Reconstruction of Real World Side Impact Vehicle Collisions Using HVE – A Case Series of Pediatric Pelvic Fracture.

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Abstract:

This paper describes the application of HVE software to reconstruction of a series of side impact automobile crashes resulting in pelvic fracture to pediatric case occupants. This paper compares crash dynamics, injury mechanisms and occupant kinematics from on-site crash investigations, with reconstruction of these cases using HVE.

In-depth investigations of eight near side impact crashes involving children (8-15 years old) with pelvic fractures were conducted. Vehicle dynamics and vehicle damage were reconstructed using the EDSMAC4 program. The acceleration pulse generated from the EDSMAC4 program was then input into the GATB module to predict the child occupant kinematics in these crashes. The results confirmed the vehicle dynamics and damage pattern as measured in the crash investigations. The HVE reconstructions of occupant kinematics suggested that initial orientation and subsequent rotation of the pelvis during the intrusion influenced the likelihood of injury.

Introduction:

The accurate simulation of motor vehicle crashes using computer simulation programs, whose inputs are supplied by on-site crash investigation, provides a means by which to understand the vehicle dynamics and occupant kinematics in a crash. One of the challenges of this approach is the novel creation of the vehicle and occupant environment that requires a tremendous amount of assumptions of vehicular properties and characteristics. The Human Vehicle Environment (HVE) program attempts to address this limitation by providing a large database of vehicle models, thus reducing the reconstruction time and run-time as compared to other programs. [1,2]

The objective of this paper was to assess the utility of the HVE program to assess child occupant kinematics. In particular, this paper focused on utilizing HVE to delineate the kinematics associated with pelvic fractures in side impact crashes. Previous studies have identified that the mechanism of pelvic injury is dependent on the mechanical structure of the pelvis, which is very different in children than in adults [6]. Because of these differences, we hypothesize that the severity of the pelvic injury is dependent on the loading pattern and pelvic orientation relative to the impact. To test this hypothesis, this study compares crash dynamics, injury mechanisms and occupant kinematics from on-site crash investigations with reconstruction of these cases using HVE in order to characterize both the pelvic kinematics and contact force during the impact.

Methods:

In-depth investigation

Crashes for this study were identified as part of the Partners for Child Passenger Safety (PCPS) project. Detailed descriptions of the study population and methods involved in data collection and analysis have been previously published. [7] Briefly, PCPS consists of a large scale, population based, child-specific crash surveillance system: insurance claims from State Farm Insurance Co. (Bloomington, IL) function as the source of subjects, with telephone survey and on-site crash investigations serving as the primary sources of data. The telephone interviews provide data for a surveillance system used to describe characteristics of the population including risk factors for injury while the crash investigations provide detailed mechanisms of injury. Data presented in this paper pertains to the crash investigation portion of the study.

Vehicles qualifying for inclusion in the surveillance system were those involving at least one child occupant $\leq$ 15 years of age riding in a model year 1990 or newer State Farm-insured vehicle. Qualifying crashes were limited to those that occurred in fifteen states and the District of Columbia, representing three large regions of the United States (East: NY, NJ, PA, DE, MD, VA, WV, NC, DC; Midwest: OH, MI, IN, IL; West: CA, NV, AZ). On a daily basis, data from qualifying and consenting claims were transferred electronically from all involved State Farm field offices to researchers at The Children's Hospital of Philadelphia and University of Pennsylvania (CHOP/Penn). Data in this initial transfer included contact information for the insured, the ages and genders of all child occupants, and a coded variable describing the medical treatment received by all child occupants.

In order to gain more detailed information about the kinematics of the child and the mechanisms and sources of the injury, a subset of the surveillance system cases were chosen for in-depth crash investigation. Cases were screened via telephone with the policyholder to confirm the medical details of the case. Contact information from selected cases was then forwarded to a crash investigation firm and a full-scale on-site crash investigation was conducted using custom child-specific data collection forms.

Crash investigation teams were dispatched to the crash scenes within 24 hours of notification to measure and document the crash environment, damage to the vehicles involved, and occupant contact points according to a standardized protocol. The on-scene investigations were supplemented by information from witnesses, crash victims, physicians, hospital medical records, police reports, and emergency medical service personnel. From this information, reports were generated that included estimates of the vehicle dynamics and occupant kinematics during the crash and detailed descriptions of the injuries sustained in the crash by body region, type of injury, and severity of injury. Delta v (the instantaneous change in velocity) was calculated using WinSmash and crush measurements of the vehicles involved.

Medical, crash, and child characteristics of the cases of pediatric pelvic fractures identified by the system were analyzed. Cases were limited to those with a principal direction of force (PDOF) of 45-135° and 225-325°.

Vehicle type was classified by decoding the vehicle identification number using VINDICATOR (Insurance Institute for Highway Safety / Highway Loss Data Institute, Arlington, VA, 2001). Restraint status of each child was determined by assimilating information from a variety of sources including careful documentation of evidence in the vehicle such as child contact points and belt marks and driver/parent, police, and EMS interviews. The cause of each pelvic injury was determined by an assessment of the direction of first impact, resultant kinematics and documented child contact points. In-depth investigations of eight right side impact crashes involving children (8-15 years old) with pelvic fractures were conducted.

Computer simulation

These cases were reconstructed and simulated using HVE (Engineering Dynamics Corporation, 1984). The CDC obtained from the in-depth crash investigation was matched with the CDC obtained from EDSMAC4 module of HVE simulation. Upon this validation of CDC, the pulse from the EDSMAC4 simulation was imported into the GATB module to show the occupant kinematics. In cases where the actual case vehicle was not available in the HVE database, a generic vehicle was used. To reduce the margin of error the generic vehicle was modeled using approximate measurements and weights from the actual case vehicle specifications. For better visualization, a suitable vehicle body type based on the case vehicle was chosen (SUV to SUV, passenger car to a passenger car, 2door car to a 2 door car. etc) and superimposed. An appropriate GATB dummy was selected for each simulation that most closely matched the case occupant based on occupant's age, weight and height.

Contact planes between the vehicle and the case occupant were created based on the original vehicle interior dimension obtained from crash investigation. For cases having severe intrusion, iterative simulations were conducted by positioning the contact planes at different positions representing the spectrum between the non-intruded side of the original vehicle side interior panel and post-impact intruded interior panel position of the case vehicle. Based upon occupant injury severity noted from the medical reports, the simulation with best contact position with acceptable contact forces between the side interior panel and the dummy hip was selected for the study.

Effects of factors such as impact location, seating position, direction of impact, pelvic orientation and contact force between the side interior and pelvis on the forces are discussed.

RESULTS

Case Studies:

Case 1: Case Vehicle, a 4-door midsize passenger car struck a tree with a Principle direction of force (PDOF) of 110 degrees. The impact was onto the right side door and floor panel with a lateral delta-V of 32 km/h and a maximum intrusion of 43 centimeter at the a-pillar. The 14-year-old male case occupant (with unknown height and weight) was seated in the right front passenger seat and was restrained by a 3-point manual lap and shoulder belt. There was also a 15-year-old female (unknown height and weight) restrained by a 3-point manual lap and shoulder belt seated in the right rear as shown in the simulation figure 1(a). A 12-year old 50th percentile dummy was used for 14-year-old case occupant and an adult 25th percentile dummy represented the 15-year-old occupant. The case occupant (14-year old) had a *right superior and inferior pubic ramus fracture, a right ischium (ramus and body) fracture, widening of sacro-iliac joint, a non-displaced vertical fracture of left sacrum, and a fractured tip of left L5 transverse process.* The case occupant had other associated injuries, i.e., disruption of urethra and bladder, loss of consciousness and severe scalp laceration. The other child occupant (15-year old) was uninjured.

The simulation demonstrates that the case occupant's lower torso moved right laterally with right side of the pelvis (ischium and iliac wing) facing towards the impact side. Because the impact was in front of the occupant, the severe intrusion of interior door panel and the floor panel most likely resulted in oblique loading of the pelvis by deforming the seat. The intruding right front door interior panel loaded the occupant's right ischium and right iliac wing from the bottom and side as the seat deformed during the impact. Total lateral contact force of 492.36 N was measured between side interior surface plane and pelvis of the dummy representing the case occupant.

The simulation demonstrated kinematics of the other occupant (15-year old) which confirmed the lack of pelvic or femur injuries. Specifically, there was no significant movement of hip towards the impact, instead her right knee and thigh contacted the side interior, which absorbed most of the energy. The contact forces between the occupant's hip and the side interior showed that there was no hip contact for the rear-seated occupant as shown in the table 1.

