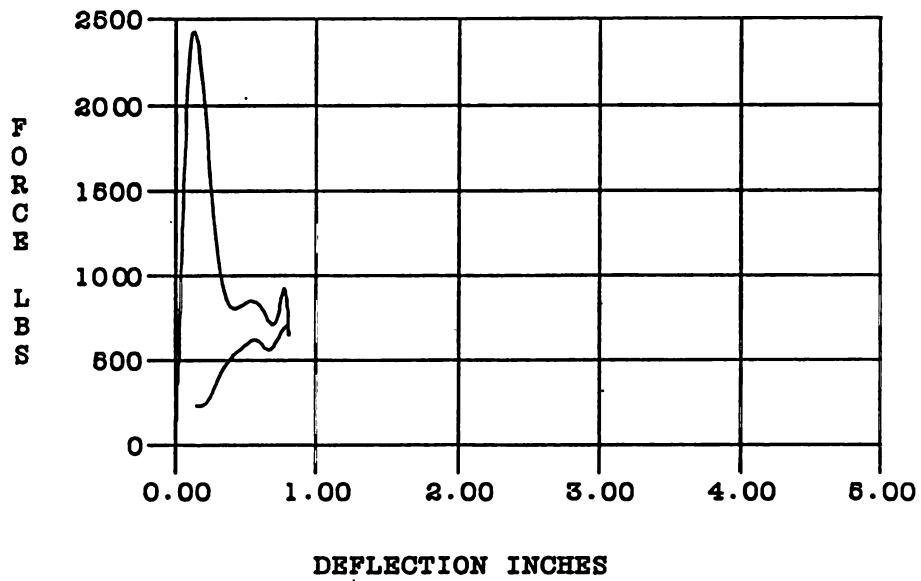


Figure 12 (Cont.)

CHARACTERISTIC CURVE #6

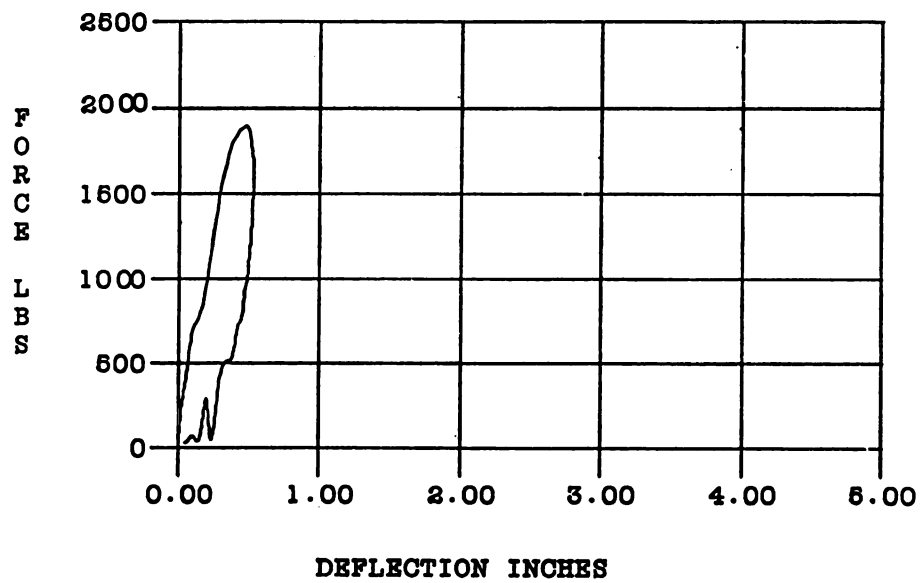


Figure 12 (Cont.)

2.3 The SMDYN Computer Model

Before implementing these characteristics into the simulation model, and thereby creating the side impact computer model, it is necessary to introduce the lumped mass, spring-damper computer model which will be used. The name of the computer program used in this thesis is SMDYN, which is an acronym for Spring-Mass-DYNamics. SMDYN treats any physical structure as a one-dimensional representation, idealized in the form of lumped masses inter-connected by massless, deformable spring elements which are characterized by non-linear force-deflection properties. The model is general in nature, allowing a large number of discrete masses with flexible connectivity [7]. Damping is present in SMDYN either through the unloading characteristics of the springs, or by supplying a force-velocity curve for each spring. Initial conditions, including deflections and velocities, can be imposed on any of the masses. Output from the model includes acceleration, velocity, and deflection of each mass, as well as forces encountered in each spring.

SMDYN implements a traditional forward integration technique in solving the equations of motion for a given system. Forward integration involves first calculating an incremental deflection for each mass based on the initial conditions, and then, consistent with this deflection, determining the forces acting on each mass by reading the

force-deflection curves connected to that mass. Once this has been done, the equations of motion for the entire system are solved. This process is repeated at each time increment. The length of time for the simulation, unloading slopes for force-deflection springs, and other relevant inputs are supplied by the user in the form of a data deck (a data file).

2.4 Simulation of Lateral Impact Tests

One method for checking the calculations performed to obtain dummy response characteristics would be to simulate the impacts performed on the mechanical dummy using the computer dummy. In other words, simulating the impacts that were used to obtain dummy characteristics should result in accelerations that are similar to the measured data obtained from the dummy impacts. To make this comparison, impacts on the upper rib, lower rib, and abdomen were simulated with the computer dummy. The representation for the simulation of the upper rib impact is shown in Figure 13. Over-plots showing responses from the mechanical dummy and computer dummy are shown in Figure 14.

When viewing the overplots shown in Figure 14, it must be noted that the computer dummy response characteristics (from SMDYN) are not identical to the raw data obtained from the lateral impact on the mechanical dummy (SID). Whenever a computer simulation of a complex physical situation is performed, the simulation is a simplified representation of

