EFFECTS OF ANGLES AND OFFSETS IN CRASH SIMULATIONS OF AUTOMOBILES WITH LIGHT TRUCKS

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ABSTRACT

Two series of finite element and lumped parameter model vehicle-to-vehicle frontal crash simulations were conducted. The vehicles modeled are the 1994 Chevrolet C-1500 light truck and the 1997 Ford Crown Victoria. The first set of simulations involves fully-engaged angled impact. Angles range from +50° to -50°. The second set simulates offset impacts in head-on vehicle crashes. The front-end overlap ranged from 20% of the average width of the vehicles to 100% (fully engaged). Driver and passenger injury is assessed using a MADYMO model of a generic automobile interior subject to the horizontal occupant compartment translation and rotations. The results of the two simulation sets are examined for qualitative changes in structural deformation modes, energy absorption, and injury. Relative injury is assessed by head injury criterion (HIC) with a 36-millisecond window and 3-millisecond chest acceleration clip. These criteria are less sensitive to occupant compartment intrusion than other injury metrics.

INTRODUCTION

The severity of injury incurred in motor vehicle crashes is governed by a complex function of initial conditions, geometric characteristics, and material properties of both the vehicles and the occupants. Small changes in these inputs can cause significant changes in the output (i.e., occupant injury) depending on the timing and geometry of the load paths that are created and destroyed within the vehicle during the deformation process. This paper characterizes the trends and the variability of the output as a function of the initial vehicle geometry.

VEHICLE-TO-VEHICLE FINITE ELEMENT SIMULATIONS

Models

The two vehicles simulated are a 1994 Chevrolet C-1500 pickup truck (Figure 1), developed by the National Crash Analysis Center [1], and a 1997 Ford Crown Victoria (Figure 2), developed by SRI International [2] and modified by Applied Research Associates, Inc. [3]. The initial velocity of each vehicle in each case is 50 kph. The models are using LS-DYNA finite element software. Characteristics of the two models are given in Table 1.

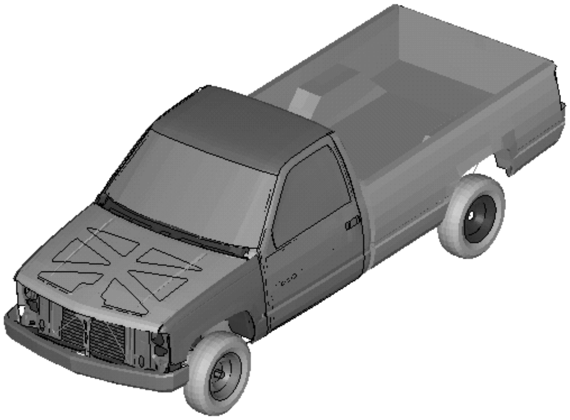

Figure 1. Chevrolet C-1500 finite element model.

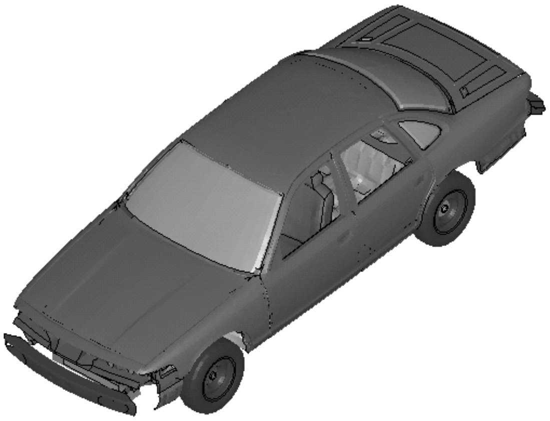

Figure 2. Ford Crown Victoria finite element model.

Table 1.
Finite Element Model Characteristics

	Chevrolet C-1500	Ford Crown Victoria
Nodes	61,403	129,957
Elements	54,054	119,231
Length	5,457 mm	5,334 mm
Width	1,980 mm	1,960 mm
Mass	1,720 kg	1,800 kg

A total of 20 simulations are run on an SGI computer using four processors. Time steps in the simulation range from 0.163 to 0.765 microseconds (μs). In nine cases, the time step was variable. As some elements experience extensive deformation, the time step can drop significantly late in the computation. This can result in the tail end of the simulation requiring a great deal of computational resources. In the other 11 cases, the time step is held fixed at 0.510 μs. LS-DYNA mass scaling was enabled, allowing the software to add mass to critical elements to bolster the maximum allowable time step for those elements. In no case does the mass of the model increase by more than 0.06%.