Case 2: Case Vehicle (4-door, midsize passenger car) was impacted with a PDOF of 60 degrees by a sport utility vehicle and the impact was a sideswipe on the right side plane of the vehicle with maximum intrusion of 35 cms at b-pillar and a lateral delta-V of 40 km/h. The 8-year-old female case occupant who is 55 inches in height and 54 lbs in weight was seated in the right front passenger seat and was restrained by a 2-point automatic shoulder belt only. *Occupant had right inferior pubic ramus fracture and left superior ramus fracture.* The occupant had other associated injuries i.e., splenic laceration, serious facial laceration and head injury and was in coma for four days.

The 9-year-old 50th percentile female dummy was used for 8-year-old case occupant for the simulation. The simulations demonstrated that, intially, the occupant experienced a submarining effect by slipping under the shoulder belt due to the frontal component of the impact force, then the occupant's lower torso moved right laterally towards the impact side and contacted the intruding side interior door panel. Figure 2(a) gives an illustration of the occupant movement using the GATB module of the HVE simulation As the seat deformed due to impact the case occupant loaded her right ishium and right ilium from the base. The counterclockwise motion of the occupant due to post impact clockwise motion of the vehicle further loaded her right hip as the occupant's motion was restricted between the twisted seat back and intruding side interior door panel. A total lateral contact force of 2241.73 N was measured between side interior surface plane and pelvis of the dummy representing the case occupant.

Case 3: Case Vehicle (4-door mid size passenger car) was impacted with a PDOF of 60 degrees by another 4-door full size passenger car. The impact was on the right front door, B-pillar and rear door of the case vehicle with a maximum intrusion at right rear door (towards b-pillar) of 52 cm and a lateral delta-V of 37 km/h. The 15-year old female case occupant (unknown height and weight) was seated in the right front passenger seat and was restrained by a 3-point manual lap and shoulder belt, and the passenger air bag deployed during the crash. The case occupant suffered a *left inferior pubic ramus fracture, a possible* *right pubic symphysis fracture, and a non displaced fracture of left L4 transverse process*. The occupant had associated injuries including loss of consciousness and post concussive syndrome.

A 12-year-old 50th percentile female dummy was chosen to represent the 15-year-old occupant. Figure 3(a) shows the occupant kinematics during the crash. It is observed from the GATB simulations that the occupant moved right laterally towards the impact side. The intruding right front side door interior panel (post-impact pictures) loaded the right iliac wing laterally and the right ischium from the base and from the side in an oblique fashion. The post impact clockwise motion and rollover of the vehicle further loaded the pelvis from bottom of the seat resulting. A total lateral contact force of 4416.95 N was measured between side interior surface plane and pelvis of the dummy representing the case occupant.

Case 4: Case Vehicle (2 dr extended cab, pickup truck) was impacted with a PDOF of 80 degrees by another pickup truck. The impact was on the right front door and b-pillar of the vehicle with maximum intrusion (37 cm) at the B-pillar and with an estimated lateral delta-V of 40-50 km/h. The 9-year- old female case occupant (unknown height and weight) was seated in the right front passenger seat and another 6-year-old male occupant (unknown height and weight) shared this seat. Both were restrained together by the same 3-point manual lap and shoulder belt and the 9 year old was outboard to the 6 year old.
The case occupant had a right superior pubic ramus fracture. There were no other associated injuries. The other child occupant suffered lower extremity fracture (right distal tibia).

The 9-year old 50th percentile female dummy was used for the 9-year-old case occupant and a 6-year old 50th percentile dummy represented the 6-year-old occupant. Due to the limitation of the restraint capability in the HVE, only the case occupant was restrained and the other occupant was unrestrained in the simulation. The simulation results shown in the figure 4(a) demonstrate that the case occupant seated near the right side door moved right laterally towards the impact side and loaded the greater trochanter of the right femur bone and the right iliac wing through the intruding right side interior door panel with protruded armrest. The other occupant seated on the left side on the same seat further loaded the case occupant's left hip from left side. A total lateral contact force of 1766.74 N was measured between side interior surface plane and pelvis of the dummy representing the case occupant.

Case 5: Case Vehicle (4-door, mid size passenger car) was struck by an extended cab pick up truck with a PDOF of 80 degrees. The impact was to the right front door with a lateral delta-V of 22 km/h. There was a maximum intrusion of 23 cm on the right front door. The 14-year-old female case occupant who was 65 inches tall and 160 lbs in weight was seated in the right front passenger seat and was unrestrained. She sustained a *fractured right pubic ramus, grade 1 spondylolisthesis (L5 moved forward of S1) and a non-displaced fracture of right hemisacrum with* no associated injuries.
The 14-year-old female case occupant was represented by a 12-year old 50th percentile female dummy. The case occupant moved forward and right laterally towards the impact. The greater trochanter of right femur bone and the right iliac wing contacted the intruding right side interior door panel.
The GATB simulation of the case occupant kinematics is shown in the figure 5(a). It can be seen from the sequence of the simulation pictures that as the case occupant impact her

right side of the hip and rotated in a clockwise motion due to post impact motion of the vehicle she further loaded the posterior end of the pelvis through left side armrest. The simulation demonstrated a significant head contact with side window glass in the simulation, but the crash investigation reported that the occupant had no head injuries. It was later observed that before the head reached the window, there is a likelihood of glass shattering. A total lateral contact force of 1857.63 N was measured between side interior surface plane and pelvis of the dummy representing the case occupant.

Case 6: Case Vehicle (4-door sport utility vehicle) was impacted with a PDOF of 70 degrees by another 4-door sport utility vehicle. The impact was on the right front door, b-pillar and right rear door of the vehicle with maximum intrusion (37 cm) at the b-pillar and with a lateral delta-V of 25 km/h. The 8-year-old male case occupant (36 inches in height, and 49 lbs in weight) was seated in the right rear and was restrained by a 3-point manual lap and shoulder belt and a 5-year-old female occupant (36 inches in height, and 50 lbs in weight) was restrained by the manual lap and shoulder belt seated in the left rear. The case occupant sustained lateral compressive loading onto the right side hip resulting in a *right superior pubic ramus fracture.* The occupant had no other associated injuries. The other occupant sustained minor contusions to right hip and right earlobe.

The 8-year-old male case occupant was represented by a a 9 yr-old 50th percentile dummy and 5-year-old by a 6-year old 50th percentile dummy. Figure 6(a) shows the sequence of pictures of the occupant simulation obtained from GATB. It is seen that the case occupant moved right laterally towards the impact. The greater trochanter of right femur bone and the right iliac wing contacted the intruding right rear door interior panel with protruded armrest. A total contact force of 2003.46 N was measured between side interior surface plane and pelvis of the dummy representing the case occupant.

Case 7: Case Vehicle (4-door full size passenger car) hit a tree with a PDOF of 90 degrees and the impact was onto the right side B-pillar and the right side floor panel with an unknown lateral delta-V. The maximum intrusion of 29 cm was at the right side sill near the b-pillar. The 13-year-old male case occupant (unknown height and weight) was seated in the right front passenger seat and was restrained by a 3-point manual lap and shoulder belt. The post-impact picture from on-site crash investigation showed that the occupant's seat was twisted and tilted to left, and was compressed laterally at the seat bight on the right side upon impact. The case occupant had a *left inferior pubic ramus fracture, a left transverse process chip fracture of L5, an anteroposterior fracture of left sacrum and left superior pubic ramus fracture*.

Figure 7(a) shows the sequence of the occupant kinematics during the crash. A 12-year old male 50th percentile dummy represented the 13-year-old male occupant. The simulation demonstrated that the case occupant's pelvis moved towards the impact. The right front seat, due to B-pillar and the floor panel intrusion, loaded the hip from side and base. The injuries that were contralateral to the applied force suggest that the pelvis rotated so that the load path minimized the loads on the right pelvis. Based on three iterative simulations by placing the side interior contact plane at different position based on intrusion values, it could be observed that the occupant's hip was held by a loose lap portion of the belt, which resulted in considerable pelvic rotation during the crash. It was observed that the lateral contact force of 366.68 N was relatively less when compared to other cases. Photos from the crash investigation showed evidence of occupant contact with the protruded armrest supporting the assertion that the primary injury mechanism involved lateral loading of the hip from the intruding interior door panel with protruded armrest.