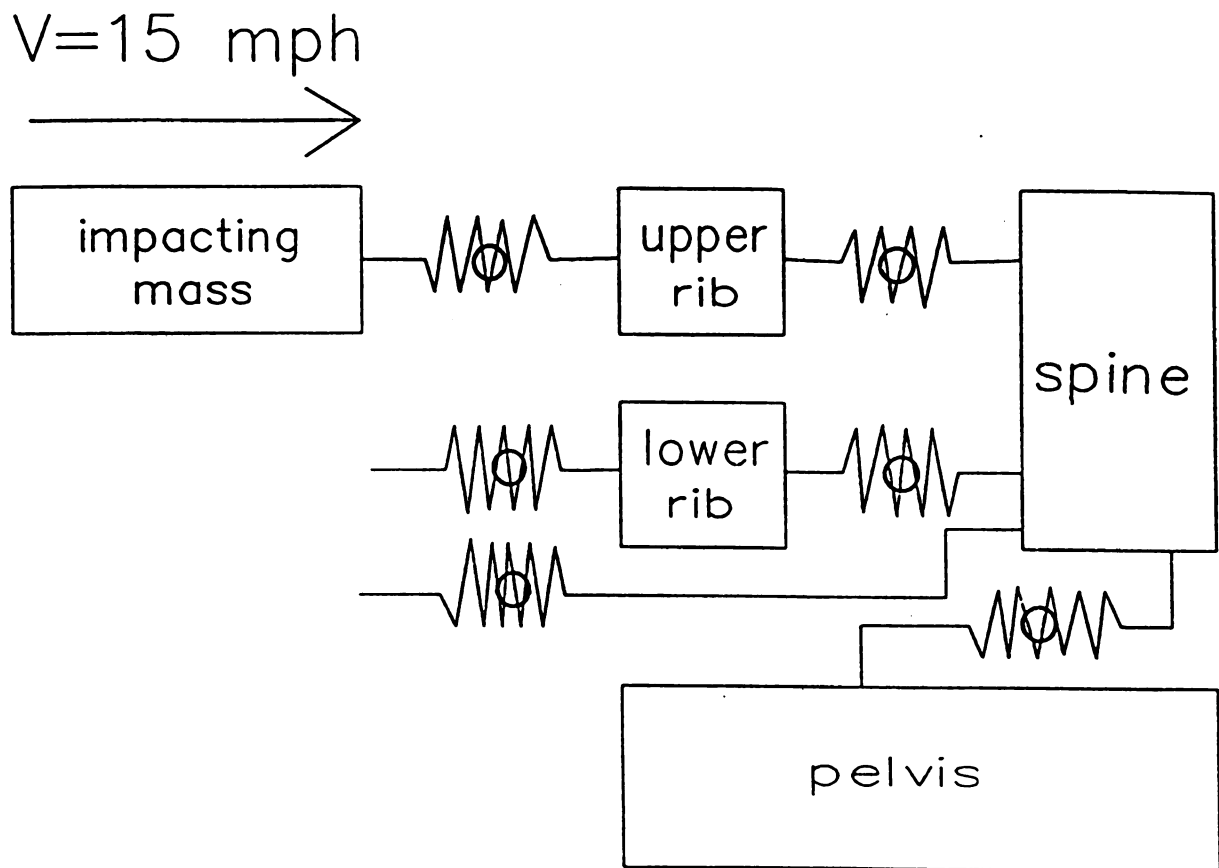


Figure 13 - SMDYN Representation of Simulation to Model the Upper Rib Impact

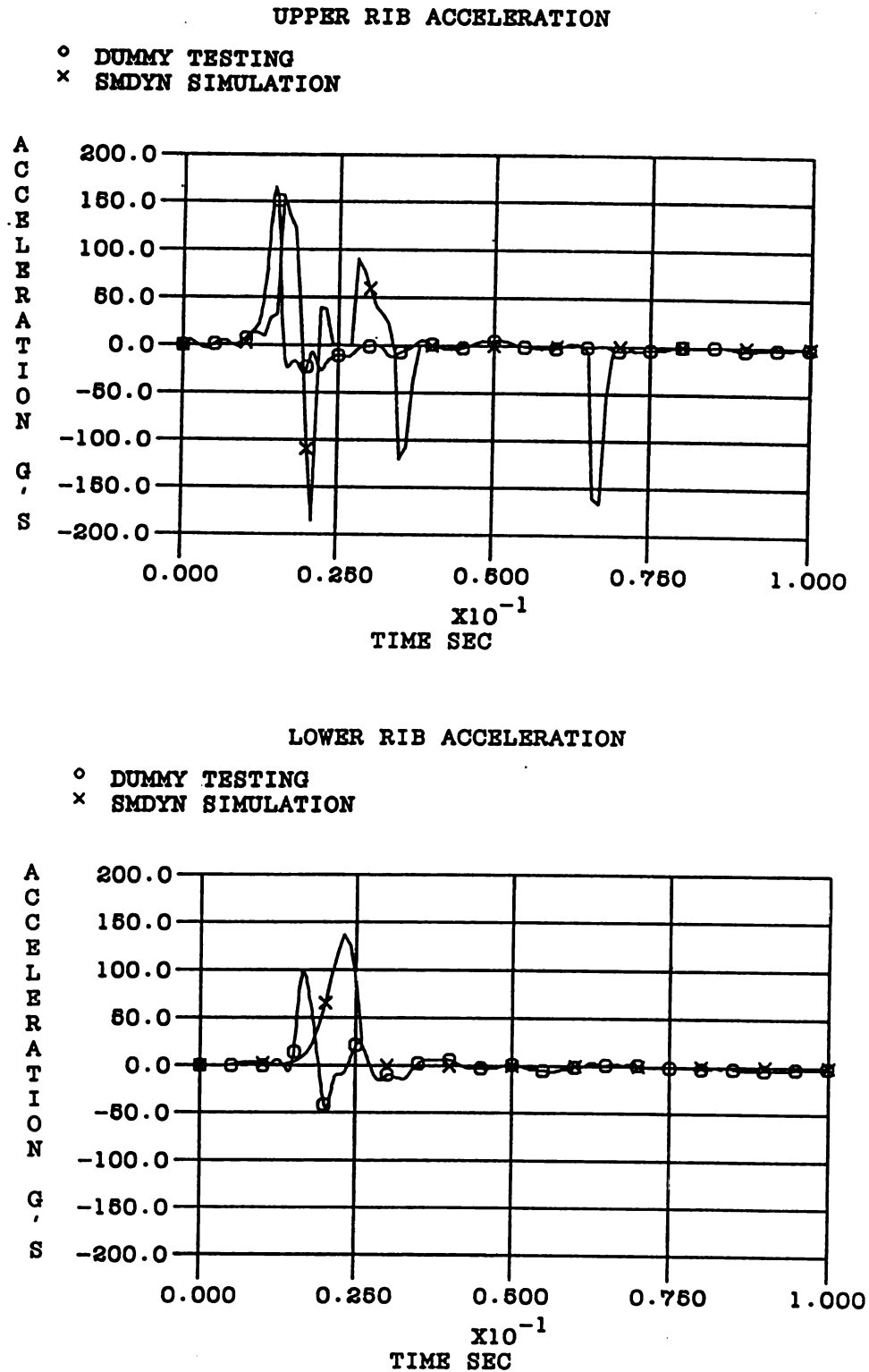
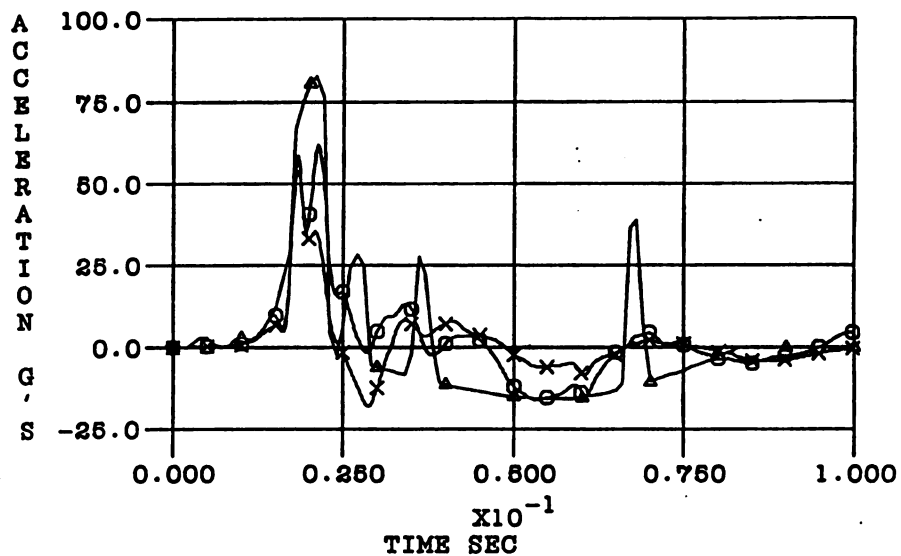


Figure 14 - Overplots of Upper Rib Impact Data and SMDYN Simulation Results (Acceleration-Time)

SPINE ACCELERATION

- ° DUMMY TESTING (UPP.)
 × DUMMY TESTING (LOW.)
 ▲ SMDYN SIMULATION



PELVIS ACCELERATION

- ° DUMMY TESTING
 × SMDYN SIMULATION

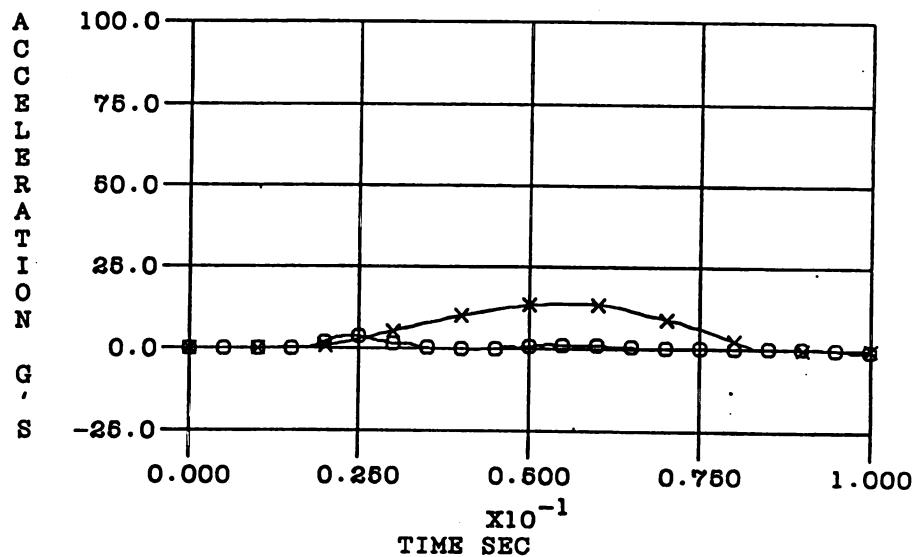


Figure 14 (Cont.)

the physical situation. This fact alone tends to allow for altered response characteristics from the simulation model. In evaluating the simulation results, one must decide whether or not the output is reasonably close to actual data, and if the results of the simulation are not reasonably close, variances between the computer simulation and actual data should be accounted for. "Reasonably close" is a judgmental decision based on factors such as maximum values, timing of peaks, and overall nature of the response curve. For the simulation model presented in this thesis, 10% to 20% variation can be considered "reasonably close".