Typical simulations run for 120 milliseconds (msec) of the crash event, although individual cases vary from 118 msec to 150 msec. Run times range from 71 to 157 hours for a 120 msec case.

Cases

Two series of vehicle-to-vehicle crash simulations are considered:

Angled Impact The first series consists of angled impact simulations. The angles considered are 0°, ±5°, ±10°, ±15°, ±20°, ±30°, ±40°, and ±50°. Both positive and negative angles are considered because the vehicle models are not laterally symmetric. The vehicles are fully engaged in each case; that is, their centerlines intersect at a point spaced equally from the two front bumpers. A typical case is shown in Figure 3.

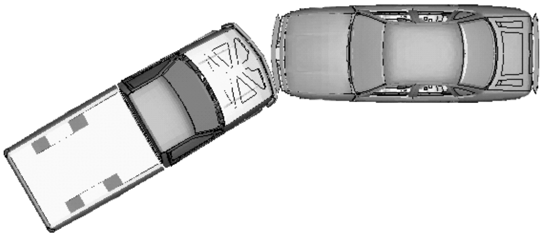

Figure 3. Top view of typical angled impact case (+30° as observed by the C-1500, -30° as observed by the Crown Victoria).

Offset Impact The second series considers the vehicles travelling in parallel but opposite directions. Their centerlines are offset to each driver's left (the negative direction as defined by NHTSA [4]). The overlap lengths considered are 20%, 40%, 60%, 80%, 90%, and 100% of the average width of the two vehicles. A typical case is shown in Figure 4.

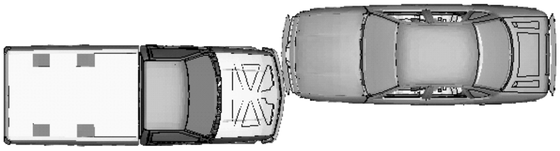

Figure 4. Top view of typical offset impact case.

Vehicle-to-Vehicle Results

Kinematics The vehicles' motions are found to be consistent with conservation of momentum. In angled crashes, both vehicles experience rotation that starts with the initial bumper contact. The contact force provides a moment that briefly starts the vehicles turning toward each other. In less than 50 msec, however, the contact forces from the deformation of the engine compartments have provided sufficient moment to rotate the vehicles away from each other

In the offset impact cases, the misalignment of the forces of impact with the centers of mass causes both vehicles to rotate counter-clockwise.

In order to quantify the kinematics of the vehicles for further analyses, the motion of accelerometers fixed to the cross-member behind the driver's seat is determined. The locations are those of actual accelerometers in crash tests of these vehicles. Accelerometers are depicted as black rectangles in Figures 5 and 6. The motion of these devices describes the overall translation and rotation of the occupant compartment.

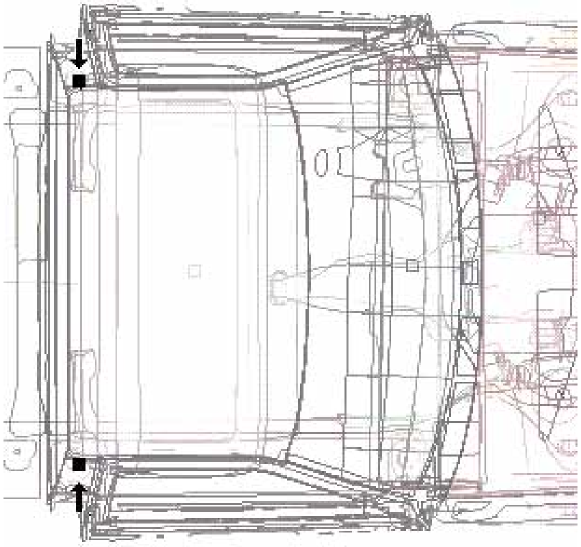

Figure 5. Top view of accelerometer locations behind seats in Chevrolet C-1500 model.

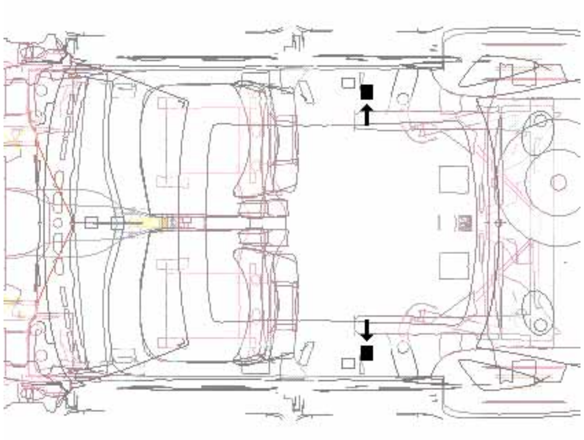

Figure 6. Top view of accelerometer locations behind seats in Ford Crown Victoria model.