Case 8: Case Vehicle (4-door, mid size passenger car) was struck by a 4-door SUV with a PDOF of 70 degrees. The impact was onto the B-pillar, right front door and right rear door with maximum intrusion (34 cm) at the b-pillar and with a lateral delta-V of 26 km/h. The 14-year old female case occupant (66 inches height, 145 lbs weight) was seated in the right front and was restrained by a 2-point automatic shoulder belt without a lap restraint as shown in figure 8(a). Crash investigation revealed that the occupant's seat was compressed laterally at the seat bight showing the load path. The case *occupant had a fractured right superior and inferior pubic ramus extending into pubic symphysis and a sacroiliac avulsion fracture at the wing.* The occupant had associated injuries, including a head injury with loss of consciousness.

A 12-year old 50th percentile dummy represented the 14-year-old female occupant in the simulation. The simulation (figure 8(a)) demonstrated that there was significant oblique lateral loading in this crash. The occupant's pelvis moved forward and right laterally towards the impact side and the right lateral posterior plane of ilium contacted the intruding B-pillar at the right side seat bight. Based on the simulation, the possible mechanism for the head injury might have been due to the head contacting with the window sill as the occupant moved forward. A total lateral contact force of 4997.03 N was measured between side interior surface plane and pelvis of the dummy representing the case occupant.

Discussions:

The force values obtained from the contact forces between the pelvis and side interior panel (contact planes) were used to identify the pattern of loading sustained by the pelvis in these crashes. The total, normal and frictional forces of pelvis in table 1 are an indication for the oblique loading of pelvis in these cases. There was a relatively greater frictional force between the side interior contact plane and the pelvis in cases having multiple pelvic fractures. In cases where the normal and frictional forces measured in sumation were relatively low were further analyzed using crash investigation data. Large intrusion in these cases showed the evidence of increased severity of injury to pelvis. These observations were further supported by measurements in cases involving more than one occupant. In these cases, the severity of injury was greater for occupants seated near to the intrusion and location of impact.

The case studies and their simulations presented confirmed the damage pattern as measured in the crash investigations. The CDC bound by seven character codes obtained from in-depth crash investigation was matched based on force direction, area of deformation, specific longitudinal or lateral area, specific vertical or lateral area, type of damage distribution and deformation extent (CDC–SAE J224 MAR80). The comparative CDC results from simulation showed 100% accuracy in deformation location and type of damage distribution. The specific longitudinal and vertical location values were up to 90% accurate as the simulations were run with an assumption of crashes occurring on a flat surface (flat road). There was a $\pm 5°$ of variation in principal direction of force.

It was noted that the likelihood of injury was not only due to the initial orientation and subsequent rotation of the pelvis during the intrusion, but also due to the oblique loading of pelvis during the crash. The primary cause for injury was further supported with pictures from the in-depth crash investigation showing the contact points on the side interior and deformed occupants' seats. Most of the case vehicles had protruded side interior panels with arm rests, which might have influenced the injury pattern in these cases. The results are based on a small sample of cases from multidisciplinary accident investigations and hence, definitive statistical conclusions are not possible. This study has shown that for the HVE software to be used in a more meaningful way for the study between the occupant and vehicle, further development of the software in this area is required.

Limitations:

Based on the in-depth crash investigations, we found that the side interior/seat intrusion into occupant space was one of the prime causes for this type of pelvic injuries. HVE is limited in the measurement of contact forces on contact planes placed in the side interior of the vehicle because these contact planes do not dynamically move along with/or in the direction of intrusion. The contact force measurements were dependent on occupant movement towards the contact planes, where in real world crashes with intrusion, there are forces acting in both direction and forces will be much greater due to the movement of occupant towards the side interior and vise versa. In this study simple flat planes were constructed in occupant simulations. Contours of occupants seat, side interiors were not taken into consideration for calculation of pelvic contact in GATB module.

Further, models assumed the vehicle was traveling over a flat, horizontal surface. Variations in elevations and grades may influence the occupant's kinematics and could be analyzed by varying the friction co-efficient within the module.

The shape of the human pelvis is not ellipsoidal as we see in the GATB dummies; therefore force measurements obtained in the simulation cannot be related to actual forces on a human pelvis. However, these simulations can be used to determine possible kinematics of the pelvis, which provides insight into appropriate test conditions for future biomechanical testing that, can measure anatomical loads.

The crash investigation reported that most of the cases had contra-lateral injuries indicating the presence of distinct load paths that allow the transmission of force to the contralateral side. This could not be observed in the GATB module as GATB measures values at the CG of the ellipsoids present in the dummy.

Use of vehicles from the HVE vehicle database and GATB dummies were limited to the database present in the software used at that particular time.

ACKNOWLEDGMENTS

This study was performed as part of the Partners for Child Passenger Safety Study at The Children's Hospital of Philadelphia funded by State Farm Insurance Companies. The authors acknowledge the assistance of the entire Partners for Child Passenger Safety research team especially the contribution of the crash investigation teams of Dynamic Science Inc. under the direction of Frances Bents.

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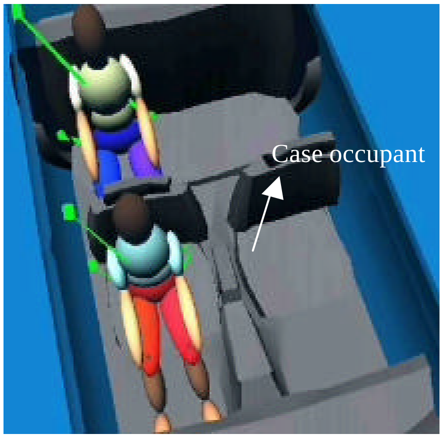
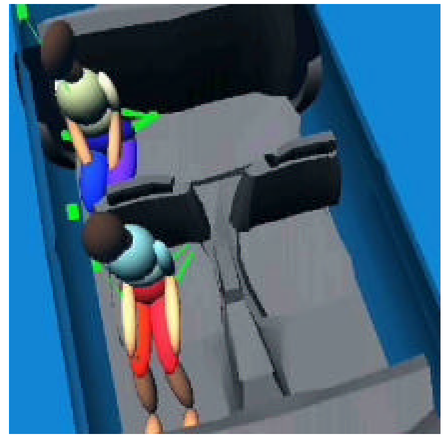
APPENDIX:

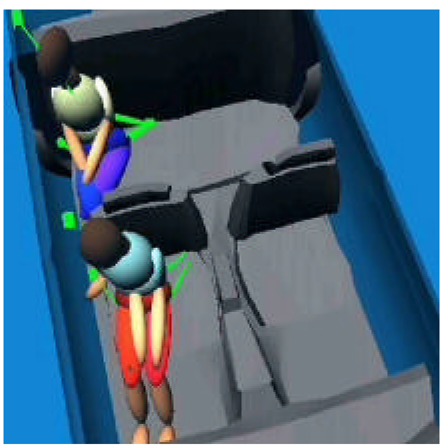
Case: 1



Initial position



Pre-impact



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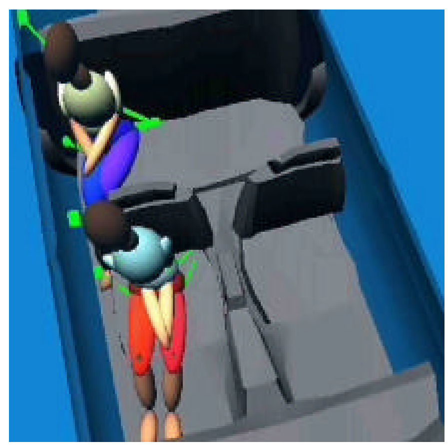


Post-impact

Figure 1(a): Sequential pictures of HVE occupant simulation.