Referring to Figure 14, is evident that correlation with regard to the upper rib is very close in magnitude (less than 10% variation) and the timing of the two peaks correlates well. Although, the SMDYN results indicate that the upper rib is under-damped. In terms of the lower rib response characteristics, a timing offset is evident between the peak values of the actual dummy and simulation results. One possible reason for this is the existence of a mechanical coupling between the upper and lower rib in the Side Impact Dummy. The couple consists of the upper rib and lower rib both being rigidly attached to the spine of the Side Impact Dummy. The difference in peak values for the lower rib response is quite significant (approximately 30%), but, since this was a lateral impact to the upper rib, it is considered secondary in nature (or, since this was a simulation to model

an impact to the upper rib, the upper rib response is most important). The spine acceleration results indicate that the model is performing well with respect to timing, but is too stiff in terms of the upper rib to spine interaction (approximately 25% variation in acceleration peaks). The pelvis acceleration results show that the accelerations experienced due to this type of lateral impact are minor compared with the accelerations experienced by the ribs or spine. The reason for this is that the dummy was seated in an upright position and because of this, the motion experienced by the pelvis due to the upper rib impact was minimal. This was due to the rotation of the dummy's torso and head "about" the pelvis.

In general, the results from this simulation, as well as the results from the lower rib and abdomen simulations, indicate that the computer dummy does respond in a fashion similar to the mechanical dummy when subjected to lateral impacts, with some differences in apparent rib stiffness and damping. This leads to the question of computer dummy performance in a full scale side impact. Before a simulation of this type can be performed, characteristics of the inner door padding and side structure must be obtained through laboratory testing.

CHAPTER 3

DOOR TESTING

3.1 Test Set-Up

Now that a computer dummy has been developed, it is necessary to obtain characteristics for the component level parts involved in a full scale side impact. During a side impact accident, the principal component interacting with the occupant is the inner door. Therefore, tests must be performed on the inner door to obtain the characteristic curves which would then be used in the simulation model. The vehicle chosen for the simulation was a 1985 Ford LTD. This vehicle was chosen because of the availability of actual, full scale side impact crash data, in which a standard Side Impact Dummy was used [8].

Tests were performed on three Ford LTD doors at MGA Research Corporation in Akron, New York. These tests consisted of statically loading the door in a manner which would best simulate the dynamic loading which takes place on the door in a full scale side impact. The method used in testing each door was to first deform the exterior of the door 3.5 inches with a rigid, rectangular plate of dimensions

16" x 20", and maintain this deformation until additional static tests were performed on the interior surface of the door. The amount of deformation on the exterior of the door (3.5 inches) is an approximation of the amount of deformation present in a full scale side impact when the occupant first contacts the interior padding of the door. While still holding the external loading device at 3.5 inches, the interior of the door was statically loaded with a rounded face at four different contact points of the dummy. Data collection for this test consisted of recording force and deflection values from each loading device throughout the procedure. Photographs of the loading devices and test set-up in general are shown in Figure 15. The four contact points (the upper rib, lower rib, abdomen, and pelvis), were determined by placing a Side Impact Dummy into a 1985 Ford LTD in an upright, seated position and interpolating contact areas to the interior surface of the closed door. Photographs of the dummy seated in the vehicle, as well as a drawing indicating the position of the measured contact points on the interior surface of the door, are shown in Figure 16.

Three doors were tested in this fashion. The first and third doors were loaded in the same order in terms of contact points (pelvis first, followed by abdomen, lower rib, and upper rib). The second door was loaded in the opposite order. This procedure was used to evaluate the repeatability of this method of testing. Measured force-deflection

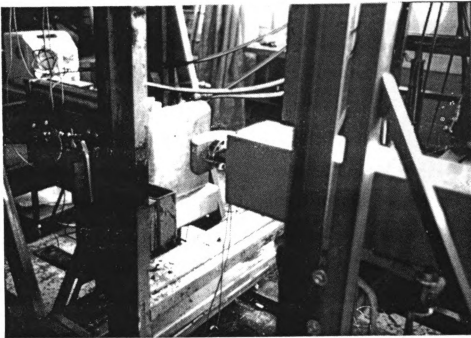


Figure 15 - Ford LTD Door Testing: a) Photograph of the Loading Devices Used b) Photograph of Test Set-up (With Door Mounted)

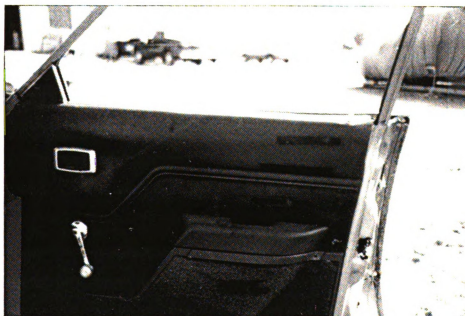
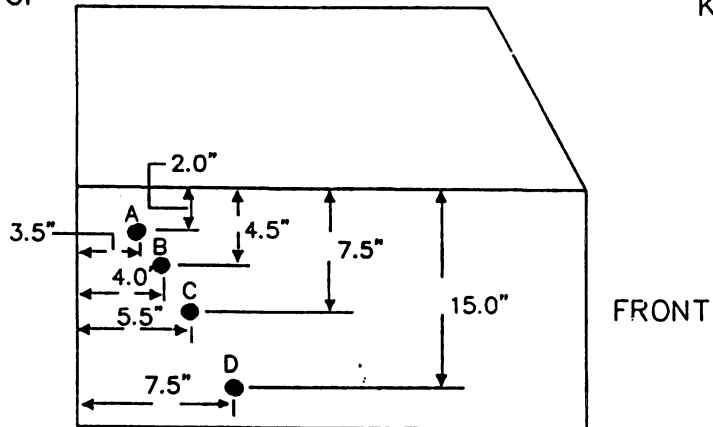


Figure 16 - Contact Points of Side Impact Dummy on LTD Door
a) Photograph of Dummy Seated in LTD
b) Photograph Showing Contact Locations
c) Diagram of Contact Locations

DRIVER DOOR:

TOP



KEY:

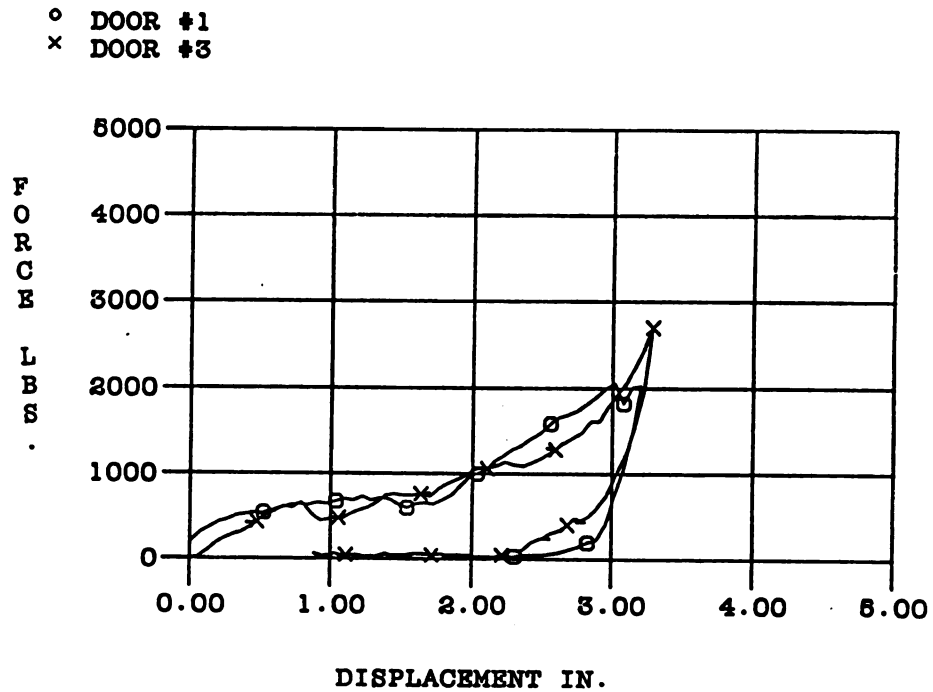
- = contact point
- A - upper rib contact area
- B - lower rib contact area
- C - abdomen contact area
- D - pelvis contact area

Figure 16 (Cont.)

properties are shown in Figure 17. Figure 18 contains post-test photographs of the three doors. With respect to repeatability, these results are quite favorable in that the force-deflection characteristics measured for doors #1 and #3 are very similar. The characteristics for door #2 are somewhat different than the characteristics for doors #1 and #3, mainly due to the order of loading of the contact points, and the effects of permanent deformation. Each door exhibited increasing permanent deformation as each successive loading was performed.

Evaluating this test procedure in terms of feasibility and usefulness cannot be done until the results obtained from the door testing are implemented into the side impact computer simulation. Once this has been done, evaluations regarding test set-up and test conditions can be made.