Energy The initial kinetic energy is dissipated throughout the crash event. There is some residual final velocity in each simulation. In the more direct crashes (less than 20° angle or an overlap length of more than 50% of the average width), the final kinetic energy is less than 10% of the initial value.

Kinetic energy is dissipated through several mechanisms. It is primarily converted into internal energy of deformed components. Energy is also transformed into potential energy associated with upward displacements and even dissipated by friction with the floor.

Significant energy is associated with the zero energy deformation modes of under-integrated elements ("hourglassing"). Since these elements are more computationally efficient, the LS-DYNA manual [5] recommends their use. The manual also recommends that the hourglass energy be kept below 10% of the internal energy in the model. In some of these simulations, the hourglass energy exceeds these guidelines but most of the energy is restricted to some small brackets in the engine compartments and the solid elements in the brakes of the Crown Victoria. The deformation of these components is not excessive. Hence, the global kinematics of the occupant compartment are reasonable. When the energy from these components is disregarded, the hourglass energy is never more than 12% of the internal energy.

Deformation A typical deformation pattern is shown in Figure 7. The sheet metal panels deform considerably. Much of the internal energy (energy of deformation) is found in the side rails that form the vehicle's frame. The frame rails are designed with some strategic curvature to encourage buckling at advantageous locations. The C-1500's rails tend to buckle near the front bumper, allowing the crushing of components in front of the engine to progress before buckling initiates behind the engine. In the Crown Victoria, the rails buckle and rotate upward. This rotation was observed in the validation of the Crown Victoria model [2] against actual crash tests of a similar model year vehicle [6]. Figure 8 shows the deformed side rails at the t = 150 msec point in the baseline case.

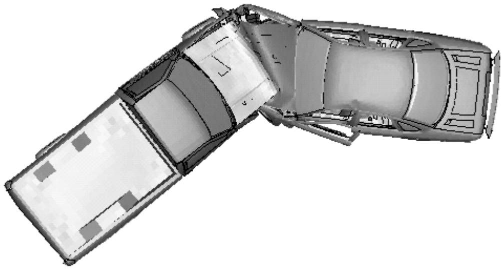

Figure 7. Top view of typical deformation of vehicles in a crash simulation.

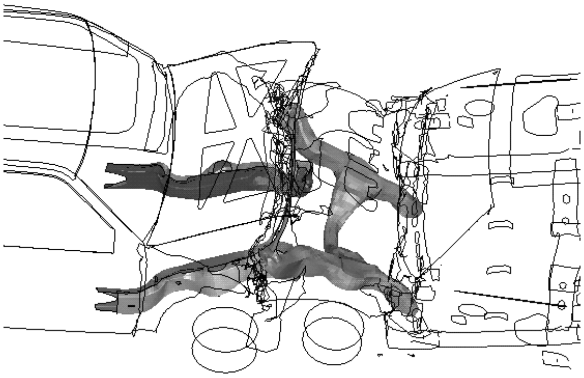

Figure 8. Deformation of vehicle side rails (C-1500, left; Crown Victoria, right) at t = 150 msec in the baseline crash simulation.

For higher angle and higher offset cases, the load, and therefore significant deformation, tended to be restricted to one side rail of each vehicle. Figure 9 shows the final deformation of the rails in an offset case in which the two driver side rails nearly lined up, resulting in extensive deformation of those rails, whereas the passenger side rails were not substantially deformed. In the high angle cases, the frames tended to bend rather than buckle. This bending causes the engine compartments to shear. An example is shown in Figure 10.

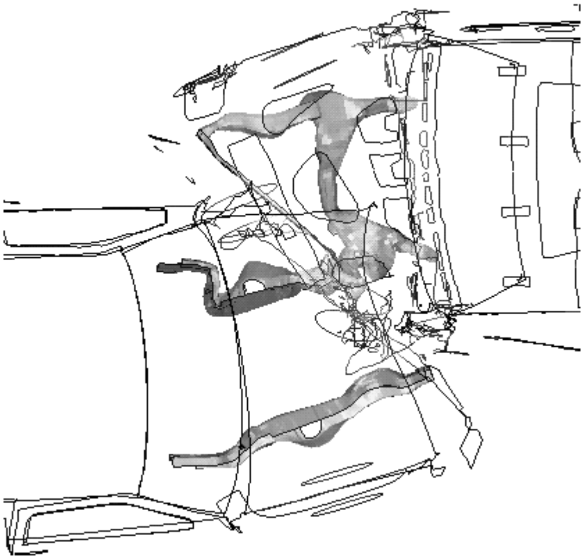

Figure 9. Top view of deformation of vehicle side rails (C-1500, left; Crown Victoria, right) at 120 msec in the offset crash simulation (overlap length = 60% of average width).