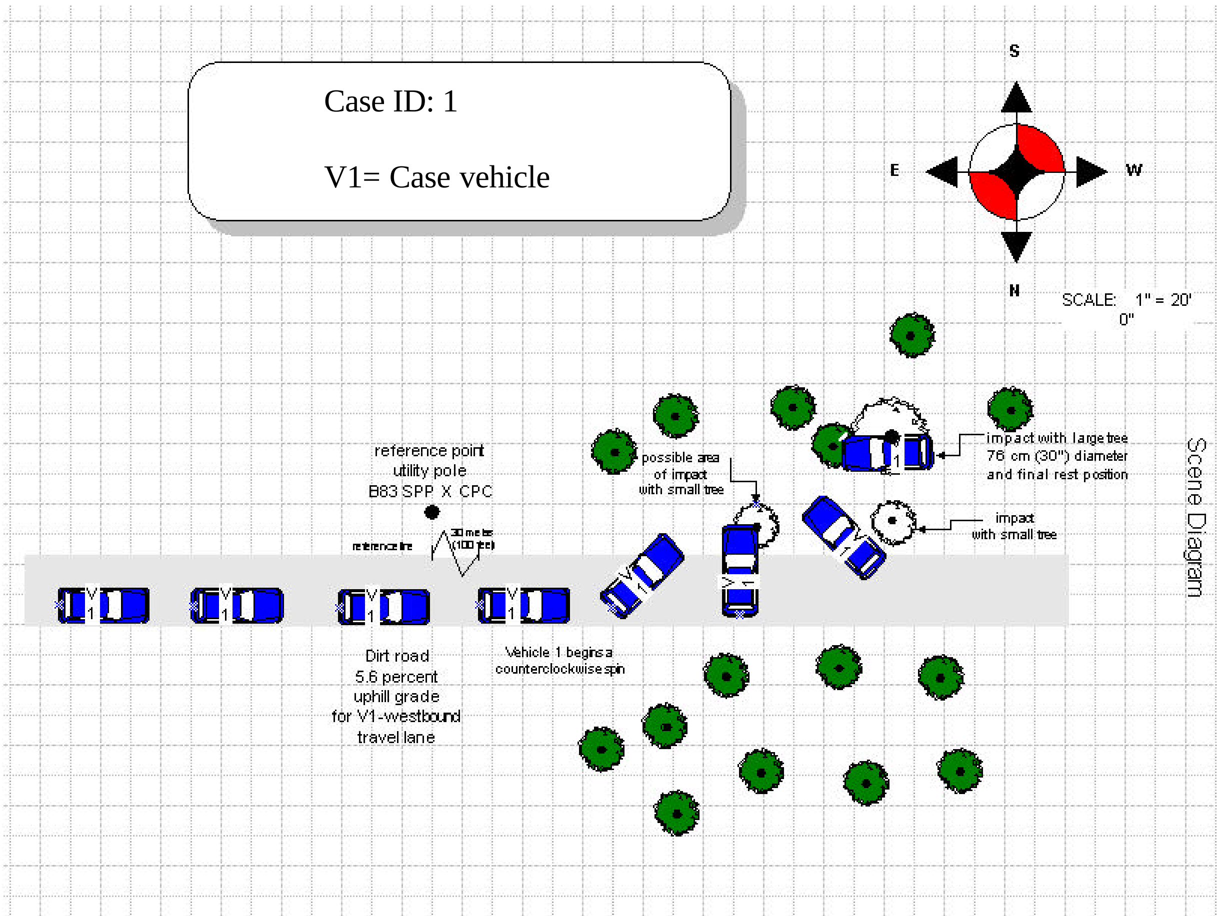
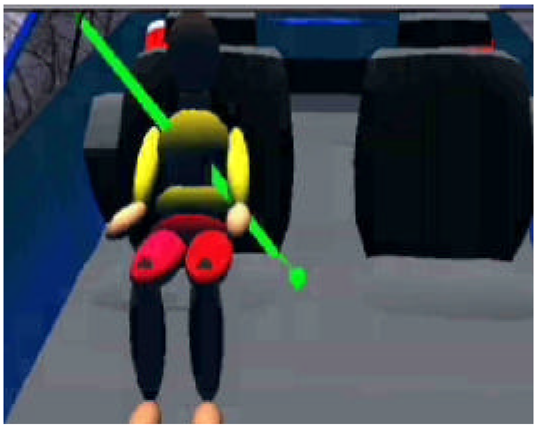


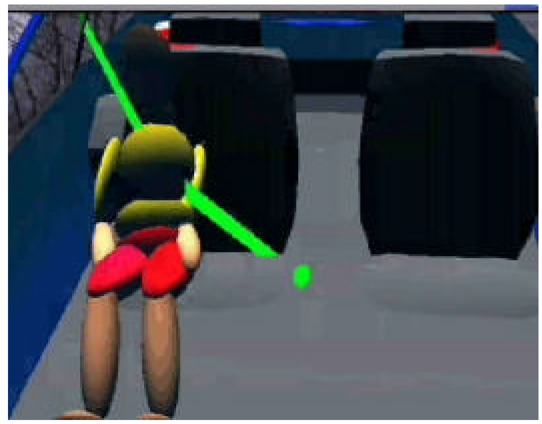
Figure 1(b): Scene diagram.

Figure 1(c): Vehicel damage picture from crash investigation.

Case 2:

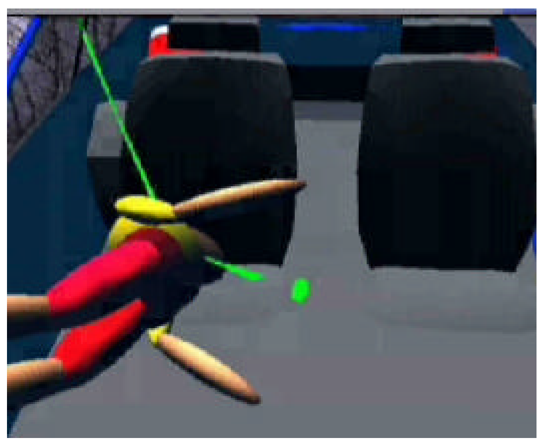


Initial position



Pre-impact

Impact



Post-impact

Figure 2(a): Sequential pictures of HVE occupant simulation.

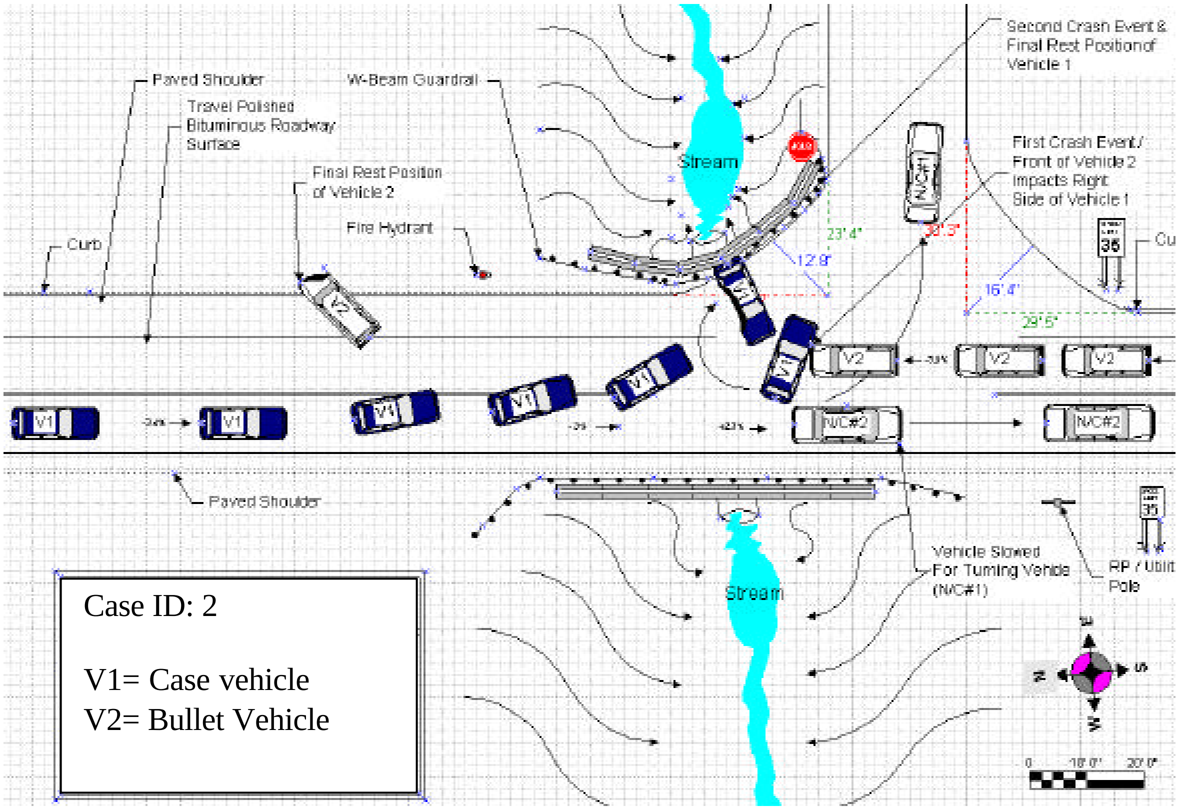


Figure 2(b): Scene diagram.