UPPER RIB CONTACT POINT



LOWER RIB CONTACT POINT

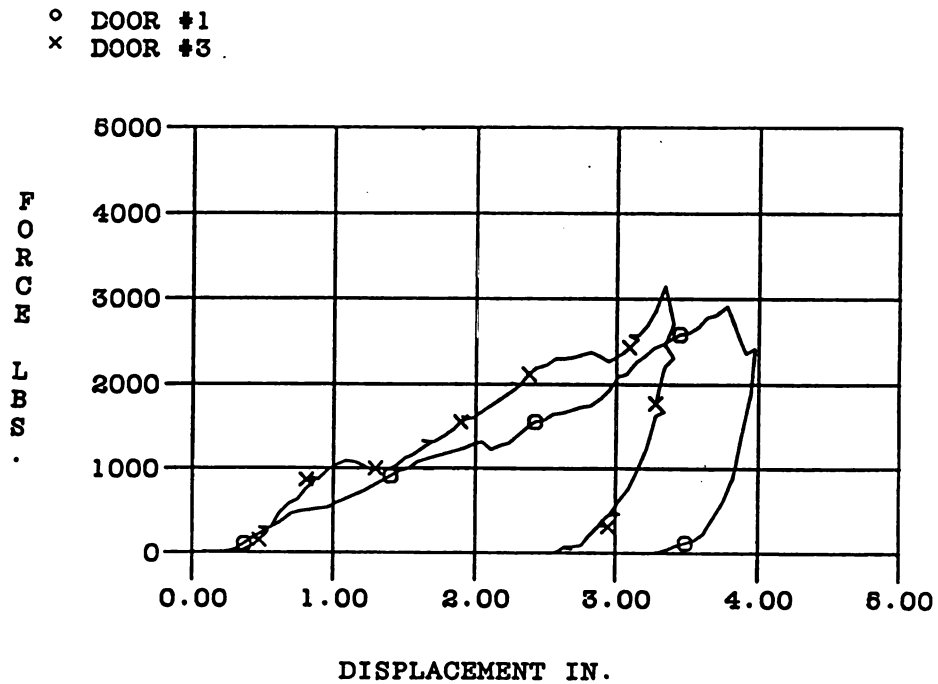
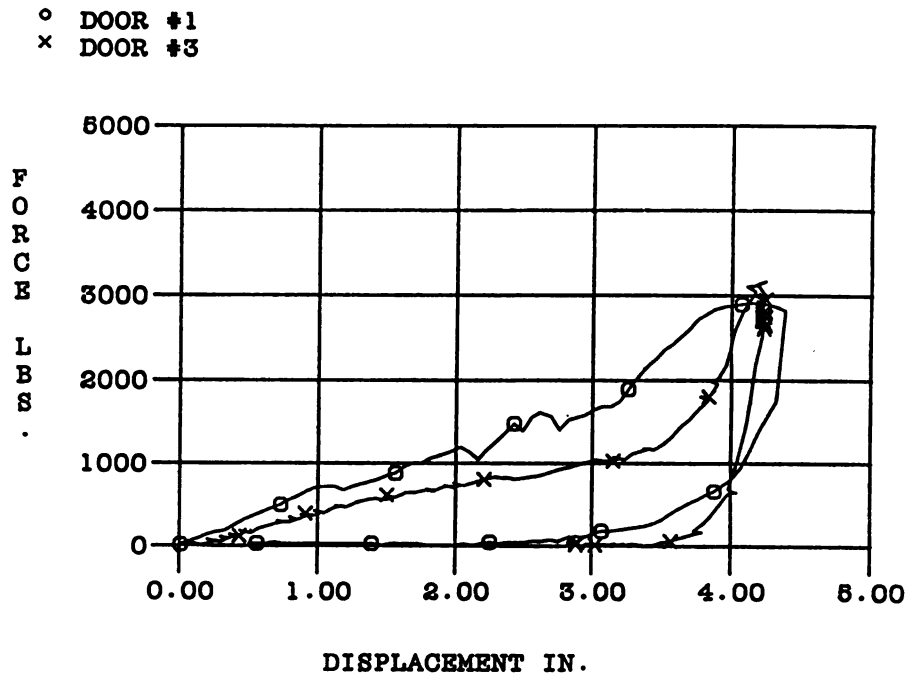


Figure 17 - Force-Deflection Curves From LTD Door Testing
(Doors #1, #2 and #3)

ABDOMEN CONTACT POINT



PELVIS CONTACT POINT

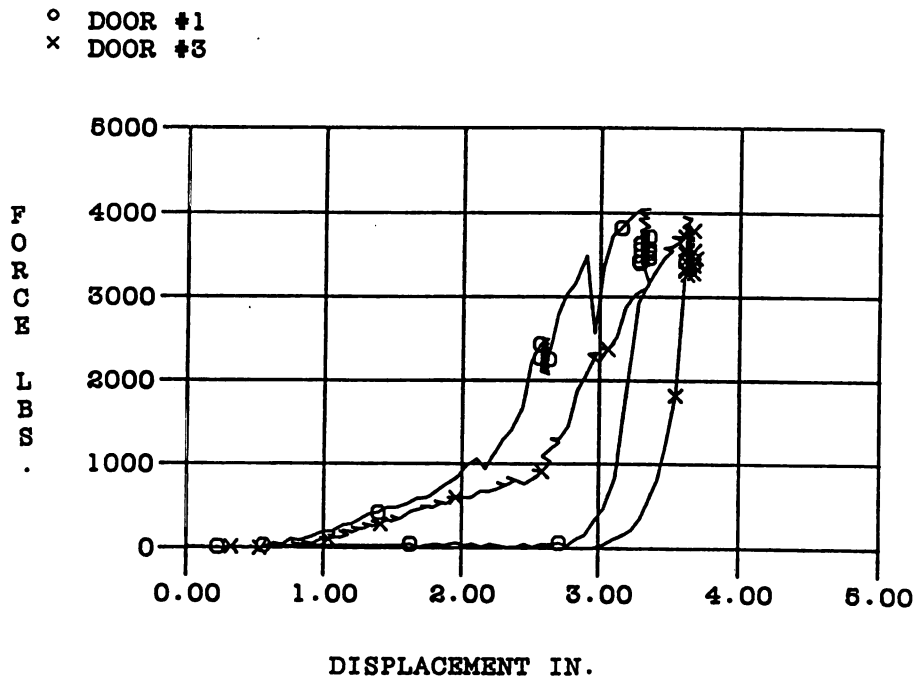
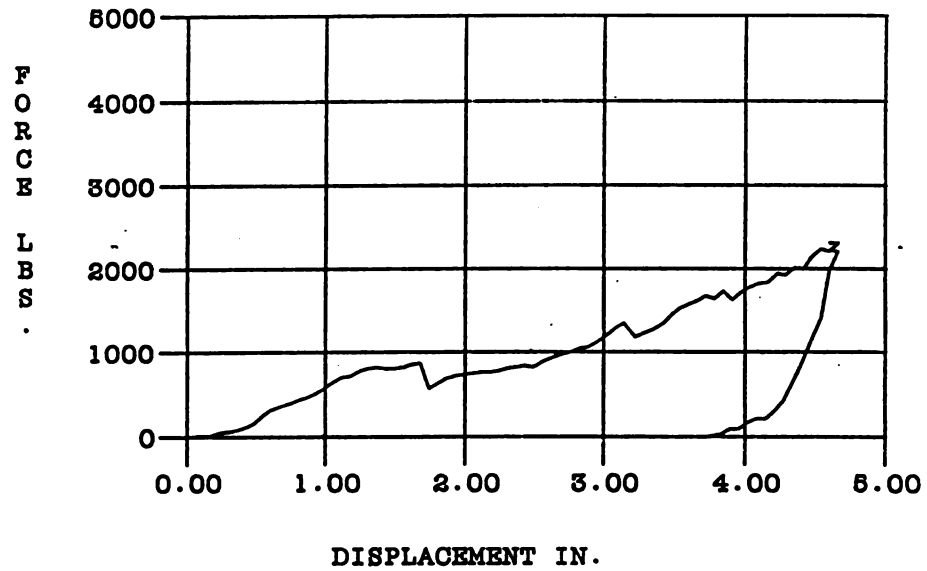


Figure 17 (Cont.)