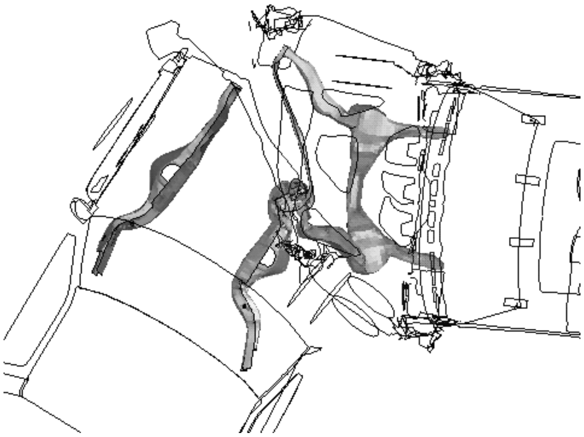

Figure 10. Top view of deformation of vehicle side rails (C-1500, left; Crown Victoria, right) at 120 msec in the offset crash simulation (angle = 50° from C-1500 reference).

INJURY PREDICTIONS FROM LUMPED PARAMETER MODELS

Models

A generic MADYMO lumped parameter model of a vehicle interior and occupant is used to calculate the numerical value of two injury predictors [7]. Verified MADYMO occupant compartment models do not exist for either vehicle. Thus, the driver and passenger models used are based on a 1998 Ford Explorer developed at the Volpe Center [8]. The simulation uses the simple MADYMO seat belts in lieu of the more complicated finite element belt models. No fuse belts or belt slack is modeled. The occupants are modeled with representations of Hybrid III anthropomorphic dummies supplied with the MADYMO software. The vehicle models are shown after airbag deployment in Figures 11 and 12.

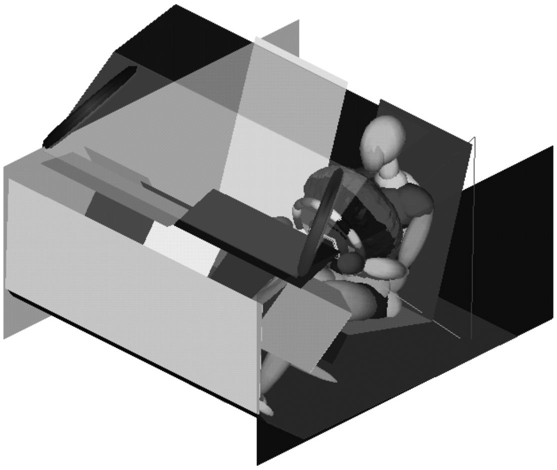

Figure 11. MADYMO model of driver in generic occupant compartment after airbag deployment.

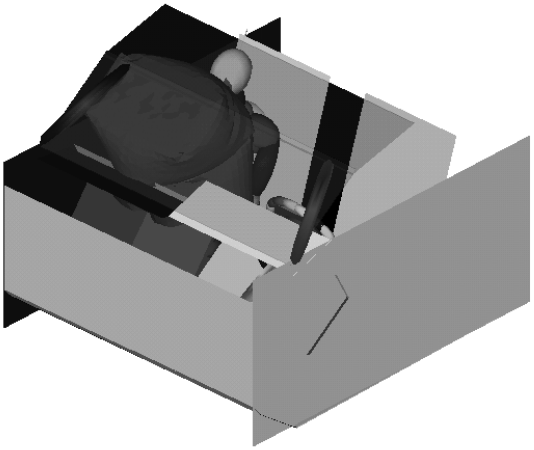

Figure 12. MADYMO model of passenger in generic occupant compartment after airbag deployment.

Input to the lumped parameter simulations consists of the longitudinal and transverse displacement of the vehicle as well as the vehicle rotation as calculated in the original vehicle coordinates from the finite element simulation.

Injury Criteria

The 3-msec chest acceleration clip and the 36-msec window head injury criterion (HIC) are determined for the dummy in each passenger and driver simulation. Each finite element model generated four lumped parameter simulations - one for each occupant of both vehicles. Other injury predictors, such as femur loads, may be more sensitive to details of occupant compartment intrusion. Intrusion is not modeled in the lumped parameter models beyond a generic intrusion experienced in the baseline Explorer case. For this reason, other injury parameters are not reported.