Figure 2(c): Vehicel damage picture from crash investigation.

Case: 3

Initial position

Pre-impact

Impact

Post-impact

Figure 3(a): Sequential pictures of HVE occupant simulation.

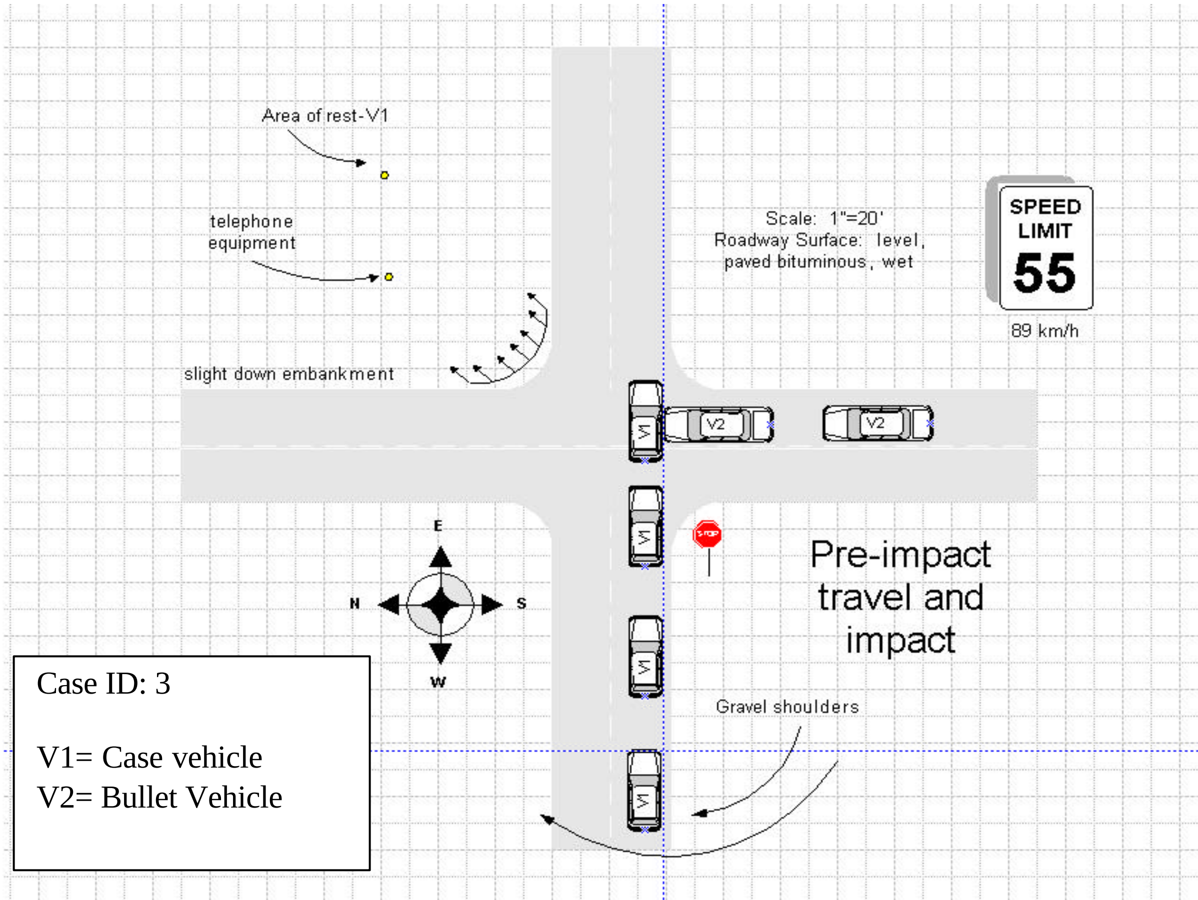


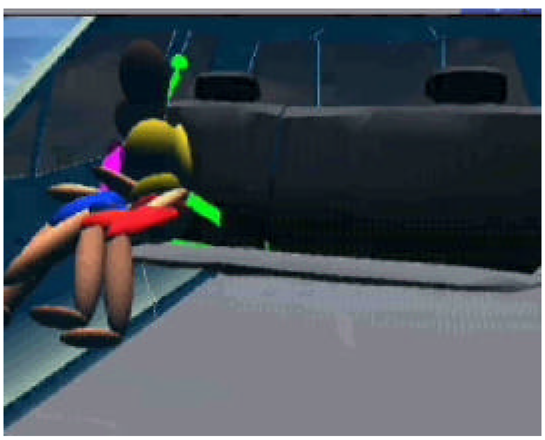
Figure 3(b): Scene diagram.

Figure 2(c): Vehicel damage picture from crash investigation.

Case: 4


Initial position


Pre-impact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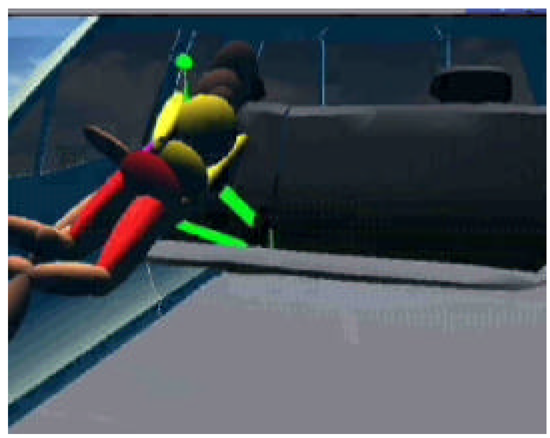

Post-impact

Figure 4(a): Sequential pictures of HVE occupant simulation.

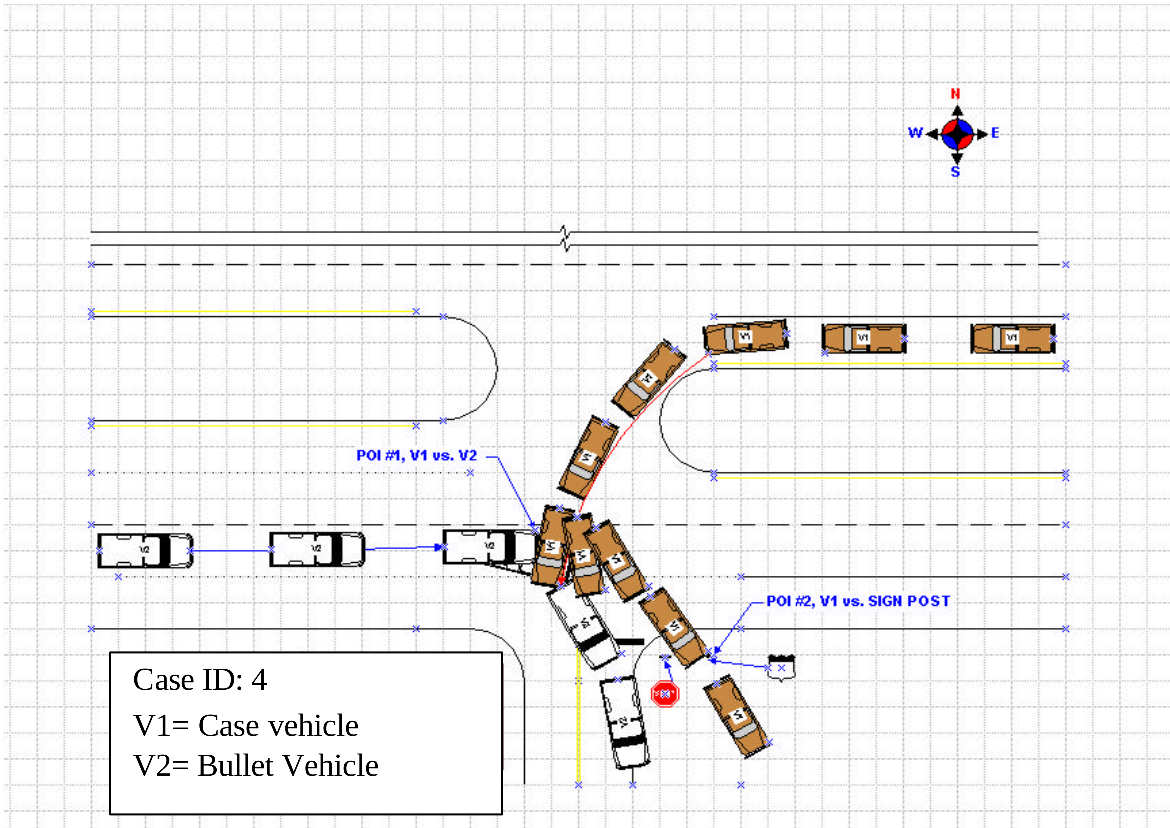


Figure 4(b): Scene diagram.