UPPER RIB CONTACT POINT

DOOR #2



LOWER RIB CONTACT POINT

DOOR #2

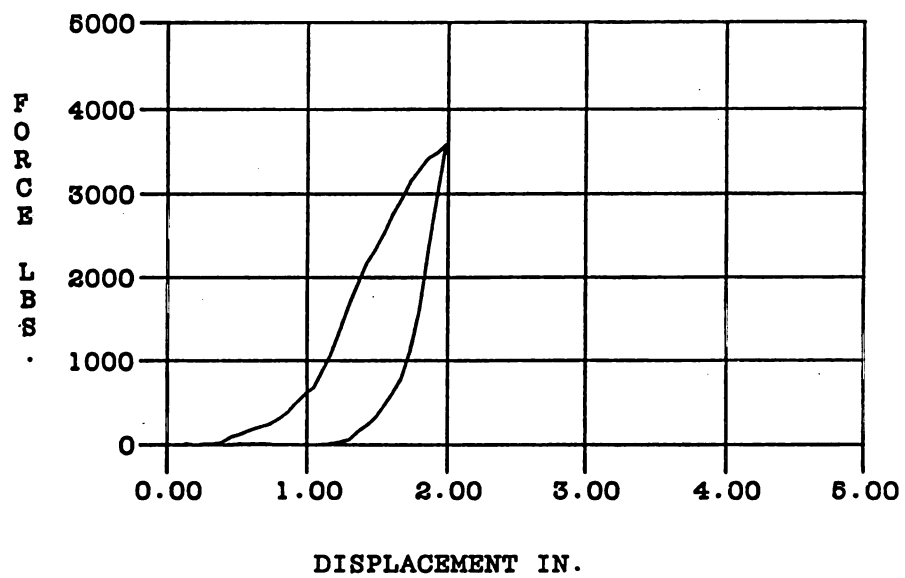
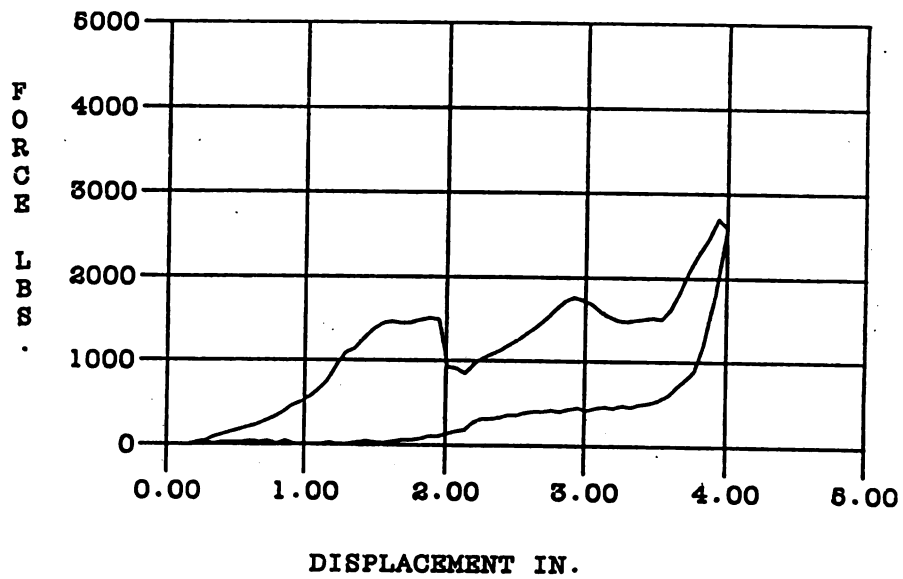


Figure 17 (Cont.)

ABDOMEN CONTACT POINT

DOOR #2



PELVIS CONTACT POINT

DOOR #2

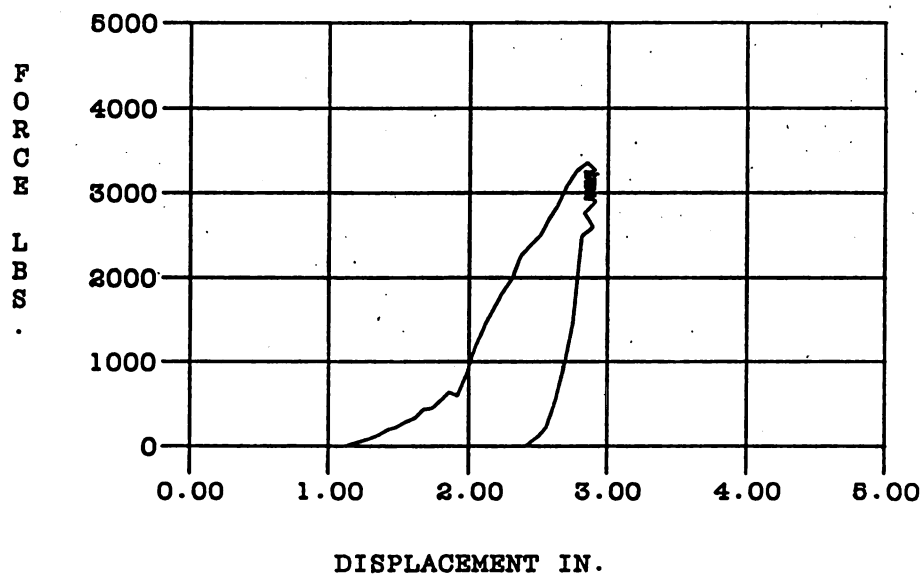


Figure 17 (Cont.)

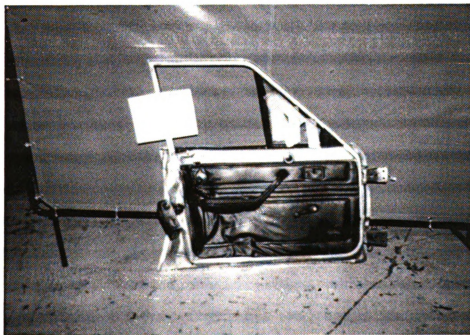
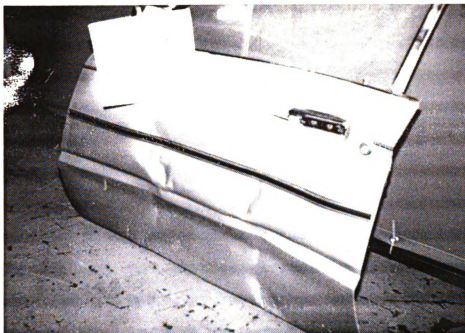