Figures 13 and 14 show the chest acceleration results for the angled impact and offset impact cases, respectively. The values of chest acceleration parameters show lower values at higher impact angle and shorter overlap lengths. The decreases probably result from the amount of time over which deceleration took place and the amount of kinetic energy that was dissipated. That is, the higher angle or greater offset cases experience less vehicle deceleration, allowing the airbag and seatbelts to decelerate the occupants more gradually. There also seems to be an effect of the direction of rotation for the two occupants. For example, a clockwise rotation (as seen from above) tends to align the shoulder belt better with the relative motion of the passenger, and therefore seemed to slightly improve the chest acceleration parameter of the passenger with the opposite effect on the driver. Within the variability of the analysis, this effect manifests in Figures 13 and 14 as a decrease in the distance between the driver (solid symbol) and passenger (outline symbol) values of chest acceleration as one progresses toward more positive angles or shorter overlap lengths.

Figures 15 and 16 exhibit the HIC results for the angled impact and offset impact cases, respectively. Some of the HIC values computed at large angles or small overlaps are lower than might be experienced in an actual vehicle-to-vehicle test because the large vehicle rotation and increased residual kinetic energy could result in a severe head impact with the door. An example of this phenomenon is shown for a driver in Figure 17. The generic MADYMO occupant compartment model does not include any details of the door structure. Inclusion of those features could significantly affect HIC results. Furthermore, the time windows in which some HIC values are calculated extend to the end of the simulation. In these cases, the HIC values are shown as a dotted line in the figure in order to indicate the trend of HIC values without door impact and to serve as a lower bound.

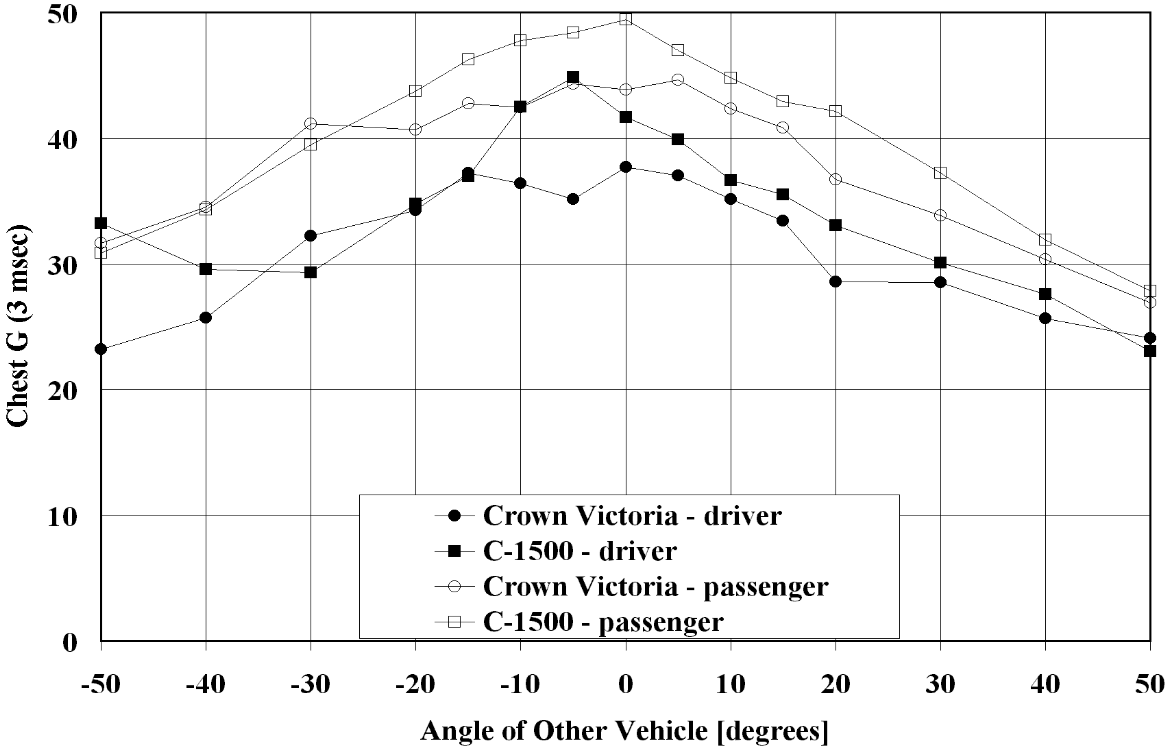

Figure 13. Three-millisecond clip chest acceleration results for angled impact cases.