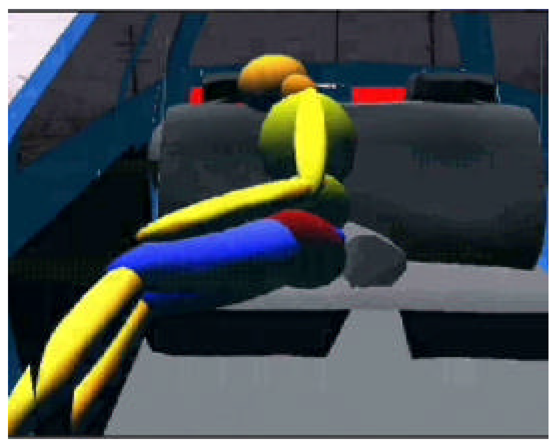
Figure 4(c): Vehicel damage picture from crash investigation.

Case: 5

Initial position

Pre-impact

Impact



Post-impact

Figure 5(a): Sequential pictures of HVE occupant simulation.

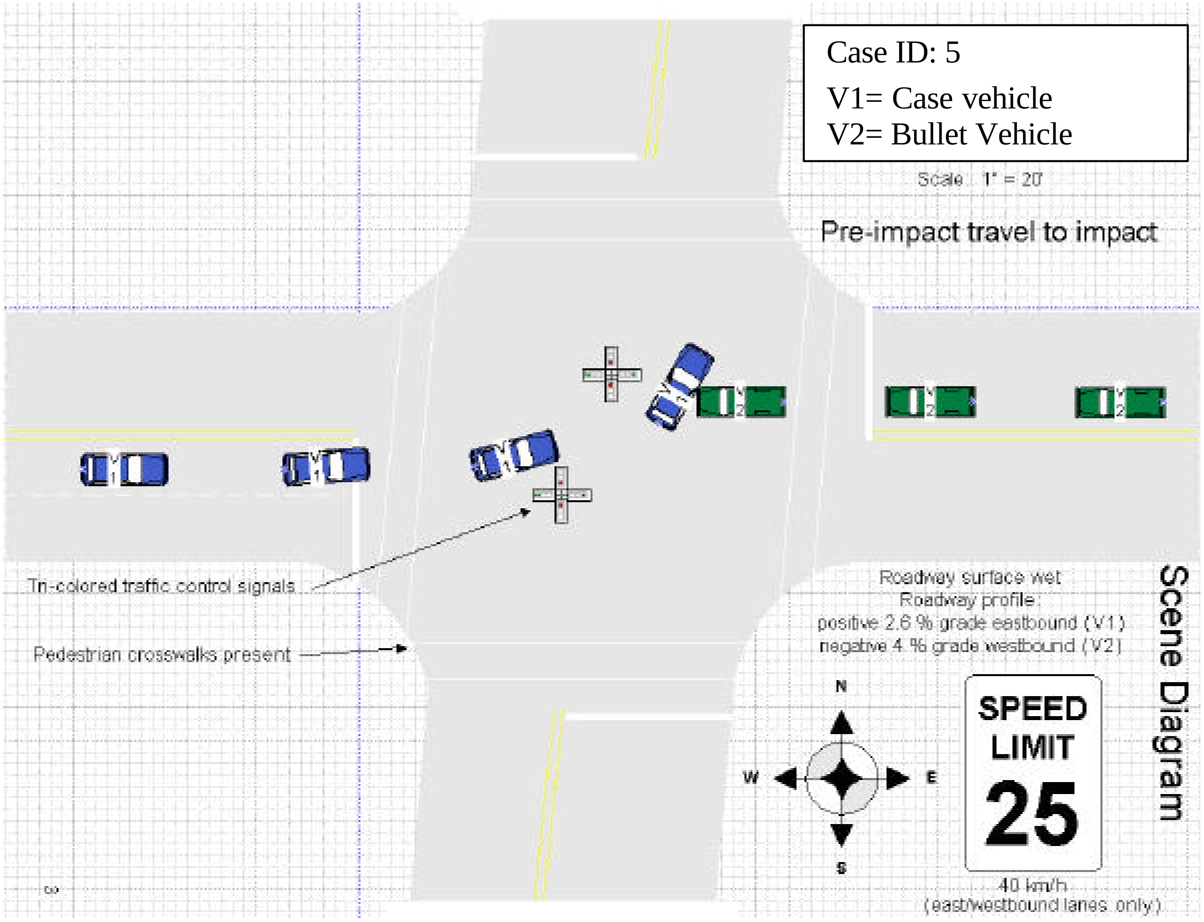


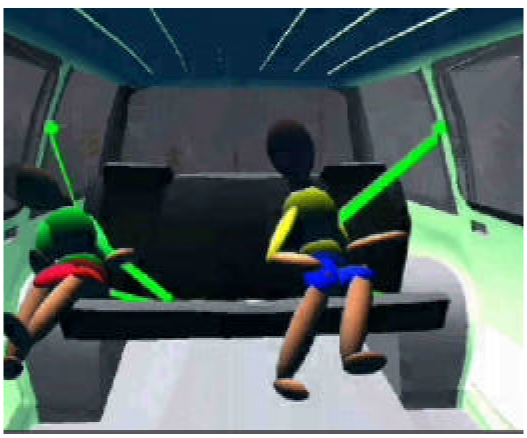
Figure 5(b): Scene diagram.

Figure 5(c): Vehicel damage picture from crash investigation.

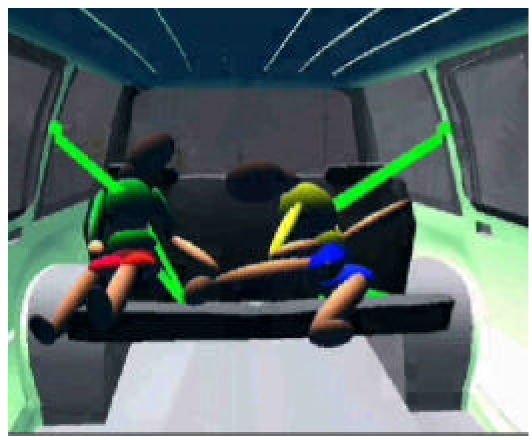
Case: 6 **(CHANGE the PICTURES)**

Initial position

Pre-impact



Impact



Post-impact

Figure 6(a): Sequential pictures of HVE occupant simulation.

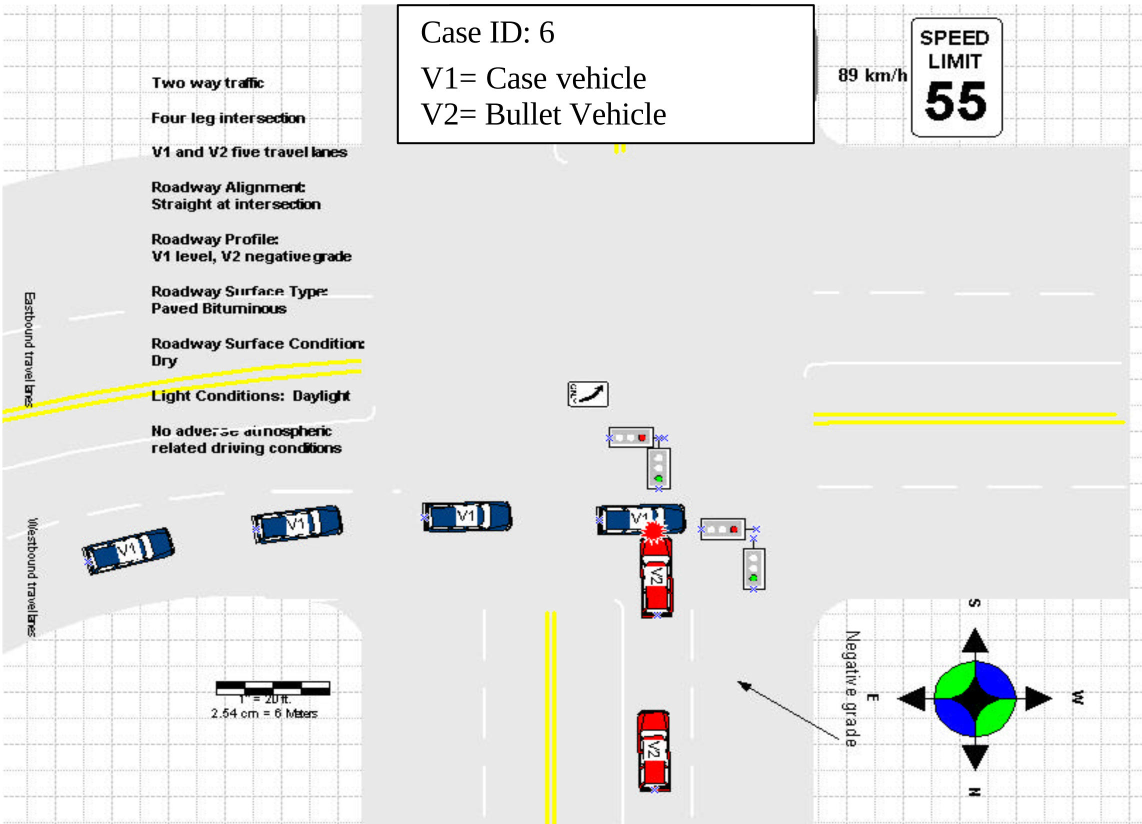


Figure 6(b): Scene diagram.