Figure 18 - Post Test Photographs of LTD Door a) Exterior
b) Interior

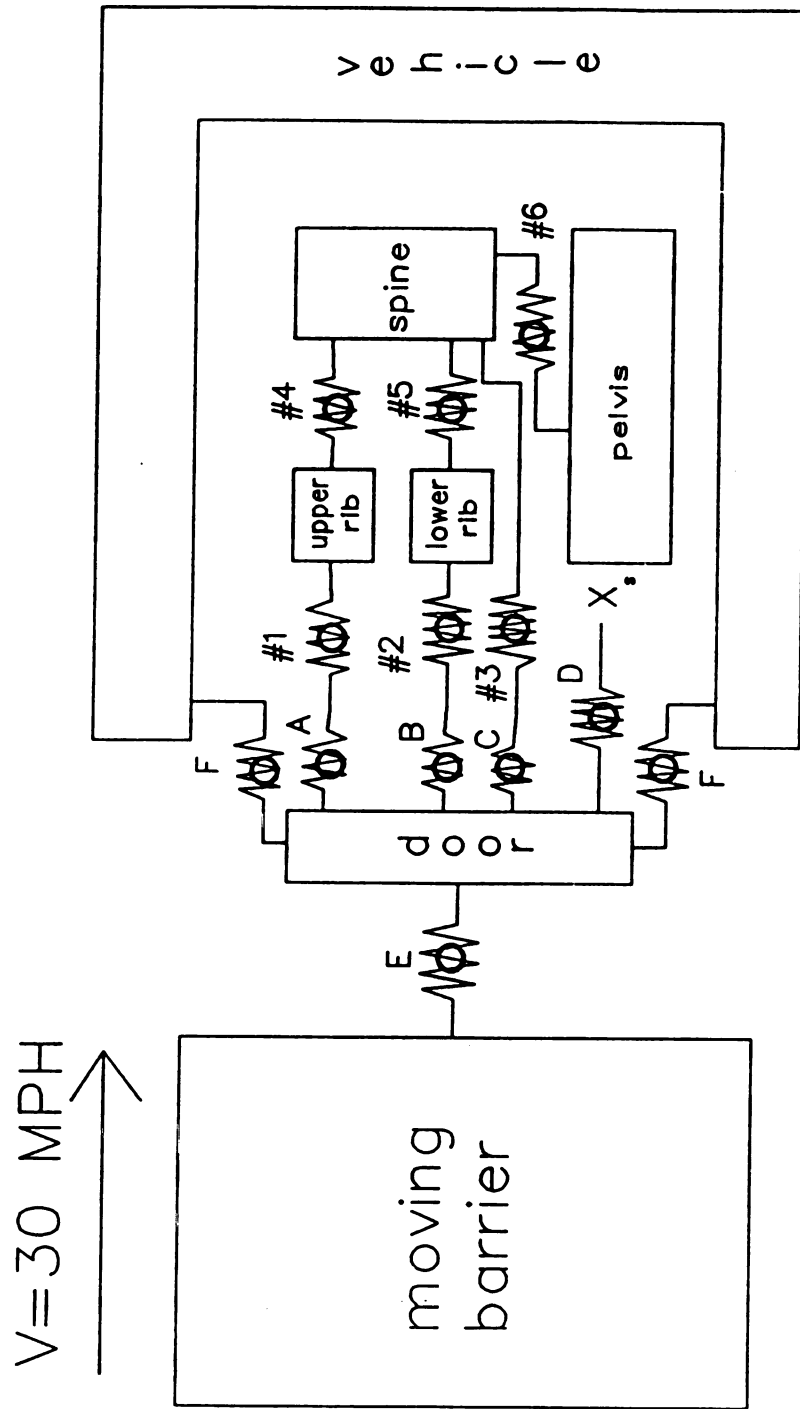
CHAPTER 4

SIDE IMPACT COMPUTER SIMULATION

4.1 SMDYN Representation

Now that characteristics for the Side Impact Dummy and the Ford LTD door have been developed, it is appropriate to implement these characteristics into a computer simulation of a full scale side impact and compare the results obtained with actual crash test data. In terms of the CTP approach, this would be considered Step IV. The actual crash test being simulated was a full scale side impact test performed in 1985 at the Transportation Research Center of Ohio. The test was a 33.5 mph, crabbed angle impact. The dummy used was a standard Side Impact Dummy. The SMDYN system of masses and mass-connectors modeling this impact are shown in Figure 19. As mentioned previously, this configuration is an improved version of the system of masses shown in Figure 3.

In Figure 19, the characteristics for mass-connectors #1 through #5 are the characteristics shown in Figure 12 (obtained through dummy testing), while the characteristics for mass-connectors A, B, C, and D are shown in Figure 17 (obtained through LTD door testing). Specifically, the



$X_s = 1$ " spacing between pelvis and door

Figure 19 - SMDYN Representation To Model Full Scale Ford LTD Side Impact

characteristics for mass-connectors A and B are the force-deflection properties for the upper rib and lower rib contact points on door #2. The characteristics for mass-connectors C and D are the force-deflection properties for the abdomen and pelvis contact points on door #1. As mentioned earlier, the characteristics for mass-connector #6 (pelvis-spine interaction) were obtained from side impact literature. The characteristics for mass-connectors E and F were obtained from a standard CTP test performed previously on a 1985 Ford LTD [6]. When representing a characteristic curve in the SMDYN data deck, a piece-wise linear fit of the characteristic curve was used.

When viewing Figure 19, it can be seen that three of the mass-connectors on the interior of the door (upper rib, lower rib, and abdomen contact areas) are in series with the corresponding mass-connectors of the dummy. This is due to the fact that the pre-test conditions for the full scale side impact being modeled were that the Side Impact Dummy was placed directly in contact with the interior surface of the door before impact [8]. Normally, the dummy would be placed in a seated upright position, with a 6 to 8 inch space between the side of the dummy and the interior surface of the door. The one-inch space between the pelvis and interior surface of the door (as shown in Figure 19) was also a test condition [9]. For the SMDYN data deck, each pair of mass-connectors in series was combined into one mass-connector. This was done by

adding the displacements from each mass-connector in series over the range of forces encountered in each mass-connector. This process results in correct force-deflection properties for two mass-connectors in series. As stated earlier, reasonable unloading slopes were assigned for each mass-connector in the model.

The weights of the masses in Figure 19 are as follows:

moving barrier = 3000 lbs.

vehicle door = 123 lbs.

vehicle mass = 2900 lbs.

upper rib = 9.5 lbs.

spine = 31.6 lbs.

lower rib = 9.5 lbs.

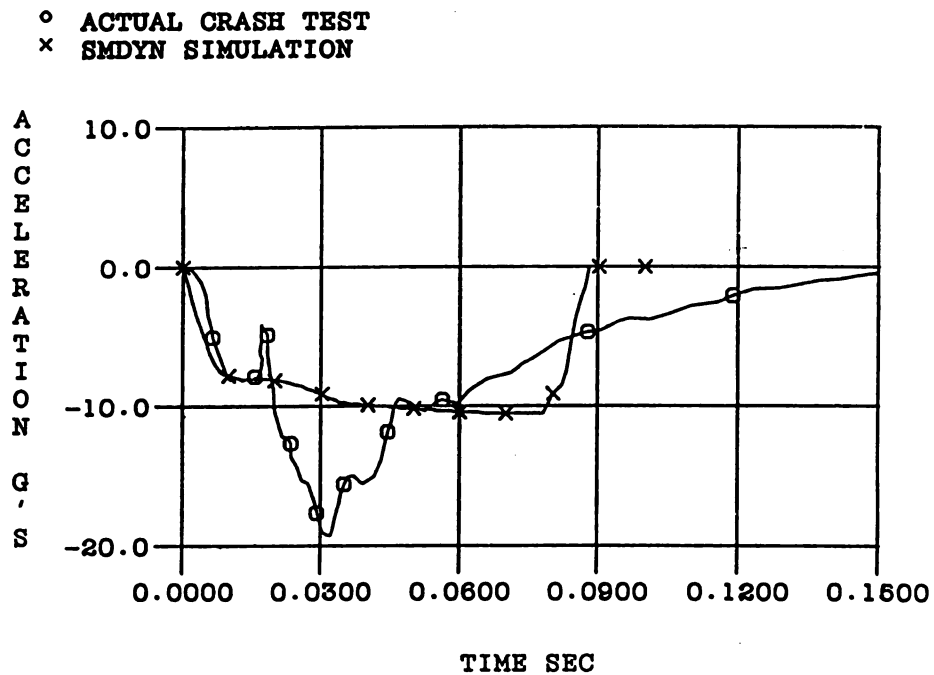
pelvis = 36.0 lbs.

The mass values for the upper rib, lower rib, and spine were found by dismantling the Side Impact Dummy and weighing the individual parts. The value for the pelvis is approximate in that it is difficult to determine how much the legs of the dummy contribute to the effective mass of the pelvis. The weight of the pelvis (36 lbs.) is consistent with values used in other simulation models regarding side impacts [10]. Mass values for the moving barrier, vehicle door, and test vehicle were taken from the technical report of the full scale Ford LTD side impact crash test [8].

4.2 Comparison of Simulation Results with Actual Crash Data

Figure 20 contains overplots of the simulation output and actual crash test data (accelerations). When considering the moving barrier and vehicle responses, the simulation is on the low side (approximately 10 G's difference for the moving barrier and 20 G's difference for the test vehicle with regard to peak values). One possible reason for this may be that static force-deflection data was used instead of dynamic data for the mass-connector between the moving barrier and vehicle. In view of this, the model can be considered inadequate with regard to the vehicle and moving barrier response. Since the main focus of this thesis was the occupant response, the moving barrier and vehicle results were not analyzed further. When examining the door response, it is evident that the simulation model is performing quite well (less than 10% variation for peak values). This is also the case for the upper rib response. The differences in the lower rib accelerations indicate that the model is too stiff (a peak of 145 G's for SMDYN simulation compared to a peak of 109 G's for the actual response data). The initial conditions for this side impact (specifically, the dummy being placed in contact with the door) may contribute to the timing offset found in these curves. The spine acceleration results indicate that the model is performing well (less than 15% variation). In terms of the pelvis response, the model appears to be too