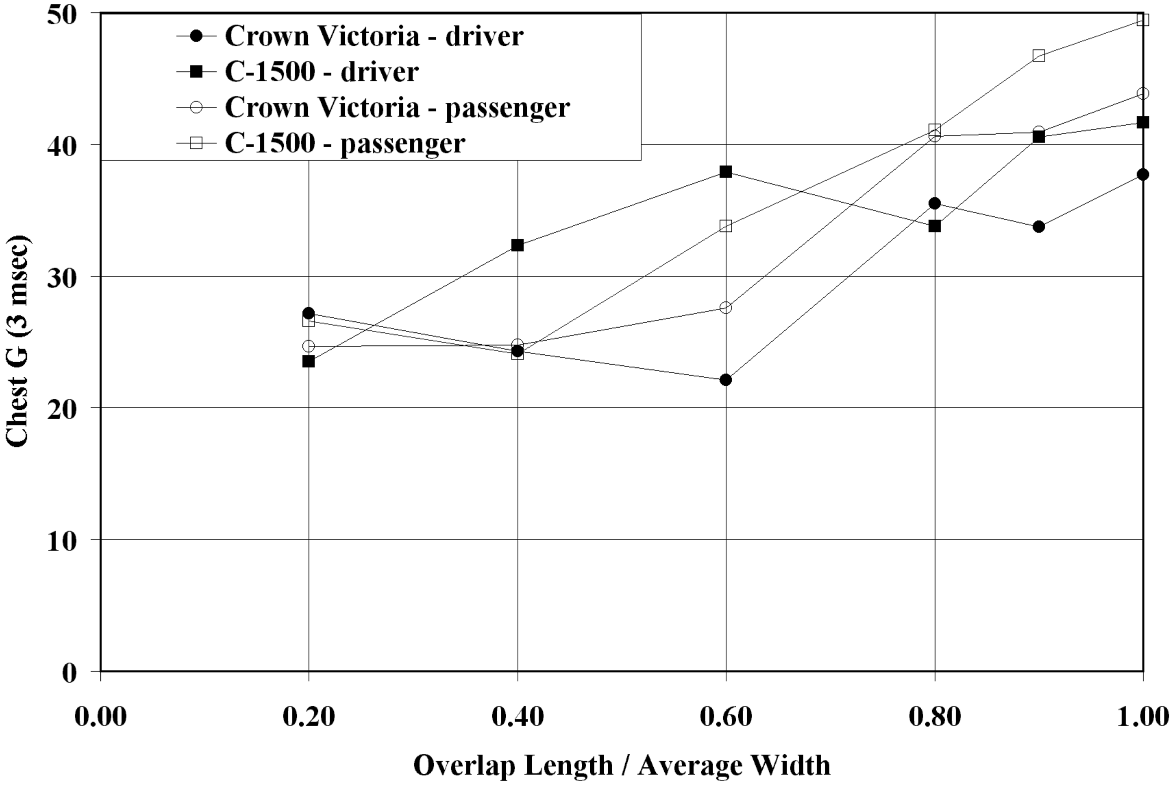

Figure 14. Three-millisecond clip chest acceleration results for offset impact cases.