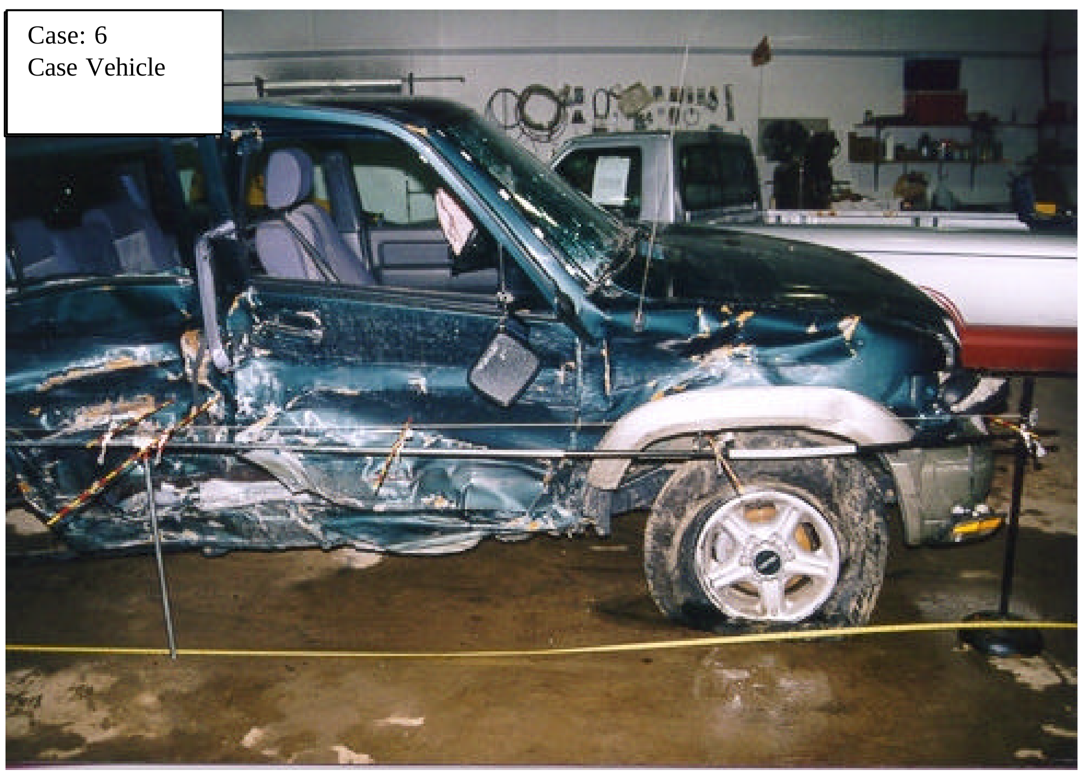
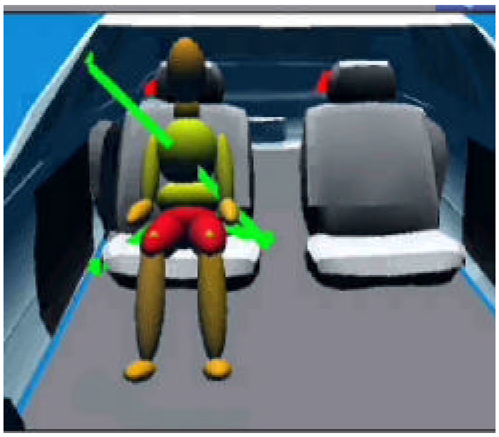


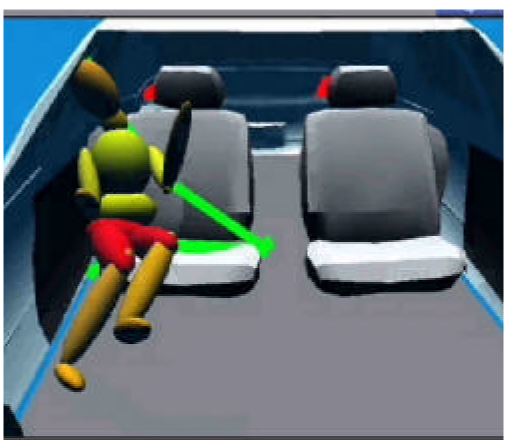
Figure 6(c): Vehicel damage picture from crash investigation.

Case: 7

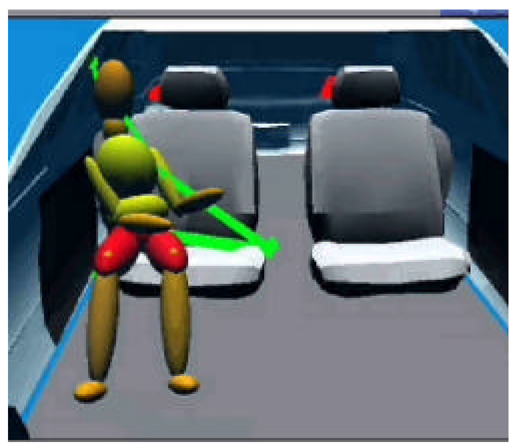


Initial position

Pre-impact



Impact



Post-impact

Figure 7(a): Sequential pictures of HVE occupant simulation.

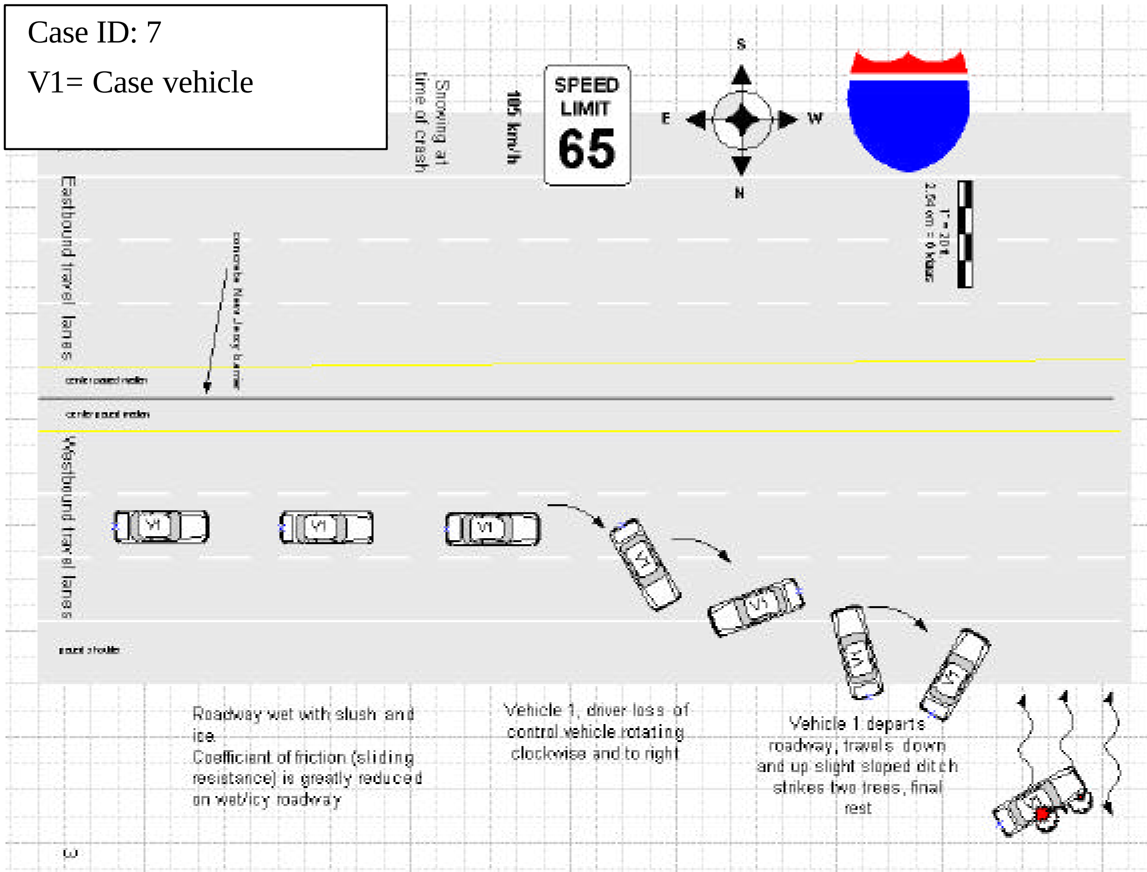
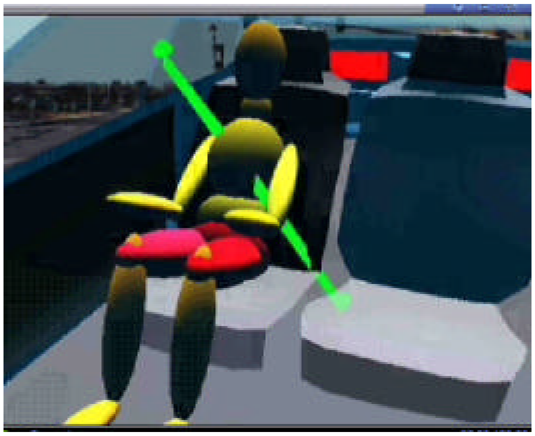