MOVING BARRIER ACCELERATION



TEST VEHICLE ACCELERATION

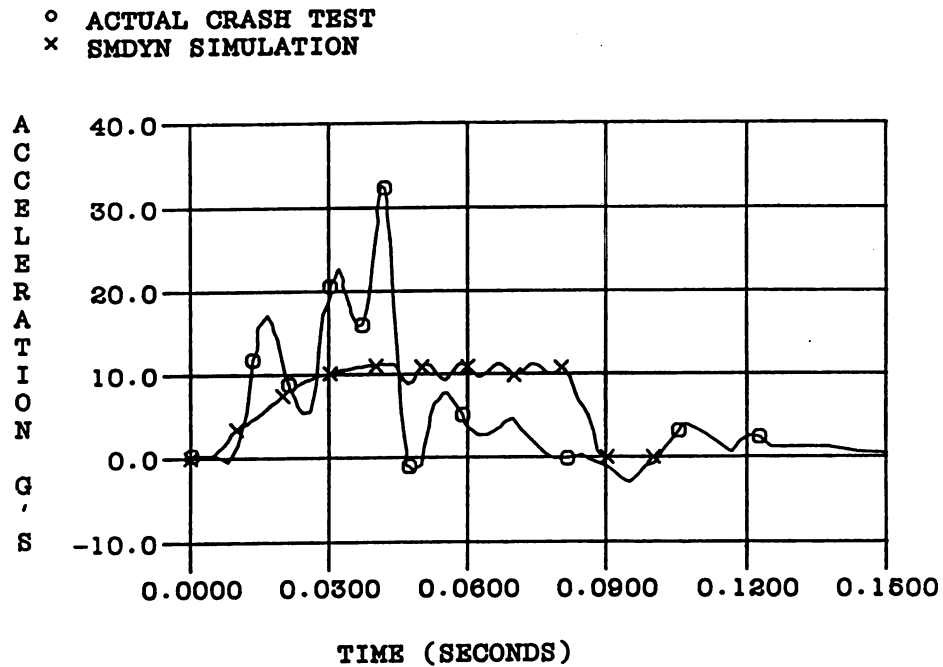
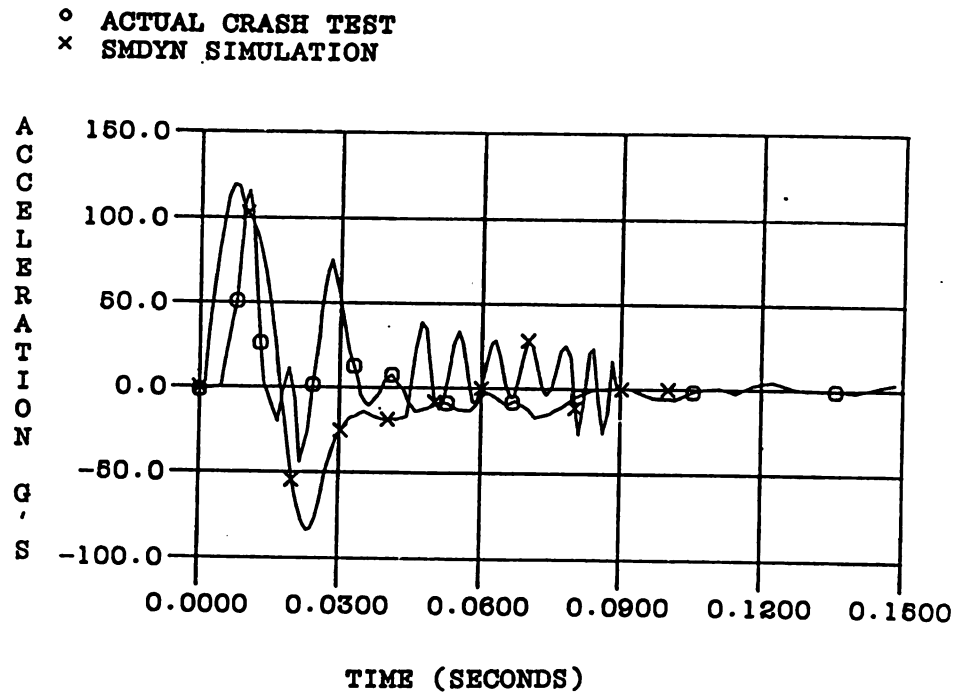


Figure 20 - Overplots of Ford LTD Side Impact Data and SMDYN Simulation Results (Acceleration-Time)

DOOR ACCELERATION



UPPER RIB ACCELERATION

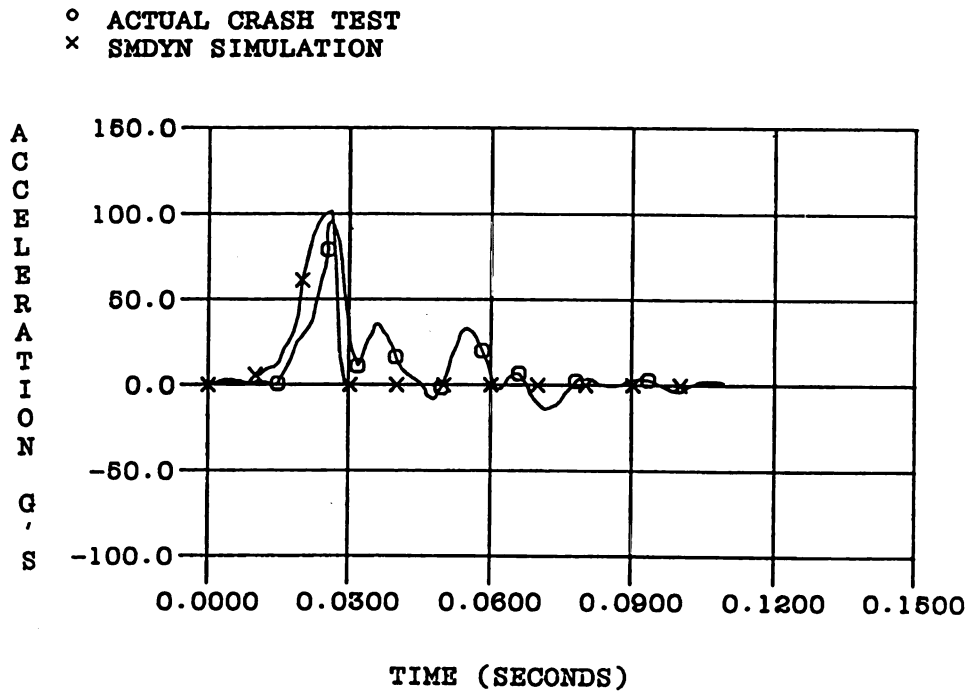
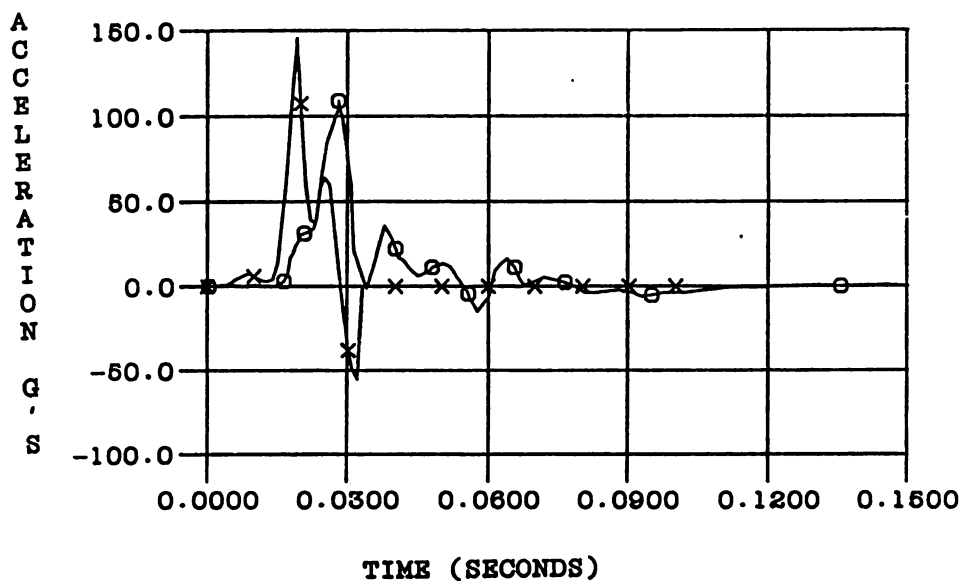


Figure 20 (Cont.)

LOWER RIB ACCELERATION

° ACTUAL CRASH TEST
x SMDYN SIMULATION



SPINE ACCELERATION

° ACTUAL TEST (UPPER)
x ACTUAL TEST (LOWER)
▲ SMDYN SIMULATION

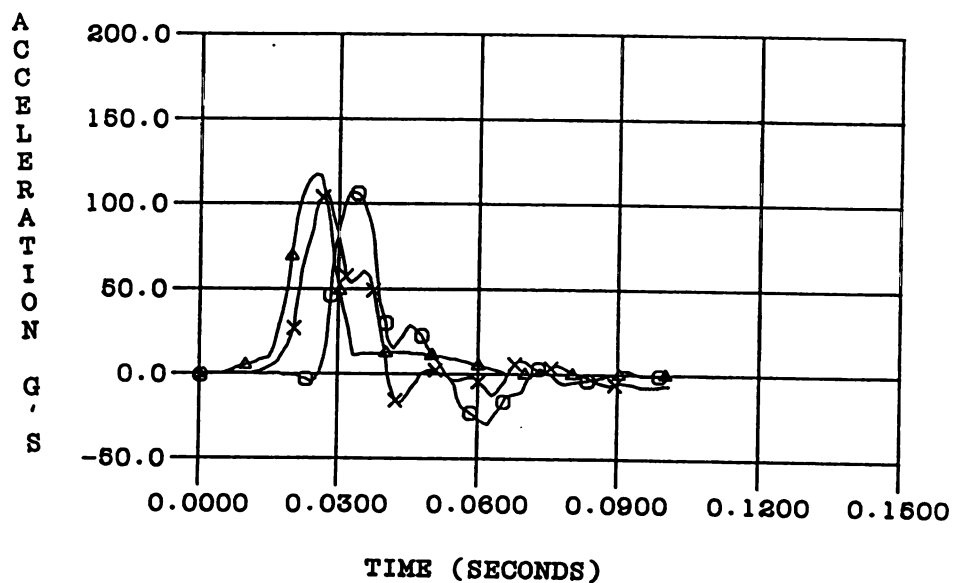


Figure 20 (Cont.)