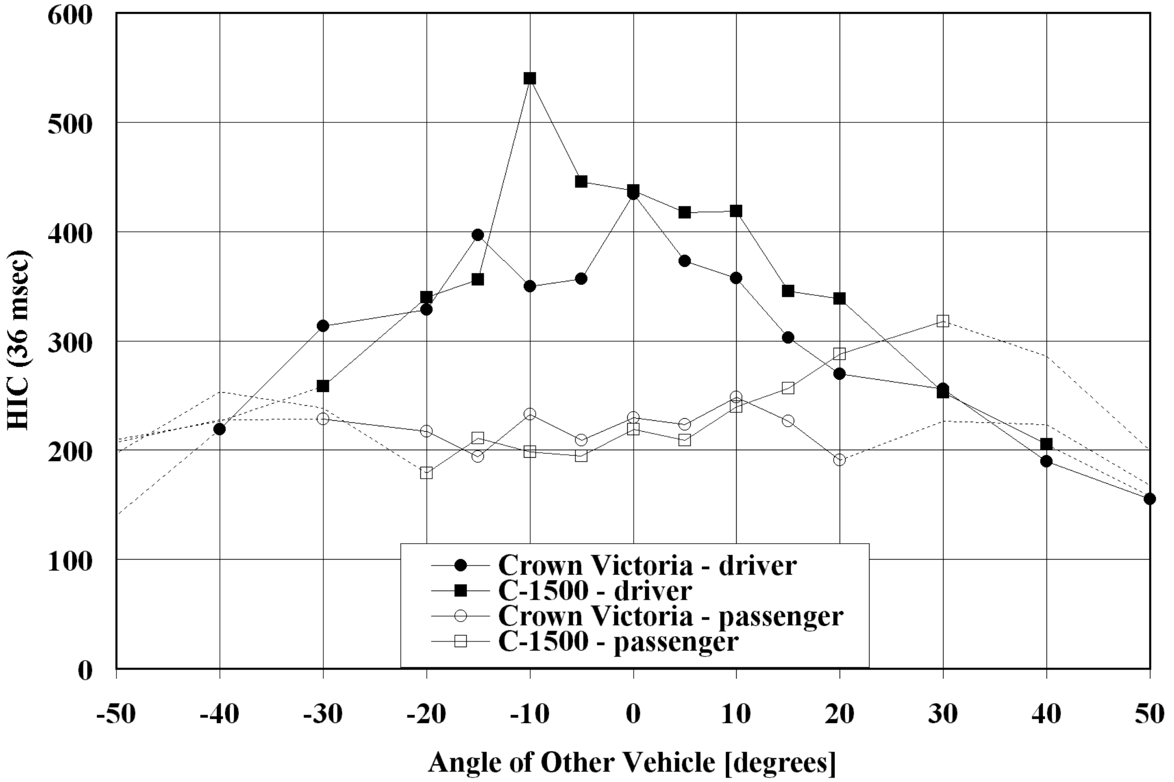

Figure 15. Head Injury Criterion (36-msec window) results for angled impact cases.

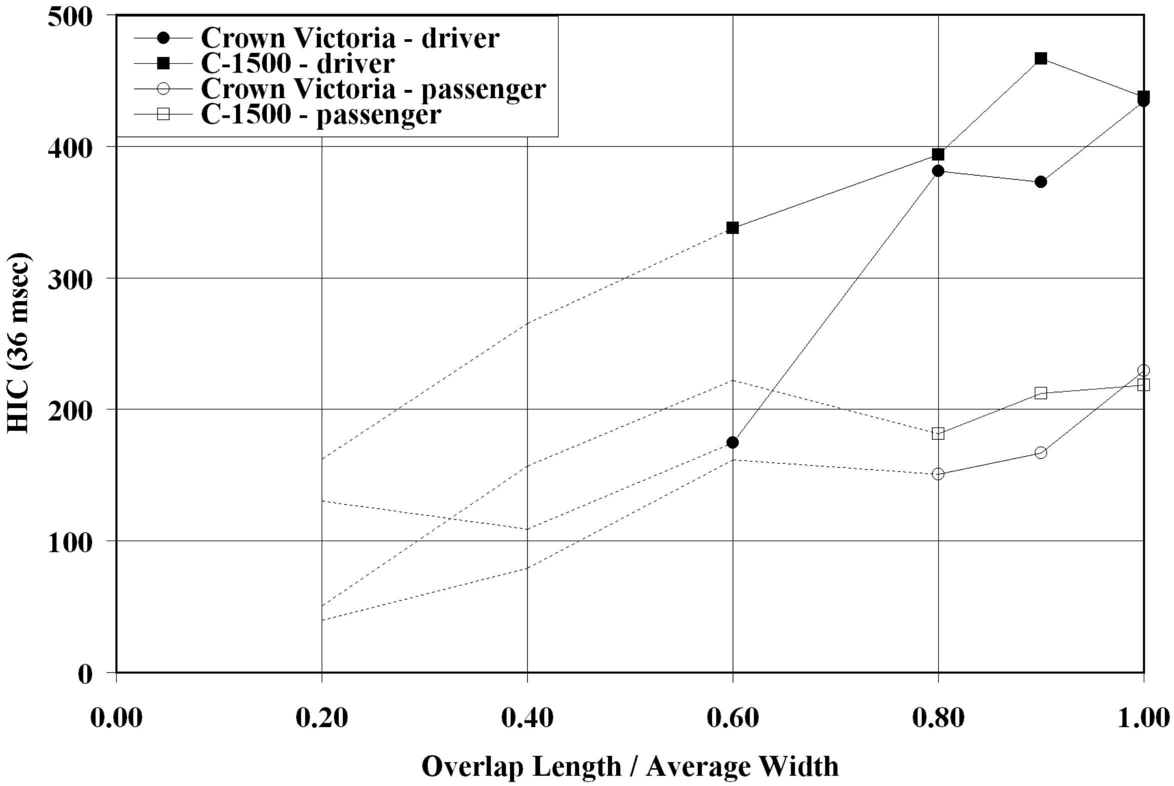

Figure 16. Head Injury Criterion (36-msec window) results for offset impact cases.