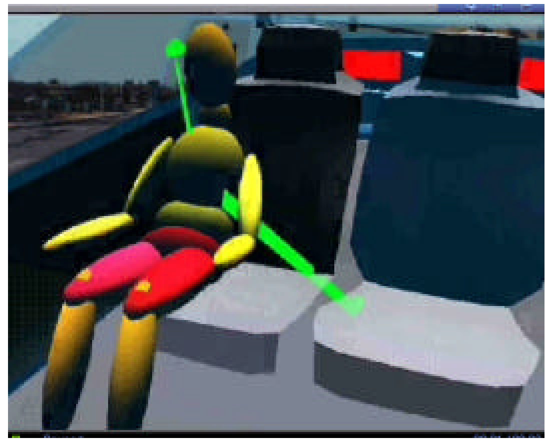
Figure 7(b): Scene diagram.

Figure 7(c): Vehicel damage picture from crash investigation.

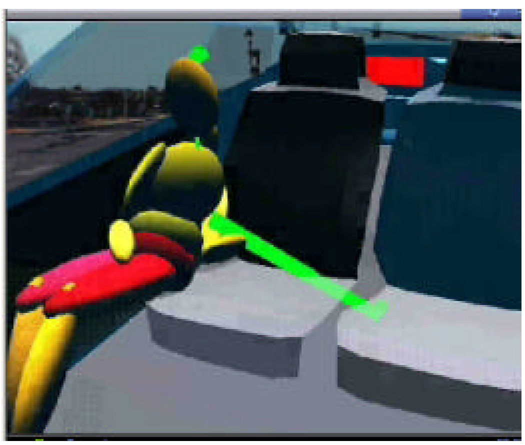
Case: 8



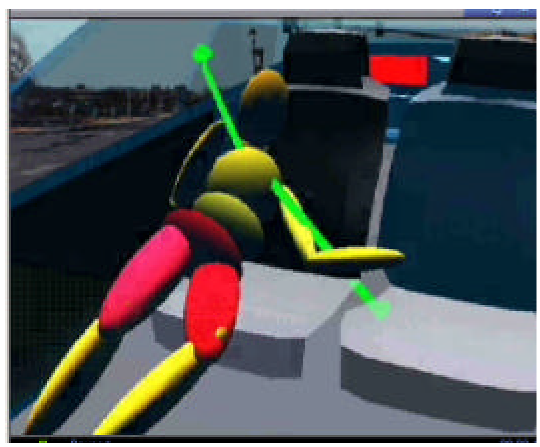
Initial position



Pre-impact



Impact



Post-impact

Figure 8(a): Sequential pictures of HVE occupant simulation.

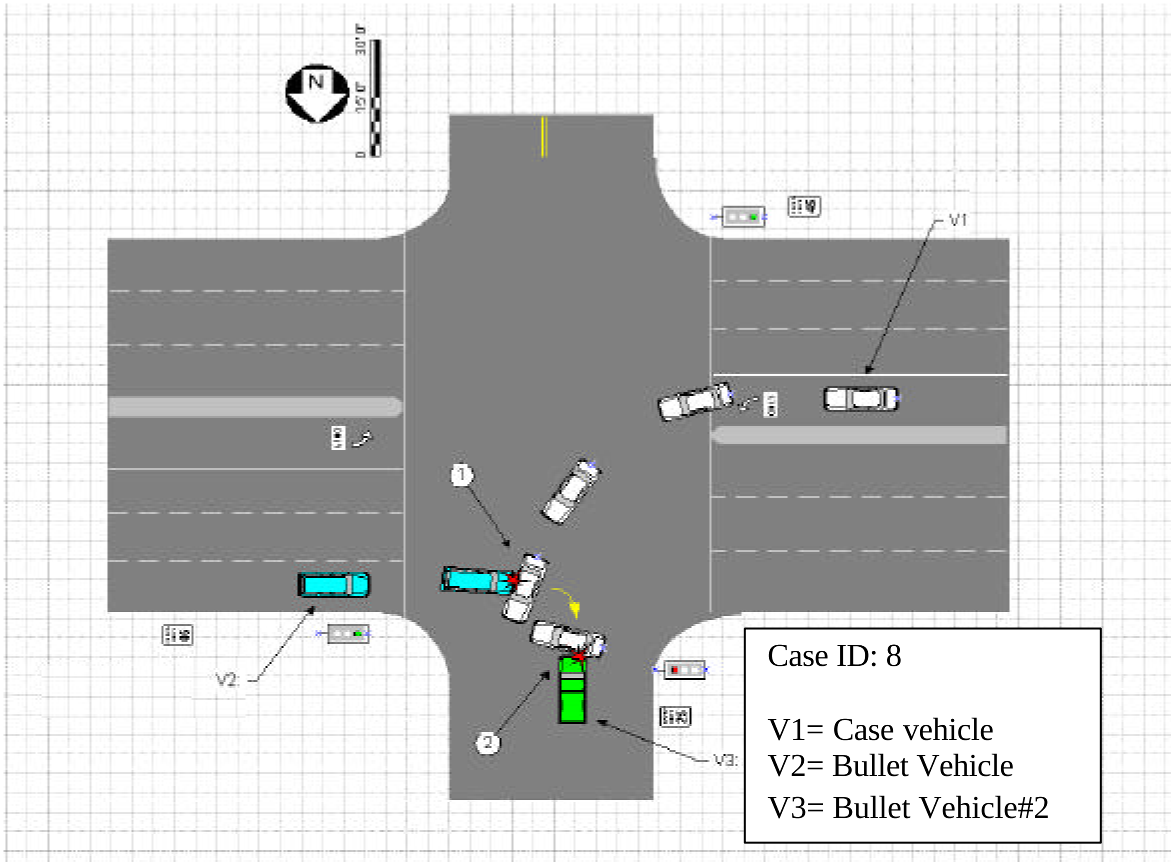


Figure 8(b): Scene diagram.

Figure 8(c): Vehicel damage picture from crash investigation.

Table 1.

Case I.D.	Total force	Normal force	Frictional force	
	N	N	N	
1	492.36	440.38	220.19	
2	2241.73	2005.06	1002.53	
3	4416.95	3950.64	1975.32	
4	1766.74	1580.22	790.11	
6	2003.46	1791.95	895.98	
7	366.68	259.28	259.28	
8	4997.03	4615.08	2234.43	
5	1857.63	1661.52	830.76	Pelvis contact force for front occ.
5	1164.79	1041.82	520.91	Knee contact force for rear occ.