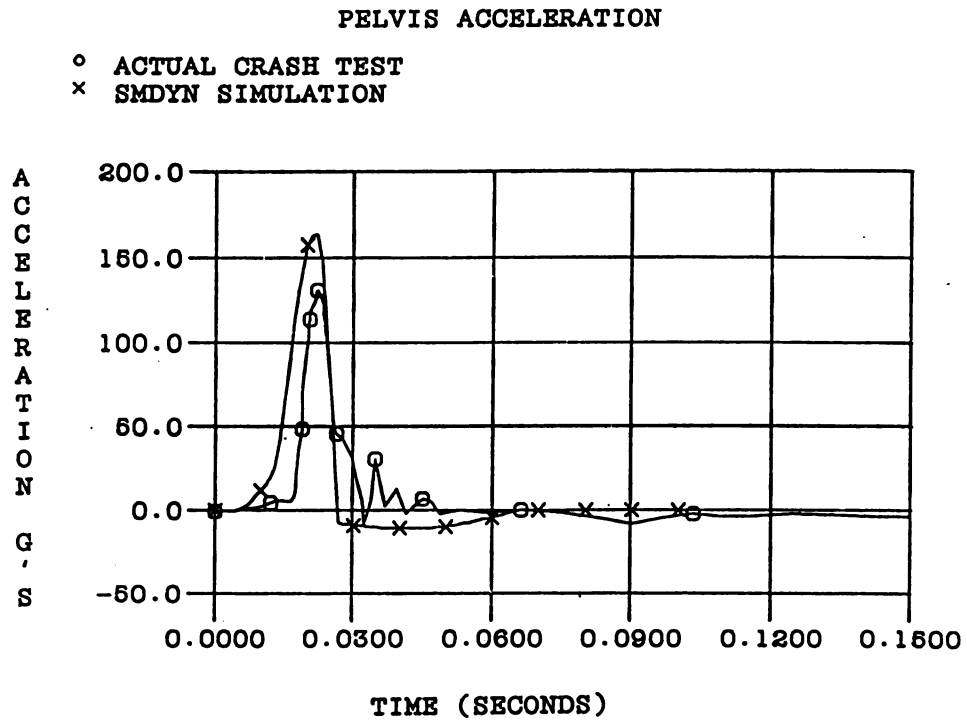


Figure 20 (Cont.)

stiff (a peak of 160 G's for SMDYN simulation compared to a peak of 131 G's for the actual response data). One possible reason for this may be that the rotation of the dummy cannot be effectively modeled with only one dimension. Summarizing, the model appears to be more than adequate in terms of the door, upper rib, and spine. The model performs reasonably well with respect to the lower rib and pelvis, while the model is poor when considering the moving barrier and vehicle responses.

At this point, an explanation is necessary as to why acceleration data, and not velocity or deflection data, is the principal output being presented here. One reason for this is based on the assumption that if the acceleration response of a mass compares favorably to actual crash test data, it follows that the velocity and deflection responses for that mass will most likely compare even better, since they are calculated by integrating the acceleration curve with respect to time. The reason that the velocity and deflection responses will probably compare even more favorably to actual crash test data is that the integration of a response curve tends to smooth out irregularities of the data. Another reason to focus on accelerations, and not velocities or deflections, is that the accelerations experienced by a mass are directly related to the forces being encountered by that mass. These forces are the principle cause of injury to the occupant. With this in mind, it is appropriate to put primary

emphasis on acceleration data.

Once again, when analyzing the overplots shown in Figure 20, it is evident that the computer dummy responds in a manner similar to the mechanical dummy. If these results were obtained during the vehicle development stage, the next course of action would be to use this model to evaluate design changes in either the inner door padding or side structure stiffness. It is at this point that the benefits of computer simulation become apparent. To determine whether a design change is favorable or unfavorable in terms of occupant response, an engineer has only to run the computer model with the proposed changes incorporated into the data deck. Obviously, much time and effort in evaluating design changes is conserved with this method.

4.3 Occupant Injury Criteria

From the occupant response data, a measure of injury severity can be calculated. Occupant injury is the principal focus of crashworthiness. In terms of side impacts, one injury index often used by both industry and government is the Thoracic Trauma Index (TTI). TTI is an acceleration based index which indicates the severity of inertial forces that could crush the rib cage and damage internal organs. TTI is a simple calculation based on the maximum rib and lower spine accelerations. TTI is only one of the injury indexes used in

side impact research. Another popular injury index is based on the deflection of the rib cage relative to the spine.

One of the benefits of the type of simulation presented here is that virtually any injury index (either acceleration based or deflection based) could be used since the SMDYN model implementation gives acceleration, velocity, deflection, and force data as its output. The output of the simulation could then be manipulated in any fashion to generate specific injury indexes. Now that a simulation of a full scale side impact for a vehicle has been developed, it is necessary to discuss the specific uses of such a simulation model, as well as the strengths and weaknesses of the procedure used in this thesis.

CHAPTER 5

CONCLUSIONS AND FUTURE RESEARCH

The computer model developed, as well as the procedure used in this thesis, can definitely aid in the process of side impact design in terms of occupant safety. Is this procedure the final answer for developing a reasonably safe vehicle with regard to side impacts? Undoubtedly not. The procedure used in this thesis is one tool available to engineers in side impact vehicle design. If this procedure is implemented along with other common design approaches (full scale crash tests, other forms of laboratory testing, as well as finite element and boundary element methods), a sufficiently safe vehicle (with regard to side impacts) can be developed in an efficient and timely manner.

When considering the advantages of the procedure used in this thesis, it should be noted that all of the advantages of the CTP approach mentioned in Chapter 1 apply to this procedure, since this procedure is an enhanced version of CTP. The procedure used in this thesis has a few important advantages over the standard CTP approach. One of these advantages is an improved computer dummy (an expanded four mass representation). The computer dummy used in this thesis

allows an engineer to better investigate the nature of injuries experienced in side impacts. Another advantage is found in the method used to obtain inner door padding characteristics. Not only is the door represented by four characteristic curves (as opposed to one for the standard CTP approach), but the test procedure used to obtain these characteristics no longer requires a complete body-in-white, only a vehicle door. The method used in door testing is also much easier to perform than the complete CTP laboratory test. How beneficial these improvements to CTP are is a difficult question to answer without actually applying them to a new vehicle during the development stage.

Although the procedure used in this thesis has some advantages over CTP in general, there are still many areas which can be improved upon. Further improvements to the procedure used in this thesis (as well as the CTP approach in general) is directly related to possible future research areas. Perhaps the greatest enhancement to this procedure would be to upgrade the computer simulation to two dimensions. This would allow an engineer to investigate the potential for head and neck injuries, as well as further examine the nature of injuries to the spine. Another improvement to this approach would be to develop response characteristics for the other mechanical side impact dummies used today in industry, these being EUROSID (a dummy used in Europe) and BIOSID (a dummy developed by General Motors). One other potential

research area would be to further examine the simulation model developed in this thesis. In addition to the actual full scale side impact simulated in this thesis, there were fifteen other side impacts with different test conditions (additional inner door padding, different dummy positioning, etc.) that were performed on the 1985 Ford LTD [9]. Exercising the simulation model through a variety of cases would be extremely beneficial. Another possible research area in terms of occupant response would be to investigate the effects of the seat, as well as the possible addition of a moveable, padded armrest between the occupant and the door. One more possible research area could be the development of an airbag in the door which inflates upon impact, thereby providing occupant protection in a manner similar to the use of air bags in frontal impacts. Although some of the research areas mentioned above are not directly related to the procedure presented in this thesis, the work performed in this thesis could serve as a starting point in numerous areas of side impact research.

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