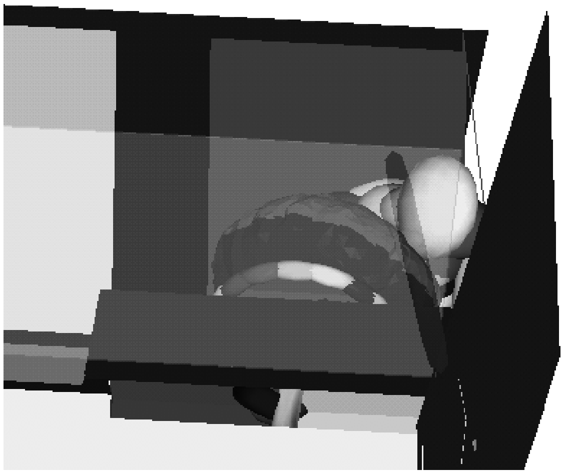

Figure 17. Head impact with driver's door after large vehicle rotation.

DISCUSSION OF GENERAL TRENDS

Notwithstanding the possibility of impact between the head and the door, HIC values decrease with decreasing overlap length and increasing angle of impact. Much of the variability in the figures likely results from effects of details of the load paths in the vehicle front end that are created and destroyed during the crash event, as well as from the details of the dummy's contact with the occupant compartment interior.

There is an indication of a potentially important effect at small angles or offsets. For example, in all four data sets plotted in Figure 15, there is a point at 10° to 15° on either side of the full frontal case that seems to exist above the trend. In such cases, there is a small amount of vehicle rotation. Thus, there is little change in the relative velocity of the head or chest during early phases of the crash event, but there is a potentially significant effect on the efficiency of the airbag if its center is misaligned with the motion of the occupant.

These trends are consistent with results of crash tests reported by Ragland and Dalrymple [9]. They described vehicle-to-vehicle collisions between 1989 Toyota Celicas and 1989 Hyundai Excels at 90% overlap length and 63.5% overlap length as well as vehicle-to-full barrier and vehicle-to-half barrier tests of these vehicles. For both drivers and one passenger, the worst head and chest injury parameters occurred in the 90% overlap case.

The results indicate that the driver tends to have higher HIC values. This could be an effect of the shorter stopping distance in front of the driver (as a result of the steering wheel) and the necessarily smaller airbag and higher airbag loads. The large passenger airbag might also explain the narrower range of HIC values for passengers. Conversely, the passenger has higher chest acceleration values, at least for the seatbelt models in use in this analysis. It is possible that the more gentle deployment of the airbag, which reduces accelerations of the head, reduces any synergy of the airbag working with the seatbelt to lower peak chest acceleration.

In offset impacts, any benefits a driver receives from a favorable rotation of the occupant compartment may be neutralized by the relative severity of the impact. There is also the potential for other injuries as occupant compartment intrusion concentrated on that side. The same might also be inferred for passengers in offset crashes concentrated on the passenger side.

CONCLUSIONS

Differences in fully engaged impact angle or overlap length do have significant effects on damage, deformation, and occupant injury in vehicle-to-vehicle crashes between light trucks and automobiles. In general, larger angles or shorter overlap lengths slow down the dissipation of energy and therefore reduce the severity of the impact. There is a competing effect, however, in that vehicle rotation can cause the alignment of the occupant with the seat belt and airbag to be adversely affected. The worst case scenario may be small offsets or angles that do little to reduce the severity of the vehicle acceleration while significantly affecting the orientation of the safety systems.

Large vehicle rotation cases were not simulated to the point at which potential high-energy head impacts with a door were evaluated. Because of the opportunity for head-door contact, it appears that in an angled impact case the occupant closer to the point of impact will have increased chance of injury. The occupant opposite the impact location moves more toward the centerline of the occupant compartment, and will therefore not hit a door. Furthermore, the seat belt lines of force more directly oppose the relative motion of that occupant. This provides more effective deceleration with less moment on the torso.

In offset impacts, it is advantageous to be on the side away from the center of the impact. This is likely to be true despite any benefit the other occupant might receive from a favorable rotation of the vehicle.

In the computational model used herein, drivers tend to have higher HIC values while passengers tend to have higher chest acceleration. These results seem to be effects of the size and location of the airbags.

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